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Fine-Grained Soil Liquefaction Effects in Christchurch, New Zealand

By

Christine Zahra Beyzaei

A dissertation submitted in partial satisfaction of the

requirements for the degree of

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in

Engineering – Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Jonathan D. Bray, Chair

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Abstract

Fine-Grained Soil Liquefaction Effects in Christchurch, New Zealand

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Doctor of Philosophy in Engineering – Civil and Environmental Engineering

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Professor Jonathan D. Bray, Chair

Liquefaction damage from the 2010-2011 Canterbury earthquake sequence devastated parts of Christchurch, New Zealand. There were many sites where state-of-practice liquefaction assessment procedures indicated liquefaction would be expected to occur, and surface manifestations of liquefaction were observed. However, there were also numerous sites, which were predominantly silty soil sites, where state-of-practice liquefaction assessment procedures indicated that liquefaction would be expected to occur, but no surface manifestations of liquefaction were observed. This discrepancy between state-of-practice liquefaction assessments and post-earthquake liquefaction observations led to the development of the research program presented in this dissertation. Several silty soil sites were selected for investigation to further our understanding of fine-grained soil liquefaction response and to evaluate potential limitations in the current state-of-practice liquefaction assessment procedures, which are based primarily on case histories and laboratory testing of sands. This dissertation investigates the liquefaction response of silty soil sites through no-liquefaction case histories from the Canterbury earthquake sequence, evaluating depositional environment effects on observed liquefaction performance, site characterization of silty soil deposits, and laboratory testing to characterize element-scale cyclic response.

Depositional environment effects are evaluated through regional CPT-based analyses and site-specific comparisons. Stratified silty soil swamp deposits are shown to have mitigating effects on the manifestation of liquefaction beyond what can be captured by simplified liquefaction assessment procedures in Christchurch. Differing surficial geology and depositional environments are found through examining historical documents to explain in part the limitations of current liquefaction assessment procedures in the swamps of southwest Christchurch, which contain stratified silt/sand deposits or thick silt layers. Consideration of depositional environment distinguishes between liquefaction performances that could not be differentiated through the CPT-based assessment alone. CPT resolution is not sufficient to capture the thin layering at these stratified sites, and the simplified liquefaction assessment methods do not take into account the effects of the stratification on pore water pressure movement within a soil profile. Continuous sampling and careful logging of high-quality samples provides important insights on in-situ stratification at these silty soil swamp sites, discerning differences in stratigraphy resulting from differences in depositional environment.

Site investigation techniques are evaluated at the silty soil case history sites to discern their capability to characterize thin layers and groundwater table fluctuation, two potential causes for the discrepancies between state-of-practice liquefaction assessments and post-earthquake liquefaction observations. CPT, mini-CPT, sonic borings, and high-quality sampling are critiqued in terms of their ability to capture thin layer stratigraphy, which is of importance for liquefaction assessment. Piezometers, sonic borings, high-quality sampling, crosshole testing, and regional groundwater maps are evaluated to assess their ability to capture groundwater table fluctuation. CPT, mini-CPT, and conventional sonic borings offer important information for site characterization, but they do not capture full details of thin layering at silty soil sites. Detailed logging of high-quality samples captures the actual in-situ layering that helps explain limitations of simplified liquefaction assessment procedures. Use of multiple groundwater measurement methods more fully illuminate fluctuating groundwater conditions. Subsurface investigation programs should utilize tools that characterize features impacting liquefaction potential in adequate detail for the intended engineering purpose. Use of multiple, complementary investigation techniques provides the most robust assessment.

A field investigation and advanced laboratory testing program was conducted in Christchurch. High-quality samples were obtained using a Dames & Moore hydraulic fixed-piston thin-walled sampler for cyclic triaxial testing to characterize the liquefaction response of silty soils at the no-liquefaction sites in southwest Christchurch. These natural silty soil specimens contained heterogeneity and variability that should be considered and is difficult, if not impossible, to replicated with laboratory-prepared specimens. Test results for stress-strain response and axial strain accumulation indicate a nuanced range of transitional responses for these intermediate soils. Post-liquefaction reconsolidation testing shows clear differences in specimen response, ranging from "sand-like" immediate reconsolidation to time-dependent reconsolidation. Simplified liquefaction assessment procedures estimate significant liquefaction at these case history sites and yet no liquefaction manifestations were observed during the Canterbury earthquake sequence. Laboratory estimates of cyclic resistance (CRR) are consistent with estimates from the simplified procedures, and both estimates of CRR are well below simplified procedure estimates of seismic demand (CSR). Depositional characteristics such as thin-layering of fine sand and silt may be why manifestations of liquefaction were not observed at these sites. Post-liquefaction reconsolidation testing provides insight that water and ejecta may not accumulate in these stratified silty soils as they would accumulate in thick deposits of liquefiable clean sands. Additional mitigating factors may also contribute to the discrepancy between simplified procedure estimates of liquefaction and the lack of liquefaction observed at these sites. The interaction of several factors contributing to observed liquefaction response at these silty soil sites indicates that in-situ "system" response should be considered and that further research on silty soils is warranted.

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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

Liquefaction research has been motivated largely by understanding post-earthquake observations of liquefaction damage. Well-documented case histories serve as the primary basis for understanding liquefaction response, with laboratory testing used to explore cyclic response characteristics that cannot be isolated for examination in field case histories and with numerical analyses being used to generalize and extend understanding to support analysis and design. Early research on liquefaction focused primarily on clean sand case histories with surface manifestations of liquefaction that resulted in severe damage. The profession recognized the need for simplified liquefaction assessment methods that could be implemented by practicing engineers to assess and design for this geotechnical hazard. Empirically-based simplified methods were developed (i.e., Seed & Idriss 1971), underpinned by laboratory-based research and principles of mechanics. The earliest methods were based on relatively few case histories. As more earthquakes were observed and documented, these case histories were added to the databases used to develop the simplified methods, and the methods were refined. Laboratory testing investigated aspects of liquefaction response that could not be understood fully from field observations (e.g., Ishihara 1985). Several decades of liquefaction research have resulted in a general consensus on simplified methods for liquefaction assessment (e.g., Youd et al. 2001, Seed et al. 2003, Boulanger & Idriss 2016). However, the case history database and body of laboratory testing supporting the development of these methods have continued to focus primarily on sandy soils, which are the predominant soil type in the liquefaction case histories database.

Recent earthquakes have highlighted the need for further understanding the liquefaction response of fine-grained soils that may be susceptible to liquefaction. The case histories from Adapazari during the 1999 Kocaeli, Turkey earthquake demonstrated that fine-grained soils can liquefy with severe consequences (Bray et al. 2004, Bray & Sancio 2006). A framework arising from recent observations is that of separating soils into “sand-like” and “clay-like” behavior (Idriss & Boulanger 2008). With the cyclic response of sands relatively well-established, the profession has moved toward further understanding the cyclic response of fine-grained (“silty”) soils (e.g., Thevanayagam & Martin 2002, Sancio et al. 2002, Wijewickreme & Sanin 2004, Bray & Sancio 2006, Boulanger & Idriss 2006, Donahue et al. 2007). The term “silty soils” represents a broad range of soil types and in-situ deposits, encompassing silty sand, sandy silt, nonplastic silt, and low-to-moderate plasticity clayey silt and comprising a range of transitional liquefaction response between the sand-like and clay-like designations. Liquefaction response of these silty soils depends much on the soil characteristics (e.g., fines content, plasticity, and mineralogy), method of deposition or specimen preparation, and within-specimen or deposit heterogeneities (e.g., layering, organic matter). Research is needed on both field performance and laboratory-based characterization to advance the state of knowledge on liquefaction of silty soils. The primary focus of this dissertation is to further understanding on the cyclic response of fine-grained (silty) soils through both field performance observations and laboratory testing.

The case histories used to develop the simplified procedures for evaluating liquefaction triggering categorized sites as “liquefaction” or “no-liquefaction” sites based on post-earthquake observations of surface manifestations of liquefaction, implicitly pairing triggering and manifestations. Current state-of-practice simplified methods address primarily liquefaction triggering; several additional methods assess the consequences of liquefaction, such as the effects

of volumetric strain and vertical settlements (e.g., Ishihara & Yoshimine 1992, Tokimatsu & Seed 1987, Zhang et al. 2002). Post-earthquake field investigations were understandably biased toward observations of surface manifestations and liquefaction damage. While this responded to the immediate need to understand the most prevalent liquefaction cases and to develop practical design procedures, it resulted in underrepresentation of no-liquefaction cases in the case history dataset.

The recently published National Academy of Engineering report identified several areas of liquefaction assessment in need of further research (NASEM 2016). These include, as described in the preceding paragraphs: the continued evaluation of the simplified methods through new case histories, the characterization of silty soil cyclic response, and the development of no-liquefaction case histories. This dissertation presents research motivated by these needs, through evaluation of case histories from the 2010-2011 Canterbury earthquake sequence.

Liquefaction damage from the 2010-2011 Canterbury earthquake sequence devastated Christchurch, New Zealand. Multiple earthquake events triggered widespread liquefaction throughout over 30% of the built environment, affecting buildings, infrastructure networks, and critical lifeline systems. Extensive and well-documented post-earthquake field observations from the Canterbury earthquake sequence (e.g., Green & Cubrinovski 2010, Cubrinovski et al. 2011, New Zealand Geotechnical Database) provide an unprecedented opportunity to evaluate the efficacy of current state-of-practice liquefaction assessment methodologies. Research following the Canterbury earthquake sequence has found state-of-practice simplified liquefaction assessment methods work well across much of Christchurch (e.g., van Ballegooy et al. 2014, Russell & van Ballegooy 2015, Maurer et al. 2015). However, there are important cases where evidence of liquefaction was absent at many sites, despite state-of-practice methods indicating liquefaction was expected to occur (i.e., no-liquefaction “false positive” sites). These cases were predominantly concentrated in the southwest part of Christchurch, an area known among local engineers for its silty soil conditions. This discrepancy between post-earthquake field observations and state-of-practice liquefaction estimations led to development of the research program presented herein.

To investigate thoroughly why the state-of-practice liquefaction assessment methods, which implicitly pair triggering and manifestations, may have over-estimated the occurrence of liquefaction at silty soil sites in southwestern Christchurch, a comprehensive study called the “silty soils project” was undertaken by researchers at the Univ. of Canterbury, Univ. of California, Berkeley, the Univ. of Texas at Austin, and Tonkin + Taylor, Ltd. This study consisted of field testing and subsurface investigations, advanced laboratory testing of high-quality (“undisturbed”) specimens, and numerical analysis to investigate the liquefaction resistance of the silty soil deposits. The research presented in this dissertation was conducted as part of the silty soils project and through collaborations on related projects. The primary objectives of this doctoral research are to characterize the cyclic resistance of the selected Christchurch silty soils, to compare laboratory data with state-of-practice methods, and to assess other factors that may limit the liquefaction susceptibility of the silty soils or surface manifestations of liquefaction occurring at-depth.

Recognizing that the silty soils considered in this research differ from the majority of the empirical case-history database, this dissertation first evaluates the depositional environment in the southwest part of Christchurch which formed the subsurface conditions at the case history sites. Depositional environment effects on liquefaction observations are assessed at both the regional and site-specific level. To translate depositional environment effects into quantifiable data for advancing research and practical applications, site investigation techniques are considered in the context of capturing detailed features arising from depositional environment differences that may affect liquefaction potential at a site (e.g., thin layers and groundwater table fluctuation). Current

site investigation practices for liquefaction assessment were developed for “typical” liquefaction cases (i.e., sandy sites). For soil deposits that differ from the majority of the case history database, alternative site investigation techniques may be needed to characterize relevant features. The following chapter of this dissertation thus evaluates conventional and alternative investigation techniques for site characterization at silty soil sites. Advanced laboratory testing then is presented to characterize the cyclic resistance of the silty soils at the element scale. Cyclic triaxial testing and post-liquefaction reconsolidation testing lend insight into the cyclic response of the silty soils that can be used to understand their response within the sand-like vs. clay-like response framework and provide the basis for extrapolating laboratory behavior to field response through the post-earthquake field observations and underlying geomechanics. Through consideration of depositional environment, site characterization, and laboratory testing, this research contributes to advancing the state of knowledge on liquefaction response of silty soils, evaluates the simplified methods with new case histories, and develops no-liquefaction case histories at silty soil sites.

1.2 ORGANIZATION

This dissertation is organized around three primary research topics: (i) depositional environment effects, (ii) site characterization to capture thin-layer stratigraphy and groundwater conditions, and (iii) field sampling and laboratory testing to evaluate cyclic resistance of silty soils. The following chapters explore these topics in terms of how they may affect liquefaction manifestation at a site.

- Chapter 2 presents regional analysis and site-specific data to examine the effects of depositional environment on post-earthquake liquefaction observations from the Canterbury earthquake sequence. Stratified silt/sand and silt-dominant swamp deposits are shown to have a mitigating effect on liquefaction potential estimated using simplified methods. Depositional environment has not been explicitly considered in the development of the empirical liquefaction assessment methods currently in use. The analysis presented in this chapter takes a more quantitative approach and provides evidence and motivation for the incorporation of depositional environment in the simplified methods.
- Chapter 3 considers subsurface characterization using conventional and alternative investigation techniques, aimed at improved characterization of features affecting liquefaction potential at a site. This work considers site investigations in the context of liquefaction assessment and compares how well different investigation techniques capture features such as thin-layer stratigraphy and groundwater table fluctuation, which are identified as possible mitigating factors for liquefaction potential or manifestation at a site.
- Chapter 4 characterizes liquefaction response of silty soils through cyclic triaxial testing of high-quality specimens obtained at silty soil case history sites in Christchurch, New Zealand. Laboratory test data are presented to characterize the cyclic response of silty soils ranging from silty sands to low-plasticity silts. Post-liquefaction reconsolidation response is also presented. In addition to the material presented in Chapter 4, Appendix C provides further data and insights regarding the cyclic triaxial testing of high-quality (“undisturbed”) specimens. Appendix D presents a subsequent steady-state testing program conducted on reconstituted specimens using the soil obtained from the high-quality specimens.
- Chapter 5 summarizes the presented research and provides conclusions with a focus on key insights and recommendations for future research.

CHAPTER 2: DEPOSITIONAL ENVIRONMENT EFFECTS ON OBSERVED LIQUEFACTION PERFORMANCE IN SILT SWAMPS DURING THE CANTERBURY EARTHQUAKE SEQUENCE

The contents of this chapter are primarily from a journal article submitted to Soil Dynamics and Earthquake Engineering by Beyzaei, C.Z., Bray, J.D., van Ballegooy, S., Cubrinovski, M., and Bastin, S. entitled: “Depositional Environment Effects on Observed Liquefaction Performance in Silt Swamps during the Canterbury Earthquake Sequence,” which was under review when this dissertation was submitted.

2.1 INTRODUCTION

Liquefaction from the 2010-2011 Canterbury earthquake sequence damaged much of the built environment in Christchurch, New Zealand. State-of-practice (SOP) liquefaction triggering procedures have been shown to work well across much of Christchurch (van Ballegooy et al. 2014). However, there are important cases where liquefaction assessment methods indicate that there should have been severe liquefaction-induced ground failure, yet none was observed (i.e., “false-positive” sites) (e.g., van Ballegooy et al. 2014, McGann et al. 2015, Russell & van Ballegooy 2015, Maurer et al. 2015). Post-earthquake reconnaissance investigators noted surface manifestations of liquefaction damage were not frequently observed in the northwestern and southwestern suburbs of Christchurch. The Liquefaction Severity Number (LSN) captures much of the observed liquefaction-induced ground failure across the affected areas of Christchurch, but it over-estimates liquefaction damage in the southwest part of the city (Figure 2.1). The southwestern area of Christchurch is known among local engineers for its silty soil conditions.

To investigate thoroughly why SOP liquefaction assessment procedures, which implicitly pair triggering and manifestations, may have over-estimated the occurrence of liquefaction at silty soil sites in the southwestern part of Christchurch, a comprehensive study called the “silty soils project” was undertaken by researchers at the Univ. of Canterbury, Univ. of California, Berkeley, the Univ. of Texas at Austin, and Tonkin + Taylor, Ltd. (Beyzaei et al. 2015, Stringer et al. 2015, UC Berkeley & Univ. of Canterbury 2016). They conducted field testing, laboratory testing, and numerical analyses to investigate the liquefaction resistance of silty soil deposits. The focus of efforts of that study were to explore potential factors such as: stratification of interbedded sandy and silty soils, soil fabric, particle angularity, groundwater table fluctuations that produce a thicker non-liquefiable crust of unsaturated soil, and uniform particle size distribution of fine sands and coarse silts where slight shifts can significantly affect the estimated fines content and resulting liquefaction triggering assessment. Additionally, it is possible that some soil layers at these sites did liquefy, but surface manifestations were prevented.

A potentially important overarching factor that was not explored in that study is the role of shallow surficial geology and the differing depositional environments that exist across the Canterbury Plains in which Christchurch was built. Youd & Perkins (1978), among others, identified the critical role of surficial geology on liquefaction susceptibility, and their work serves as the basis for many regional liquefaction susceptibility maps. However, the incorporation of surficial geology and depositional environment effects on liquefaction assessments are not often considered quantitatively on a project-specific basis in engineering practice, especially when there is an abundance of geotechnical investigation data available. The goal of this focused study is to

provide regional and site-specific case history data that may lead to the development of procedures for directly incorporating depositional environment in liquefaction assessments. In this paper, case histories that illustrate the subsurface conditions where liquefaction manifestations were over-estimated in the southwestern part of Christchurch are discussed with a focus on depositional environment and its role in liquefaction. Differing depositional environments throughout southwest Christchurch are investigated and compared with greater Christchurch through regional assessment. Key factors are evaluated in the context of depositional environment, moving from more qualitative to quantitative observations. Implications for practice and paths forward for future research are also presented.

2.2 DEPOSITIONAL ENVIRONMENT AND SHALLOW SUBSURFACE CONDITIONS

2.2.1 Importance of Depositional Environment

The potential importance of depositional environment in liquefaction assessments has been recognized previously. Youd & Perkins (1978) enumerate several key factors affecting liquefaction-induced ground failure susceptibility. They explicitly include sedimentation process, age of deposition, and geologic history. Sedimentary deposits are then qualitatively characterized by their general distribution of cohesionless sediments, and assigned likelihoods of liquefaction susceptibility based on empirical observations. Seed (1979) cites the influences of “*method of placement or soil structure*” and “*age since deposition or placement*” as factors that need to be considered in selecting design values for liquefaction assessment. Liquefaction research has focused primarily on cohesionless free-draining soil deposits, but Seed (1979) notes that even “*a single layer of relatively impervious fine sand or silt in such a deposit would completely invalidate the results of pore pressure dissipation computations for vertical flow.*” This detail is especially relevant for the layered Christchurch swamp deposits composed of silty fine sand, silt, and organic silt that are discussed in this paper.

While consideration of surficial geology is often included during the early stages of investigation, it tends to recede into the background as in-situ and laboratory test data are obtained. Youd & Perkins (1978) focus on data available from field observations, but Seed (1979) and Idriss & Boulanger (2008) also note the important effects of depositional method, fabric, and environmental factors on laboratory testing. For example, laboratory testing by Ladd (1974, 1977) and Mulilis et al. (1977) clearly showed that the effects of fabric can vary the cyclic resistance ratio by almost a factor of two. To understand the true in-situ characteristics of a soil deposit, Seed (1979) recommends obtaining the “*best possible undisturbed samples*” and using considerable judgement to interpret how the characteristics of those samples will affect in-situ liquefaction behavior of the deposit.

2.2.2 Christchurch Overview and Geologic Formation Processes

Christchurch is located on the east coast of the South Island of New Zealand, in a complex geologic and geomorphic environment with dominant influences from alluvial and coastal depositional processes (Figure 2.2). The city is primarily situated upon the low-relief and low-elevation alluvial outwash plain of the braided Waimakariri River, which flows eastward from the Southern Alps to the Pacific Ocean. At its southern edge, greater Christchurch is bound by the Port

Hills of Banks Peninsula, which comprises the eroded remnants of a Miocene volcanic complex (Brown & Weeber 1992).

The central and eastern areas of Christchurch are predominantly underlain by alluvial sands, silts, and drained peat swamps, which are interbedded with estuarine dune and foreshore sand to silt. The western suburbs are underlain by alluvial sands, silts, and gravels (Brown & Weeber 1992). Interbedded estuarine, dune and foreshore sands were deposited by shoreline progradation and marine regression following the mid-Holocene high-stand. Shorelines reached ~3 km west of the present central city and ~10 km inland from the modern coastline at ~6,500 years before present (Brown & Weeber 1992). Alluvial sands, silts, and gravels were initially deposited by the Waimakariri River, which regularly avulsed across the region prior to European settlement. These sediments have subsequently been reworked and redeposited by meandering rivers and streams which also flooded and avulsed across the area (Brown & Weeber 1992, Cowie 1957). Two main meandering rivers are present within the city: the Avon River which runs eastward through the Central Business District (CBD) and coastal neighborhoods, and the Heathcote River which runs eastward through the southern suburbs of the city before reaching the coast. The co-evolution of the floodplain and coastal landscapes within central and eastern Christchurch resulted in significant spatial heterogeneity within the subsurface sediments (Brown & Weeber 1992).

The alluvial sediments west of the CBD also vary spatially as a result of the avulsion of the Waimakariri River across the alluvial plain, and subsequent re-working by the Avon and Heathcote rivers. The braided Waimakariri River generally consists of a series of coalescing channels comprised predominantly of channelized gravels and sands, which are separated by gravel and sand bars. In comparison, the meandering Avon and Heathcote rivers comprise single sinuous channels comprised largely of fine sands. The alluvial plain proximal to braided and meandering rivers is generally comprised of overbank deposits of fine sand to silt deposited as the river overtops its banks. In the case of the Waimakariri River, it may also form channels containing gravels and sands. Back-swamps comprised of sand, silt, and peat generally form distal to the river where standing water remains following flood events and may be vegetated (Fryirs & Brierly 2013). These swamps may contain thinly interbedded sand and silt lenses, with the silt layers likely to thicken and sands layers thinning with increasing distance from the river. Although much of Christchurch is underlain by interspersed pockets of swamp-like deposits, several larger swamp zones, highlighted in Figure 2.3 and outlined in Figures 2.1 and 2.4, have formed in low-lying areas distal to the river and are characteristic silt-dominant back-swamp deposits comprised of silt, fine sand, and organics.

2.2.3 Regional Assessment

Due to the complex and varied nature of the depositional settings across Christchurch, similar areas of the city should be considered when assessing liquefaction performance to avoid comparing coastal beach deposits with inland river sand and silt deposits. Accordingly, Christchurch is subdivided into four quadrants centered on the CBD: the southwest (SW), northwest (NW), northeast (NE), and southeast (SE) quadrants. The SW quadrant is located at the base of the Port Hills and characterized by silty and swampy soil deposits. The NW quadrant is located closer to the Waimakariri River than the SW quadrant and is also characterized by silty and swampy soil deposits, but without the depositional effects from the Port Hills. Its swamp deposits contain thicker layers of peat relative to the SW quadrant. Being closer to the current

position of the Waimakariri River, the NW quadrant sediments are also likely to be relatively younger than those in the SW. The NE and SE quadrants contain interlayered coastal and fluvial sediments, and thus differ greatly from the more inland environments of the SW and NW quadrants. The eastern suburbs do not show the liquefaction triggering over-estimation seen in the western suburbs. Their depositional environment produced thicker layers of clean sands, which are largely the basis of current liquefaction assessment methods. This paper focuses primarily on the SW quadrant of Christchurch, which shows the most pervasive liquefaction over-estimation. The NW quadrant is included in the regional assessment as it contains similar soils to the SW quadrant and had similar discrepancies between liquefaction estimations and observations (albeit less dramatic).

Geologic maps and historical maps may be used to discern the shallow geology of Christchurch. The geologic maps currently available for greater Christchurch provide a broad overview of the surficial sediments. They are at a scale too coarse for a detailed evaluation (Brackley 2012). Conversely, the historical maps provide a relatively detailed description of the surficial sediments and vegetation. They can be used in conjunction with the regional geology to interpret shallow subsurface conditions. There are several versions of historical maps available, many of which are based on the “Black Maps,” with slight variations in locations of roads, rivers, streams, and swamps (Wilson 1989; NZGD a,b). These maps often state that they are “for illustrative purposes only” and the roads used as reference points may not precisely align with the roads as they exist today. But by using these maps, which date back to the 1850s, it is possible to discern the Christchurch near-surface ground conditions prior to the city’s development.

Historical maps may additionally be used to interpret spatial variability in the surface manifestation of liquefaction observed during the Canterbury earthquake sequence. For example, an isolated linear liquefaction feature was observed at the northeast corner of the Madras Street and Armagh Street intersection in the CBD, in an area otherwise characterized by minimal to no observations of liquefaction (Zupan 2014). In one of the historical maps, this feature is shown to correspond to a stream channel which was likely buried either naturally or during Christchurch’s development (Figure 2.3, Wilson 1989). This stream channel is not shown on all maps (NZGD a), thus highlighting the importance of reviewing alternative map sources to better understand the overall subsurface environment and to interpret post-earthquake liquefaction field observations. This example shows that the use of historical maps is not only appropriate, but further supports that spatial variability in surficial geology is critically important to understand in a liquefaction assessment.

Figure 2.3 shows a historical map overlay with six silty soil case history sites to be considered, focusing on the SW quadrant that had the greatest over-estimations of liquefaction. Five “no-liquefaction” sites are located in or near swamp regions, while one “liquefaction” site is located far from a swamp region in all directions. Many different surface descriptions are used in these historical maps; in this discussion “swamp regions” or “swamps” refer to large continuous, coherent silty back-swamp zones distal to the river, rather than areas classified as a mix of broken ground, surface water, fern grass, and localized swamp pockets. This is an important distinction, because shallow deposits are highly variable within the complex depositional environment of greater Christchurch. The low-lying areas of Christchurch contained many pockets of swampy and marshy soils, but it is in these large swamp zones where the depositional environment was consistent enough to have created significantly different subsurface conditions. In Figure 2.3, the 1989 Sibley map (Wilson 1989), based on an 1856 historical map, highlights swamp zones that

are consistent with those shown in the New Zealand Geotechnical Database (NZGD) – Environmental Ecology layer (NZGD b), which is a 1996 revision of the 1989 Sibley map.

Regional plots of cone penetration test (CPT) soil behavior type index (I_c, Robertson 2009) show consistency of soil type with depth in the outlined swamp zones (Figure 2.4). Thus, the surficial swamp zones identified in the 1856 map (shown in Figure 2.3) represent persistent geologic features (i.e., substantial swamp basins). This interpretation is consistent with the geologic observations by Forsyth et al. 2008 and GNS Science (Brackley 2012) that swamp basins formed over time in areas of Christchurch with conducive topography. Another interpretation of surficial geology is provided by GNS Science (Begg et al. 2015), which matches the historical map and regional plot interpretations over much of the southwest part of the city, but with some deviation around Site 14, Site 21, and Site 23 in classifications of swamp basins, interchannel troughs, and raised channels. Therefore, the historically mapped swamp zones in Christchurch may be used to categorize them as geologically different in terms of depositional environment.

The historical maps were compiled from surface observations at the time of European settlement, while the geomorphic map is based on subsurface deposits and surface landforms. Thus, in some areas, swamp zones delineated in the historical map and geomorphic map may differ, depending on the depth range and corresponding depositional period being considered. Spatial variability at the surface and at depth can make this environment difficult to characterize, so the engineer should employ judgement and consider the intended purpose of resources when making interpretations. Deposited sediments are likely to spatially and temporally vary as a result of river avulsion and subsequent shifts in depositional settings across the area. Subsurface sediments may transition between swamp-like deposits, interfluvial deposits, and channel deposits with depth, reflecting the varied depositional history at a site. The variability in these deposits and relative thicknesses of strata from the different depositional settings may provide additional insight on marginal liquefaction case history sites. For the current analysis, the controlling influence of shallow soils on liquefaction behavior and the distribution of post-earthquake liquefaction observations support interpretation of silt-swamp locations according to the regional plots and historical map.

2.3 EVALUATION OF SOIL LIQUEFACTION CASE HISTORIES

2.3.1 Canterbury Earthquake Sequence

The 2010-2011 Canterbury earthquake sequence consisted of four main earthquake events: the 4 September 2010 Darfield earthquake (M_w 7.1), the 22 February 2011 Christchurch earthquake (M_w 6.2), the 13 June 2011 earthquakes (M_w 5.3 and M_w 6.0), and the 23 December 2011 earthquakes (M_w 5.8 and M_w 5.9) (e.g., Brackley 2012, Christophersen et al. 2013, GNS Science). Post-earthquake reconnaissance investigations and subsequent research programs have focused primarily on the Darfield and Christchurch events. Ground shaking from the Darfield event was relatively uniform throughout Christchurch, because the event was more distant from Christchurch so there was little attenuation of motion across the city. Liquefaction manifestations were observed primarily along the Avon River in the eastern suburbs of Christchurch, although the source of the Darfield earthquake was west of the city. Ground shaking from the Christchurch event was variable throughout greater Christchurch, because the event occurred close to the city under the Port Hills to the south. Severe liquefaction manifestations were observed throughout over 30% of the city and suburbs, concentrated predominantly in central and eastern Christchurch

(e.g., Green & Cubrinovski 2010, Cubrinovski et al. 2011). Details of the Canterbury earthquake sequence have been extensively published previously (e.g., Christophersen et al. 2013, GNS Science, Green & Cubrinovski 2010, Cubrinovski et al. 2011); only relevant details are provided in this paper to aid in understanding liquefaction observations as compared with state-of-practice liquefaction estimates.

2.3.2 Liquefaction

Liquefaction field case histories are typically classified as “Liquefaction” or “No Liquefaction” cases in the development of empirically-based simplified liquefaction triggering procedures. The classification is based on whether or not surface manifestations of liquefaction damage were observed, which implicitly pairs liquefaction triggering with surface manifestations. This convention is continued herein. It is possible that some of the soil layers within the “No Liquefaction” classified sites in the SW quadrant of Christchurch did in fact liquefy, but surface manifestations (such as ejecta or cracking) and significant differential ground settlement did not occur, and overall ground settlement was not discernable by eye. Pre-event and post-event LiDAR data are available across Christchurch for evaluating vertical ground surface subsidence (Russell & van Ballegooy 2015), but the resolution of that data is sufficiently coarse so that potential ground settlements on the order of 50-150 mm are within the margins of error for interpreting these data at any given location. However, LiDAR data are able to measure ground surface subsidence at a regional scale to a much smaller margin of error. At a regional scale, LiDAR data show that ground surface settlements did occur in the SW part of the city, but they were small (i.e., on the order of 0.1 m compared with 0.5 to 1.0 m in eastern Christchurch) and too gradual to affect the building and utility performance at a majority of sites within this area of Christchurch.

2.3.3 Insights from CPT profiles

The primary method of geotechnical subsurface investigation in Christchurch is the CPT. Post-earthquake governmental guidance (MBIE 2012) recommends CPT testing at residential and commercial developments, which has led to a large quantity of available CPT data, in addition to post-earthquake CPTs that were conducted throughout the city for insurance and research purposes. It is instructive to examine CPT profiles across Christchurch at sites that did or did not show surface manifestations of liquefaction during the Canterbury earthquake sequence. The influence of ground shaking level is considered by binning data by peak ground acceleration (PGA). The data presented in Figure 2.5 combine CPT traces across Christchurch for the four main events of the Canterbury earthquake sequence, binning the CPT traces by PGA scaled to $M_w=6.0$ and coloring the CPT traces by post-earthquake observation for that event. PGA values varied across Christchurch (more so for the Christchurch event than the Darfield event), so this approach conveys the variation in observations with regard to PGA rather than tying observations to the events, and allows for looking at increasing liquefaction observations with increasing PGA levels. PGA values in Figure 2.5 are based on median estimates from Bradley & Hughes (2012), which are magnitude-scaled based on Idriss & Boulanger (2008).

Figure 2.5 shows clear trends in the characteristics of the CPT traces for sites that did or did not liquefy. Sites with liquefaction at $\text{PGA} < 0.3g$ had consistent, thick layers of clean sands, whereas no-liquefaction sites had silty soil layers or highly stratified silt/sand deposits. Many of these no-liquefaction sites are those for which standard assessment methods estimate significant

liquefaction should have occurred. As PGA increases, more silty soil and stratified silt/sand deposits are observed to have liquefied, with a significant change occurring at PGA levels above 0.4 g. It is possible that some of the no-liquefaction silty soil sites shown in Figure 2.3 could have liquefied had they been subjected to higher PGAs. The focus of this study is six silty soil sites that were strongly shaken by the 22 FEB 2011 Christchurch earthquake, which caused estimated median PGAs of approximately 0.32-0.46 g (M_w 6.0-scaled PGAs of 0.33-0.49 g). These intense levels of ground shaking should have produced liquefaction manifestations in these silty soil sites according to SOP liquefaction triggering evaluation procedures.

2.3.4 Regional Assessment

The Canterbury earthquake sequence dataset provides an unprecedented amount of well-documented pre- and post-earthquake data that have been made publically available. These data include geotechnical and ground motion characterization for multiple earthquake events over a large geographic region encompassing urban, suburban, and rural areas. Figures 2.1 and 2.5 illustrate the value of these data on the regional scale. With this regional perspective, researchers gain an appreciation for the distributed effects and general trends throughout Christchurch. Representative individual case history sites can then be selected to investigate details that are obscured at the regional level. Considering both regional data and site-specific analyses provide the most robust insights.

2.3.5 Site-Specific Subsurface Investigations

In the first phase of the silty soils project, sites with consistent target I_c silty soil layers ($I_c \sim 2.2$ -2.8) and clear discrepancies between triggering estimates and post-earthquake observations were identified through the use of CPTs, sonic borings, direct push crosshole seismic testing, and laboratory testing of bulk samples (Beyzaei et al. 2015, Stringer et al. 2015, UC Berkeley & Univ of Canterbury 2016, Tonkin & Taylor, UT-Austin, Stokoe et al. 2014, Wotherspoon et al. 2015). Five silty soil sites were then selected for in-depth investigation with high-quality (“undisturbed”) sampling and advanced laboratory testing to evaluate cyclic resistance. Four no-liquefaction silty soil sites were selected, along with one marginal silty soil site where liquefaction was not observed after the lower intensity 4 SEP 2010 Darfield event, but significant liquefaction was observed after the higher intensity 22 FEB 2011 Christchurch event. Additionally, clean sand liquefaction sites from along the Avon River were also selected to establish a baseline reference for comparison at sites that performed as the clean sand-based liquefaction assessment procedures indicated they would perform. The four no-liquefaction silty soil sites are: Site 2 - Gainsborough, Site 21 - Caulfield, Site 23 - Riccarton, and Site 33 - Cashmere. The one liquefaction silty soil site is Site 14 - Barrington. The clean sand site considered in this study is EQC-3 - Avondale, which was also investigated extensively through the Ground Improvement Trials (NZGD). All sites were level ground free-field sites (i.e., public parks, open areas, single-family residential construction), with the exception of Site 23 which is a level ground site occupied by a two-story commercial structure and parking lot. The silty soils project field sampling and laboratory testing program are further discussed in Beyzaei et al. 2015, Stringer et al. 2015, and upcoming papers.

High-quality continuous sampling and detailed logging were performed later in June 2016 at Site 14, Site 33, and at a new site located 200 m west of Site 23, which was no longer accessible, to evaluate soil stratigraphy in greater detail and assess how well the standard CPT (10 or 15 cm²)

and mini-CPT (5 cm²) could capture soil layering (Mini-CPT & DM Project 2016). The new site, herein called Site 37 - Clarence, is a no-liquefaction silty soil level ground site occupied by a one-story commercial structure and parking lot in the Riccarton swamp area.

Silty soil site locations are shown in Figure 2.3 and geographic coordinates are listed in Table 2.1. Figure 2.6 presents the subsurface profiles in the upper 7 m at the six silty soil sites (Figure 2.6,a-f) and one representative clean sand site (Figure 2.6g), showing CPT tip resistance (q_c), soil behavior type index (I_c), and estimated high and low groundwater table (GWT) depths. Shallow soils at these sites range from clean sands, to silty sands, to nonplastic silts, and low plasticity silts (plasticity index, $PI \leq 15$). Lees et al. (2015) found that I_c could be used to categorize soil types in a general sense across Christchurch, averaging I_c over 0.5 m depth intervals. However, important details resulting from depositional environment, such as thinly interbedded silty sand and sandy silt deposits, may not be distinguished with the CPT as will be discussed later. The upper 7 m was selected for closer examination in this study, because the critical layer and other key soil layers were captured within that depth range at each of the case history sites. Although all six sites consist of “silty soils,” the side-by-side comparison of q_c and I_c profiles shows differences in the stratification and consistency of layers within each profile, especially when compared with the representative clean sand site.

2.3.6 Liquefaction Assessment

The majority of structures in greater Christchurch are residential and low-rise commercial structures. Considering these sites as free-field sites, liquefaction triggering was assessed using SOP simplified CPT-based methods for comparison with post-earthquake liquefaction observations.

The Boulanger & Idriss (2016), Moss et al. (2006), and Robertson & Wride (1998) CPT-based methods were used to evaluate liquefaction triggering for the case history sites. As presented in previous publications (Beyzaei et al. 2015, Stringer et al. 2015), a significant portion of each profile is susceptible to liquefaction based on these methods, but surface evidence of liquefaction is not observed at the no-liquefaction sites in both post-earthquake investigations and later examinations of post-earthquake liquefaction observation maps publically available from the NZGD. The LSN parameter was used as the primary index for assessing liquefaction vulnerability at the sites. Developed by van Ballegooy et al. (2014) and calibrated using observations from the Canterbury earthquake sequence, LSN utilizes estimated post-liquefaction volumetric reconsolidation strain (ε_v) with an inverse depth (z) weighting function to calculate an index of liquefaction vulnerability defined by Equation 1:

$$LSN = 1000 \int \frac{\varepsilon_v}{z} dz \quad (1)$$

The Boulanger & Idriss (2016) method (“BI16”) estimates the lowest LSN values of the three simplified methods, but these values still represent a significant over-estimation of liquefaction manifestations at the silty soil sites in the southwest quadrant of Christchurch. SOP estimates and field observations of liquefaction are compared in Table 2.1. Liquefaction assessment profiles of cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) for the 22 FEB 2011 Christchurch event are depicted in Figure 2.7 for CPT-based analysis using BI16. Simplified methods indicate liquefaction would be expected at all sites, but liquefaction was observed at only Site 14 and EQC-3 during post-earthquake reconnaissance. The settlement profile for Site 23 (Figure 2.7, c-2) using

Zhang et al. (2002) demonstrates the incremental accumulation of settlement throughout the profile, in contrast to more typical cases where settlement arises primarily from a clearly defined critical layer.

There are several components to the simplified assessment that can affect estimations of liquefaction triggering and consequences, such as: PGA, GWT, elimination of transitional I_c values, I_c cut-off, fines content correlation, and probability of liquefaction triggering (model uncertainty). PGA was estimated using the contour maps developed by Bradley & Hughes (2012) and GWT depths were estimated using the GWT maps provided by the NZGD. I_c cut-off was set at $I_c = 2.6$ based on the findings of Lees et al. (2015), which showed that I_c appropriately classifies soils into sand-like and clay-like behaviors at the regional scale in Christchurch. Within the bounds of reasonable assumptions for each parameter (e.g., using also the 16th and 84th percentile PGA values), SOP methods still estimate liquefaction triggering at the no-liquefaction sites.

2.3.7 Post-Earthquake Liquefaction Observations

Post-earthquake reconnaissance investigations during the Canterbury earthquake sequence consisted of aerial photography, on-the-ground property observations, and on-the-ground road observations (NZGD). Separate liquefaction observation maps were developed for each of these post-earthquake observation methods. Liquefaction damage during the 4 SEP 2010 Darfield event was mostly limited to along the Avon River and into the eastern suburbs. The southwest region of the city was not flown over following the Darfield event and only select areas were visited. Additionally, few homeowners filed liquefaction land damage claims in the SW quadrant of the city. Post-earthquake reconnaissance investigations were focused in areas with reports of liquefaction, and if there had been such reports from the case history sites in the southwest quadrant, investigators would have been sent to those areas. Therefore, all evidence supports the inference that no liquefaction occurred at the SW silty soil case history sites due to the Darfield earthquake. Reconnaissance investigations were extensive following the 22 FEB 2011 Christchurch event; aerial photography is available at all sites, which are also covered within the liquefaction observation maps. These photographs and maps confirm the assessment of the no-liquefaction and liquefaction sites for the Christchurch event. Final assessments using all field observation data are provided in Table 2.1.

The 4 SEP 2010 Darfield and 22 FEB 2011 Christchurch earthquakes induced CSR values sufficient for SOP methods to estimate liquefaction triggering at the silty soil sites. This paper focuses on the more significant Christchurch event in discussing estimated seismic performance, because it produced the highest seismic demand within the greater Christchurch area. We also focus on the Christchurch event, because there are field observations with which to compare the SOP liquefaction estimates, rather than the inferences that must be made for the Darfield event. Site 14 provides an interesting case history across these multiple earthquake events; it is inferred to have no liquefaction during the Darfield event, but was observed to have liquefied during the Christchurch event, which confirms the intensity of ground shaking has a threshold for causing liquefaction.

Liquefaction observation maps such as Figure 2.1 provide useful information on a regional scale, but they do not convey fully the severity and spatial distribution of liquefaction observations at the silty soil sites. Aerial photographs provide important information in that context. Figure 2.8 shows Site 14 and Site 33 following the Christchurch event. Site 14 (“liquefaction”) shows multiple sand boils distributed across the site, whereas Site 33 (representative of “no-liquefaction”)

shows no surface manifestations of liquefaction within the site extents. A few sand boils are evident at further distances (i.e., on the order of 150 m from the Site 33 CPT). This spatial distribution becomes more relevant as the discussion delves further into the effects of depositional environment.

2.4 EFFECTS OF SWAMP DEPOSITIONAL ENVIRONMENT ON LIQUEFACTION

It is important to re-emphasize that liquefaction case histories are classified by observed manifestations at the ground surface. Liquefaction could be triggered at-depth, but if no consequences are observed at the ground surface, then for the current liquefaction assessment framework, the case history is classified as “no-liquefaction.”

Focusing on the SW swamp zones of Christchurch, Figure 2.9 provides the Christchurch and Darfield earthquake LSN distributions for CPTs within the “Riccarton” and “Hoon Hay/Cashmere” swamp zones, with the area around Site 14 (Barrington) provided for comparison (refer to Figure 2.3). Filters were used to remove CPTs with depths less than 10 m and predrill depths greater than the depth to groundwater. Only the top 10 m of each CPT trace was evaluated when calculating LSN. The resulting LSN distributions are centered on an LSN value of approximately 22-30, and the majority of the data falls within the range of LSN = 15 to 45. Russell & van Ballegooy (2015) found in their liquefaction-induced land damage assessment that moderate to severe liquefaction was more likely for LSN values exceeding 16 using the Boulanger & Idriss (2016) method. This more quantitatively confirms the initial observations from Figure 2.1 that indeed, the SW region of Christchurch is an area of liquefaction triggering over-estimation, and that within swamp zones, estimated LSN values indicate liquefaction is expected to occur, in direct contrast with the observations of none to minor surface manifestations of liquefaction.

Delving further into this trend using aerial photographs, in moving from the edge toward the center of swamp zones, surface manifestations of liquefaction decrease until reaching large areas where no surface manifestations of liquefaction are observed. Thus, liquefaction can be evaluated in three zones: outside of swamps, transitional zones at the edges of swamps, and within swamps. The thickness of consistent silty soil swamp-type deposits will tend to increase moving from the edge toward the center of a large, persistent swamp, where silt deposits are likely to be thickest. The transition distance for a swamp varies based on several factors, including its spatial extent, thickness, depositional setting (e.g., proximity to river), and paleo-topography, so it would be inappropriate to apply a single transition distance for all swamps in such a dynamic environment. Within the swamps in the SW quadrant of Christchurch, there is almost no evidence or infrequent evidence of liquefaction (Figure 2.1). At the edges of swamps, likely in the transitional zone, there is some evidence of liquefaction, varying on a site-by-site basis, such as at Sites 2 and 33. Within Site 2 (located at the edge of a swamp), there is no evidence of liquefaction, but sand boils and ejecta occur intermittently at nearby surrounding sites. A similar situation occurs at Site 33, where there is more evidence of ejecta in the nearby developed residential areas. These observations support the post-earthquake reconnaissance investigations that noted general trends of no liquefaction in the silty and swampy SW area of Christchurch, but by looking in detail at the near surface sediments, it is possible to move past the general trends and use historical locations of now-buried features to understand the post-earthquake observations in more detail.

On a regional scale, Figure 2.10 presents LSN distributions for CPTs across greater Christchurch, showing: a) CPTs outside swamp areas, b) CPTs within swamp areas in the NE and

SE, and c) CPTs within swamp areas in the NW and SW. To eliminate the CPT density bias in the eastern suburbs and CBD, an area-based method was used by interpolating LSN values between each CPT location and dividing this surface into 25 m x 25 m wide tiles. The median LSN value in each tile was then matched with the corresponding land damage observation category shown in Figure 2.1. For the analyses presented in Figure 2.10, a buffer width of 200 m was applied from the marked perimeter of each well-defined swamp, to account for uncertainties in swamp boundary location and likely transitional area into the swamp deposits. CPTs in this buffer were excluded from the analyses, in an attempt to more clearly show the performance outside and within swamps (i.e., CPTs in likely transitional areas have not been included in the analyses). Although the mapped extent of each swamp is taken as the edge of the swamp for these analyses, the actual swamp extents may vary somewhat from the historical map depiction. The filters described for Figure 2.9 were also applied for Figure 2.10.

The distribution in Figure 2.10a shows that outside of swamps, LSN is able to capture overall differences in damage patterns across the city. In Figure 2.10b, the LSN distribution for areas with no liquefaction damage is lower than the LSN distribution for areas with minor to moderate and moderate to severe liquefaction damage. This means that for the eastern (less silty, more sandy) swamps, LSN is able to differentiate between areas that are likely to perform well and areas that are likely to perform poorly. In Figure 2.10c, the LSN distribution for areas with no liquefaction damage is high (i.e., over-estimating) and almost the same as the distribution of LSN for areas with minor to moderate liquefaction damage. This means that for the western (more silty and less sandy) swamps, LSN is not able to differentiate between areas that are likely to perform well and areas that are likely to perform poorly, as well as providing an overall over-estimation of liquefaction manifestation. The observations from these histograms are consistent with the visual comparisons of the calculated LSN contours with the respective land damage maps shown in Figure 2.1.

2.5 STRATIGRAPHY AND GROUNDWATER TABLE EFFECTS

The individual case history sites discussed previously are examined more closely to investigate further how swamp-type deposition might affect key factors that lead to the discrepancies between liquefaction triggering estimations and field observations. The potential over-estimation factors can be considered in other studies to assess if the simplified SOP liquefaction triggering procedures are applicable and in what ways the SOP procedures can be interpreted to capture the swamp depositional environment effect for the Christchurch soils. Two likely reasons for the apparent over-estimation that can be considered through both regional and site-specific assessments in the context of a swamp depositional environment are: i) groundwater table effects, and ii) soil stratigraphy, which results directly from depositional environment.

2.5.1 Groundwater Table

Figure 2.11 shows a depth to GWT map for greater Christchurch at the time of the Darfield event (NZGD). Note the location of the blue regions, corresponding to locations of high GWT. These locations coincide with the locations of the case histories, both liquefaction and no-liquefaction. This should not be surprising, because a high GWT is conducive to the occurrence of liquefaction, but it is interesting to note that both the liquefaction and no-liquefaction sites are in high GWT regions. If analyses were only to consider the regional groundwater table distribution,

without considering the underlying geology, they would not differentiate between the no-liquefaction and liquefaction case history sites.

Estimated high and low GWT levels shown in Figure 2.6 were based on piezometer readings, sonic boring core samples, and direct push crosshole testing estimates of depth to full saturation. These details provide a more nuanced depiction of the groundwater conditions at each site based on the post-Canterbury earthquake sequence GWT regime. Groundwater conditions in Christchurch are seasonably variable, typically fluctuating on the order of a meter or so. Direct push crosshole seismic testing performed by Stokoe, Cox, and others (e.g., UT-Austin, Stokoe et al. 2014) at the case history sites shows that the estimated depth to 100% saturation (corresponding to compression wave (V_p) velocities around 1500 m/s) can be well below the estimated high GWT. At some sites, compression wave velocities were less than 1500 m/s below the estimated low GWT. However, values of V_p remain generally well above 800 m/s, indicating that soils are saturated or nearly saturated for the purpose of liquefaction assessment (i.e., $V_p = 800$ m/s corresponds to sufficiently high levels of saturation such that the increase in cyclic resistance (as compared with 100% saturation) is less than 20% (Tsukamoto et al. 2002)). Within the zone of GWT fluctuation, soils may be subject to partial saturation, but below the estimated low GWT soils can be considered fully saturated. This observation is confirmed with T+T sonic boring core samples that show iron-stained and mottled layers with root voids and desiccation in the zones of GWT fluctuation (Tonkin + Taylor).

Seasonal GWT fluctuation in the upper siltier soils at these sites contributes to the development of a “pseudo-non-liquefiable crust.” It is not necessarily an intact non-liquefiable crust in the manner described by Ishihara (1985), but a pseudo-crust of silty soils that may have root matter that reinforces the pseudo-crust to increase its effectiveness as a barrier. Alternatively, it may have root voids and sandy seams that may prevent it from being a homogeneous barrier against surface manifestation of liquefaction. The nature of the pseudo-crust will vary by site, and in some cases may be sufficient as a cap over liquefaction ejecta, depending on the degree of saturation, integrity of the pseudo-crust, and the quantity of ejecta moving toward the ground surface.

2.5.2 Stratigraphy

Figure 2.6 shows the CPT subsurface profile in the upper 7 m below ground surface at each case history site. Examining the q_c and I_c traces, differences in stratigraphy are readily apparent, especially when compared with the EQC-3 clean sand profile. Site 23 is the most highly stratified profile, with interbedded thin layers of fine sand and silt on the order of centimeters. Site 14 is the closest to a “typical” liquefaction site such as EQC-3, having the thickest continuous layer of sandy material. These profiles are not easily separated a priori into well-defined subsurface characterization categories. Although Site 14 has the thickest layer of sandy material, it is not significantly thicker than the sandy layer at Site 33. Although Site 23 has the most stratified CPT trace, it may be that other sites have thin-layer stratification not identified by the CPT.

Subsurface interpretations from the standard CPT and sonic boring method are compared with photographs of specimens from high-quality samples and detailed logging to evaluate subsurface characterization in greater detail and assess the in-situ characteristics of soil layering in these varying depositional environments. The goal of this part of the study is to discern differences in stratigraphy resulting from differences in depositional environment.

Figure 2.12 shows sonic boring core samples (Tonkin + Taylor) from Sites 14 and 33 for comparison with the CPT traces in Figure 2.6, illustrating differences in the zone of GWT fluctuation (pseudo-crust), soil type transitions with depth through sands to siltier material, and the difference in deeper silty material. Color changes, iron-staining, and root matter indicate the zone of GWT fluctuation, while varying color, sample consistency, and free-water indicate transitions in soil type. Figure 2.13 provides photographs of high-quality samples (Mini-CPT & DM Project 2016) from the sandy layers at these two sites, highlighting differences in those sandy layers that are not sufficiently captured by the CPT or sonic boring. Figure 2.14 shows a high-quality specimen (post-cyclic testing) that illustrates the scale of layering at Site 23 (Beyzaei et al. 2015), which is on the order of millimeters and centimeters. CPT data and sonic borings provide a well-rounded overview of subsurface conditions, but do not provide sufficient resolution on the scale needed to illuminate differences among these sites resulting from differing depositional environments. Detailed logging during the continuous sampling program (Mini-CPT & DM Project 2016) showed clearly the differences in depositional environment between Riccarton (Site 37 and Site 23), Barrington (Site 14), and Cashmere (Site 33). The Site 23 and Site 33 samples both show thick, continuous deposits of interlayered silt, silty sand, and sand, with the sandy layer at Site 33 interrupted by thinner silt layers. In contrast, the Site 14 samples show a thick, relatively continuous deposit composed primarily of silty sand, with some cleaner sand layers. Additionally, the logging program also revealed the scale at which sand, silt, and organic layers and pockets may be discontinuous in the variable Christchurch environment, which tends toward three-dimensional subsurface geometry. This type of environment is difficult to simplify to a two-dimensional geometry or a one-dimensional soil column for the purposes of simplified liquefaction assessment. Implicit in the discussion of stratigraphy are the effects of vertical and lateral heterogeneity and interlayer hydraulic connectivity.

2.6 CASE HISTORY SITE COMPARISONS

Direct comparisons between no-liquefaction and liquefaction case history sites provide further insight on the post-Canterbury earthquake sequence liquefaction observations. The representative clean sand site (EQC-3) is compared with Site 14, which did not respond entirely consistently with SOP liquefaction triggering methods for the 4 SEP 2010 Darfield event, but did for the 22 FEB 2011 Christchurch event. Site 14 is then compared with Site 23 to assess the effects of a highly stratified profile and with Site 33 to assess the differences in two seemingly similar sites that exhibited different surface manifestations of liquefaction. The comparison between Site 14, Site 23, and Site 33 for the Christchurch event observations allows for an evaluation of differing responses within the group of silty soil sites for a single earthquake event, considering the potential effects of depositional environment within the same context.

2.6.1 EQC-3 vs. Site 14

EQC-3 (eastern suburbs) represents a typical liquefaction site, with a thick clean sand deposit and post-earthquake observations that match the performance estimated using simplified liquefaction triggering methods. Site 14 (SW non-swamp) is the silty soil site that most closely approximates a typical clean sand deposit, but it does include a somewhat intact crust and contains silty soils even in the cleaner sand layer. At Site 14, SOP simplified methods indicate liquefaction was expected to occur and surface manifestations of liquefaction were indeed observed for the 22

FEB 2011 Christchurch event. However, simplified methods indicate liquefaction was also expected to occur at a lower PGA, but surface manifestations of liquefaction were not observed for the 4 SEP 2010 Darfield event. This differing liquefaction performance represents a marginal case that can help define further the liquefaction triggering curves for borderline cases, with Site 14 exhibiting differing liquefaction performance in the Christchurch and Darfield events. The inconsistency may arise from the silty nature of some of the soils, changes in depositional environment over time (e.g., deeper soils possibly more similar to swamp-type deposits), PGA threshold, or GWT depth and non-liquefiable crust issues. All these factors may have worked together to mitigate liquefaction manifestation during the Darfield event, but during the Christchurch event Site 14 performed as expected based on the simplified methods.

2.6.2 Site 14 vs. Site 23

CPT traces at Site 14 (SW non-swamp) and Site 23 (SW swamp) differ considerably. The CPT at Site 23 identifies significant stratification (albeit at a coarser resolution than that shown in Figure 2.14), but it is not well-interpreted with the simplified methods because of the scale of the thin-layer stratification. The simplified liquefaction triggering evaluation procedures estimate a highly stratified subsurface of liquefiable and non-liquefiable layers (on the order of centimeters) at Site 23 as compared with the continuous liquefiable layer at Site 14 (Figure 2.7). It is possible that these thin fine sand and coarse silt seams may have generated high excess pore water pressures, but they could not communicate these pressures between the layers due to interbedded layers of non-liquefiable soils between them. The high excess pore water pressures in the thin liquefied layers would then remain in place with no upward ejecta flow. Lateral pore water pressure movement is also possible, but given the heterogeneous nature of these soils, it may be prohibited by siltier layers or pockets and lateral pinching of sand lenses. It is also possible that the siltier layers might liquefy later than the sandier layers, but the potentially high pore water pressures that develop at different times in these layers do not coalesce sufficiently to produce significant ejecta at the ground surface.

2.6.3 Site 14 vs. Site 33

CPT traces at Site 14 (SW non-swamp) and Site 33 (SW swamp) are similar. Both have a pseudo-crust underlain by a sandy layer that is then underlain by siltier soils. Site 14 has a slightly less intact crust than Site 33, with Site 14 high-quality samples showing sandier layers within the crust, likely indicating a decrease in its capping potential (supported by the CSR vs. CRR profiles in Figure 2.7). A reasonable hypothesis is that the shallow sandy layer governs the development of liquefaction manifestations at each site and would be responsible for creating an upward path for ejecta to reach the ground surface (seen as critical layers in Figure 2.7). Considering groundwater table fluctuation and saturation, direct push crosshole seismic testing (UT-Austin) shows that compression wave (V_p) velocities at Site 33 are lower than at Site 14, below the estimated low GWT ($V_p \approx 900$ m/s and 1500 m/s, respectively). However, V_p values at Site 33 are still greater than 800 m/s, indicating that saturation is sufficient for liquefaction to occur and significant increases in cyclic resistance are not expected (Tsukamoto et al. 2002).

Examining the detailed characteristics of the sandy layer is where depositional environment differences between the two sites become clearer. Figure 2.12 and Figure 2.13 show photographs of the sonic boring core samples (Tonkin + Taylor) and high-quality samples from the sandy soil

layer (Mini-CPT & DM Project 2016) at Site 14 and Site 33, to show details of the stratification within portions of the CPT profile identified as sands. Silt seams and laminations are evident in the sample from Site 33, including a clear silt layer on the order of 1 cm and thin organic seams. In contrast, the sample from Site 14 only has some minor layering of silt and sand within a more homogeneous silty sand to sand matrix. This difference in stratification is a function of the differing depositional environments between the two sites. Depending on the frequency and thickness of the silt layers at Site 33, they could significantly impact the liquefaction potential of the sandy layer identified with the CPT. This detail in the layering is not seen in the sonic boring, and is only hinted at in the CPT trace in the two points where the sandy soil reaches slightly higher I_c values. High-quality continuous sampling is required to see the level of resolution required to differentiate the layering at these two sites.

2.6.4 Findings

Stratification within soil deposits is only captured partially or is not captured at all by the CPT. In the latter case, thin contrasting layers are missed by the resolution available with the CPT (i.e., “smearing” across a thin layer due to the relative thickness of the layer compared with the diameter of the cone). Thus, CPT-based liquefaction assessment procedures may not provide estimations consistent with observations. The stratification issues are a result of the depositional environment differences between Site 14 (SW non-swamp) and sites 23 and 33 (SW swamp).

CPT tip resistance thin-layer corrections are available to correct reduced tip resistance measurements in a thin, stiff layer within a thick, soft stratum (Robertson & Fear 1995; Ahmadi & Robertson 2005). These corrections are typically applied for thin layers with thicknesses of 30 cm or greater, where the thin layer is a single stiffer layer within an overall softer stratum. However, for the silty soil sites considered in this study, the interbedded nature of the subsurface profiles and the scale of the silt and sand layering (i.e., on the order of mm and cm) differs from the cases for which current thin-layer correction factors have been developed. The alternating stiffer and softer layers at the silty soil sites create a complex composite system in which the CPT zone of influence will capture several layers. As currently developed, thin-layer corrections do not apply to the in-situ conditions at the studied silty soil sites.

The differing depositional environments also lead to different fabrics at each site. While this relationship may be understood abstractly, it is difficult to capture confidently without high-quality sampling. Additionally, without continuous sampling and detailed logging, it is difficult to characterize a sandy layer such as at Site 33. Samples taken at one meter intervals may miss silt seams, or provide a subsurface picture that is too sparse to confidently move forward with characterization for numerical modeling. Continuous sampling also provides information on groundwater table fluctuation and the pseudo-crust, improving on the resolution available with a sonic boring or CPT, and providing insight on the three-dimensional variability of stratigraphy in these depositional environments.

2.7 CONCLUSIONS

Discrepancies between surface manifestations of liquefaction and estimates using established liquefaction procedures were explored at several silty soil and highly stratified silt/sand sites in Christchurch, New Zealand. Persistent swamp zones were identified through examination of historical maps and confirmed by CPT profiles. Swamp soil deposits are shown through the

regional CPT-based analyses to have mitigating effects on the manifestation of liquefaction beyond what can be currently characterized and quantified by simplified liquefaction triggering evaluation procedures. Differing surficial geology and depositional environments were found to explain in part the limitations of SOP simplified liquefaction triggering procedures at highly stratified silty soil sites, with swamp environments leading to sites with defined silt layers and more stratified silt/sand deposits. Consideration of depositional environment distinguishes between liquefaction performances that could not be discerned through the CPT-based assessment alone. These features are difficult to capture in forward-modeling for estimating liquefaction potential and consequences using currently available SOP liquefaction assessment methods. CPT resolution is insufficient for subsurface characterization at these highly stratified sites, and the simplified liquefaction assessment methods do not take into account the effects of such stratification regarding hydraulic connectivity and pore water pressure movement through a stratum.

Differences in stratigraphy resulting from differences in depositional environment were identified through detailed evaluations of in-situ layering obtained using high-quality sampling and careful logging of samples. The CPT did not have sufficient resolution to discern soil layering that was often only millimeters or centimeters thick. Although useful for evaluating groundwater table fluctuations and general soil type transitions, sonic borings typically destroy the intricate soil layering at these sites. Therefore, continuous sampling followed by careful logging of high-quality samples provides important insights beyond what can be captured with the CPT and rapid soil exploration methods for liquefaction assessment at these thinly layered silty soil sites.

At sites where simplified methods may not be fully applicable, liquefaction assessments should consider the: a) regional scale (depositional environment), b) site scale (shallow subsurface, GWT fluctuation, pseudo-crust, stratification), and c) specimen scale (gradations, FC, I_c , PI, minerology). Additional work is warranted to investigate fully alternative hypotheses that may also contribute to the limitations of current liquefaction triggering procedures.

2.8 IMPLICATIONS FOR PRACTICE AND FURTHER RESEARCH

Where historical or geologic maps and preliminary subsurface investigations indicate a complex depositional environment or a depositional environment different from those of a majority of the liquefaction case history dataset, it would be beneficial to conduct high-quality continuous sampling for enhanced characterization of stratigraphy impacting liquefaction potential and to assess the most appropriate methods for evaluating those strata. Simplified liquefaction evaluation procedures were developed largely for clean sand deposits, and silt and stratified silt/sand deposits are not well represented in the database used to develop the SOP simplified liquefaction assessment procedures.

When the SOP liquefaction assessment methods do not capture adequately the subsurface characteristics of a site, continuous sampling with detailed soil logging through visual evaluation and conventional lab testing may provide a sufficient basis for evaluating the likelihood of liquefaction triggering at the site. It can also provide the information required to perform nonlinear effective stress analyses that may provide further insight. Detailed soil logging enables targeted sampling for advanced laboratory testing, if desired, and it provides calibration of the CPT that may have not provided sufficient resolution for characterizing layering in complex depositional environments.

The evidence presented in this paper makes a compelling case for targeted investigation of this issue on projects and further research to include depositional and geologic considerations in liquefaction analysis. Depositional environment can matter much in developing a robust assessment of liquefaction potential at a site. Given the variability of natural deposits, as noted by Youd & Perkins (1978), a straightforward incorporation of surficial geology and important depositional environments, such as swamps, can be challenging. However, consideration of these issues through a geologic/historical study of the region and through a site-specific investigation that includes continuous high-quality sampling will afford the engineer the information required to employ judgment in the overall assessment.

This focused study was based on a relatively small sample size located primarily in the southwest region of Christchurch. However, it confirmed that regional CPT analysis provides evidence that surficial geology in the form of silt swamp deposits have a mitigating effect on liquefaction manifestation at silty soil sites during the Canterbury earthquake sequence. However, the findings presented in this paper are only applicable for free-field or light construction sites; liquefaction may have manifested at the ground surface had there been 4-6 story buildings at each site, as was observed in Adapazari, Turkey (Bray et al. 2004). Additionally, considering the trend shown in Figure 2.5, liquefaction may have manifested at the ground surface had earthquake ground shaking been higher or longer at each site. Additional work on the important role depositional environment can play in the seismic performance of the ground is warranted.

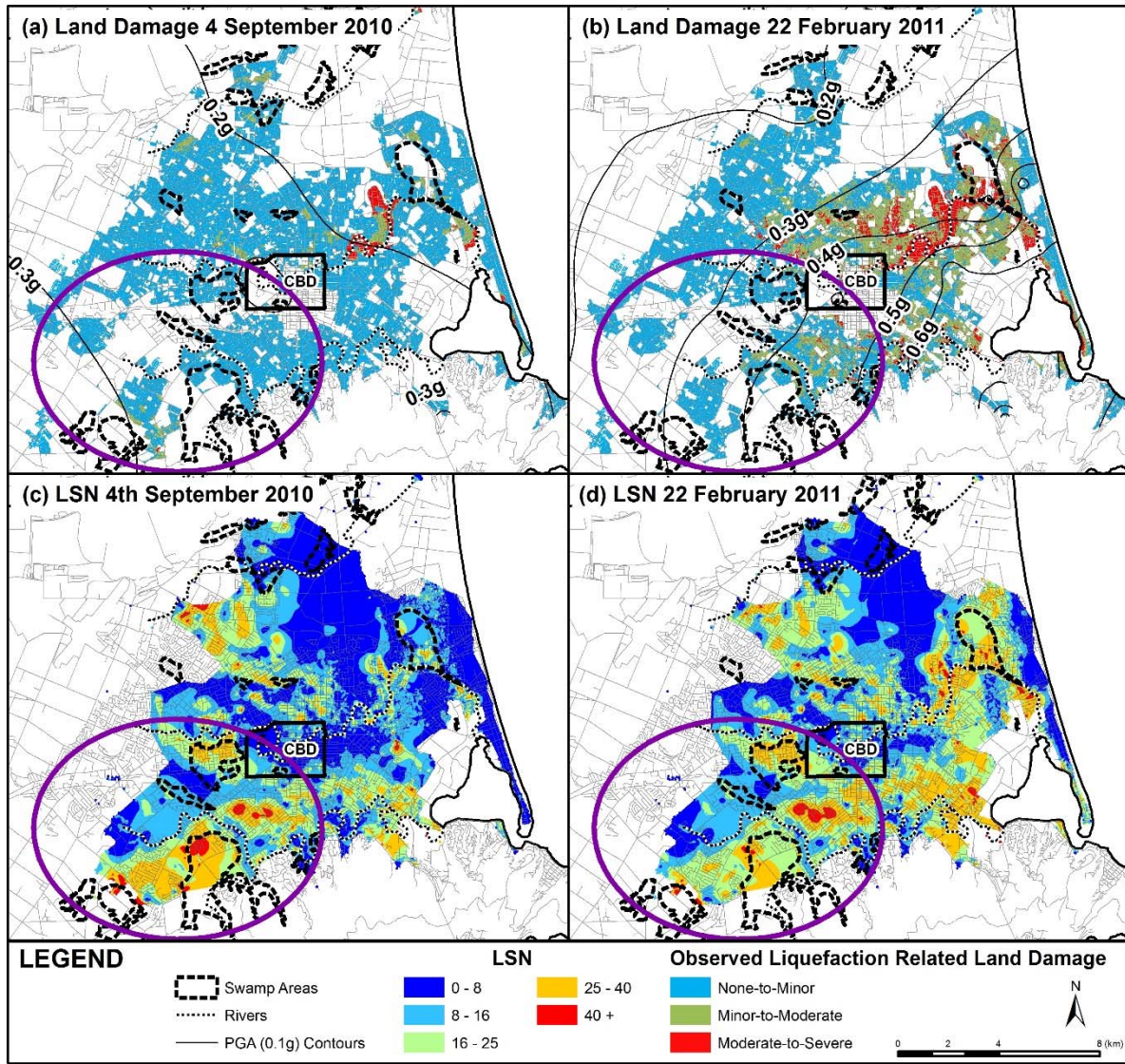


Figure 2.1: (a,b) Liquefaction-related land damage observations, and (c,d) distribution of Liquefaction Severity Number (LSN) in Christchurch for the 4 SEP 2010 Darfield and 22 FEB 2011 Christchurch earthquakes, respectively. The Central Business District (CBD) is outlined, and the circled area indicates the study region of SW Christchurch. Note the over-estimation of LSN in the circled areas of (c,d) compared to observations in (a,b). Swamp zone outlines from NZGD; median PGA contours from Bradley & Hughes 2012.

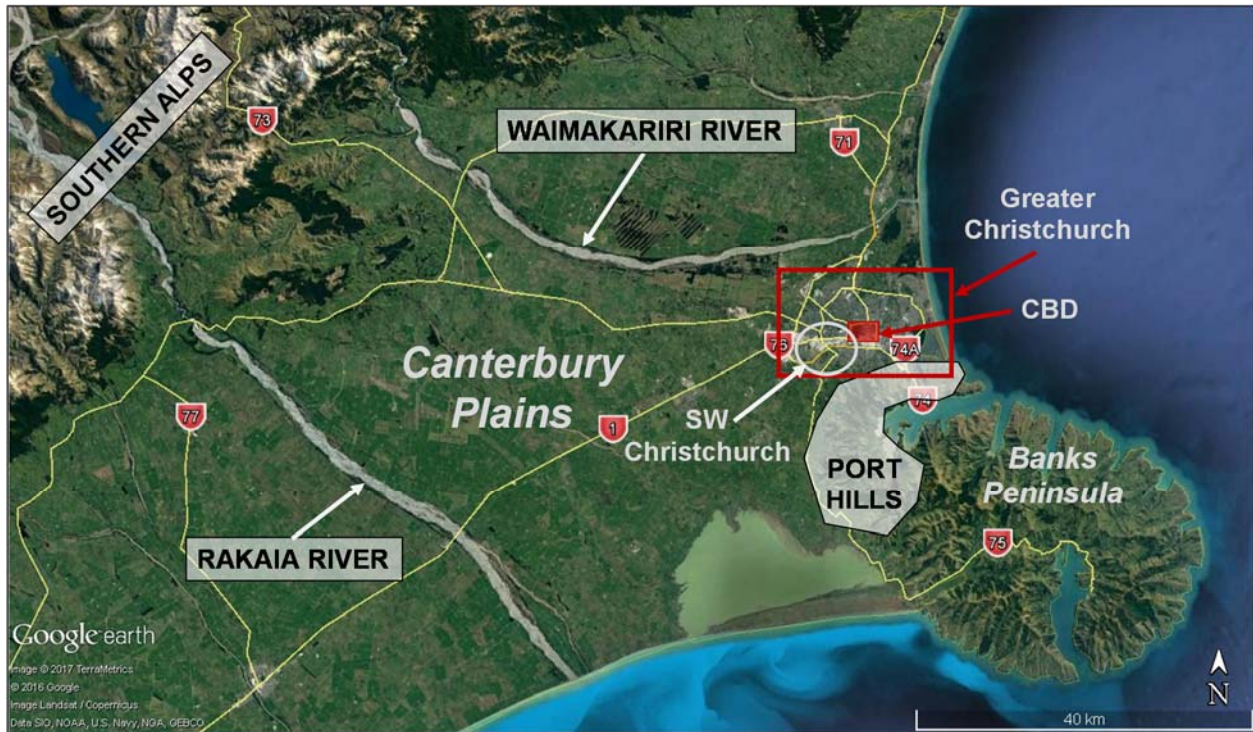


Figure 2.2: Location of Christchurch within the regional geologic setting (modified from Google EarthTM). Major geomorphic features that influence the depositional environment are highlighted. Note the proximity of Christchurch to the current position of the Waimakariri River, which is the dominant fluvial influence in Christchurch, the Port Hills, and the coastline. Circled area indicates study region of SW Christchurch.

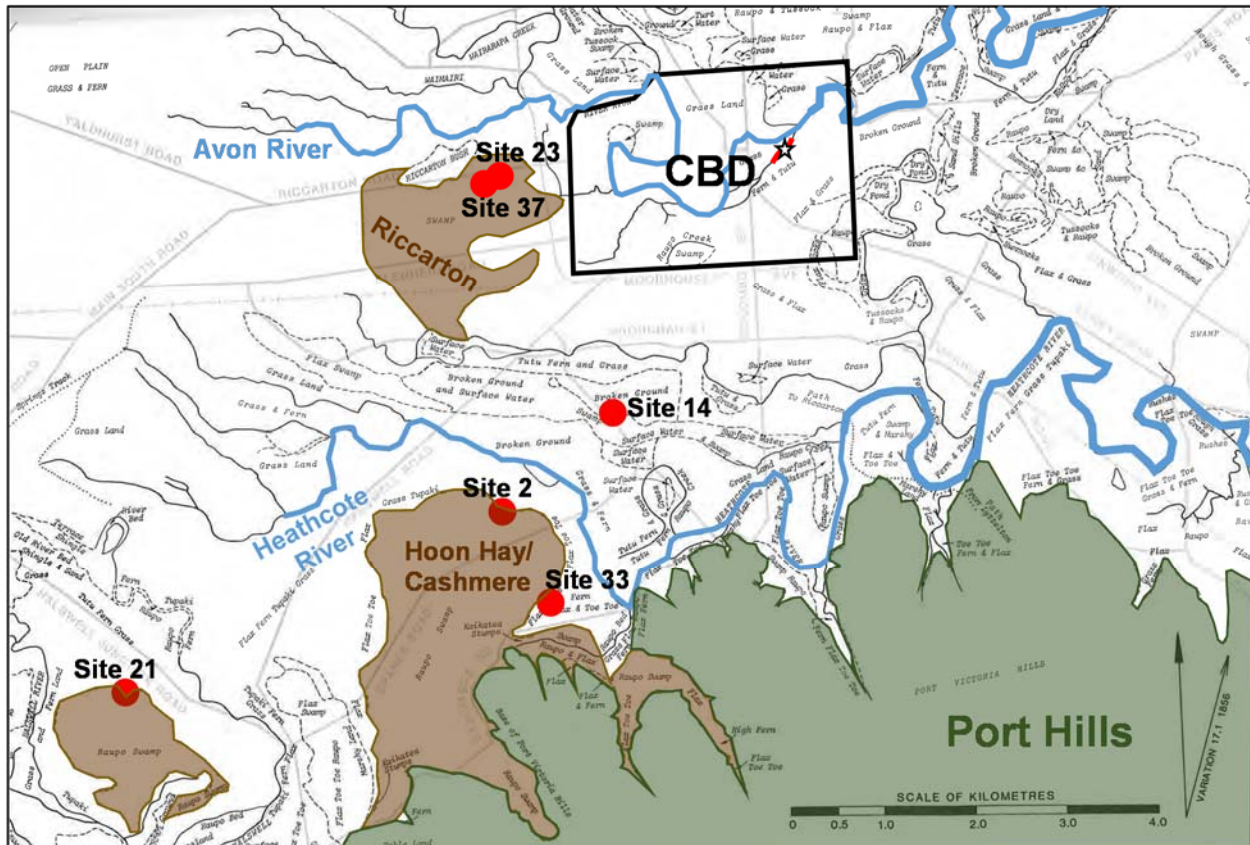


Figure 2.3: SW Christchurch; modified from 1989 Sibley Map (Wilson 1989), which is compiled from 1856 Black Maps (NZGD). Brown shaded regions show swamp areas, green shaded region shows Port Hills. The silty soil no-liquefaction sites are located in or near swamp regions, while the silty soil marginal liquefaction site (Site 14 – Barrington) is located away from the swamp regions. The Madras St. & Armagh St. buried stream channel in the CBD is highlighted with a star and red line.

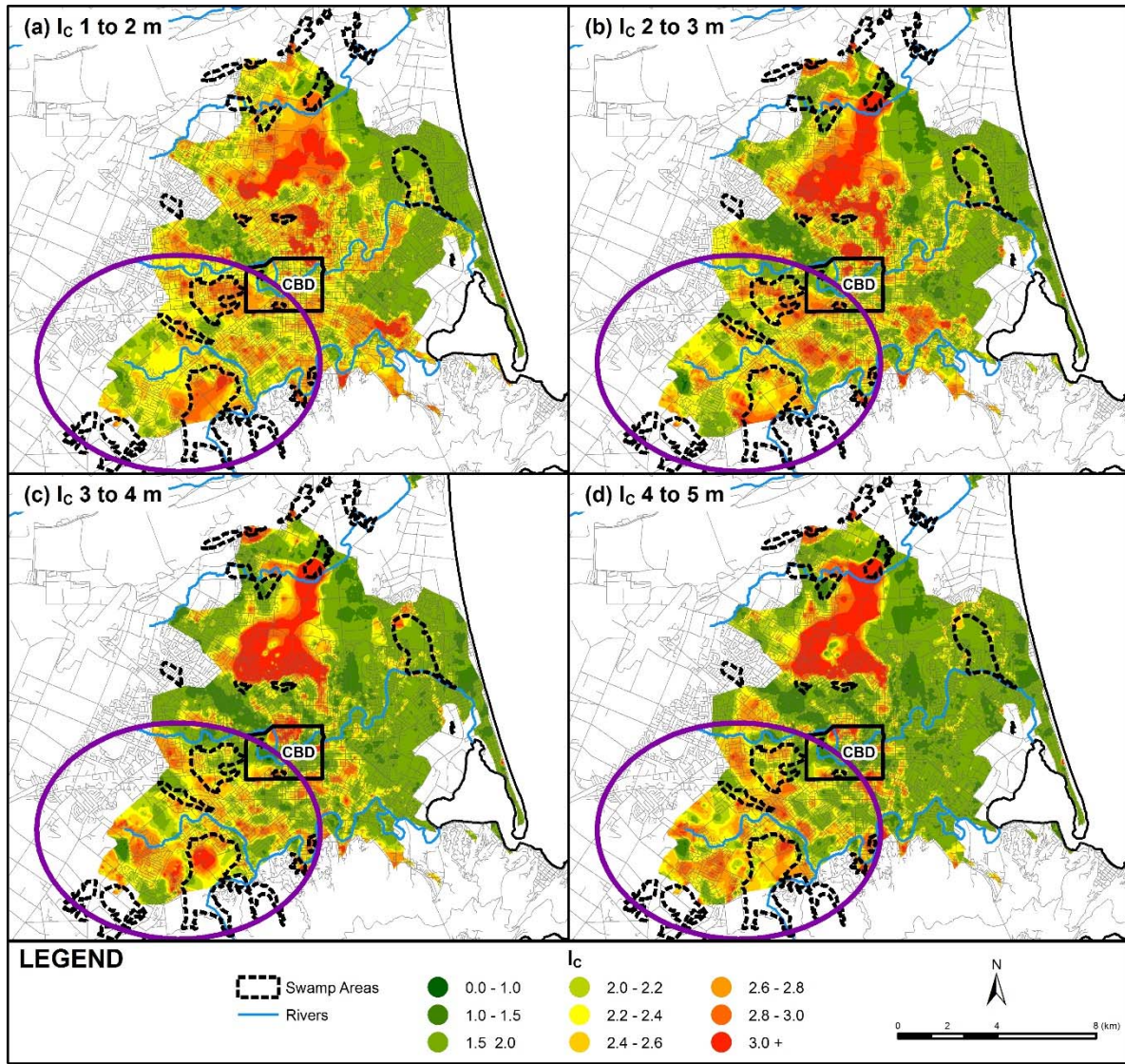


Figure 2.4: Distribution of CPT soil behavior type index (I_c) values over one-meter depth intervals from depths of 1 m to 5 m. Shaded contours interpolated from available CPT data. Circled area indicates study region of SW Christchurch.

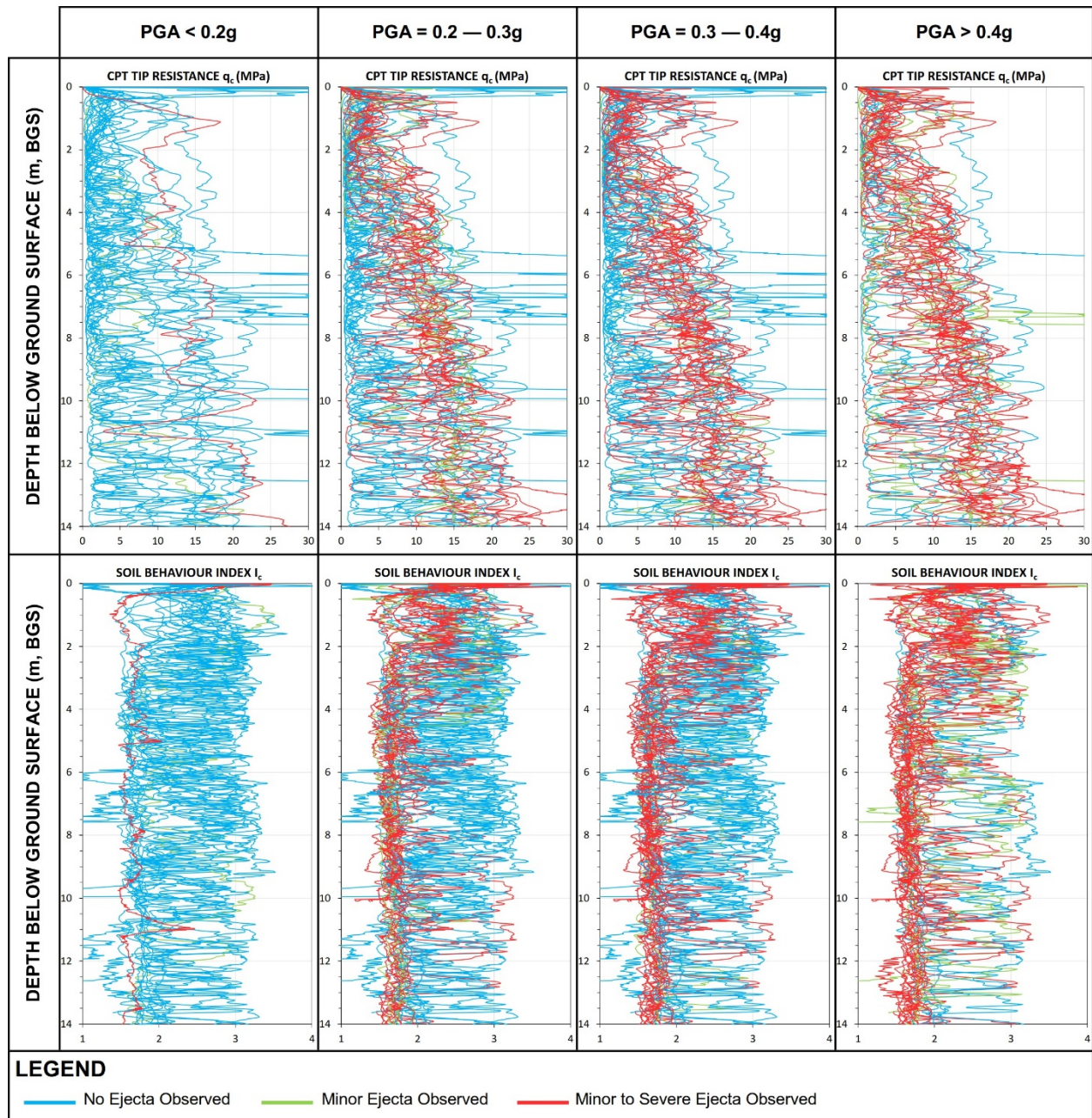


Figure 2.5: CPT tip resistance (q_c) and soil behavior type index (I_c) profiles for selected sites throughout Christchurch. Liquefaction observations are shown in: blue (no ejecta within 50 m radius of CPT), green (minor ejecta - approximately less than 5% of ground surface covered by ejecta within 50 m radius of CPT), and red (minor to severe ejecta – approximately more than 5% of ground surface covered by ejecta within 50 m radius of CPT) for the four main events of the Canterbury earthquake sequence for median PGA shaking levels for an equivalent M_w 6.0 event.

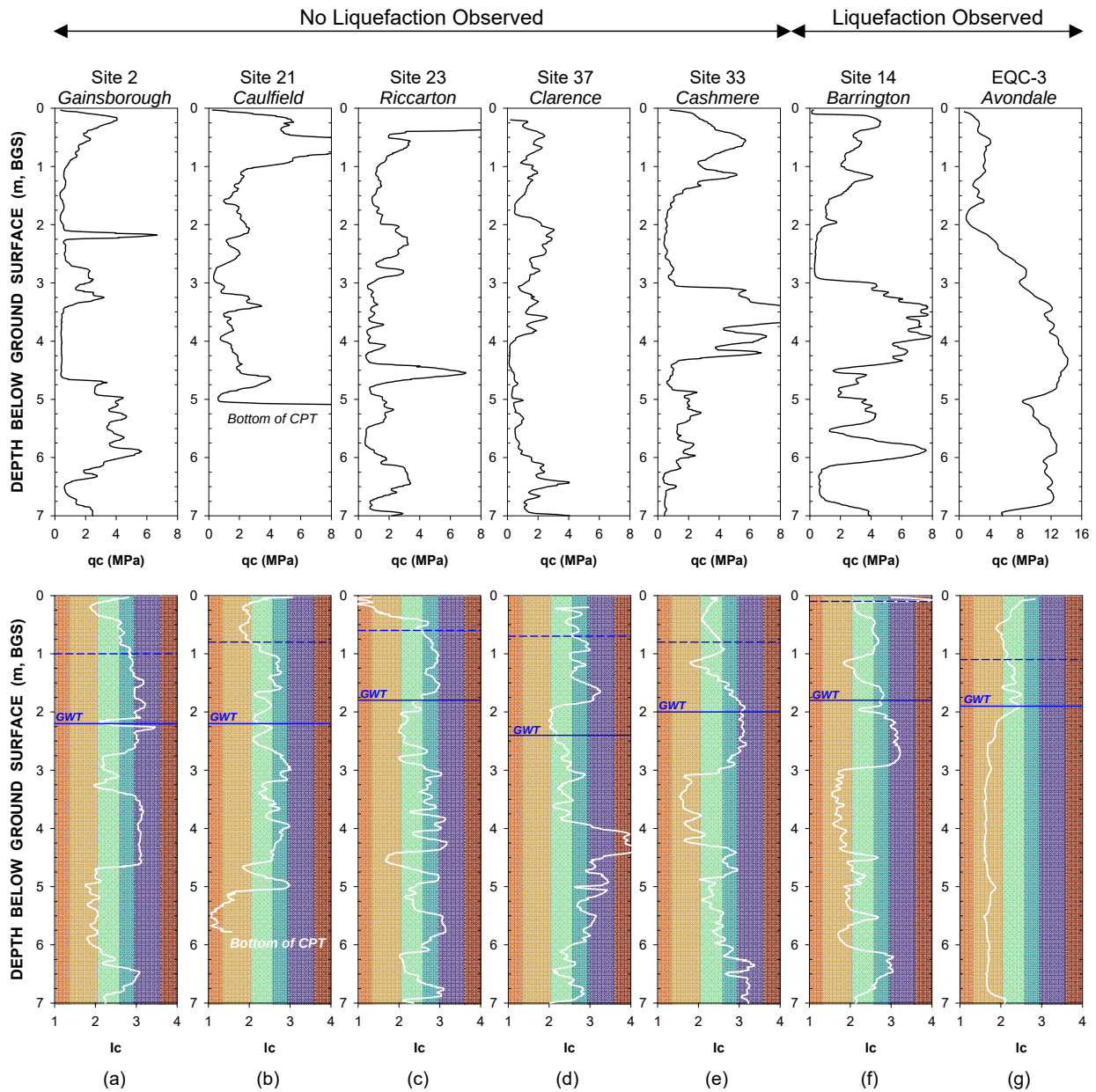


Figure 2.6: CPT tip resistance (q_c) and soil behavior type index (I_c) profiles for six silty soil sites (a-f) and one representative clean sand site (g). Estimated high (dashed line) and low (solid line) groundwater tables are also shown.

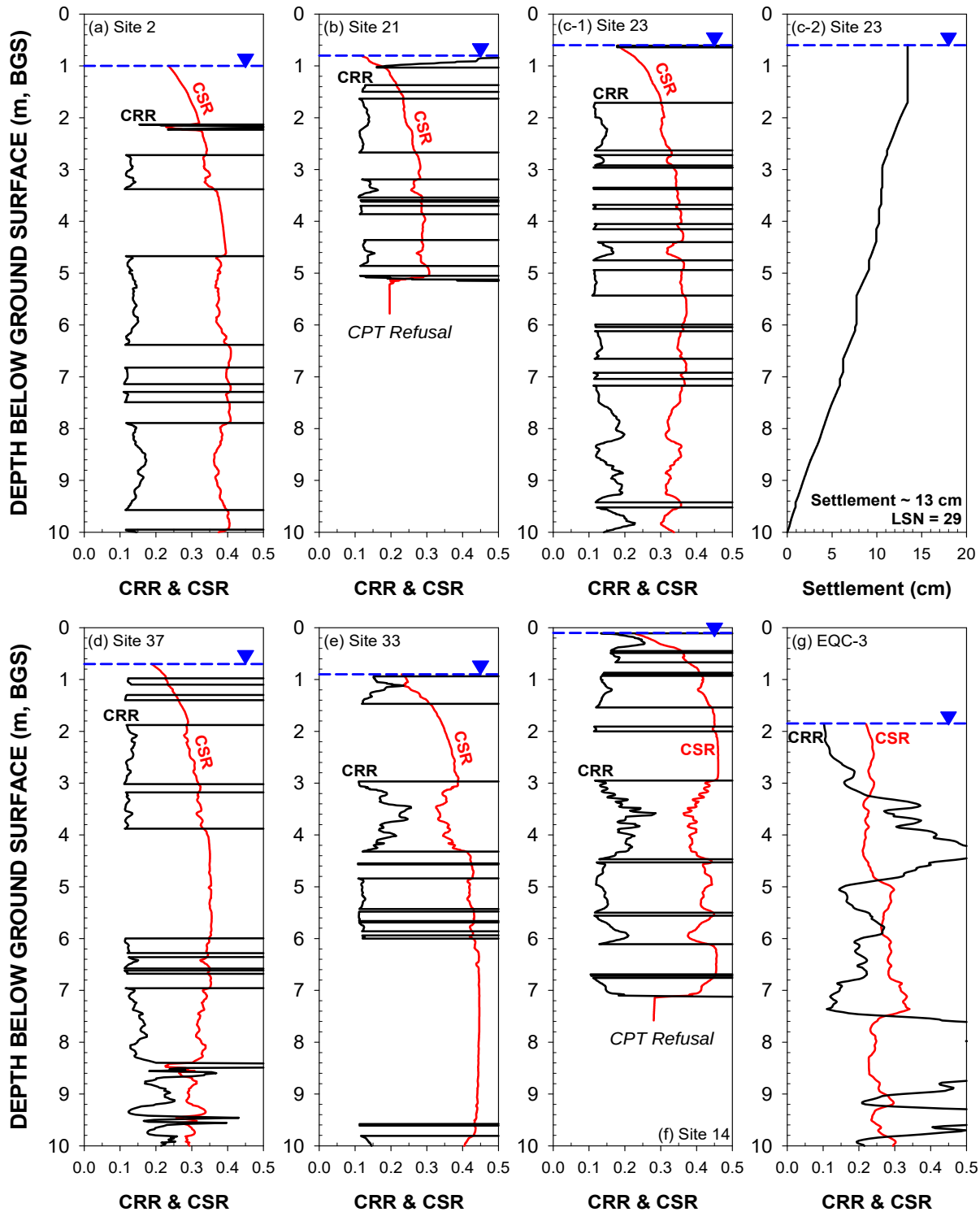


Figure 2.7: Cyclic resistance ratio (CRR) and cyclic stress ratio (CSR) profiles for the 22 FEB 2011 Christchurch event using Boulanger & Idriss 2016 ($P_L=15\%$, PGAs in Table 1, unit weight = 18.5 kN/m^3). NZGD Location IDs for CPTs: (a) 36417, (b) 36419, (c) 36420, (d) 72117, (e) 36421, (f) 37818, (g) 21509. Settlement profile (c-2) using Zhang et al. 2002.



Figure 2.8: Aerial photographs at: (a) Site 14 (liquefaction observed) and (b) Site 33 (no liquefaction observed) after the 22 FEB 2011 Christchurch earthquake. The light brown marks in (b) are stock tracks from livestock. (modified from NZGD and Google Earth™).

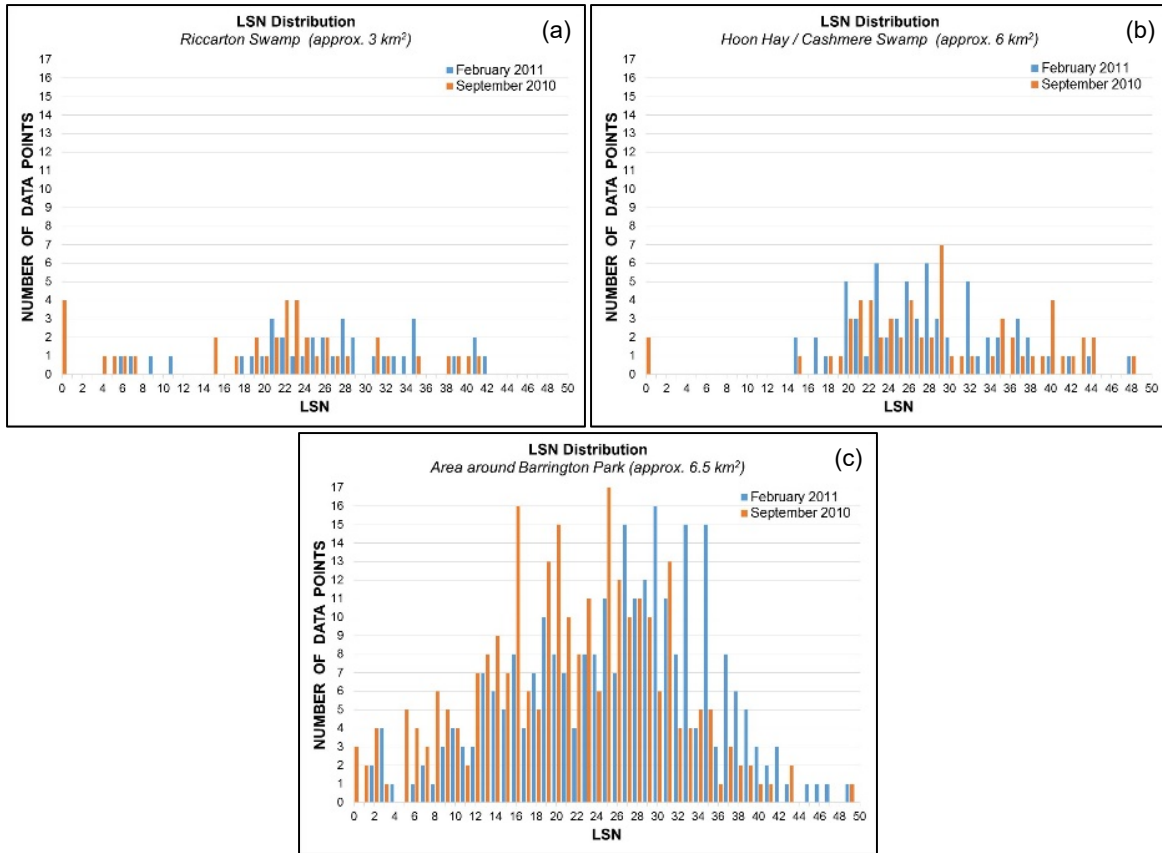


Figure 2.9: LSN distributions for CPTs within the (a) “Riccarton” and (b) “Hoon Hay/Cashmere” swamp zones and (c) around Barrington Park for the 4 SEP 2010 and 22 FEB 2011 earthquakes.

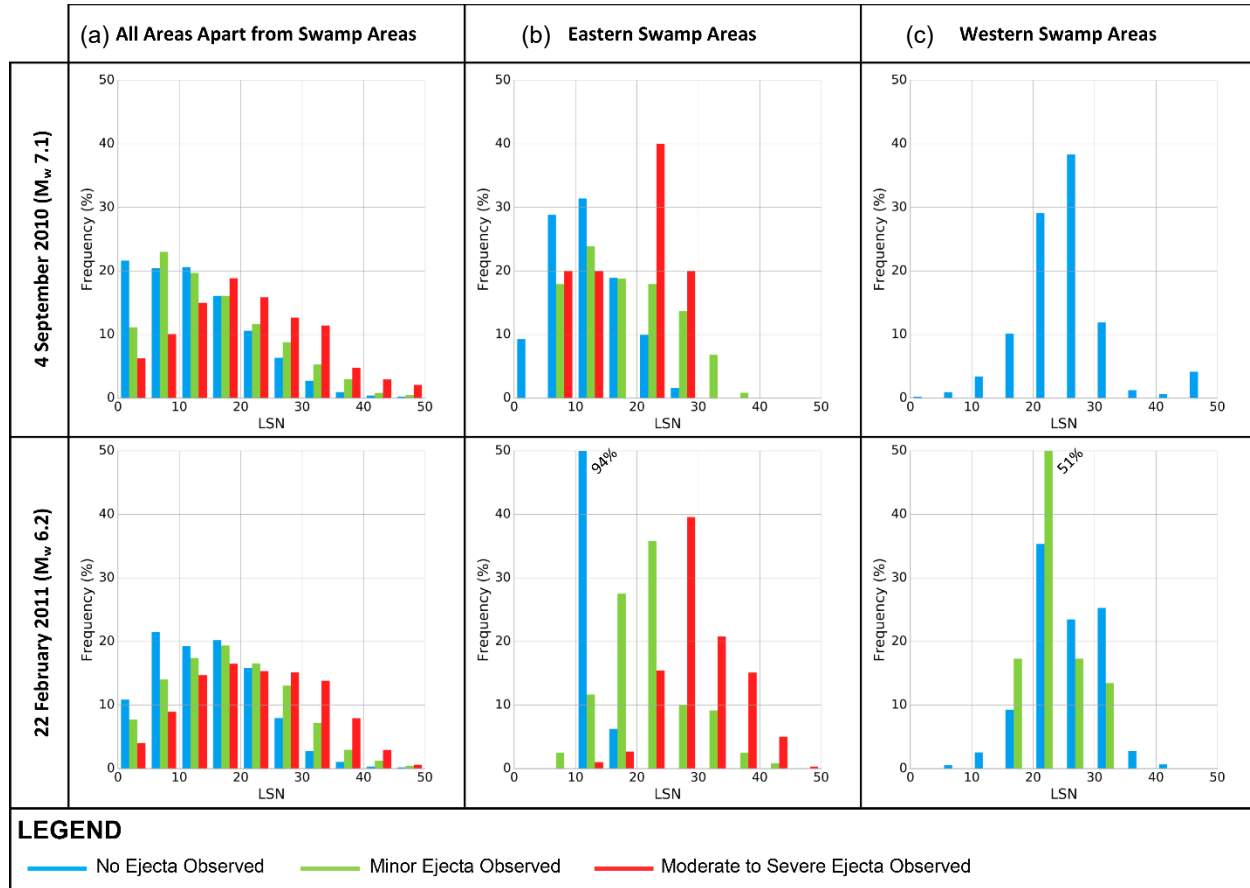


Figure 2.10: LSN distributions for CPTs across greater Christchurch. Histograms are normalized for the purpose of comparing distributions (vertical axis shows frequency rather than CPT count), but in the western swamp areas there are much larger areas of blue relative to the areas of green (refer to Figure 2.1).

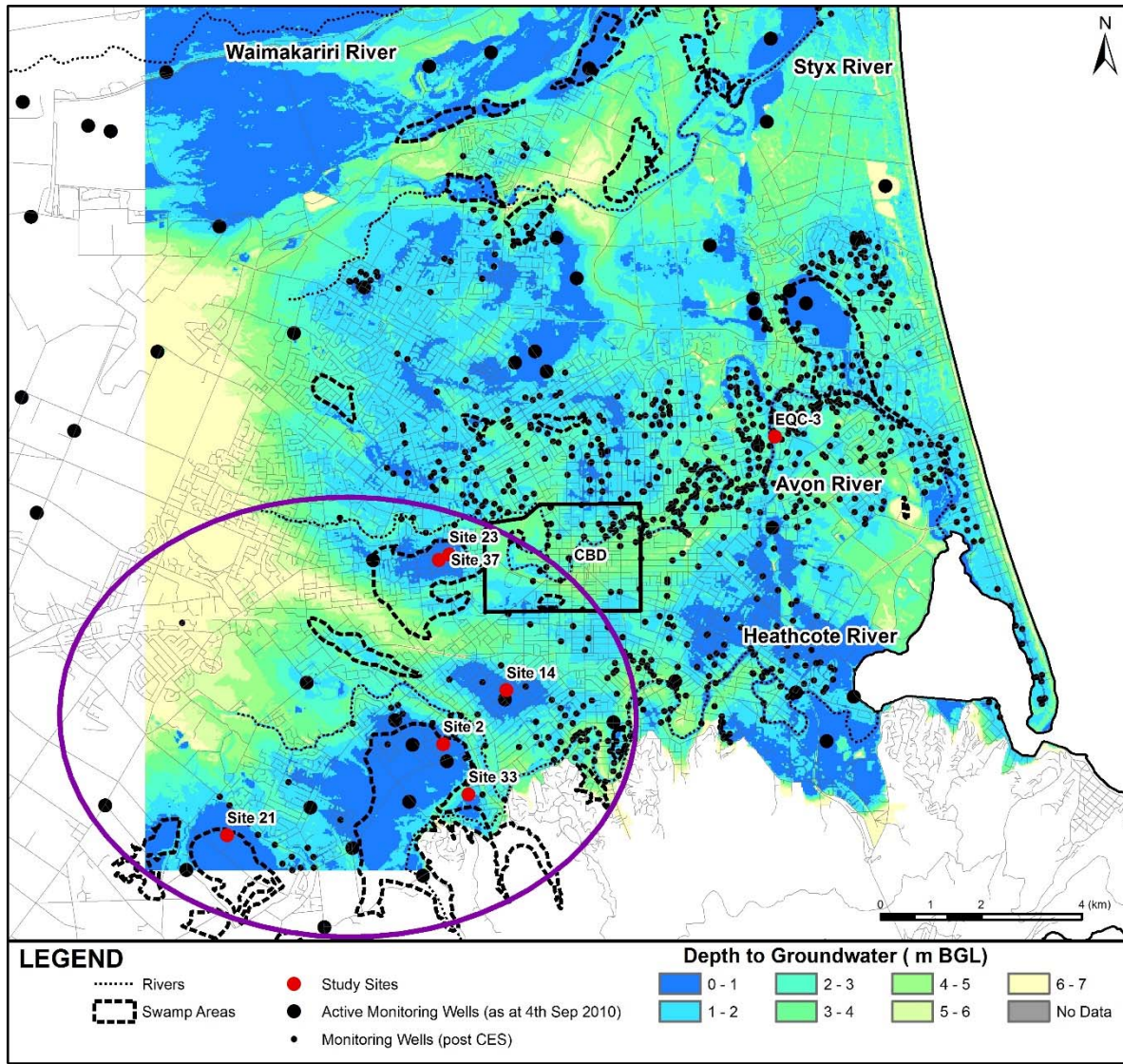


Figure 2.11: Estimated GWT depths immediately prior to the Darfield earthquake. On the regional scale, areas of high GWT cannot be used as the primary indicator to discern areas of liquefaction damage. Circled area indicates study region of SW Christchurch.

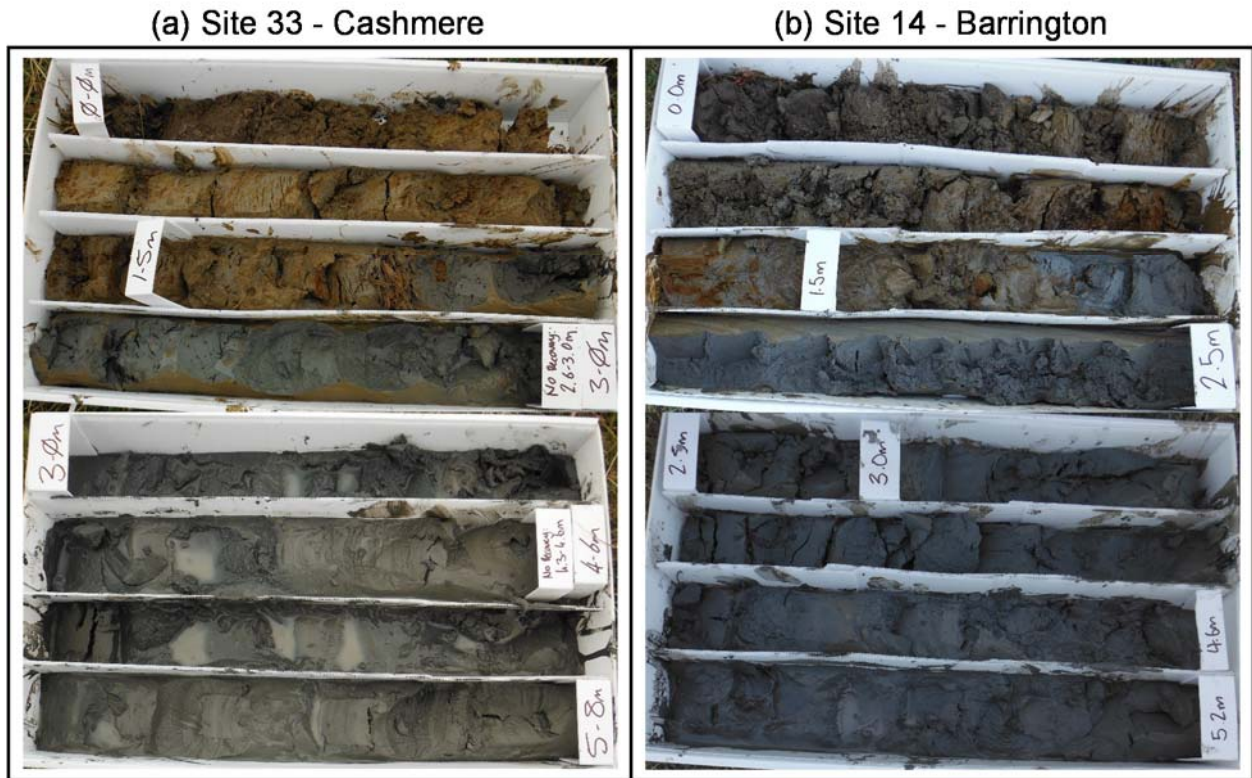


Figure 2.12: Sonic boring core box photographs (Tonkin + Taylor): (a) Site 33, depth of 0-5.8 m and (b) Site 14, depth of 0-5.2 m. Estimated zones of GWT fluctuation: (a) Site 33, 0-1.8 m and (b) Site 14, 0-1.8 m.

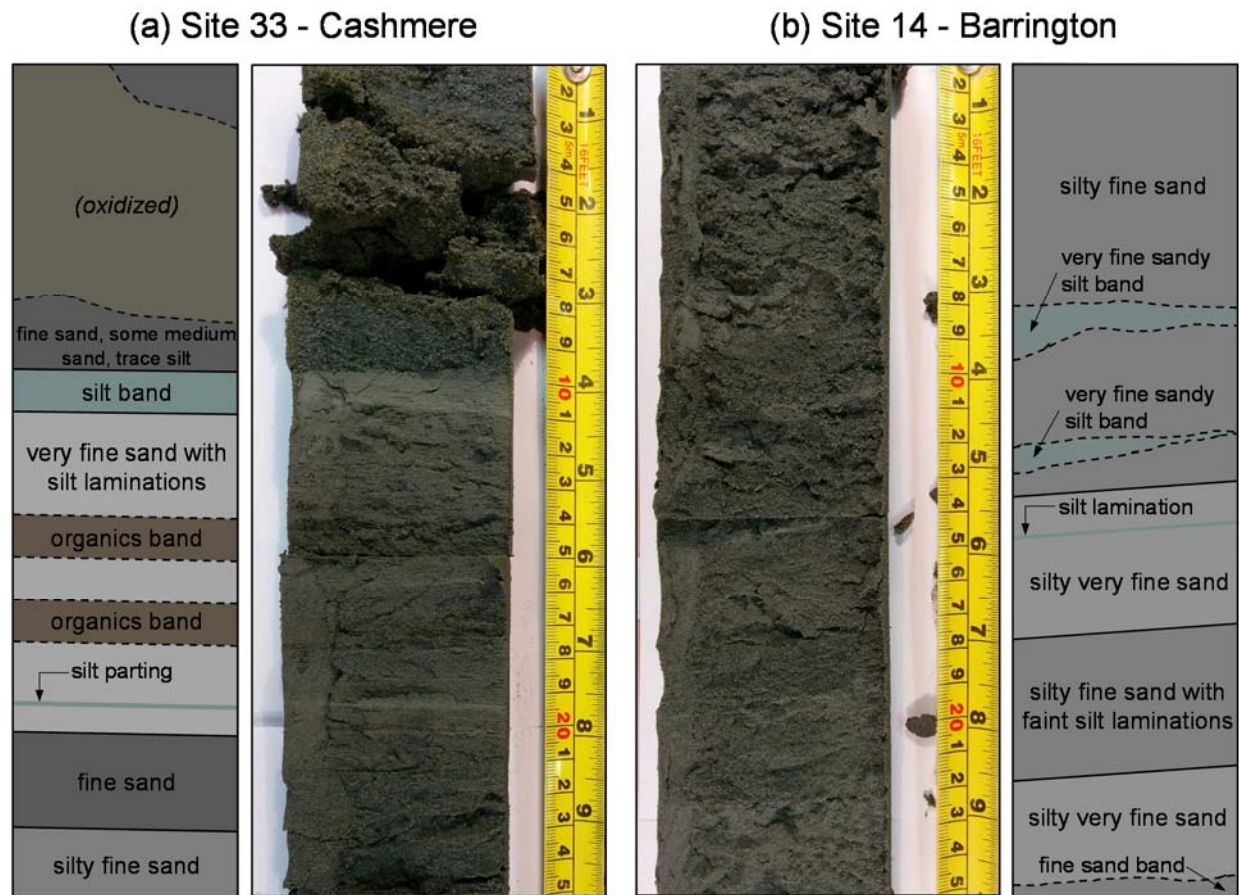


Figure 2.13: High-quality samples (Mini-CPT & DM Project 2016) from the sandy layers at: (a) Site 33 and (b) Site 14. Both samples from depth 3.65-4.10m, cropped to show upper 25 cm of sample.



Figure 2.14: High-quality specimen (post-cyclic testing) from Site 23 (depth 3.39 m) showing layering from the stratified part of the CPT profile (specimen height approximately 14 cm). Note varying silt and sand content throughout specimen, silt laminations, and organic laminations/content.

CHAPTER 3: CHARACTERIZATION OF SILTY SOIL SITES WITH THIN LAYERS AND GROUNDWATER TABLE FLUCTUATION

The contents of this chapter are primarily from a journal article submitted to the ASCE Journal of Geotechnical and Geoenvironmental Engineering by C.Z. Beyzaei, J.D. Bray, M. Cubrinovski, S. Bastin, M. Stringer, M. Jacka, S. van Ballegooy, M. Riemer, and F.J. Wentz entitled: “Characterization of Silty Soil Sites with Thin Layers and Groundwater Table Fluctuation,” which was under review when this dissertation was submitted.

3.1 INTRODUCTION

During the 2010-2011 Canterbury earthquake sequence, multiple earthquake events triggered widespread damaging liquefaction that affected infrastructure in Christchurch, New Zealand. The amount of extensive repeated liquefaction was unprecedented in a modern urban setting. Following the earthquakes, researchers conducted extensive investigations throughout Christchurch (e.g., Cubrinovski et al. 2011). These efforts have been significantly enhanced by the development of the New Zealand Geotechnical Database (NZGD) – a vast regional dataset of subsurface investigation data, consisting of cone penetration tests (CPTs), borehole logs, piezometer readings, shear and compression wave velocity measurements, and post-earthquake observations. Several studies have investigated the occurrence and effects of soil liquefaction. This chapter focuses on sites where post-earthquake liquefaction manifestations were not observed at the ground surface, despite established CPT-based simplified liquefaction assessment procedures indicating liquefaction would be expected to occur. These “no-liquefaction” sites that were investigated are concentrated in the southwestern suburbs of Christchurch and characterized predominantly by silty soil subsurface profiles. Comprehensive subsurface investigations at these silty soil sites revealed interbedded silt and sand deposits. Ongoing research efforts indicate that interbedded silty and sandy soil thin-layer stratigraphy and groundwater table fluctuation are primary factors for the discrepancies between post-earthquake liquefaction observations and simplified method liquefaction estimations (e.g., Cubrinovski et al. 2017). This chapter evaluates the ability of several subsurface investigation techniques to characterize these features.

3.2 CHALLENGES IN SITE CHARACTERIZATION FOR LIQUEFACTION ASSESSMENT OF SILTY SOILS

Conventional site investigation techniques (e.g., CPTs or soil borings with interval sampling) are efficient, provide penetration resistance values for design, and capture major stratum changes. However, they may not capture important details of thin layering and fluctuating groundwater conditions. Alternative investigation techniques such as the mini-CPT and high-quality continuous sampling may provide effective ways to characterize subsurface conditions in greater detail. The mini-CPT utilizes a smaller diameter cone than the conventional CPT, reducing the zone of influence and potentially increasing the resolution obtained in characterizing the subsurface profile. Detailed logging of continuously retrieved soil samples in a controlled setting allows for photographing and taking subsamples of distinct soil layers for index testing at carefully tracked depths. Detailed logging of high-quality continuous samples requires additional effort and may not always be warranted. However, it can provide important insights for those cases where

depositional environment and geologic maps and preliminary site investigations indicate that conventional subsurface characterization tools may be inadequate. The investigation techniques used to characterize stratigraphy can also provide data on groundwater conditions. Considering groundwater level estimates from multiple methods may better characterize important groundwater table fluctuations. These issues are explored in this study.

Christchurch is located in a complex geologic setting, with dominant influences from alluvial and coastal depositional processes. The city is predominantly located upon the alluvial gravels, sands, and silts comprising the outwash plain of the braided Waimakariri River, which have been reworked and redeposited by meandering rivers within the city. Sediments within central and eastern Christchurch are interfingered with coastal and marine fine sands to silts associated with coastline progradation and marine regression (Brown & Weeber 1992). Significant spatial variability exists in the subsurface sediments across the city as a result of the varied and dynamic depositional environments. The southwest region of Christchurch, in which the silty soil study sites are concentrated, is located within the distal flood plains and associated back-swamps of the meandering rivers within the region. The distal floodplain deposits typically comprise thinly interlayered sand and silt strata, while silt-dominant profiles with relatively thick silt layering are present in the silty back-swamps. For the silty soil sites discussed herein, thin layering refers to interbedded distinct layers of silt and sand, gradational zones with increasing or decreasing fines, and laminated silts. The scale of these layers or zones is on the order of millimeters to a few centimeters. Thin layering may occur in strata that are highly interbedded or intermittently within more consistent strata. Thin layers of interbedded silty and sandy materials differ from the particle-scale concepts of fabric (i.e., particle and void arrangement) or structure (i.e., the “*combined effects of fabric, composition, and interparticle forces*,” Mitchell & Soga 2005). For these Christchurch silty soils, the sand and silt layers are comprised commonly of fine sands and coarse silts.

Interbedded thin layers of sand and silt can affect liquefaction potential through their pore water pressure generation, cyclic resistance, hydraulic connectivity, post-liquefaction reconsolidation, and ejecta potential. These effects can limit the potential for liquefaction manifestations at the ground surface. Element laboratory testing indicates that the cyclic resistances of these silty soils are consistent with those estimated from CPT-based procedures (Beyzaei et al. 2017a). However, silt layers within a sand deposit can inhibit water flow and thus affect the system response of an interbedded soil deposit. Seed (1979) notes that even “*a single layer of relatively impervious fine sand or silt in such a deposit would completely invalidate the results of pore pressure dissipation computations for vertical flow*.” Thinly interbedded layers of low-permeability soils mitigate liquefaction manifestations by limiting the development of a thick hydraulically connected liquefiable unit capable of generating significant ejecta and upward flow (Cubrinovski et al. 2017). Thus, interbedded silt and sand deposits should be considered as a soil system wherein the overall response of the deposit cannot be characterized by evaluating each soil layer individually.

Groundwater conditions dictate the portion of the subsurface profile that is potentially liquefiable, with groundwater table fluctuations, artesian conditions, and partially-saturated layers resulting in a complex groundwater regime at the silty soil sites. Groundwater conditions also help define the non-liquefiable crust which can limit manifestations of liquefaction at the ground surface. Ishihara (1985) provides a method to assess the capping potential of an overlying non-liquefiable layer by comparing its thickness with the thickness of an underlying liquefiable layer for a given level of ground shaking. Both groundwater conditions and soil conditions will affect the thickness and integrity of a potentially non-liquefiable crust and its ability to limit surface

manifestations of liquefaction. Detailed characterization of groundwater fluctuations and the non-liquefiable crust may be of importance in liquefaction assessment. For case histories where no liquefaction manifestations were observed at the ground surface, it is difficult to distinguish the relative contributions of the fluctuating groundwater effect and the interbedded silt and sand layer effect discussed previously. This underscores the need for detailed site characterization, to allow for a more comprehensive and well-founded assessment of the contributions from each component.

3.3 SITE INVESTIGATIONS

The silty soil sites shown in Figure 3.1 were investigated by researchers from the University of California - Berkeley, University of Canterbury, University of Texas at Austin, and Tonkin + Taylor, Ltd. through the “silty soils project” and related research (e.g., Beyzaei et al. 2015, 2017a; Stringer et al. 2015). Subsurface investigations included sonic borings, piezometers, CPTs, mini-CPTs, mud-rotary borings with high-quality (“undisturbed”) Dames & Moore (DM) or Gel-Push (GP) sampling (e.g., Markham et al. 2016, Taylor 2015), and direct push crosshole seismic testing (e.g., Stokoe et al. 2014). Investigation data and regional groundwater table maps (T+T 2013, van Ballegooy et al. 2014) are publically available in the NZGD. Table 3.1 summarizes the investigations at each site. In this study, the results of subsurface investigations using conventional techniques are compared with those from alternative investigation techniques at representative silty soil sites to investigate their effectiveness in characterizing interbedded silty soil sites with fluctuating groundwater levels.

Subsurface investigation layouts were oriented and spaced to minimize separation distances (while maintaining sufficient distance to avoid disturbance) and produce a dense array of in-situ tests at each site. The shallow alluvial subsurface environment in Christchurch can vary spatially over short distances (e.g., 5 m). Maintaining spacing of less than 3 m between in-situ tests typically resulted in a reasonably consistent subsurface profile at each site and allowed for direct comparisons between investigation techniques. Disturbance to surrounding soil is caused primarily by penetration and vibration. Sonic borings were judged likely to induce the most disturbance to the soil, followed by mud-rotary borings, CPTs, and mini-CPTs in order of decreasing disturbance. Direct push crosshole seismic testing utilizes conventional CPT probes (Stokoe et al. 2014) with auger-anchors for the CPT rig typically extended 1.5 m below ground surface (BGS). When possible, in-situ tests were advanced in the order allowing for the overall closest spacing (e.g., CPT advanced prior to boring). Site investigation layouts are available at the NZGD. Figure 3.2 illustrates a typical subsurface investigation layout for this study.

3.3.1 Site Descriptions

The study sites are level-ground sites consisting of open areas or light 1-2 story structures. They are considered free-field sites and can be assessed using CPT-based simplified liquefaction assessment procedures (e.g., Boulanger & Idriss 2016). At all sites, the simplified liquefaction assessment procedures using 16%-84% peak ground acceleration (PGA, Bradley 2014) values estimate significant liquefaction potential (Beyzaei et al. 2015, 2017b; Stringer et al. 2015). Similarly, the Ishihara (1985) method indicates that surface manifestations of liquefaction would be expected at the silty soil sites, although the subsurface profiles and groundwater conditions do not quite fit within the Ishihara framework. Three representative sites were selected to investigate key aspects of characterizing thin-layer stratigraphy for liquefaction assessment: sites 14, 33, and

37. CPT tip resistance (q_c) and soil behavior type index (I_c) profiles illustrate the subsurface conditions encountered at these sites in Figure 3.3. Simplified soil layers are also shown. Site investigations focused on subsurface characterization for liquefaction assessment, emphasizing the shallow depths that govern liquefaction performance (e.g., 0-10 m BGS). All sites have non-liquefiable crusts of varying thickness and integrity. These sites represent increasingly layered profiles with a thick, relatively consistent silty sand layer (Site 14), a relatively consistent sand layer with some indication of silty soil thin layering (Site 33), and interlayered silty soils with varying organics (Site 37, also representative of Site 23).

The subsurface profile at each site consists primarily of silty soils, but there are key differences that may impact the potential for liquefaction manifestations to occur. Site 14 is a marginal liquefaction case history site with silty sand critical layers. Liquefaction manifestations were not observed following the 2010 Darfield earthquake (50% PGA = 0.23 g), but were observed following the 2011 Christchurch earthquake (50% PGA = 0.42 g); both earthquakes are estimated to induce significant liquefaction settlements at Site 14 using the simplified methods (e.g., Zhang et al. 2002). Sites 33 and 37 are “no-liquefaction” case history sites wherein CPT methods indicate liquefaction manifestation for the Darfield and Christchurch earthquakes (Site 33: 50% PGA = 0.25 and 0.46 g , and Site 37: 50% PGA = 0.21 and 0.36 g , respectively) due to the presence of a sand critical layer and interlayered silty sand/sandy silt critical layer at each site respectively. Additionally, the critical layer at Site 37 is near the $I_c = 2.6$ cut-off typically used in simplified liquefaction assessments. The selected sites represent the range of soil conditions encountered at the sites shown in Figure 3.1 (i.e., sand, silty sand, sandy silt, non-plastic silt, and low-to-moderate plasticity clayey silt).

Groundwater conditions at each site are estimated to fluctuate as shown in Figure 3.3 based on site-specific data (e.g., sonic boring cores, piezometer data, and crosshole testing). The regional groundwater table maps provide groundwater level estimates at the time of the Darfield and Christchurch earthquakes as well as post-earthquake 15th, 50th, and 85th percentile surfaces (T+T 2013, van Ballegooy et al. 2014). The site-specific data are typically relied upon over the regional maps as they capture groundwater table (GWT) fluctuations that are likely to lead to partially saturated conditions below the NZGD groundwater levels and provide a more robust characterization of groundwater conditions at a site. Comparisons of GWT estimates from the various site investigation techniques will be discussed later in this chapter.

3.3.2 Conventional Site Investigation Techniques

Conventional investigation techniques used in site characterization for liquefaction assessment typically consist of cone penetration tests (CPTs) or mud-rotary borings with standard penetration test (SPT) samples. An overview of these conventional investigation techniques is presented below.

3.3.2.1 Cone Penetration Tests

CPTs can provide a continuous profile of significant data, including tip resistance (q_c), sleeve friction (f_s) and pore water pressure (u_2), which is interpreted to develop subsurface profiles. Some CPT equipment can retrieve soil samples for index testing. Shallow refusal may be an issue. CPT data and stratigraphy interpretation are affected by the cone diameter relative to the scale of soil layering and soil type. Conventional cones are either 10 cm² (35.7 mm diameter) or 15 cm²

(43.7 mm diameter). CPT data are typically recorded at depth intervals of 10-50 mm, with readings affected by a zone of influence of as small as 2-3 cone diameters in soft soils up to 20 cone diameters in stiff soils (Lunne et al. 1997). Assuming a zone of influence of at least 5 cone diameters for a loose sandy silt, each reading of a 10-cm² cone represents an average value over a thickness of at least 180 mm. Interlayered soils with contrasting stiffness have two primary effects on CPT measurements (Ahmadi & Robertson 2005): (i) limiting the tip resistance of sand layers within softer soil layers, and (ii) incorrect classification of soil type because of the zone of influence and “drag length” of the friction sleeve. These two effects, often described respectively as “sensing ahead” or “smearing,” respectively, require judgement or soil samples when interpreting CPT data to develop subsurface profiles. A conventional CPT does not have the resolution required to characterize thin soil layers that may be on the order of only a few millimeters to a few centimeters thick.

Thin-layer corrections have been recommended for adjusting the measured tip resistances within stiff layers located between softer soils. Thin-layer correction curves for conventional cones are based on a single stiff thin layer within a homogeneous soft thick deposit and change steeply for layer thicknesses less than 500 mm; the recommended relationships are typically applied to layers that are at least 200-300 mm thick. Ahmadi & Robertson (2005) examined the effects of layered deposits on q_c measurements through numerical simulations and found that sand layers less than 150 mm thick are too thin to develop the fully mobilized tip resistance in the sand layer. Youd et al. (2001) state that the correction “*applies only to thin stiff layers embedded within thick soft layers,*” which does not correspond to subsurface conditions at the silty soil case history sites. At the studied sites, the subsurface soils are not clearly contrasting “stiff” or “soft” layers, and instead, typically consist of highly interlayered silty sands, sandy silts, silts, and clayey silts. Within the zone of influence of at least 180 mm thick for the conventional cone in sandy silt, the combined influence of multiple thin soil layers will be captured. There are no reliable procedures available currently to correct the q_c value measured at the highly interlayered silty soil sites with distinct soil layers thinner than 150 mm.

3.3.2.2 Soil Borings

Mud-rotary borings with SPTs are often used to characterize sites for liquefaction assessment. However, there are numerous limitations in the use of the SPT (e.g., Youd et al. 2001). Without energy measurements, the SPT blow count value (N) is uncertain (Sancio & Bray 2005). SPT samples are disturbed due to the manner in which they are retrieved, and as they are typically taken at 1-m to 1.5-m depth intervals, key features may be missed. Sample recovery can be an issue in some soil deposits, and a sand catcher should not be used, because it affects the SPT N -value.

Current practice in Christchurch favors sonic borings with core samples to establish the subsurface profile combined with CPTs to characterize penetration resistance for liquefaction assessment. The sonic boring cores provide disturbed soil samples due to intense vibration during boring advancement (Wentz & Dickenson 2013). Moreover, they may be significantly disturbed depending on soil type, method of retrieval, transportation, and storage. Core samples are typically retrieved in plastic core barrels of 1.5 m length and conventionally stored in the core barrel itself or shaken (or washed) out of the barrel into a core box for storage. This method of retrieval, coupled with the lack of sample confinement and disturbing effects during handling, results in a sample that is often highly disturbed, such that in-situ thin layering may not be preserved.

Additionally, it can be difficult to carefully track sample depths because of separation and compression of soil in the core barrel or box. Thus, sonic borings provide a potentially continuous, but rough characterization of the subsurface profile and major strata. Figure 3.4 shows an example of sonic boring core samples placed in core boxes in the field prior to transportation. Major stratum changes are visible, but thin-layering is not well preserved or readily observed. Sonic boring core sample quality could potentially be improved through more careful handling, storage, and transportation procedures than conventionally employed. However, the sonic drilling method itself induces significant vibrations and disturbance during the sampling process. Disturbance is especially pronounced for the loose sandy soil layers most often of concern for liquefaction assessment.

3.3.3 Alternative Site Investigation Techniques

The interlayering of silty soils in southwest Christchurch necessitates more in-depth subsurface investigations to evaluate the ability of conventional investigation techniques to provide detailed site characterization for liquefaction assessment. Two alternative techniques are explored in this study. The miniature CPT (mini-CPT) was proposed as an alternative to the conventional CPT to capture soil layering in greater detail while still utilizing CPT-based methods for liquefaction assessments without increasing costs excessively. Continuous high-quality sampling with detailed logging of the retrieved samples was performed to establish what is considered the actual in-situ layering of the silty soil deposits in Christchurch, for use in evaluating the mini-CPT and conventional site investigation tools. The following sections describe briefly each alternative method.

3.3.3.1 Mini-CPT

Mini-CPTs provide higher resolution on soil layering due to the smaller cone diameter compared with the conventional CPT. Investigations presented in this chapter utilized the ConeTec 5-cm² mini-CPT, which is capable of measuring q_c , f_s , and u_2 . Individual load cells are used for the tip resistance and sleeve friction (i.e., not a subtraction cone), which enables more reliable measurements (Lunne et al. 1997). Inclinator instrumentation is not included. The 25.2-mm diameter 5-cm² cone produces a zone of influence at least 120 mm thick in loose sandy silt. The reduced zone of influence should allow for a more detailed characterization of soil layering, but its scale is still larger than that of the thin layers at the silty soil sites. A 2-cm² mini-CPT was not used because it did not include a pore water pressure sensor (due to physical space limitations within the probe), was a subtraction cone, and was less suitable for the variable Christchurch soil deposits because of potential difficulties with controlling verticality, maxing out the load cell, reaching refusal at too shallow a depth, and damage to the cone.

During the mini-CPT field program, equipment and measurement issues were encountered in several soundings. These included voltage discrepancies between the cone and recorded baseline file, unacceptable baseline shifts, a sharp drop in recordings, and subdued recordings relative to the standard cone. Six mini-CPTs provided usable data from the ten mini-CPTs that were advanced. Of the four mini-CPTs that were not usable, one exhibited an unexpected drop in tip resistance and three exhibited subdued tip resistance. In a post-testing equipment examination and recalibration by ConeTec, no mechanical faults could be identified. Electrical and power supply

problems were postulated as potential causes of the issues encountered. Data from recordings that did not pass ConeTec's quality checks were not included in the site investigation records.

3.3.3.2 Continuous High-Quality Sampling

High-quality ("undisturbed") soil sampling was conducted using the Dames & Moore (DM) hydraulic fixed-piston thin-walled tube sampler in mud-rotary borings (Figure 3.5). Smooth brass sample tubes (outer diameter = 63.5 mm, inner diameter = 61.2 mm) with a constant inner diameter and a sample length of 450 mm were used. Continuous sampling was conducted from a depth of 0.5 m to 6.8 m below ground surface (Figure 3.3) to obtain a continuous profile in the shallow soils governing liquefaction response and manifestations at these sites. Thin layering was preserved in the DM samples. Markham et al. (2016) provide further details on the DM sampler and its performance in Christchurch soils.

3.4 DEVELOPMENT OF THE HIGH-QUALITY SAMPLING SOIL PROFILE

Continuous high-quality samples were logged in detail to establish the actual soil profile for the upper 6.8 m at sites 14, 33, and 37. The resulting sample logs document features potentially affecting liquefaction response, which are not readily observed or measured through conventional investigation techniques. The detailed logging presented in this chapter characterizes the occurrence, scale, and soil type of thin layers occurring at silty soil sites and provides insight on gradational zones, organic content, groundwater table fluctuation, and water movement. Actual layering profiles from the representative sites were established to identify differences potentially affecting the occurrence and manifestation of liquefaction and for comparison with the sonic boring, CPT, and mini-CPT to assess the level of detail obtained. In addition to assessing the layering structure of silty soil deposits, the detailed logging also characterizes important details and potential thickness of the non-liquefiable crust, which is another key component of the system response of a potentially liquefiable soil deposit.

Laboratory extrusion of high-quality DM samples was performed by extruding the sample in the same direction in which it entered the tube to reduce disturbance. Some samples (e.g., often sandier or stiffer soils, or soils that squeezed out during extrusion) required cutting the sample tube to avoid excessive compression at the bottom of the specimen. Samples were extruded vertically, removed with a wire saw in segments approximately 15 cm tall to avoid collapse under self-weight, and marked upon removal from the extruder to ensure proper alignment of segments. Samples were scored with a spatula and manually split open lengthwise to avoid smearing the inside surfaces. Samples were then photographed and logged collaboratively by a geotechnical engineer and an engineering geologist. Visual, tactile, and auditory observations were used to develop the detailed log for each sample considering geotechnical and geologic classifications (e.g., ASTM D2487, D2488, D1535). Noted features included extrusion details, color, soil type, consistency, moisture, layering, gradation zones, voids, organic content, iron-staining, and mottling.

Extruded samples demonstrated that high-quality sampling preserves in-situ layering. This prevents mixing of fines and allows for selective subsampling with careful depth tracking, in contrast with bulk samples obtained from disturbed sonic cores or SPT samples. After completing a detailed log for each sample, several subsamples for index testing were selected at carefully tracked depths within the 450-mm long soil sample. Subsamples were selected to characterize both

the overall stratum characteristics and within-stratum variability. Typically, three subsamples were taken from each sample. In cases with significant layering, subsamples were closely spaced to assess variability over depth intervals of centimeters. Each subsample typically encompassed a depth interval of 20-140 mm. Some layers were so thin that subsamples could not be selected from the individual layer or a sufficient quantity of soil could not be obtained for index testing. This detailed logging of continuous high-quality samples, combined with the dense array of CPTs and borings, allows for the actual subsurface profile to be developed confidently.

Plasticity index (PI) and hydrometer testing were conducted on subsamples following ASTM standards D4318 and D422. Soil index testing tended to confirm visual classifications from detailed logging. However, several samples visually classified as silty sands were classified as sandy silts (with just over 50% fines content) based on index testing, emphasizing the difficulty in conventional classification of these borderline fine sands/coarse silts and the importance of depth-tracked subsampling and soil index testing of layered silty soils in alluvial environments such as in Christchurch. The index testing of subsamples also emphasized the importance of not mixing soil over depth intervals that produce a composite soil that does not reflect the actual in-situ composition of each discrete soil layer. Characterization of bulk samples can result in a misleading liquefaction assessment.

3.4.1 Detailed Logging: Layering Types

Sample photographs in Figure 3.6 illustrate the stark contacts, distinct thin-layering, and gradational zones often found in the soil samples retrieved from the soil deposits created in the dynamic fluvial environment of the Canterbury Plains. These samples also demonstrate the nature of many of the silty soils in Christchurch, which consist of uniform fine sand-sized particles and uniform coarse silt-sized particles. In these cases of uniform, nonplastic to low-PI, quartz silty sands or sandy silts, fines content determined using the #200 sieve (i.e., 75 μm) is likely insignificant in describing key aspects of soil behavior; soil gradation and plasticity will be of greater importance as evidenced by laboratory testing (Beyzaei et al. 2017a) and the practical experience in Christchurch of several of this paper's authors. Soil samples from sites 14, 33, and 37 repeatedly demonstrated these characteristics: silts, sandy silts, and silty sands occurring in distinct layering sequences, less distinct layering sequences, and gradational zones that are not easily characterized by a single fines content or grain-size composition. Evaluating detailed logs leads to a more complete characterization of features affecting liquefaction potential at a site.

A major challenge in the detailed characterization of thin layering of predominantly fine sands and coarse silts is defining what constitutes a discrete layer. Detailed logs aimed to capture all changes in visual classification. Layers were identified and noted for any observed differences, including differences such as the predominant sand grain type (e.g., medium vs. fine sand). The layering established to characterize the actual in-situ soil profile could be subsequently re-assessed to consider layering with regard to more general soil type or hydraulic conductivity changes that may affect pore water pressure generation and dissipation during liquefaction, resulting in combining some layers. The depth interval over which multiple layers may be combined, which at the silty soil sites is often on the order of only 50-100 mm, will depend on potential differences in response to be captured. However, understanding those differences in response in a layered deposit depends heavily on the interval captured in an "undisturbed" cyclic testing specimen. Beyzaei et al. 2017a showed differences in liquefaction response primarily due to plasticity, but it is difficult to estimate plasticity when layers are too thin to obtain enough soil for index testing.

Figure 3.7 provides graphical detailed logs and photographs for two soil samples from the same depth at Sites 14 and 33 to compare soil layering in the critical layer at each site. The stratigraphy features captured by the detailed logs lend insight into differences between the two sites that may affect liquefaction manifestation at the ground surface (noting the important caveat that these free-field sites may have performed differently had there been heavy structures at each site). Site 14 (Figure 3.7b) shows a more consistent sandier silty sand matrix, while Site 33 (Figure 3.7a) shows a sand stratum with intermittent distinct silt layers and zones of thinly layered silty soils within the sand stratum. There is clear, distinct thin-layering on the scale of millimeters and centimeters at Site 33; whereas Site 14 is characterized more by gradational zones and less distinct, contrasting layering. Manifestations of liquefaction were observed at Site 14 and not at Site 33 for the intense shaking of the Christchurch earthquake (50% PGA = 0.42 *g* and 0.46 *g*, respectively). The tactile classifications of detailed logs and index testing of subsamples are required to distinguish the nuanced soil layering that affected the differing responses of these sites. Such differences are not well-captured by conventional investigation methods, as will be discussed in the following section.

3.5 THIN-LAYER STRATIGRAPHY COMPARISONS

The occurrence of thin layers within a stratum may be intermittent or characteristic of the stratum as a whole (e.g., varved glacial soils). To assess the effectiveness of conventional and alternative site investigation techniques at capturing the layering details of the actual in-situ profile established using detailed logging, conventional CPT and mini-CPT are compared with the detailed logging of continuous high-quality samples. Conventional sonic borings provide too rough a characterization to identify and to characterize thin-layering, although they provide useful preliminary data on major strata. Shear wave velocity profiles, such as from direct push crosshole seismic testing, are also useful for interpreting major stratum changes, but they do not provide the level of detail necessary to discern thin-layering on the order of millimeters and centimeters, such as may affect liquefaction potential at these interbedded sandy/silty soil sites.

3.5.1 Mini-CPT

Figure 3.8 compares the mini-CPT and conventional CPT at Sites 14, 33, and 37. At these sites, the mini-CPT generally matches the conventional CPT for tip resistance (q_c) and soil behavior type index (I_c). A comparison of the profiles at major stratum changes (i.e., at about 3 m BGS at Sites 14 and 33, and at about 2 m BGS at Site 37) confirms that the data do not need to be depth-adjusted to account for differences in ground surface elevation between the closely spaced CPTs. At sites with multiple mini-CPTs, there is some variation among the mini-CPT profiles, but their subsurface characterization produces essentially the same profile as does the conventional CPT. Contrary to what was hoped by one of the funding agencies, the 5-cm² mini-CPT does not lead to significantly improved resolution over the conventional CPT for the sites studied. However, the evaluation of multiple mini-CPTs highlights additional variability in the subsurface conditions. At Site 33, the mini-CPTs also show systematically higher tip resistance measurements in the thin sand layers within the interbedded zone of the sand stratum, indicating an improvement on q_c measurement relative to the conventional CPT, which is consistent with the understanding of thin-layer effects on q_c estimates discussed previously.

3.5.2 Detailed Logging

Figure 3.9 compares a detailed log and photograph of a high-quality soil sample, mini-CPT and conventional CPT traces, and sonic boring core sample photograph from the same depth at Site 33. The mini-CPT and conventional CPT cones cannot detect the thin layers of the actual soil deposit over this depth interval; they obscure the true nature and scale of the in-situ layering. The two mini-CPT traces indicate slightly more variation of soil properties with depth and importantly the inherent lateral spatial variability of the soil deposit over short distances. For the purpose of liquefaction assessment, the detailed log based on careful examination of high-quality samples and accompanying photograph provide valuable insights on thin-layering that can influence pore water pressure dissipation. The vertical hydraulic connectivity across what was identified by the CPT as a relatively homogenous sand layer with slightly siltier points is restricted in the actual soil deposit by numerous layers of silt. The conventional sonic boring produced a soil sample without sufficient resolution for characterization of the actual in-situ layering.

Particle size distributions from hydrometer testing on the detailed logging subsamples indicate the broad range of soil types encountered at the sites studied. As shown in Figure 3.10, soil types range from clean sand to clayey silt. There are several key observations to be made from examining these plots: (i) the broad range of soil types present (Figure 3.10a,b,c); (ii) significant variation of soils over small depth intervals (Figure 3.10b,c); and (iii) uniformity of the particle size distribution curves (Figure 3.10b). An additional issue is the potential difference in characterization depending on the test method used. Figure 3.10d presents particle size distributions for two samples at approximately the same depth in adjacent borings, representing a difference observed between hydrometer data and the laser method alternative for finer particle sizes, most noticeable in clay-size fraction (< 0.002 mm). Hydrometer data showed a clay-size fraction up to 40%, whereas the laser method did not show a clay-size fraction greater than 5% for any soils tested. Hydrometer data also indicate that soils tend to be siltier than visual classifications from detailed logging, which emphasizes the challenges in using fines content to characterize silty soil deposits wherein the soils have uniform particle distributions with varying amounts of the soil falling just above or below the #200 sieve. Conventional soil samples, which often mix soil from different layers during collection of bulk samples and require thorough mixing before index testing as per ASTM, and the CPT, which measures cone tip resistance and sleeve friction over a zone larger than the scale of the thinly layered soil deposit, cannot capture the detail of these key aspects of the soil deposits at the silty soil sites in Christchurch.

3.5.3 CPT-based Correlations

Correlations to estimate engineering properties from CPT data are often employed. A primary CPT-based correlation used in liquefaction assessment is that of fines content (FC) and soil behavior type index (I_c). Much research has focused on the FC- I_c correlation, with recent efforts focused on the Christchurch-specific dataset (Robinson et al. 2013; Lees et al. 2015; Boulanger & Idriss 2016). Typically, a bulk sample wherein the soil is thoroughly mixed for index testing is used to estimate FC which is then correlated with I_c from a CPT at some distance from the boring. However, soil deposits with interbedded thin layers are not well characterized by such samples. Additionally, in spatially variable environments such as Christchurch, horizontal separation distance between an adjacent boring and CPT may lead to misleading correlations. The dense arrays of subsurface investigations in this study provide carefully depth-tracked soil

subsamples from closely spaced borings and CPTs to evaluate the FC- I_c correlation with greater precision than what is typically available. Subsamples were selected to ensure a representative FC for the depth being subsampled. This study tracked FC variations over depth intervals of a few centimeters in borings performed within a meter or so of multiple CPTs performed before the soil boring.

To supplement the detailed logging data from this study, a set of FC- I_c data from the silty soils project cyclic triaxial (CTX) specimens (Beyzaei et al. 2015, 2017a; Stringer et al. 2015) with particle size distributions obtained via laser diffraction method are also considered. Detailed logging subsamples cover depth intervals ranging from 10-20 mm to 100+ mm, while CTX specimens typically cover a 140-mm depth interval corresponding to the test specimen nominal height. Borings were typically no more than 3 m from the CPT used for this comparison. The close spacing of the dense array and careful tracking of sample depths provides the opportunity for comparisons using two datasets of greater precision than typically achieved.

Figure 3.11 presents FC- I_c data from the two aforementioned studies with the Boulanger & Idriss (2016) (“BI16”) FC- I_c correlation. Data shown in Figure 3.11 minimize potential correlation issues due to spatial variability through the dense array and due to averaging of FC over large depth intervals through careful depth-tracking of subsamples. The scatter of data in Figure 3.11 indicates that the FC- I_c correlation, as currently established, does not accurately reflect the layered in-situ conditions at the studied silty soil sites in Christchurch. Based on the CPT comparison with detailed logging, the clear issue is that the CPT (and I_c) cannot capture adequately stratification of these thin-layers. The FC- I_c correlation is based on I_c , so in these soils it is not necessarily an issue of the correlation needing to be refined. Instead, the CPT cannot identify the scale of the layering which means that I_c measurements do not reflect in-situ layering, and the FC of the soil will not match the correlation-based estimate in thinly layered deposits. For these soils, I_c is smeared over thin layers and presents averages that are not aligned with the actual nature of the in-situ soil deposit in the same way that mixed bulk samples without careful depth-tracking create an average soil that is not representative of in-situ conditions. In addition to distinct layering, gradational zones as shown in Figure 3.6 are also not necessarily well-represented by a single FC estimate. Other parameters estimated from CPTs, such as relative density (which also requires proper estimates of e_{max} and e_{min} for comparison with retrieved or in-situ soil), encounter similar issues in these interbedded soil deposits. The practical engineering need to simplify subsurface profiles and develop average estimates of soil properties should be balanced with the need to understand the implications of the averaging that occurs in developing correlations before applying them in engineering practice.

The studies assessing Christchurch-specific FC- I_c data against the BI16 correlation developed for liquefaction triggering assessment typically consider large geographic regions and bulk samples that may combine soil over not well-tracked depth intervals from sonic borings, approaching the correlation through the statistical assessment of a large dataset rather than a detailed view at individual sites. Detailed data such as produced by this study should be considered for possible revisions to the FC- I_c correlation, as well as considering whether or not CPT data (and the interpreted parameter I_c) accurately capture in-situ soil conditions at the level needed for liquefaction assessment at layered silty soil sites and the correlation’s applicability in different soil types and depositional environments.

3.6 GROUNDWATER TABLE CONDITIONS

Liquefaction occurs in saturated soils through the generation of excess pore water pressure. Thus, the groundwater conditions are crucial to assessing liquefaction at a site, especially in regions where the groundwater table may fluctuate significantly. In some cases, a sensitivity analysis on groundwater conditions will be sufficient for liquefaction assessment in practice, but for cases where a fluctuating groundwater table, liquefiable layers, and foundation level coincide, a more thorough characterization of groundwater conditions may be warranted.

The conventional and alternative site investigation techniques discussed previously for characterization of thin layering also provide the opportunity for refining groundwater level estimates. Piezometers, sonic boring core samples, direct push crosshole seismic testing, high-quality samples, and regional groundwater models provide data on groundwater table depth and fluctuation at the silty soil sites. Measurements by these methods were performed at different times following the Canterbury earthquake sequence, often separated by months or years. Each method measures data within a different length of time and has a different rate of measurement (e.g., piezometers can provide continuous measurement, while soil samples can indicate fluctuating conditions over time through iron-staining). These differences contribute to variation in the estimated groundwater levels, because each method measures a different facet of often dynamic groundwater conditions. Within Christchurch, seasonal groundwater table fluctuations can be on the order of 1-1.5 m. Artesian conditions exist in some cases (i.e., head higher than ground surface), as well as cases where groundwater head is higher than hydrostatic conditions but not quite artesian. Groundwater levels obtained from these multiple methods that measure different features of groundwater conditions allow for estimating the range of groundwater table fluctuation, including high and low estimates.

Piezometers are considered the primary site-specific source of GWT characterization. They provide direct point measurements of groundwater level readings over time, capturing seasonal fluctuations if operated over a long period (Figure 3.12). However, piezometers only reflect the standing water level at the time of each measurement and do not capture zones of partial saturation. Sonic boring core samples and high-quality samples provide insight on GWT fluctuation through observations of iron-staining, mottling, discoloration, and where the samples become wet. The depth at which iron-staining ceases is the estimated low GWT. Issues with tracking depths in conventional sonic borings may affect the accuracy to which GWT depths can be estimated. Figure 3.13 presents DM sample photographs from the zone of GWT fluctuation at Site 14, showing the condition of iron-staining and sandier portions that affect the integrity of the non-liquefiable crust. For sites where the integrity of the nonliquefiable layer is in question, detailed logging allows for thorough characterization including soil type, root voids, and organic content. Compression wave velocities (V_p) such as from crosshole seismic testing provide insight on saturation with depth. Partially-saturated conditions may increase the thickness of the non-liquefiable layer, depending on the degree of saturation and corresponding increase in cyclic resistance. Typically, $V_p \geq 1500$ m/s is considered full saturation and $V_p \lesssim 500$ m/s is considered unsaturated. Depths with V_p between these values are considered partially saturated, with liquefaction resistance increasing as saturation decreases. Laboratory testing on clean sands has indicated that V_p values as low as 800-900 m/s may increase cyclic resistance by approximately 20% (Tsukamoto et al. 2002). The depth to full saturation is taken as an estimate of the low groundwater table, although ongoing research is investigating the potential occurrence and effects of partial saturation below the estimated low GWT (Cubrinovski et al. 2017; Brady Cox, personal communication). Regional groundwater table

maps provide estimates of the groundwater table for the 2010 Darfield earthquake, 2011 Christchurch earthquake, and the post-December 2011 groundwater regime (T+T 2013, van Ballegooy et al. 2014). The groundwater models used to develop the regional maps cross-correlate water level records from piezometers installed prior to the Canterbury earthquake sequence with water levels from piezometers that were installed after the Canterbury earthquake sequence and backward extrapolate the post-CES water level records using seasonal fluctuations to project groundwater levels immediately prior to the earthquake events (T+T 2013).

Figure 3.14 summarizes groundwater data from piezometers, sonic borings, DM samples, and direct push crosshole seismic testing, illustrating the different groundwater levels estimated using the different site-specific measurements. The groundwater levels shown in Figure 3.14 for the Darfield earthquake, Christchurch earthquake, and post-December 2011 regime were estimated using the regional groundwater maps. The high and low GWT depths shown in Figure 3.14 were estimated considering all available GWT data from the above described methods. For example, at Site 33, iron-staining in the sonic boring core samples indicates that soil below 1.8 m is rarely exposed to air even as the water level fluctuates, whereas crosshole testing shows full saturation at about 2.2 m depth at the time of testing. The piezometer at Site 33 provides readings within 1-2 m of the ground surface, at times within 0.5 m of the ground surface. However, the piezometer screen was installed from about 3-6 m below ground surface and slight artesian pressures are possibly being measured below 2.5 m in the sand layer capped by the overlying silt layer, with potentially 10-15 kPa artesian pressure below 2.5 m depth. Considering the above measurements, the Site 33 low GWT was estimated to be at 2 m depth. In regions with dynamic groundwater regimes such as Christchurch, it is beneficial to utilize all available data to obtain as complete a picture of groundwater conditions as possible. Any one of these techniques alone is likely not sufficient to capture definitively GWT conditions, but evaluating multiple measurements which capture various aspects of the fluctuation and high and low GWT provides a more confident characterization of GWT conditions at a site. Regional groundwater table maps (T+T 2013, van Ballegooy et al. 2014) based on piezometer data and groundwater modeling supplement this and can be used for point time/location data that is then confirmed via the site-specific groundwater characterization using the techniques discussed previously.

3.7 CONCLUSIONS

Christchurch silty soil sites can vary over depth intervals as small as a few centimeters. Mini-CPT and standard CPT smear across thin layers, because of the large size of the cone relative to the layer thickness. The cones measure average properties over zones of influence too large to capture accurately in-situ layering at the scale necessary to discern the silty soil layering that impacts liquefaction manifestations at the studied sites. The 5-cm² mini-CPT does not significantly improve thin layer characterization over the conventional CPT, but it does show increased q_c estimates in thin sand layers relative to the conventional CPT and demonstrates additional variations in the subsurface profile that can provide insight into overall interpretation for characterization. Conventional sonic borings do not adequately preserve thin layering for detailed characterization purposes.

Estimating fines content through a $FC-I_c$ correlation is unreliable in thinly interbedded silty soils, because of the limited level of detail obtained with the CPT and the typical practice of bulk sampling that mixes several discrete soil layers. Using data from widely spaced soil samples and

CPT locations is also problematic. For liquefaction assessment at silty soil sites, the focus should be on variations in hydraulic conductivity and plasticity and not fines content.

Groundwater conditions are difficult to capture at sites with significant GWT fluctuation and possible partial saturation effects. Multiple investigation techniques should be employed to obtain a robust characterization if groundwater conditions are likely to be a significant issue. If regional knowledge or preliminary investigations indicate GWT conditions are not likely to be highly variable, they could be evaluated with a sensitivity study during liquefaction assessment. However, in other cases, it is beneficial to use all tools available for critical projects to develop a robust understanding of GWT conditions at a site.

High-quality samples with a careful extrusion process and detailed logging preserve in-situ features that may impact liquefaction assessment and provide the opportunity for detailed characterization of those features. Depositional environment can indicate that high-quality sampling and detailed logging may be warranted when the site geology differs from that of the case histories used to develop the simplified liquefaction assessment methods. Conventional CPT profiles can also indicate the need for detailed logging of high-quality samples, when the profile indicates silty soil conditions that differ from better understood thick sand deposits. Continuous high-quality sampling can be performed in the potential critical layer identified by the CPT when some thin-layer stratification is suspected. Detailed logs and index testing can be used to assess the actual subsurface conditions that affect liquefaction assessment. CPT profiles can be calibrated using detailed logs of high-quality samples and then further used to assess spatial variability at a site. Further research on site characterization techniques for stratified silty soils is warranted, focusing on characterization of the actual in-situ profile and translating that profile into meaningful properties for liquefaction assessment.

Based on the findings from this study, the following approach to characterizing sites with thin soil layers and groundwater fluctuations is recommended:

1. Consider depositional environment to assess if interbedded deposits are likely to be present.
2. Conduct preliminary site investigations using conventional methods (e.g., CPT and interval-sampling) and simplified liquefaction assessment. Assess the need through sensitivity analyses and judgment for more detailed site investigations to characterize adequately the apparent critical layer, interbedded layers, and non-liquefiable crust.
3. Conduct high-quality continuous sampling and detailed logging at locations adjacent to the most representative CPTs if thinly interbedded materials are suspected.
4. Implement multiple methods to characterize complex groundwater conditions if warranted.
5. Develop soil profiles from detailed logs to characterize interbedded soils (noting variations affecting hydraulic conductivity and plasticity), the apparent critical layer, and thickness and soil type of the potentially non-liquefiable crust (noting features that may affect crust integrity or indicating zone of groundwater fluctuation).
6. Interpret site investigations considering the issues discussed in this chapter for liquefaction assessment.
7. Recognize this is an ongoing area of research and communicate the uncertainties to the client, considering the specific project and site conditions in developing a path forward toward design. It is premature to formalize recommendations for liquefaction assessment at interbedded silty soil sites with groundwater fluctuations, but the guidance on improved characterization at these sites enables the engineer to employ judgement with a more complete understanding of actual in-situ conditions.

The limitations of current site characterization and liquefaction assessment methods at silty soil sites requires reconsideration of the current approaches to liquefaction assessment. Rather than interpreting these interbedded silty soils with clean-sand equivalent properties that do not describe adequately subsurface conditions for liquefaction assessment at these sites, a more holistic approach is needed. Only high-quality continuous sampling and detailed logging can capture currently the actual ground conditions that impact seismic performance at the silty soil sites in Christchurch. Improved site characterization and understanding of the actual in-situ deposits at interbedded silty soil sites should go hand-in-hand with research through laboratory testing and numerical simulations, so that both the evaluation framework and representation of the actual characteristics of the silty soil deposit can be advanced.

Table 3.1: Summary of site investigations at the silty soil sites.

Site Name	Latitude, Longitude	Investigation Type* and NZGD Location ID				
		Sonic Boring	Mud- Rotary Boring	CPT	Mini-CPT	Direct Push Crosshole Seismic [‡]
Site 2 Gainsborough	-43.5634, 172.6016	38196	DM-1 ^a , GP-1 ^b , GP- 2 ^b , GP-3 ^b	36417	---	38176, 38177
Site 14 Barrington	-43.5553, 172.6180	38193	BH-1 ^{a,b} , BH-2 ^a , 73103 (BH-3 ^c)	37818	Mini-CPT_04	38172
Site 21 Caulfield	-43.5800, 172.5489	38194	DM-1 ^a	36419	---	38174, 38175
Site 23 Riccarton	-43.5299, 172.6036	38195	DM-1 ^a	36420	---	38170
Site 33 Cashmere	-43.5725, 172.6082	38197	DM-1 ^a , 73104 (DM-2 ^c)	36421	Mini-CPT_01, Mini-CPT_02	38171
Site 37 [†] Clarence	-43.5305, 172.6016	---	72120 (DM-1 ^c)	72117	Mini-CPT_08, Mini-CPT_09, Mini-CPT_10	---

^a Mud-rotary boring, Dames & Moore (DM) high-quality sampling for cyclic triaxial testing

^b Mud-rotary boring, Gel-Push (GP) high-quality sampling for cyclic triaxial testing

^c Mud-rotary boring, Dames & Moore (DM) high-quality continuous sampling for detailed logging

* In-situ tests listed in this table comprise the dense test array from this study. Additional in-situ tests may be available further from the dense array at each site.

[‡] Direct push crosshole seismic testing conducted by Univ. of Texas at Austin researchers (Stokoe, Cox et al.)

[†] Approximately 200 m west of Site 23 – Riccarton

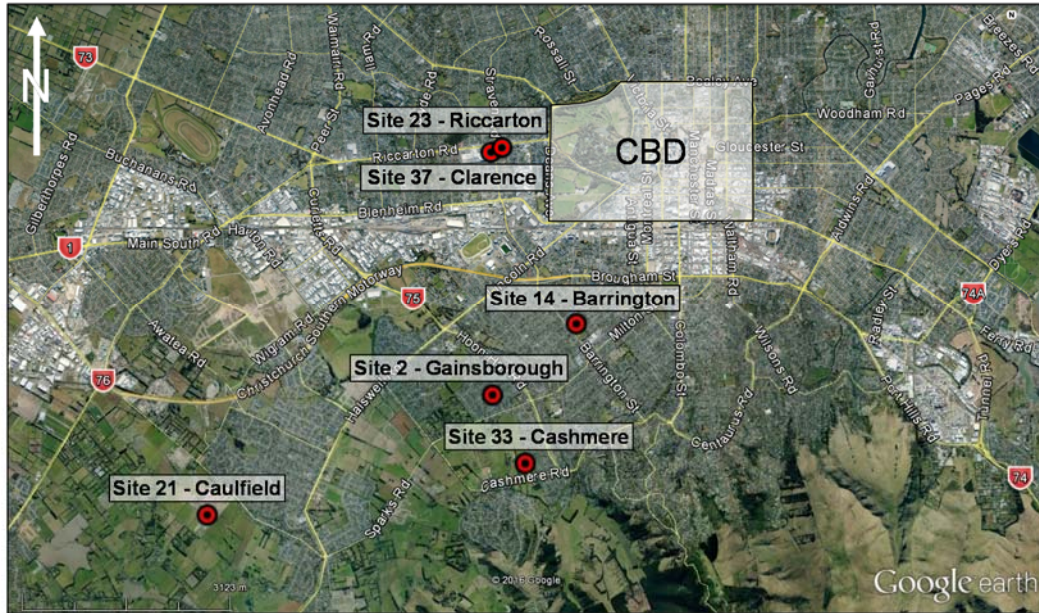


Figure 3.1: Site locations within greater Christchurch.

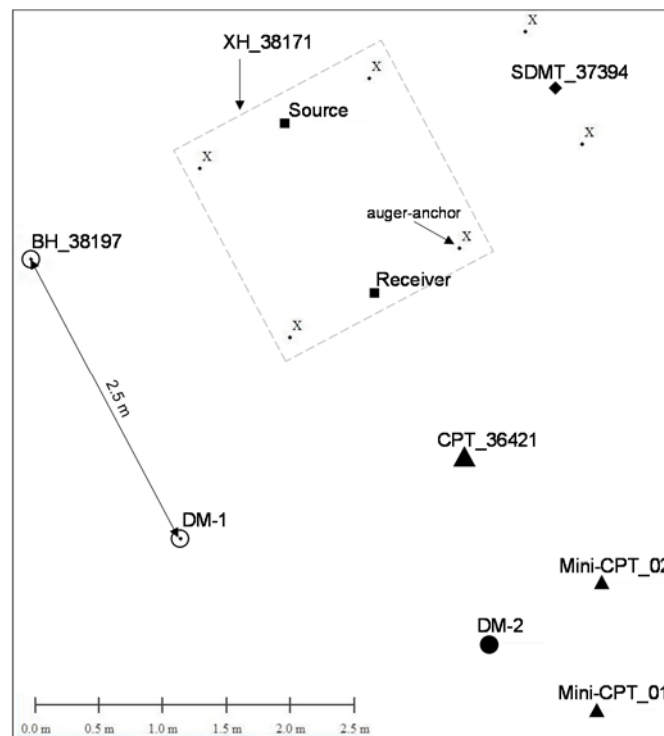


Figure 3.2: Typical dense array layout for subsurface investigations (Site 33 shown).

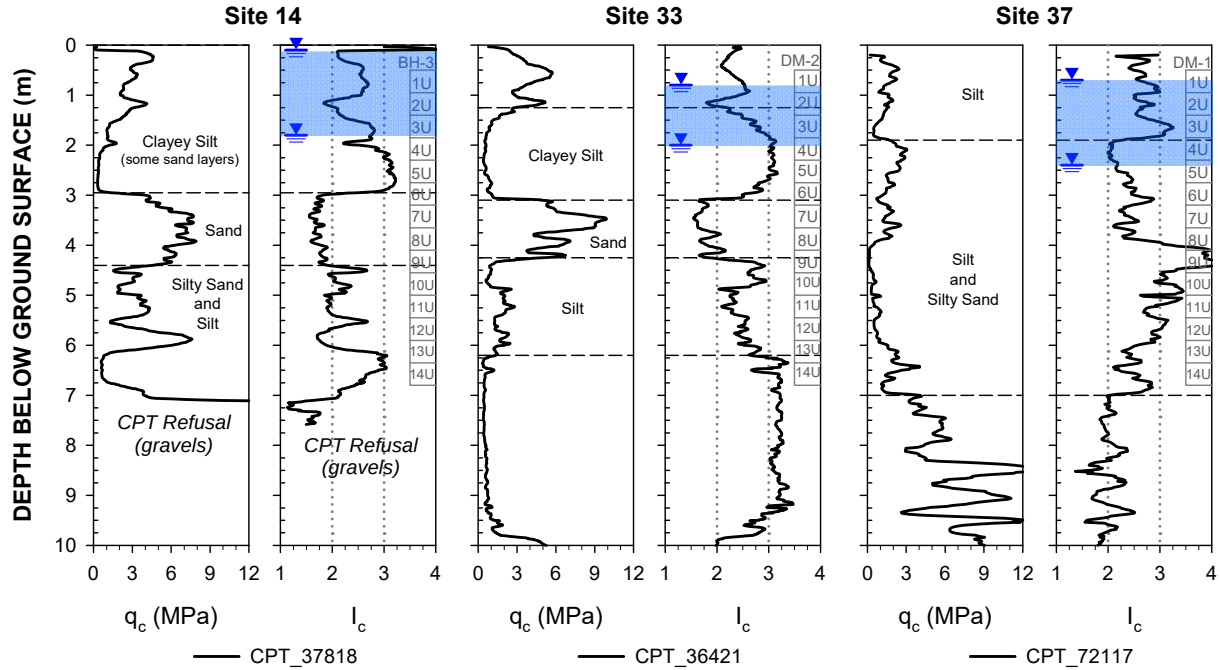


Figure 3.3: Tip resistance (q_c) and soil behavior type index (I_c) for conventional CPTs at Sites 14, 33, and 37. Data from NZGD. Simplified soil profiles, DM sample depths, and zones of GWT fluctuation also shown.

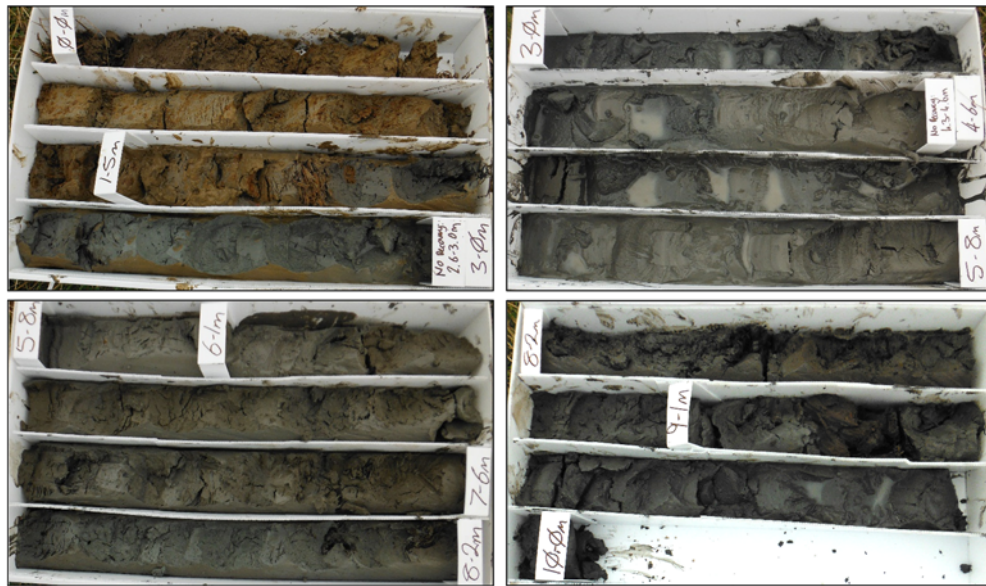


Figure 3.4: Conventional sonic boring core box samples (Site 33, BH_38197). Simplified profile: silt (0-2.45 m), silty sand (2.45-3.8 m, no recovery 2.6-3.0 m), silt (3.8-4.3 m), no recovery (4.3-4.6 m), silty sand (4.65-5.35 m), silt (5.35-9.10 m), silty sand (9.10-10.00 m, 9.25-9.35 fibrous wood). Zone of GWT fluctuation: 0-1.8 m (note iron-staining).



Figure 3.5: Dames & Moore hydraulic fixed-piston thin-walled sampler: (a) attached to drill rods (sample tube not attached), (b): with sample tube attached (immediately following sample removal from boring).

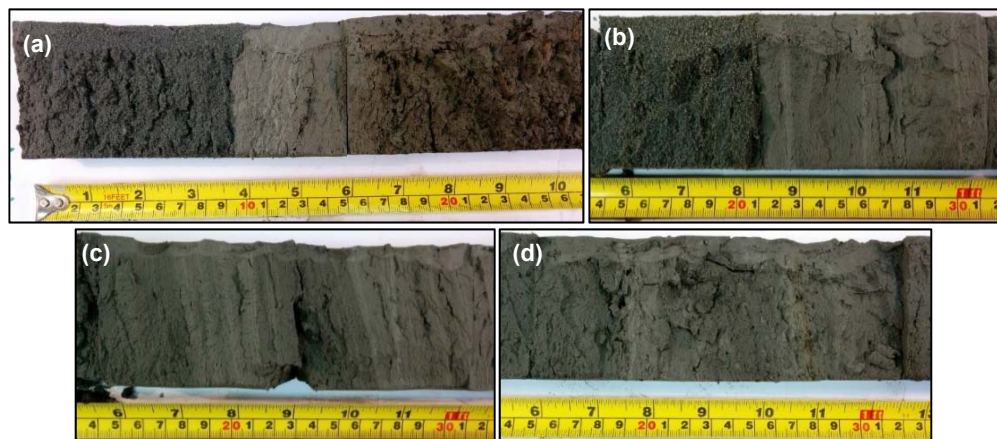


Figure 3.6: High-quality sample photographs from detailed logging showing observed layering. (a) S14-BH3-14U: sand (0-9 cm), clayey silt with silt laminations (9-15 cm), and clayey silt with organics (15 cm-end); (b) S33-DM2-9U: sand (5-21.5 cm) and silt with silt laminations; (c) S33-DM2-12U: silty sand gradation to silt (15-18 cm) and silt with silt and sand laminations, (d) S37-DM1-9U: interlayered silt, sandy silt, silty sand, and organics. Top of sample is at 0 cm mark on ruler.

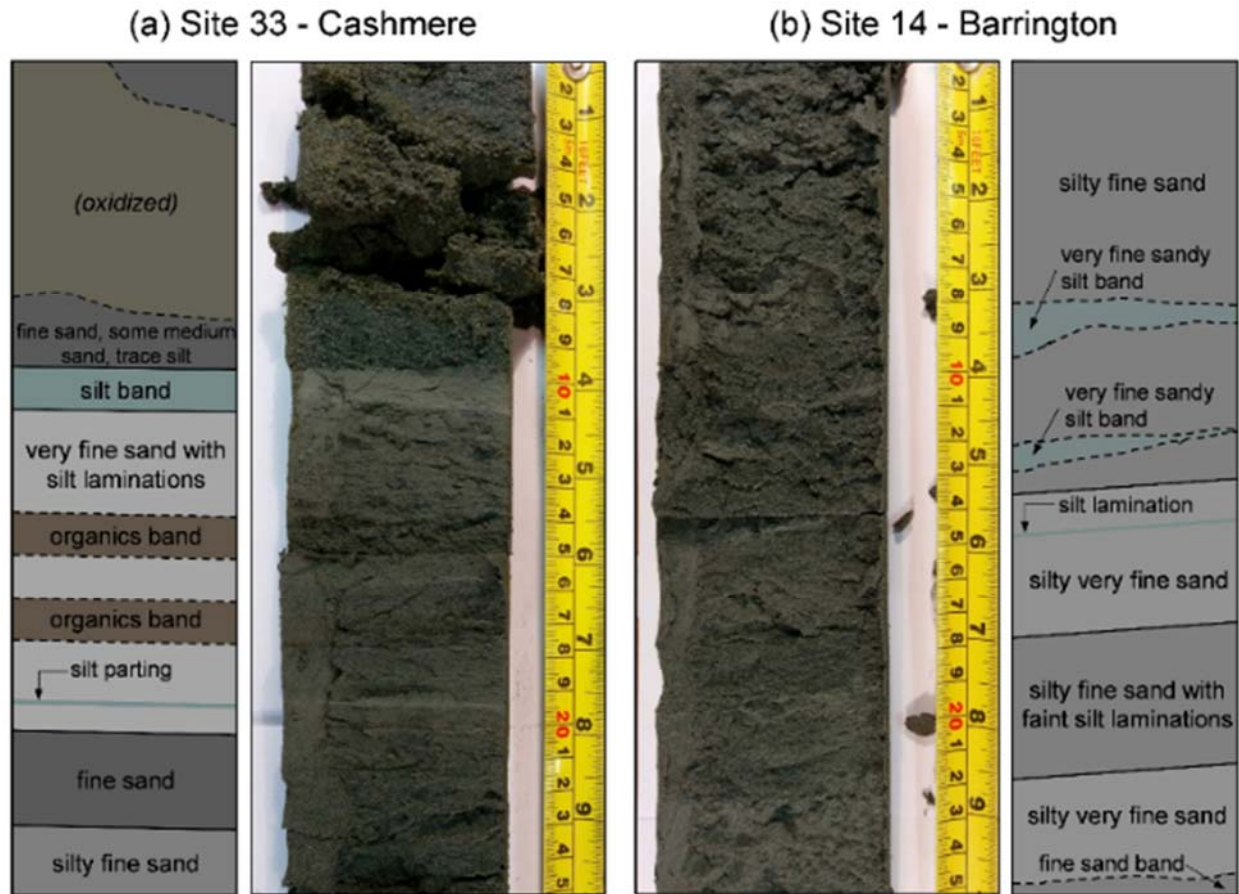


Figure 3.7: Graphic logs (from detailed logs) with DM sample photographs (from Beyzaei et al. 2017b).

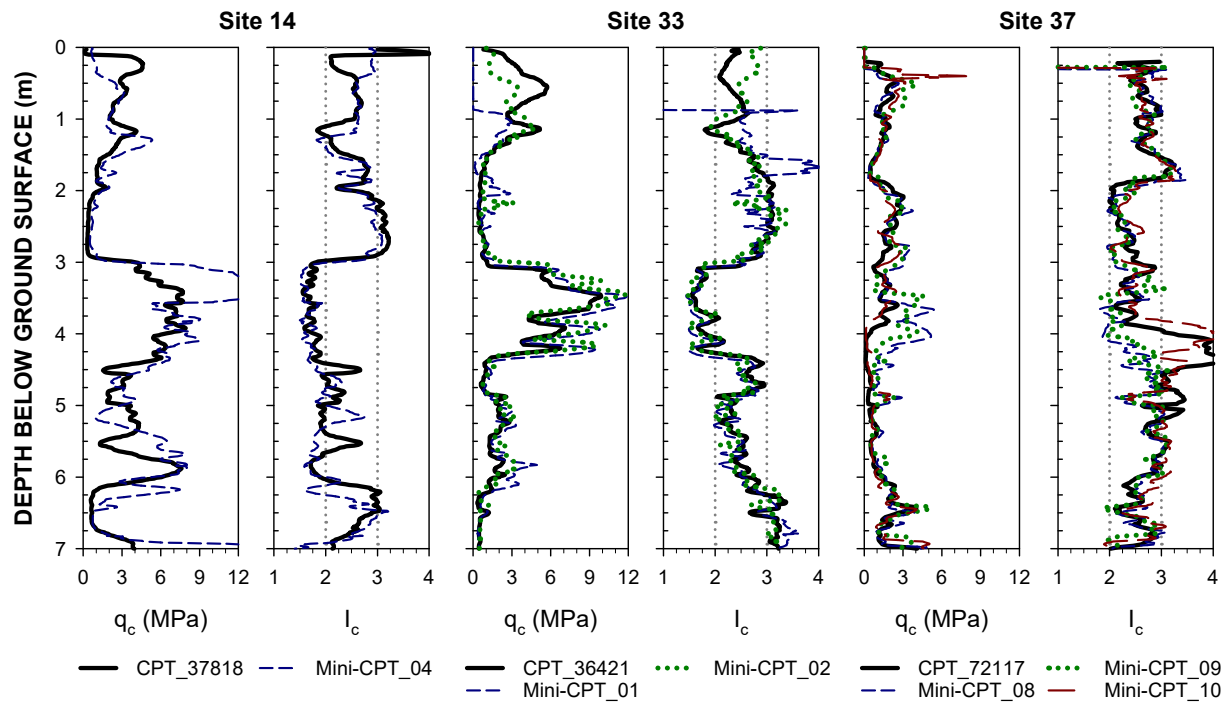


Figure 3.8: Comparison of mini-CPT and conventional CPT traces: Sites 14, 33, and 37.

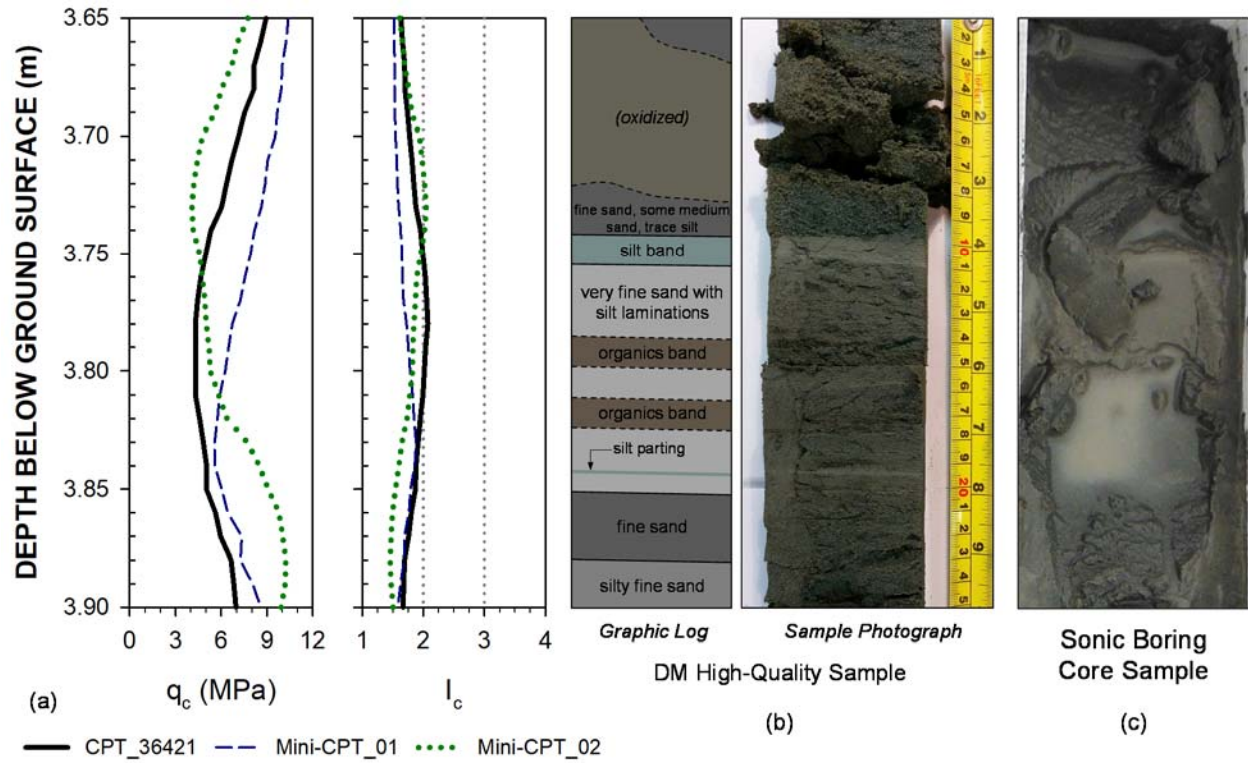


Figure 3.9: Site 33 - Cashmere (3.65-3.90 m BGS): (a) mini-CPT and conventional CPT traces, (b) high-quality sample - detailed graphic log and photograph, and (c) sonic boring core sample.

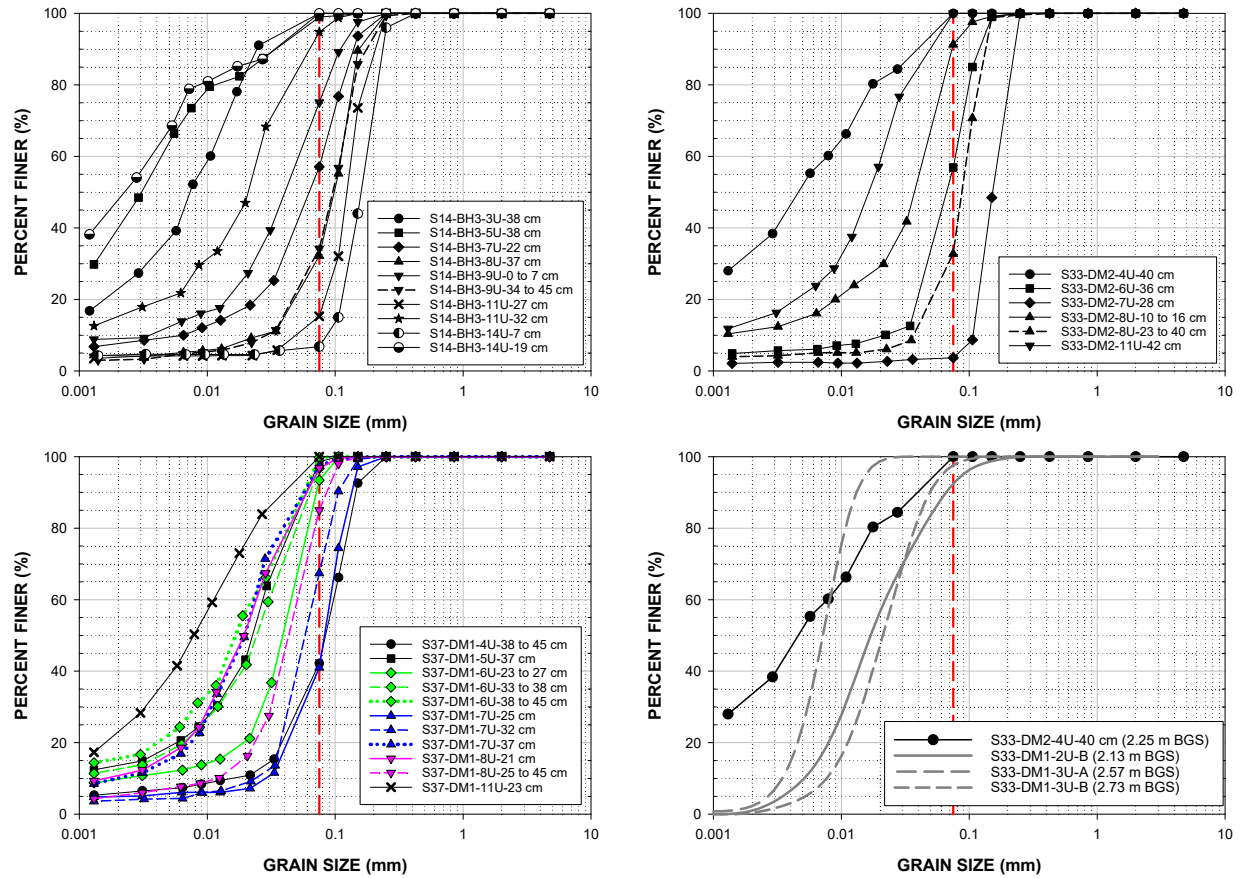


Figure 3.10: Hydrometer data from: (a) Site 14, (b) Site 33, and (c) Site 37. Hydrometer and laser method data shown in (d) to highlight differences in clay-sized fraction.

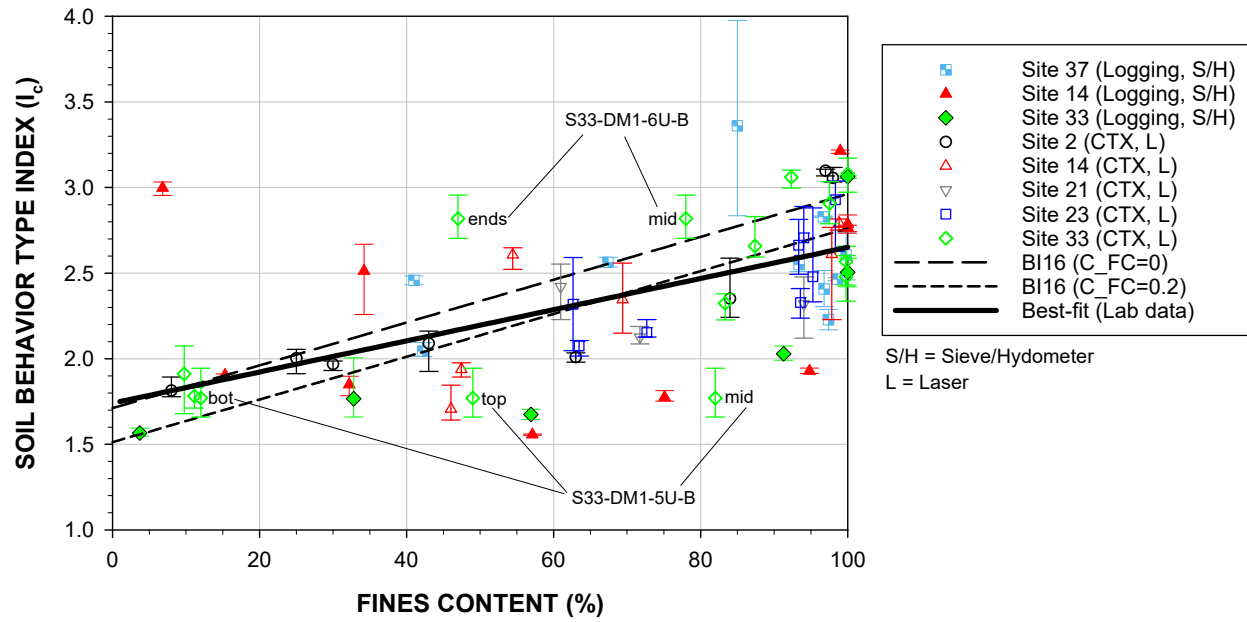


Figure 3.11: Fines content vs. I_c for detailed logging subsamples and CTX specimens. Geometric mean I_c plotted with bars to maximum and minimum I_c over depth interval. Boulanger & Idriss (2016) correlation also shown. Best-fit line through data ($I_c = 0.0091 \cdot FC + 1.7409$; $R^2 = 0.3643$) compared with BI16 correlation ($I_c = 0.0125 \cdot FC + 1.7125 - C_{FC}$).

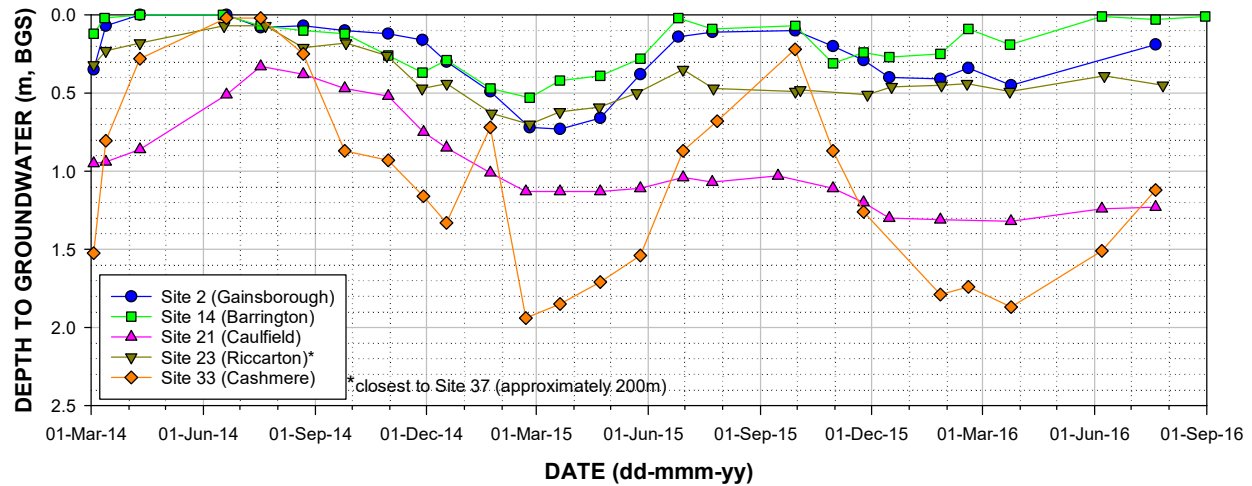


Figure 3.12: NZGD piezometer measurements from March 2014 to September 2016.

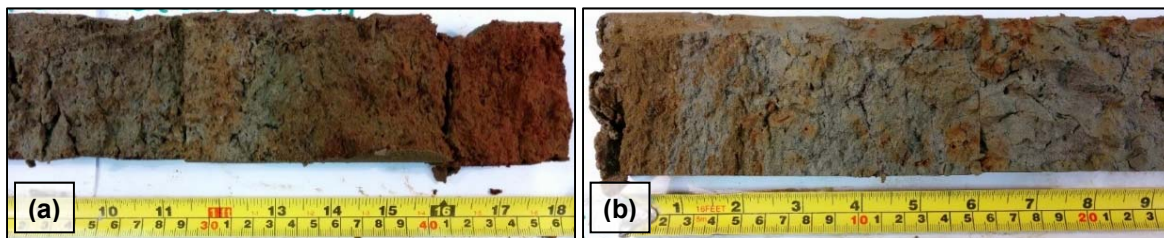


Figure 3.13: Site 14 high-quality continuous samples in zone of GWT fluctuation. Sequential samples: (a) S14-BH3-2U (22-45 cm; 1.17-1.40 m BGS), and (b) S14-BH3-3U (0-23 cm; 1.40-1.63 m BGS).

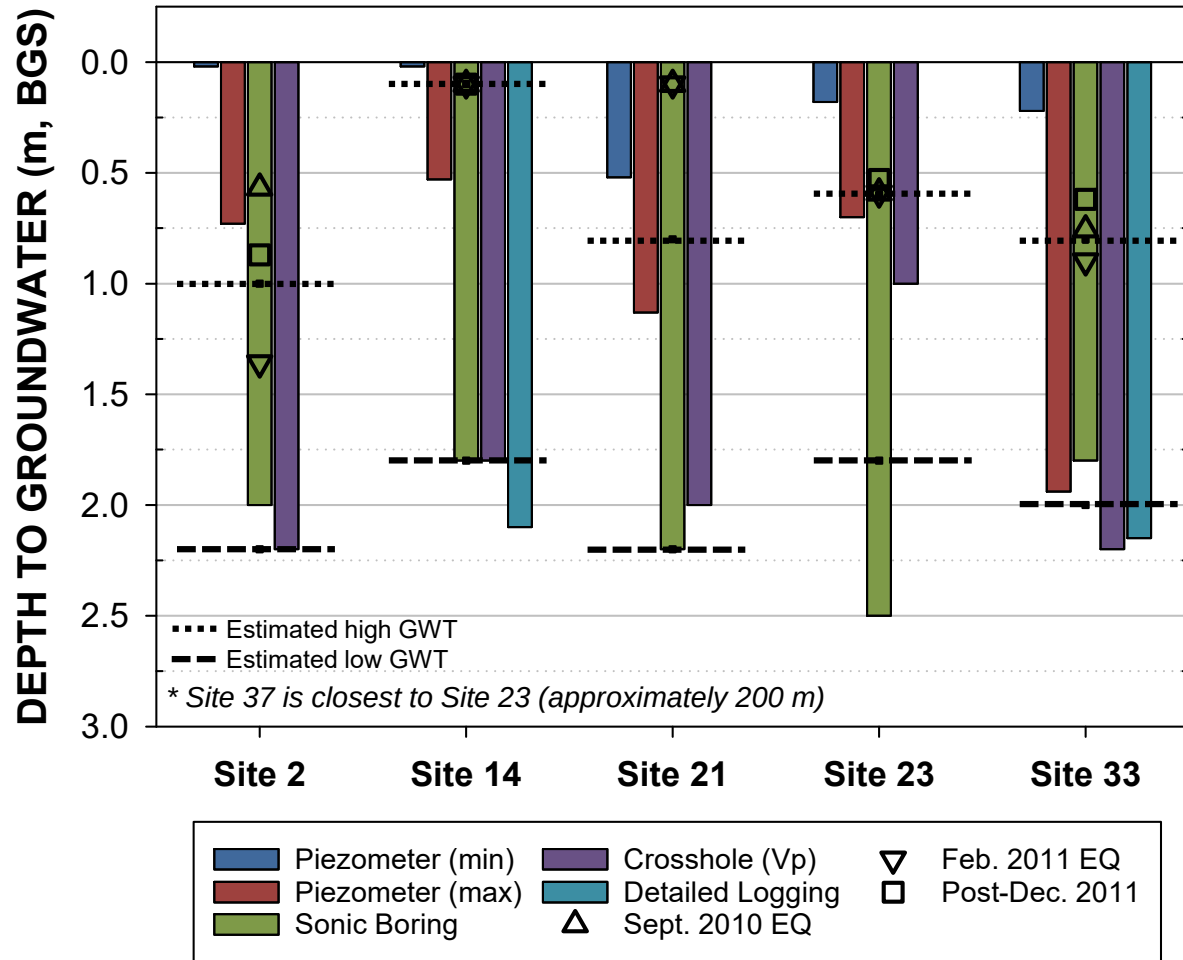


Figure 3.14: Summary of groundwater level estimates from multiple methods.

CHAPTER 4: LABORATORY-BASED CHARACTERIZATION OF SHALLOW SILTY SOILS IN SOUTHWEST CHRISTCHURCH

The contents of this chapter are primarily from a journal article submitted to Soil Dynamics and Earthquake Engineering by Beyzaei, C.Z., Bray, J.D., Cubrinovski, M., Riemer, M., and Stringer, M. entitled: “Laboratory-Based Characterization of Shallow Silty Soils in Southwest Christchurch,” which was under review when this dissertation was submitted.

4.1 INTRODUCTION

During the 2010-2011 Canterbury earthquake sequence, multiple earthquake events triggered widespread damaging liquefaction that affected buildings, infrastructure networks, and critical lifeline systems in Christchurch, New Zealand (Figure 4.1a). This degree of extensive repeated liquefaction was virtually unprecedented in a modern urban setting. However, there were also many cases where soil deposits previously thought to be potentially liquefiable did not express surface manifestations of liquefaction (Figure 4.1b). At several sites, especially sites with silty soils, state-of-practice cone penetration test (CPT)-based procedures over-estimated the occurrence and severity of liquefaction. Current liquefaction triggering procedures are largely based on observations following earthquakes at sites containing deposits of relatively clean sands. There remains considerable debate around liquefaction resistance of fine-grained soils, such as silts, including how liquefaction of silty soils might manifest damage, and the appropriate assessment procedures to employ.

This paper presents laboratory testing data and case histories for three silty soil sites that exhibited discrepancies between state-of-practice liquefaction evaluations and post-earthquake liquefaction observations. A clean sand site, which also contains a shallow layer of silty sand, is included as a point of comparison for the silty soil characterization. The primary goals of this paper are to present laboratory testing data for high-quality (“undisturbed”) natural silty soil specimens to provide insight on their cyclic response and to compare the laboratory test results with CPT-based simplified liquefaction triggering procedures to identify consistencies and discrepancies between the two approaches. The findings of the paper provide insights regarding laboratory-based characterization of the cyclic response of silty soils relative to observed earthquake performance. The natural specimen laboratory test data are combined with observational data from post-earthquake reconnaissance to advance the understanding of the cyclic response of silty soils and to improve empirical liquefaction evaluation procedures. Silty soils test data also allow for the development of more robust numerical models that capture a broader range of soils and their responses. This particular effort is part of a larger study initiated after the Canterbury earthquake sequence to characterize and to understand the seismic performance of silty soil sites. Silty soils warrant additional research; relatively little is known about their cyclic response as clean sands and plastic clays have received far greater attention.

4.2 LABORATORY TESTING TO CHARACTERIZE CYCLIC RESPONSE

Characterization of the cyclic response of soils is largely achieved through observational data and experimental data. Observational data, such as post-earthquake reconnaissance, forms the basis for databases used in developing empirical evaluation procedures. Experimental data, such

as laboratory or in-situ testing, informs field case histories and explores cyclic response characteristics that are not readily observed or easily understood in case histories. Most liquefaction cases in the current databases (e.g., Boulanger & Idriss 2016) are for relatively thick deposits of clean sand or sands with fines contents $< 35\%$. Much of the first few decades of liquefaction research focused on field observations for these deposits (e.g., Seed 1979), and laboratory testing also focused on characterization of the cyclic response of clean sands, because available case histories were predominantly associated with clean sand sites. It is difficult to obtain “undisturbed” samples in clean sand, so most laboratory testing was conducted on laboratory-prepared specimens (e.g., moist tamping). Testing of clean sands has formed the basis for our understanding of liquefaction. Considerable research has also been conducted on cyclic softening of clays, albeit significantly less than that on clean sand.

Recent earthquakes have highlighted the importance of silt liquefaction (e.g., Adapazari during the 1999 Kocaeli, Turkey earthquake; Bray & Sancio 2006). With the understanding of clean sand cyclic response relatively well-established, the profession has moved toward further understanding the cyclic response of “silty soils” (also termed “intermediate” or “fine-grained” soils). These terms describe soils with no to low plasticity and fines contents from about 35% to 100%, encompassing the broad range of soil types after the point at which fine-grained particles control the response of the soil matrix. The variability in silty soil deposits is an inherent challenge in describing and characterizing their cyclic response. There is a large range of silty soil responses possible between those of conventional “sand” and “clay” soils from which most of our understanding and procedures are derived. Currently, the cyclic response of silty soils is characterized in relation to the response of clean sands. Parameters such as fines content, plasticity index (PI), and soil behavior index type (I_c) are used to describe how a silty soil deviates from a typical clean sand and as such, how the cyclic response of a silty soil is anticipated to deviate from that of a clean sand.

Laboratory testing of silty soils has been conducted for both natural “undisturbed” specimens and laboratory-prepared specimens (e.g., Bray & Sancio, 2006; Thevanayagam & Martin, 2002; Wijewickreme & Sanin, 2004). A complicating issue with laboratory testing of natural silty soils is the determination of what constitutes a representative soil specimen. In clean sand deposits, the element-scale test specimen may be more representative of the overall stratum and less subject to within-specimen heterogeneity from layering than a silt specimen. Silty soils are formed in depositional environments such as overbank deposits or swamps, which often lead to the development of highly stratified soil deposits with fine layering sequences. Laboratory-prepared silt test specimens may not capture such in-situ characteristics. Thus, there is merit to performing laboratory tests on retrieved samples of silty soils if they can be retrieved without significant disturbance.

4.3 DEVELOPMENT OF NO-LIQUEFACTION CASE HISTORIES

The silty soil sites presented in this paper are deemed “no-liquefaction” case histories based on the current framework of categorizing sites as “liquefaction” or “no-liquefaction” by observed surface manifestations. It is possible that liquefaction occurred at-depth, but given that no surface manifestations of liquefaction were observed during post-earthquake reconnaissance, the sites are categorized as “no-liquefaction” case histories.

4.3.1 Canterbury Earthquake Sequence

The 2010-2011 Canterbury earthquake sequence consisted of four main events: the 4 September 2010 M_w 7.1 Darfield earthquake, 21 February 2011 M_w 6.2 Christchurch earthquake, 13 June 2011 M_w 5.3 and 6.0 earthquakes, and 23 December 2011 M_w 5.8 and 5.9 earthquakes. Subsequent research programs have focused on the Darfield and Christchurch earthquakes, which caused the most significant liquefaction damage throughout greater Christchurch (Figure 4.2) and were the focus of more comprehensive post-earthquake reconnaissance investigations. The June and December 2011 earthquakes require more judgement in the interpretation of their effects, owing to the paired earthquake events both occurring approximately 80 minutes apart and due to them being less studied. Much research has been published on the effects of the Canterbury earthquake sequence (e.g., van Ballegooy et al. 2014, Russell & van Ballegooy 2015, GNS Science, Green & Cubrinovski 2010, Cubrinovski et al. 2011, NZGD). Relevant details are provided in this paper.

4.3.2 Christchurch Geologic Setting

Christchurch, New Zealand is located in a complex geologic and geomorphic environment, with dominant influences from alluvial, coastal, and swamp or lagoon-type depositional processes (Brown & Weeber 1992, Forsyth et al. 2008). Bound closely to the north by the Waimakariri River, greater Christchurch is located in a coastal setting within the Canterbury Plains. The braided Waimakariri River flows eastward from the Southern Alps to the Pacific Ocean, depositing gravel, sand, and silt sediments in alluvial fan and floodplain deposits throughout the Canterbury Plains. Small rivers and streams meander through the inland areas of Christchurch, with the Avon River flowing east through the Central Business District toward the eastern coastal suburbs, and the Heathcote River flowing east through the southern suburbs of the city before reaching the coast. The southern edge of the city abuts directly the Port Hills of the Banks Peninsula volcanic remnants. Groundwater conditions throughout greater Christchurch are seasonably variable, with much of the city having a shallow groundwater table (depth of 1-3 m). Low-lying areas throughout much of southwestern Christchurch, where the case history sites are located, contain shallow soil deposits comprised of silt and fine sand.

4.3.3 Silty Soils Project

During post-earthquake reconnaissance efforts, investigators noted that surface manifestations of liquefaction damage were not frequently observed at many sites in the southwestern suburbs of Christchurch, despite state-of-practice methods indicating liquefaction would be expected. This region is known among local engineers for its silty soil conditions, and with that in mind, a comprehensive study called the “silty soils project” was undertaken by the authors as part of a research team formed by the Univ. of Canterbury, Univ. of California, Berkeley, Univ. of Texas at Austin, and Tonkin + Taylor, Ltd. (Beyzaei et al. 2015, Stringer et al. 2015, UC Berkeley & Univ. of Canterbury 2016). As part of this study, field testing and laboratory cyclic testing were conducted to investigate the liquefaction resistance of silty soils and identify reasons why state-of-practice liquefaction triggering procedures may have over-estimated the occurrence of liquefaction at silty soil sites in southwestern Christchurch. Data collected during

this research program were submitted to the New Zealand Geotechnical Database (NZGD). The sites presented in this paper are part of those investigated during the silty soils project.

4.3.3.1 Preliminary Investigation

Preliminary investigations consisting of CPT soundings, sonic borings, bulk sampling, index testing, and piezometer installations were undertaken by Tonkin + Taylor at several candidate silty soil sites that displayed discrepancies between state-of-practice assessments and post-earthquake liquefaction observations. Univ. of Texas at Austin (UT-Austin) researchers performed crosshole seismic testing at several candidate sites (NZGD, Stokoe et al. 2014). The preliminary investigations were used to characterize subsurface conditions at the candidate sites and remove sites where obvious factors likely contributed to not observing liquefaction manifestations at the ground surface (e.g., deep groundwater table, gravel layers, non-susceptible soils). From the 30⁺ candidate sites originally considered, the 8 sites shown in Figure 4.2 were selected for advanced investigation with high-quality sampling and laboratory testing.

4.3.3.2 Advanced Investigation

High-quality sampling using the Dames & Moore (DM) sampler was conducted at the selected sites from March to November 2014. Sites 2, 14, EQC-3, and EQC-6 also had high-quality sampling using a gel-push sampler; investigations at those sites are discussed elsewhere (Stringer et al. 2015). Fieldwork to retrieve high-quality soil samples was performed using mud-rotary wash borings advanced with a side-discharge tri-cone bit under supervision by the lead author. The DM sampler is a hydraulically-activated fixed-piston Osterberg-type soil sampler. Thin-walled brass sample tubes with a constant inner-diameter and beveled cutting edge were used to minimize disturbance during sampling (outer diameter = 63.5 mm, inner diameter = 61.2 mm, area ratio (Hvorslev 1949) = 7.6%). Full recovery results in a 45 cm sample length. Drainage was allowed prior to sealing with electrical tape around the plastic end caps to minimize softening of the sample ends. The top 10 cm and bottom 5 cm of each sample were not used for cyclic testing due to the higher potential for disturbance in those portions. Samples were recovered at all sites, with high-quality samples obtained at the silty soil sites and samples of varying quality obtained at the EQC clean-sand sites. Bray & Sancio (2006) and Markham et al. (2016) provide further details on the use and efficacy of the DM sampler in silty soils. All samples selected for cyclic triaxial (CTX) tests had recoveries of at least 98%, with the exception of one sample tube which had a recovery of 89%.

4.3.4 Site Descriptions & Subsurface Characterization

The three silty soil sites presented in this paper cover the range of intermediate silty soil conditions encountered during the advanced investigation. They are: Site 21 - Caulfield (-43.5800, 172.5489), Site 23 - Riccarton (-43.5299, 172.6036), and Site 33 - Cashmere (-43.5725, 172.6082). One clean sand site, EQC-4 - Avondale (-43.5014, 172.6857), is included for comparison. All sites were level-ground free-field or light construction sites during the Canterbury earthquake sequence. Sites 21 and 33 were open fields, Site 23 was occupied by a 2-story commercial structure and parking lot, and EQC-4 was occupied by a single-family residential structure. EQC-4 also has the potential for lateral spreading, located approximately 80 m from the Avon River.

Figure 4.3 provides CPT tip resistance (q_c) and soil behavior type index (I_c) profiles for Sites 21, 23, 33, and EQC-4 to illustrate the subsurface conditions encountered at each site. Simplified soil layers are also shown for each site, based on samples obtained during the advanced investigation and data from the preliminary fieldwork. Site investigation layouts for sonic borings, CPT soundings, crosshole testing, and mud-rotary borings are available at the NZGD. In the top 10 m below ground surface (BGS), Site 21 consists of silty sand and sandy silt, underlain by gravel. Site 23 consists of highly stratified silt and sandy silt with varying amounts of organic content (wood, roots) at all depths sampled. Site 33 consists of a more clearly layered profile, with clayey silt underlain by sand, underlain by silty soils, underlain by clayey soil. EQC-4 consists of a silty sand layer extending from 0-3 m BGS, underlain by cleaner sands. Site investigations focused on subsurface characterization for liquefaction assessment, emphasizing shallow depths (e.g., 0-10 m BGS) which would govern observed liquefaction performance.

Groundwater conditions at each site are estimated to fluctuate as follows, based on site-specific data (i.e., sonic boring core boxes, piezometer data, and crosshole testing): Site 21 (0.8-2.2 m BGS), Site 23 (0.6-1.8 m BGS), Site 33 (0.8-2.0 m BGS), and EQC-4 (1.9-2.8 m BGS). The NZGD groundwater table maps (NZGD), based on a regional study using piezometer data and groundwater modeling, provide groundwater level estimates of: Site 21 (0.1 m, 0.1 m BGS), Site 23 (0.6 m, 0.6 m BGS), Site 33 (0.8 m, 0.9 m BGS), and EQC-4 (2.0 m, 2.0 m BGS), for the Darfield and Christchurch earthquakes, respectively. The site-specific data are relied upon in this study as they capture groundwater fluctuations that are likely to lead to partially saturated conditions below the NZGD groundwater levels.

4.3.5 Post-Earthquake Liquefaction Observations

Post-earthquake reconnaissance investigations consisted of aerial photography, on-the-ground property observations, and on-the-ground road observations. Investigations were focused in areas with reports of liquefaction occurrence; areas that were not visited following an earthquake event are inferred to have not suffered liquefaction damage. For the Darfield earthquake, the three silty soil sites were not flown over or visited, leading to the inference that surface manifestations of liquefaction did not occur. For the Christchurch earthquake, the three silty soil sites were included in reconnaissance investigations and no liquefaction manifestations were observed at the ground surface. Moderate-to-severe liquefaction manifestations, including lateral spread and ejecta, were observed at EQC-4 following both the Darfield and Christchurch earthquakes. Detailed post-earthquake damage maps and aerial photographs are available at the NZGD.

4.3.6 Simplified Liquefaction Assessment

State-of-practice CPT-based methods indicate that liquefaction and settlement are estimated to occur at the case history sites for the Darfield and Christchurch earthquake events, regardless of the simplified method used (e.g., Boulanger & Idriss 2016, Moss et al. 2006, Robertson & Wride 1998, and Zhang et al. 2002). The Boulanger & Idriss 2016 (BI16) method typically results in lower over-estimations of liquefaction as shown for representative profiles in several studies (Beyzaei et al. 2015, Stringer et al. 2015, Beyzaei et al. 2017). Seismic demand was estimated using Bradley & Hughes 2012 and the BI16 magnitude scaling factor. Cyclic resistance was estimated using BI16, with the Robertson et al. 2009 soil behavior type index (I_c). The overburden correction factor (C_N) was limited to 1.7 for both the I_c calculation and the BI16

corrected tip resistance (q_{tIN}) calculation. Typical unit weights of the soils range from 18-19 kN/m³. All three case history sites demonstrate a similar estimation of significant liquefaction potential and settlement using the state-of-practice methods, in contrast with the post-earthquake observations of no liquefaction manifestations.

BI16 implements a fines content (FC) – soil behavior type index (I_c) correlation to estimate fines content in lieu of laboratory data. The FC- I_c correlation requires selection of a fitting parameter (C_{FC}) “*that can be adjusted based on site-specific data when available*” (Boulanger & Idriss 2014). Figure 4.4 shows FC data for the three silty soil case history sites, with the BI16 FC- I_c correlation for $C_{FC} = 0.0$ and $C_{FC} = 0.2$. Based on index testing at the silty soil sites, $C_{FC} = 0.2$ was selected for the simplified assessment. Lees et al. 2015 and Robinson et al. 2013 provide evaluations of the FC- I_c correlation for different regions of Christchurch. Based on Boulanger & Idriss (2016), C_{FC} for EQC-4 was set to $C_{FC} = -0.07$, which approximately equals the Robinson et al. 2013 correlation for liquefiable soils along the Avon River. BI16 is sensitive to selection of C_{FC} , and fines content itself can be a sensitive parameter for silty soils. It may not be the most appropriate or representative parameter for these silty soil sites considering their propensity for borderline fine sand/coarse silt particle sizes, thin-layering sequences of fine sand and silt at the scale of millimeters and centimeters, and gradational zones not easily categorized by a single FC estimate.

The parameters associated with simplified method estimates of seismic demand and soil resistance are sufficiently uncertain as to warrant full consideration. Relevant details are presented herein to establish that the no-liquefaction sites were estimated to have liquefaction and settlement regardless of the level of uncertainty in these parameters. Best-estimates and reasonable variations in the state-of-practice method parameters indicate that the silty soil case history sites would be expected to have liquefied with settlement and the influence of sensitivity analysis does not change that assessment.

4.4 LABORATORY TESTING OF SILTY SOILS

The three silty soil case history sites (Sites 21, 23, and 33) cover a range of silty soils including silty sand, non-plastic silt, and low-plasticity silt. The clean-sand reference site (EQC-4) contains a shallow layer of silty sand with organics underlain by a thick clean sand deposit. Site 33 contains a sand layer (shown in Figure 4.3) which contains silt seams observed post-testing after splitting specimens open. Representative results are presented for specimens from across the three silty soil sites, with results presented from the clean-sand site for comparison and context. Complete data for each specimen are provided in a series of geotechnical data reports available on the NZGD (UC Berkeley & Univ. of Canterbury 2016).

4.4.1 Condition of Natural Soil Samples

Natural soil samples will have some degree of heterogeneity. Much of what is presented in the literature on silts and silty soils is for specimens prepared in the laboratory by a particular method (e.g., slurry deposition, Donahue et al. 2007). Performing tests on laboratory-prepared test specimens is useful for unifying soil responses and establishing trends. However, laboratory-prepared specimens do not achieve the same in-situ soil fabric, layering structure, and deposition method as soils deposited in-situ in an alluvial environment with silt effects such as the southwest part of Christchurch. Therefore, high-quality sampling was conducted to obtain relatively

“undisturbed” samples representative of in-situ conditions to assess the cyclic response of these soils in their natural state.

When working with natural soil specimens, issues of sample quality and heterogeneity should be considered. The issue is amplified when working with specimens from shallow depths, near the zone of groundwater table fluctuation where roots, organic matter, and desiccation may affect sample integrity. Each specimen was visually inspected upon extrusion to determine if any existing features would preclude the specimen from being a candidate for CTX testing. Sample heterogeneity can occur as a stark contact between two layers within a specimen, layering, pockets, gradational zones, voids, organic content, or iron-staining and mottling. Some of these features are difficult to identify from the specimen exterior, which may be smeared during extrusion. Additionally, as some heterogeneity is inherent in natural soil, there needs to be a balance between selecting specimens that are representative of in-situ conditions and specimens that are sufficiently homogeneous to allow for meaningful interpretation of laboratory test data. When enough “heterogeneous features” occur throughout a test specimen, it may result in a level of homogeneity that is characteristic of a stratum.

Specimens selected for cyclic triaxial testing had varying degrees of natural heterogeneity, but were selected to capture the primary characteristics of the stratum being considered. Specimens with an obvious feature that deviated from typical characteristics of the stratum or would negatively impact quality of testing were discarded (e.g., a large void in the specimen). Prior to cyclic testing, specimens can only be evaluated by visual inspection based on the exterior of the specimen. After cyclic testing, each specimen was carefully split open to examine and photograph the interior surfaces, and identify any heterogeneous features within the specimen. In all cases, the interior visual inspection was included in the final evaluation of the specimen and the overall data for the stratum. Figure 4.5 shows specimen photographs of specimens demonstrating varying degrees of natural heterogeneity. Consistent with expectations for shallow alluvial Christchurch soil, many specimens tested contained visible organic content, varying from trace amounts to roots and pieces of wood.

Intra-specimen heterogeneity may affect the characterization of a unit’s cyclic resistance, especially when considering how specimen-scale relates to stratum-scale. Considering the relative size of the CTX specimens tested at these sites (i.e., nominal specimen height of 135-140 mm) and the scale of heterogeneous features (e.g., thin-layers, organic content), intra-specimen heterogeneity is not anticipated to have a disproportionate effect on the testing data if it is minimized within a stratum. Thus, while the features may potentially affect individual specimen test data, the resulting CRR curves are reasonable because the test specimens are representative of the stratum as a whole (i.e., each specimen has intra-specimen heterogeneity, but overall the inter-specimen result is relative homogeneity). Thorough characterization of the individual specimens selected and tested sheds light on the variability of a given stratum, as well as providing a basis for understanding the relative responses of specimens from the same stratum. The occurrence of thin potentially non-liquefiable layers within a specimen may have effects on the overall liquefaction potential and post-liquefaction reconsolidation response depending on where those layers occur. However, this is an issue of interpreting and extrapolating element-scale laboratory testing to understand the site-scale three-dimensional subsurface system. There are obvious limitations to testing natural soil specimens, but for environments where laboratory-prepared test specimens will not adequately represent in-situ conditions to the degree needed, researchers should work with natural soil specimens and understand the limitations of this approach to select the most appropriate specimens for testing to obtain the best possible characterization of each stratum.

4.4.2 Sample Disturbance

Quantitative methods for assessing sample disturbance in silty soils are not well-defined. Sample disturbance assessment procedures developed for clayey soils, such as the Lunne et al. (1997) “ $\Delta e/e_0$ ” criteria, cannot necessarily be applied to silty sands and non-plastic or low-plasticity silts. To evaluate potential sample disturbance for these silty soils, several qualitative and quantitative approaches were considered, including: i) capability of the sampling device, ii) observations during field sampling, transportation, handling, storage, and laboratory preparation, iii) visual inspection of specimens, iv) shear wave velocity testing, and v) cyclic triaxial test results.

The DM sampling device was developed for sampling in clay, but its capabilities have also been tested in silts and sands. Silt samples have been obtained with good results by Bray & Sancio (2006). Sands have also been sampled effectively in some cases. Markham et al. 2016 provide data showing that “relatively undisturbed” samples of SM and ML silty soils and medium dense SP and SP-SM sands ($q_{c1Ncs} > 60$) can be obtained using the DM sampler. The samples presented for the silty soil sites in this paper are SM or ML materials, and the EQC-4 site typically has $q_{c1Ncs} > 75$, soils in which the DM sampler is capable of obtaining high-quality samples.

Observations during field sampling, storage, and all actions taken to prepare a specimen for CTX testing were used to evaluate potential causes of significant sample disturbance. This may include vibrations, poor handling, and impacts. Specimens that were adversely affected between field sampling and laboratory extrusion were not considered viable candidates for CTX testing. This includes sampling issues that affect the integrity of the brass sample tube, such as encountering fine gravel, which may cause tube damage such as nicks or dents. Specimens with obvious negative features (e.g., voids, significant cracks, or separations) occurring either naturally in-situ or during sampling and handling were not considered for CTX testing. Figure 4.5 shows photographs of acceptable and unacceptable specimens.

Shear wave velocity testing was conducted on specimens from Site 33, using bender-elements installed in the CTX end caps to establish $V_{s,lab}$ immediately prior to cyclic testing (i.e., after isotropic consolidation). Figure 4.6 compares $V_{s,lab}$ with V_s estimates from crosshole testing (UT-Austin, NZGD) and the McGann et al. 2015 CPT- V_s correlation. This comparison only allows for a rough assessment of disturbance. Inconsistent V_s values from lab and field testing may indicate significant disturbance, but consistent V_s values are not sufficient to determine with certainty that the specimen is of excellent quality, because minor changes in density do not lead to large changes in V_s and compensating effects could produce consistent V_s values in disturbed specimens. The CPT- V_s correlation is based on data from throughout Christchurch, representing an overall regional estimate. Crosshole data may be affected by layered strata, distance between source and receiver, and the experimental set-up employed (Stokoe & Cox, personal communication). Note that $V_{s,lab}$ is corrected from isotropic (lab) to anisotropic (field, $K_o \approx 0.6$) conditions using the procedure outlined in Baxter et al. 2008, but the data are not overburden corrected to a reference stress of 1 atm. The V_s comparison shown in Figure 4.6 does not indicate any sign of significant sample disturbance.

To utilize all data available, cyclic testing results were evaluated for potential disturbance issues. For some clean sand samples, axial strain development during CTX testing may serve as a potential (a posteriori) indicator of sample disturbance. CTX testing data for axial strain vs. number of cycles tend to show a bias toward the extensional side for specimens that are judged to be high-quality and unaffected by disturbance (Markham et al. 2016). Specimens that may have some disturbance may show a more balanced development of extension and compression axial

strains. Although this effect cannot be evaluated prior to testing, and is difficult to quantify, it can be useful in interpreting the results of CTX testing and provides additional data about the testing and specimen relative to the other specimens from that stratum.

Although there are remaining areas of uncertainty on quantitatively and sufficiently assessing disturbance for silty soil samples, the above techniques have been employed in an attempt to minimize disturbance throughout all stages of the sampling and testing process. Based on consideration of all of the above, the specimens described in this paper are judged to be high-quality (i.e., “relatively undisturbed”).

4.4.3 Index Testing

Table 4.1 summarizes the physical characteristics of the cyclic triaxial test specimens from Sites 21, 23, 33, and EQC-4. Testing was conducted in accordance with US and NZ standards (e.g., ASTM D422, D4318, D854).

4.4.3.1 Particle Size Distributions

Particle size distributions were obtained primarily by the laser diffraction method using a Horiba LA-950 machine and assuming refractive indices for quartz. Hydrometer tests were also conducted on three specimens for comparison with the laser-based distributions. Discrepancies between the laser and hydrometer were noted for finer silt and clay particle sizes, with significant discrepancies particularly evident around the 2- μm particle size. The laser and hydrometer methods have fundamental differences. Additionally, the laser method requires a much smaller sample size, so gradations are more sensitive to specimen mixing prior to sampling and the portion of the specimen sampled for gradation. There appears to be no clearly quantifiable trend in the bias, but for these sites the laser typically estimates lower amounts of fine silt and clay-size fractions relative to the hydrometer. Fines content ($< 75 \mu\text{m}$) values presented in Table 4.1 are laser-based estimates.

Figure 4.7 presents particle size distributions for soils at the case history sites. The shaded region encompasses the range of silty soil particle size distributions across the three silty soil sites; hydrometer data are shown as discrete points to illustrate the comparison with the laser method. The silty soil specimens are typically classified by USCS as ML (sand content ranging from 0% to 39%). The Site 33 sand layer contained thin silt seams in some specimens, which were separated out for index testing as shown in Figure 4.7 and Table 4.1. The silt seams are within the range of silty soil gradations, while the sand portions are aligned with the EQC-4 sand specimens.

4.4.3.2 Atterberg Limits

Figure 4.8 presents plasticity index (PI) and liquid limit (LL) data for the silty soil sites on the USCS plasticity chart (ASTM D2487). Specimens ranged from non-plastic to low-PI. Because of the nature of the silty soil specimens, liquid limits were difficult to obtain for many specimens. The Casagrande cup with flat grooving tool was the primary method used for obtaining LL; the wedge-shaped grooving tool was used when the flat grooving tool would tear the specimen. For specimens not suitable for testing with the Casagrande cup, the fall cone method was used as an alternative. Fall cone LL were typically higher than Casagrande cup LL. Figure 4.8 presents results using the Casagrande cup (the ASTM standard). The data cluster around the borderline of ML and

CL, with most specimens classified as ML and a few points in the CL or CL-ML range. However, given the transitional nature of these soils and the borderline position of the CL and CL-ML data points, they are generally considered ML soils.

4.4.3.3 Particle Size & Shape

In liquefaction assessment methods, fines content is used to correct penetration resistance to a clean-sand equivalent for evaluation of liquefaction susceptibility. This approach is based on soil deposits of sands containing fines within the matrix; the point at which fines begin to govern behavior of the soil matrix (e.g., 35% fines content) is implicitly included. However, the silty soils (e.g. silty sands and silts) found in Christchurch are of a more borderline nature where the fine sands and coarse silts represent a steep gradation and are only separated by geotechnical definition using the No. 200 sieve. This can result in differences in fines content that can be relatively meaningless, because the “fines” are close in size and shape to the “coarse” particles. This type of soil deposit will respond differently from a medium or coarse sand with intermixed fine-grained particles.

Additionally, particle shapes of the fine sand-sized particles and silt-sized particles of Christchurch soils are often angular. This has a mitigating effect on cyclic mobility with unlimited strain potential, as they dilate easily when undergoing drained shear, especially at low confining stress in these shallow soil layers. Figure 4.9 shows scanning electron microscope (SEM) photographs of a standard test sand (Monterey 0/30, Kammerer 2002) and two specimens from the silty soil sites (with the silt specimen separated by wet sieve into coarse and fine fractions), demonstrating particle size and angularity of Christchurch soils as compared with a standard sand. The fine sand and coarse silt fractions at the silty soil sites have similar particle size and shape.

4.4.4 Cyclic Triaxial Testing

Cyclic triaxial testing was performed on 21 test specimens from the silty soil sites and 6 test specimens from the reference sand site using an updated 2014 model of the CKC triaxial testing device (Li et al. 1988). After completion of each cyclic test, specimens were reconsolidated to measure post-liquefaction volumetric strain. Cyclic testing was conducted at the Univ. of Canterbury (UC) Geomechanics Laboratory to minimize potential disturbance caused by transportation.

4.4.4.1 Specimen Preparation

Samples were stored vertically in wooden crates at the UC laboratory. The DM sample tubes were cut at the top and bottom of each specimen, with extrusion immediately prior to testing, minimizing the length of tube through which the specimen was extruded and exposure time. Specimens were tested as-extruded, with nominal height and diameter of the test specimens approximately 135-140 mm and 61 mm, respectively. After extrusion, the specimen was immediately transferred to the CKC triaxial testing cell and encased in a latex membrane without further trimming. Coarse-grained specimens were flushed with deaired water as a preliminary saturation method. Vacuum extraction was used to remove air from the specimen prior to application of cell pressure and back pressure, maintaining the saturation effective stress level by keeping a constant differential between the applied internal specimen vacuum and chamber

vacuum. Each test specimen was fully saturated using back-pressure saturation at two-thirds of the testing stress and isotropically consolidated to a testing stress of 1.1 times the estimated in-situ vertical effective stress before performing the cyclic triaxial test (B-values and testing stresses given in Table 4.2). The extrusion and specimen preparation process is further described in Markham et al. 2016.

4.4.4.2 Cyclic Response

Table 4.2 summarizes laboratory testing parameters of the specimens tested for Sites 21, 23, 33, and EQC-4. Cyclic loading was applied at a loading frequency of either 1 Hz or 0.1 Hz with a sine wave starting in compression. Loading frequency for all silty soil specimens was 1 Hz, because of the potential for rate effects in fine-grained specimens (e.g., Donahue et al. 2007). EQC-4 clean-sand specimens (6U-A, 6U-B, 7U-A) were tested at 0.1 Hz, because rate effects are not anticipated in clean sands and this rate of loading ensures equalization of pore water pressures (PWP) during cyclic testing. At 1 Hz loading in fine-grained soil, PWP are not accurately measured, because they do not equalize within the specimen at the rate at which measurements are recorded and loading is applied. Figure 4.10 presents CTX results for stress path (q vs. p') and excess PWP ratio (r_u) demonstrating un-equalized PWP measurements in silt as compared with accurate and equalized PWP measurements in sand at typical loading rates of 1 Hz and 0.1 Hz, respectively.

Figure 4.11 presents CTX results for stress-strain response and axial strain vs. number of cycles for representative specimens from the three silty soils sites and a sand specimen from EQC-4 for comparison. The cyclic responses among the four specimens are similar, with only subtle differences noticeable between the sand and non-plastic silt (Figure 4.11a,b) and the low plasticity ($PI=10$) silts (Figure 4.11c,d). As plasticity increases, the compressive strains decrease slightly and the shape of the stress-strain response changes slightly. Differences in stress-strain response and axial strain development are subtle in this range of silty soils (ML with $PI = 0 - 10$). Results typically indicate a slower build-up of strains rather than the “sudden failure” liquefaction strains associated with loose clean sands (Seed & Lee 1966).

Close inspection reveals nuances in the shapes of the initial stress-strain loops that may be overlooked when focused on the cyclic response of the specimen across a wide strain range including near the threshold of liquefaction. Figure 4.12 presents individual cycles of stress-strain response for the specimens presented in Figure 4.11. For these natural soil specimens, with some intra-specimen heterogeneity, there are only subtle differences and trends that arise in examining the data for individual cycles from this range of Christchurch soils. The soil response is transitional in nature and represents a continuum of shades of response rather than responses that can be categorized discretely. This is the challenge of characterizing silty soils, particularly natural soils that will often not be homogeneous or as well-captured at the element scale as a clean sand deposit. This is also of importance for numerical modeling, where calibration and verification studies aim to capture and match the results of laboratory testing. For silty soils such as the natural specimens presented in this paper, overall matching of laboratory data should be the main goal, while considering how to incorporate site-scale effects in the model response that will not have been captured with element testing (e.g., effect of thin-layering, heterogeneity becoming homogeneity at site-scale, vertical and lateral effects of PWP movement).

4.4.4.3 Post-Liquefaction Reconsolidation Tests

Clear differences in post-liquefaction reconsolidation are observed among the silty soils tested in this study. The reconsolidation response can be divided into soils exhibiting “sand-like” behavior, with near-instantaneous reconsolidation occurring, and soils exhibiting “non-sand-like” behavior, which covers the range from more gradual reconsolidation that occurs with minimal secondary compression to reconsolidation that exhibits a response similar to a primary and secondary consolidation curve. Indeed, observations on each specimen’s post-liquefaction reconsolidation response help to group specimens that are not easily subdivided based on the FC parameter and the assumption of specimen homogeneity. Silty soils tested from Sites 21, 23, and 33 cover the range of responses from “sand-like” to “non-sand-like” behaviors. Specimens exhibiting post-liquefaction reconsolidation response closer to “sand-like” behavior also exhibit cyclic testing PWP equalization closer to that of a clean sand, with responses ranging from unequalized PWP measurements for higher PI silts to more equalized PWP measurements for non-plastic silts.

Representative curves are shown in Figure 4.13, along with a plot of estimated final volumetric strain vs. maximum shear strain during CTX testing. Data from 0-50 sec have been cropped to remove initial transient data from equilibration of water in the volume change indicator of the CKC device (although some remains from 50-60 seconds for specimens EQC4-DM2-4U-A, S21-DM1-3U-A, and S21-DM1-3U-B). Specimen EQC4-DM2-4U-A had a greater amount of organics compared with EQC4-DM2-3U-A/B, and specimens S21-DM1-3U-A/B are non-plastic silts, which is why those specimens do not equilibrate as quickly as the clean sands or respond as slowly as the low-plasticity silt specimens. Estimated final volumetric strain is based on the estimated volumetric strain at the end of primary reconsolidation for those soils exhibiting a “non-sand-like” response. “Sand-like” soils have a clear final volumetric strain. Regardless of the response with time, all specimens end at a volumetric strain in the range of approximately 1.5-3.5%, with sand specimens having lower final volumetric strains (~1.5-2.5%) than silty soils (~2-3.5%). This range of post-liquefaction reconsolidation volumetric strains is within the range of medium dense to dense sand presented by Ishihara & Yoshimine (1992). Lateral drainage is not allowed in the CTX specimens, and reconsolidation time curves may be influenced by the laboratory condition of double drainage. These features should be considered when interpreting laboratory response to determine possible field behavior. This interpretation and extrapolation from laboratory-to-field warrants further research, but it is clear that the differences observed in laboratory reconsolidation curves can be important when evaluating field performance.

4.5 LIQUEFACTION RESISTANCE INTERPRETATION

4.5.1 Laboratory-based Cyclic Resistance Curves

Laboratory-based interpretations of liquefaction resistance typically derive from strain-based or pore water pressure generation criteria. For CTX testing of silty soils, two liquefaction criteria were selected: (i) the number of cycles to 3% single-amplitude axial strain and (ii) the number of cycles to 5% double-amplitude axial strain. Given the fine-grained nature of the soils tested, and the 1 Hz frequency of loading, pore water pressure measurement for this testing is not an accurate measurement of equalized pore water pressures throughout the specimen and precludes the use of an excess pore water pressure ratio criterion.

Figure 4.14 presents CTX testing cyclic resistance curves for Sites 21 and 23. Specimens were grouped by q_c , I_c , depth, and visual inspection for development of cyclic resistance curves. Specimens from Site 33 were difficult to group for developing CRR curves, because of the variation in soil types and variation in cyclic response of the transitional soil types within the “silty soil” layer.

4.5.2 Comparison with Simplified Methods

Overall, laboratory-based estimates of cyclic resistance (CRR_{Lab}) are in agreement with simplified method estimates of cyclic resistance ratio using Boulanger & Idriss (2016) (CRR_{BI16}). For comparison with CRR_{BI16} , CRR_{Lab} is estimated from cyclic resistance curves as shown in Figure 4.14 at 15 cycles of loading, corresponding to M_w 7.5 and corrected using factors for triaxial-to-simple shear and multidirectional shaking to obtain CRR_{Field} . The triaxial-to-simple shear factor (C_r) varies based on soil type and overconsolidation; $C_r \approx 0.75$ is reasonable for normally consolidated ($K_o \approx 0.6$) fine-grained soils based on Sancio (2003). The multidirectional shaking factor of 0.9 is based on Seed (1979). More recent work by Kammerer (2002) indicates that the multidirectional shaking factor can vary more than found by Seed (1979); hence, this is another source of uncertainty in adjusting laboratory test results to capture field performance. Model uncertainty in CRR_{BI16} is considered by using the 15-85th percentile probability of liquefaction values. The 15th percentile approximates the deterministic approach typically used in practice. For the three silty soil sites presented in this paper, CRR_{Lab} estimates are approximately 0.24-0.32, which equate to CRR_{Field} estimates of approximately 0.16-0.22 using the triaxial-to-simple shear and multidirectional shaking correction factors. CRR_{BI16} is approximately 0.11-0.20 at the 15th percentile level and 0.17-0.25 at the 85th percentile level. Thus, the laboratory derived CRR_{Field} values are reasonably consistent with the 15-85th percentile ranges of the CRR_{BI16} relationship.

Thus, the laboratory testing program produced CRR values consistent with the field-based empirical simplified method estimates of CRR. Additionally, both estimates of CRR are well below simplified method estimates of seismic demand (i.e., $CSR \sim 0.25$ -0.50, so the critical factor of safety is $FS \approx 0.5$ across the three silty soil sites). Therefore, laboratory estimates of cyclic resistance cannot explain why these silty soil sites did not manifest liquefaction at the ground surface. Under the intense shaking of the Christchurch earthquake, these soils likely developed high pore water pressures as measured in the laboratory tests. However, the sites did not exhibit surface manifestations of liquefaction because of other factors. The factors that likely contribute to mitigating the effects of liquefaction at these silty soils sites are not captured by the element-scale laboratory CTX test specimens. Instead, there are likely geologic and depositional environment factors such as highly stratified silt deposits with thin-layering that need to be considered. This is the focus of ongoing research.

4.6 CONCLUSIONS

The laboratory testing described in this paper provides data and insight on the cyclic response of natural silty soil specimens. Intermediate silty soils exhibit transitional responses that are difficult to characterize with the parameters that have been developed for the conventional “sand” vs. “clay” framework. This study advances our understanding of the cyclic response of in-situ silty soils by providing test results that display a range of transitional soil responses of

intermediate soils. Moreover, the study provides insights for developing effective laboratory test programs, guiding liquefaction assessments, and calibrating numerical models.

The cyclic response and axial strain development of the silty soil test specimens are nuanced. There are only subtle differences between the cyclic responses of fine sand, non-plastic silt, and $PI=10$ silt. In contrast, the post-liquefaction reconsolidation time curves present easily identifiable differences ranging from “sand-like” to “non-sand like” response. Clean fine sands and non-plastic silts tend to exhibit “sand-like” reconsolidation volumetric responses wherein the specimen reaches near-immediate final volumetric strain. Low- PI silts tend to exhibit “non-sand like” reconsolidation volumetric responses wherein the specimen may undergo primary and secondary reconsolidation over time before reaching a point at which the final volumetric strain can be estimated. These differences have implications for pore water pressure movement and ejecta development, especially when considered with the layered nature of the silty soil sites. The impacts of these laboratory-based differences can be extrapolated using engineering judgement to post-liquefaction field manifestations and settlement potential, considering adjustments from element-scale to site-scale and site stratigraphy effects (vertically and laterally).

Specimen variability and heterogeneity should be considered when interpreting the cyclic response of natural silt soils. Natural soils will have heterogeneities and soil structure that are difficult, if not impossible, to replicate with laboratory-prepared specimens. Consideration of relative scale effects and overall stratum characterization will enable more effective testing programs that move towards better understanding of in-situ silty soil cyclic response.

The cyclic resistance and strain development data are useful in assessing the liquefaction resistance of the silty soils at the three case history sites. State-of-practice simplified liquefaction evaluation procedures indicated all three sites should have expressed surface manifestations of liquefaction during the intense Christchurch earthquake shaking. The laboratory CTX results also indicate that the soils tested should have liquefied for this event. Yet, no manifestations were observed. The CTX test strain data indicate these low penetration resistance silty soils do not exhibit cyclic mobility with unlimited strain potential at the onset of liquefaction such as that observed with loose clean sand specimens. Instead, the silty soils exhibit cyclic mobility with limited strain response, even when characterized with low CRR values due to low equivalent-clean sand penetration resistances. Additionally, the slow pore water pressure dissipation response during post-liquefaction reconsolidation tests indicates that these silty soils would not likely accumulate a large amount of water or the flow velocity necessary to form ejecta, especially considering the intense fine layering of the silty soil deposits and their relatively low vertical hydraulic conductivity.

These data, combined with the post-liquefaction reconsolidation data, provide detailed soil characterization to go with the detailed post-earthquake observations at the case history sites for incorporation in the global dataset and the next generation of liquefaction assessment methods. The combination of laboratory testing and field observations provides robust “no-liquefaction” case histories that can enable model refinements to reduce the discrepancies between state-of-practice assessments and post-earthquake observations at silty soil sites. Further research on the cyclic response of highly stratified silty soils is warranted.



Figure 4.1: (a) Liquefaction Site (from GEER Report No. 27), and (b) No-liquefaction Site (from Mr. Rick Wentz of Wentz-Pacific, Ltd.) in Christchurch.

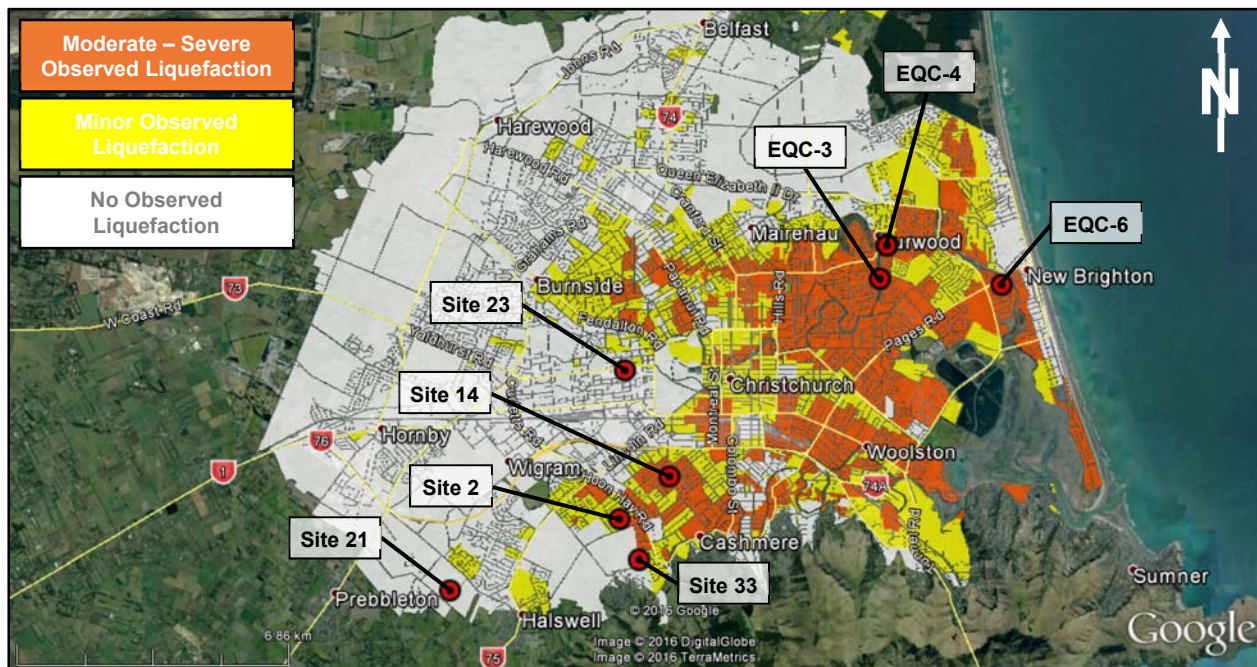


Figure 4.2: Generalized liquefaction observations following the Christchurch earthquake as interpreted from aerial photography (from NZGD). Silty soil project sites are also shown.

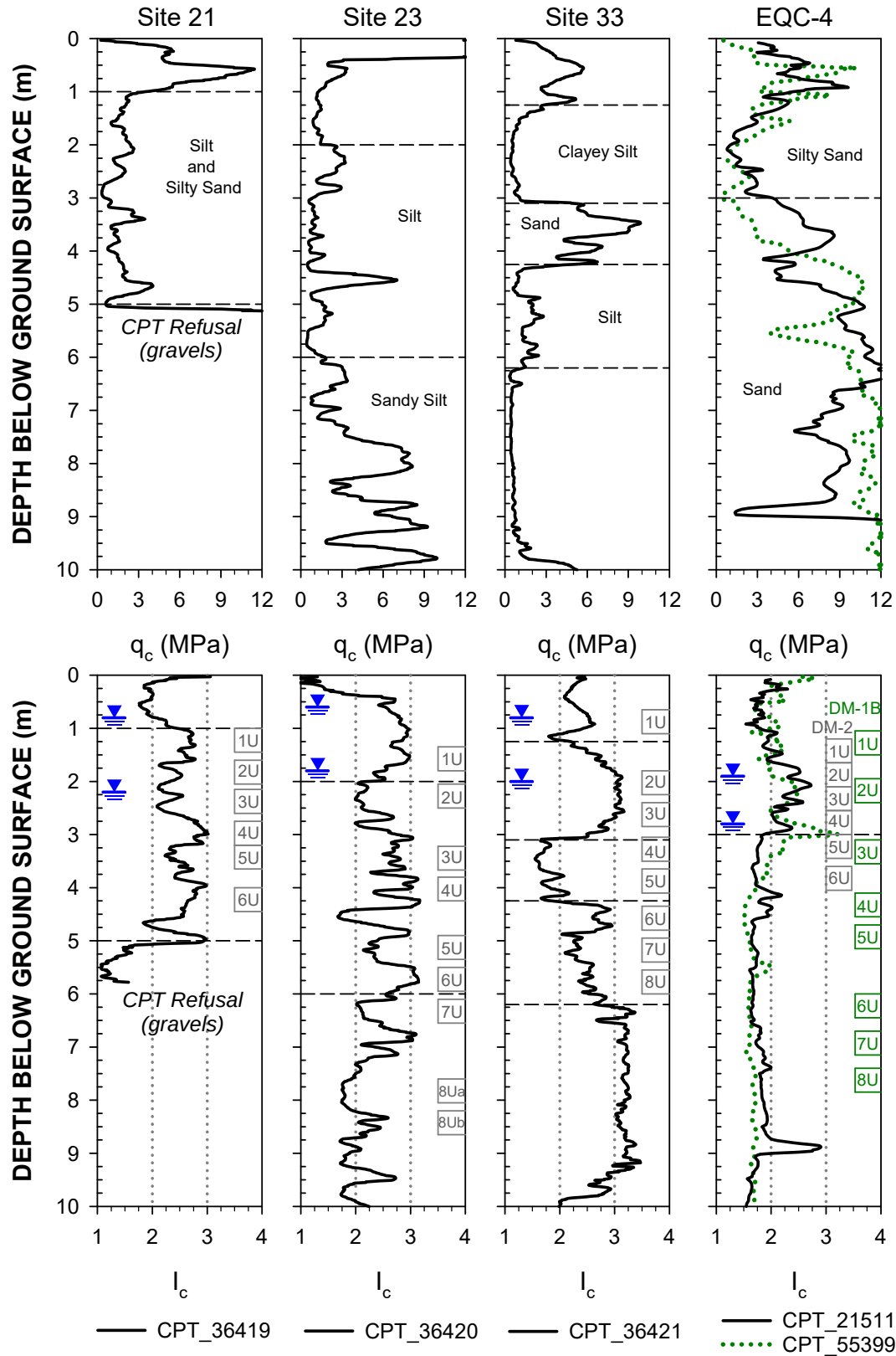


Figure 4.3: CPT traces of tip resistance (q_c) and soil behavior type index (I_c). CPT data from NZGD. Simplified soil layers, DM sample depths, and zones of GWT fluctuation are also shown.

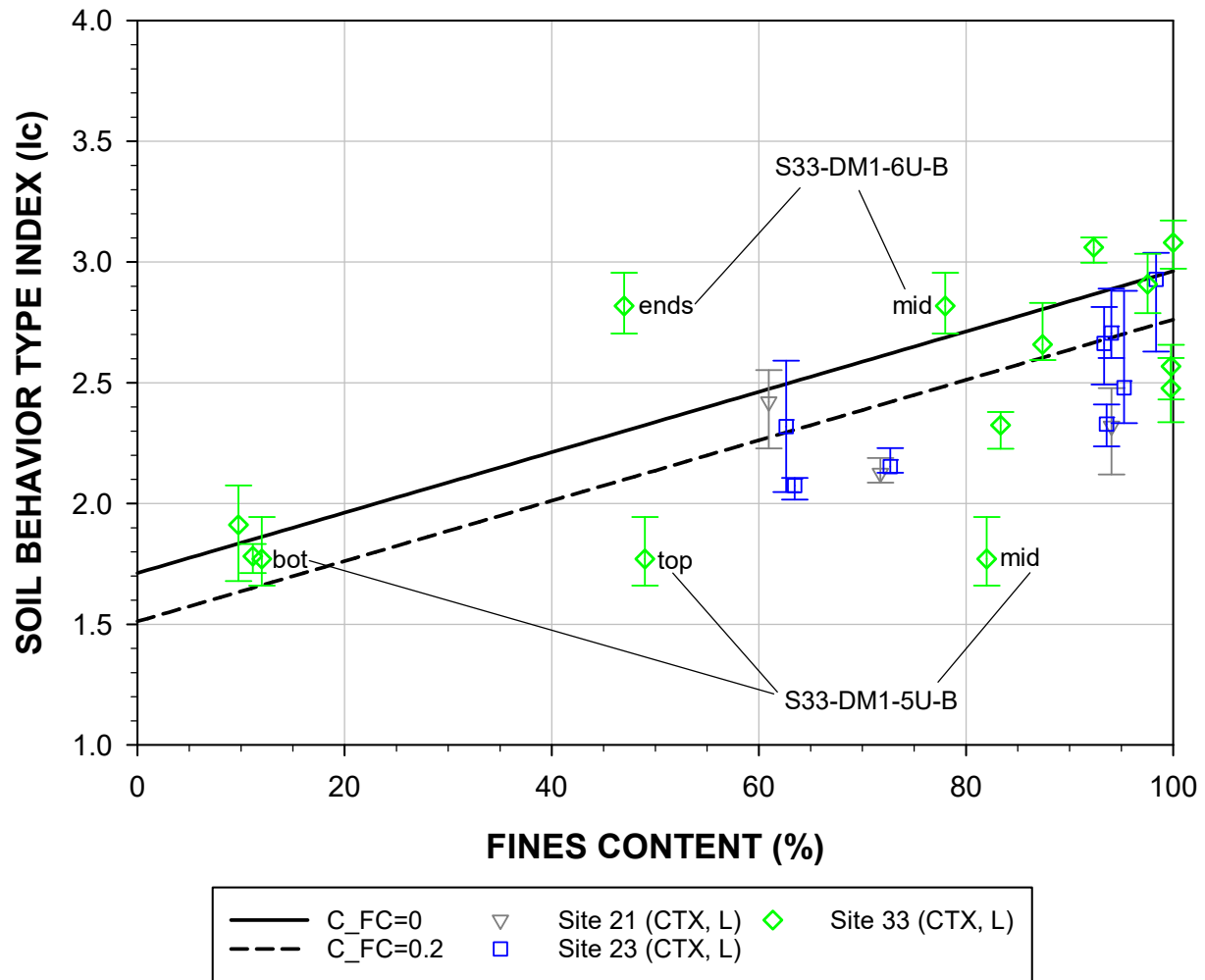


Figure 4.4: Fines Content vs. I_c correlation. Geometric mean I_c is shown with maximum and minimum I_c over specimen depth interval of 14 cm. “CTX” indicates specimens tested in CTX. “L” indicates particle size distribution by laser method.



Figure 4.5: Representative CTX test specimens demonstrating varying degrees of heterogeneity. Acceptable: (a) Clean Sand (EQC3-DM1-5U-A), (b) PI=0 Silt (S21-DM1-3U-A), (c) PI=10 Silt (S33-DM1-8U-A), (d) PI=6 Silt (S23-DM1-5U-A), (e) PI=6 Silt (S23-DM1-7U-A). Acceptable, results require more interpretation: (f) Non-plastic Silty Sand/Silt (S33-DM1-6U-B), (g) PI=0 Silt (S33-DM1-7U-A). Unacceptable: (h) Clean Sand (S33-DM1-4U-B) – separation/void evident in tube, possibly disturbed during sampling.

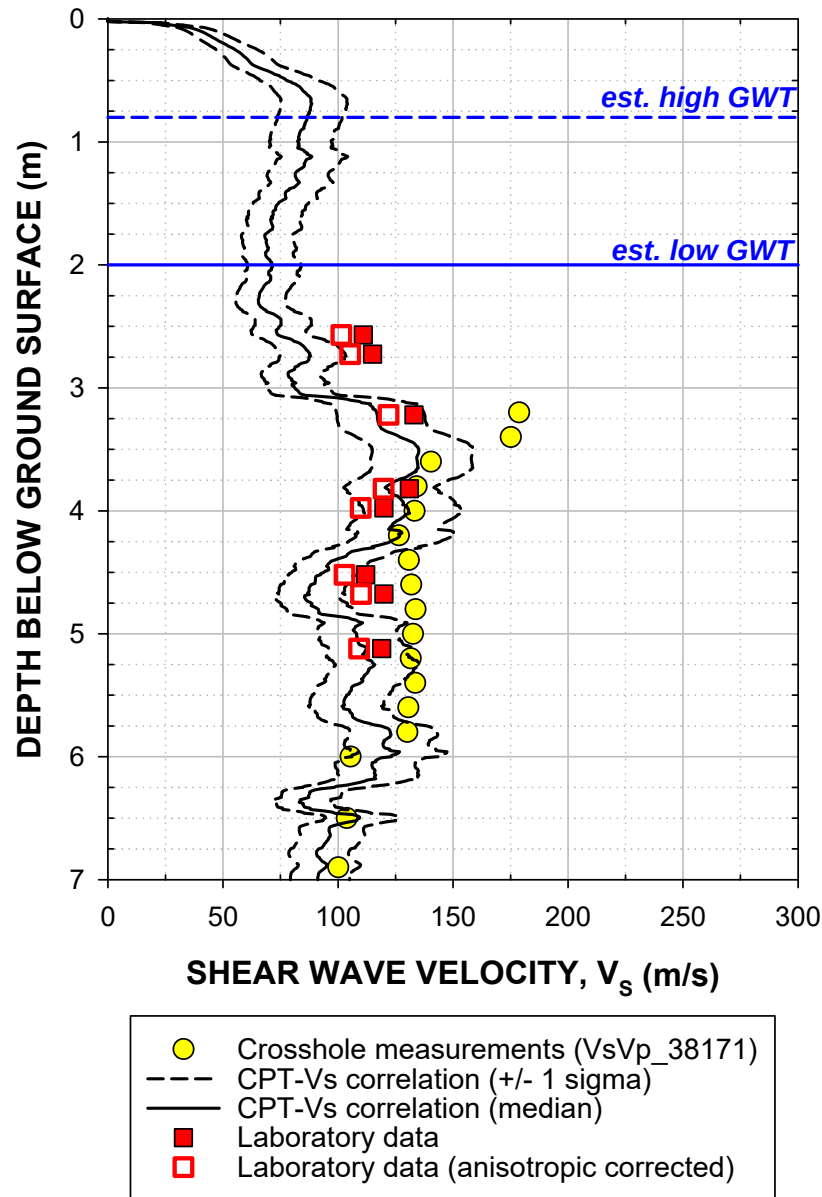


Figure 4.6: Site 33 laboratory specimen binder element V_s measurements compared to CPT- V_s correlation (McGann et al. 2015) and crosshole seismic measurements (Stokoe et al., UT-Austin; available at NZGD). Laboratory data shown as-measured (isotropic conditions) and corrected to anisotropic conditions approximating in-situ conditions.

Table 4.1: Characteristics of test specimens at Site 21, Site 23, Site 33, and EQC-4.

Specimen	Mid-Depth (m)	$q_{tLN,cs}$ Geomean (min - max)	I_c Geomean (min - max)	$FC_{75\mu m}$ (%)	D50 (μm)	LL	PI	USCS	G_s
S21-DM1-2U-A	1.77	91 (87 - 97)	2.32 (2.12 - 2.48)	94	37	26; 28; 22	2; 8; 2	ML; CL; ML	2.72
S21-DM1-3U-A	2.32	77 (76 - 80)	2.42 (2.23 - 2.55)	61	65	n/a	NP	ML	---
S21-DM1-3U-B	2.475	83 (81 - 85)	2.13 (2.09 - 2.19)	72	57	n/a	NP	ML	2.69
S23-DM1-3U-A	3.39	73 (70 - 77)	2.66 (2.49 - 2.81)	91	33	28	5	ML	2.72
S23-DM1-3U-B	3.545	71 (67 - 74)	2.71 (2.60 - 2.89)	92	32	33	7	ML	---
S23-DM1-4U-B	4.125	76 (67 - 82)	2.49 (2.35 - 2.88)	94	16	30	4	ML	---
S23-DM1-5U-A	5.07	79 (77 - 81)	2.38 (2.29 - 2.46)	94	19	33; 30	9; 6	ML	2.72
S23-DM1-7U-A	6.27	92 (89 - 94)	2.12 (2.06 - 2.15)	69	14	27	6	CL-ML	---
S23-DM1-7U-B	6.425	95 (93 - 97)	2.20 (2.17 - 2.27)	75	44	27; 25	7; 5	CL-ML	2.69
S23-DM1-8U-B-A	8.37	88 (83 - 92)	2.36 (2.08 - 2.63)	60	38	24	NP	ML	2.67
S33-DM1-2U-B	2.125	65 (64 - 67)	3.06 (3.00 - 3.10)	92	17	41	15	ML	2.67
S33-DM1-3U-A	2.57	67 (64 - 71)	3.08 (2.97 - 3.17)	100	7	38	12	ML	2.70
S33-DM1-3U-B	2.725	73 (71 - 76)	2.91 (2.79 - 3.03)	98	21	26	5	CL-ML	---
S33-DM1-4U-A	3.22	120 (117 - 122)	1.82 (1.76 - 1.86)	11	127	---	---	SP-SM	2.68
S33-DM1-5U-A	3.82	118 (115 - 125)	1.95 (1.72 - 2.10)	10	116	---	---	SP-SM	2.69
S33-DM1-5U-B	3.975	126 (117 - 131)	1.81 (1.70 - 1.99)	49, 82, 12	75, 41, 135	23	NP	SM, ML, SP-SM	---
S33-DM1-6U-A	4.52	70 (70 - 72)	2.68 (2.62 - 2.83)	87	33	23	1	ML	2.69
S33-DM1-6U-B	4.675	66 (64 - 68)	2.83 (2.72 - 2.96)	47, 78	78, 49	n/a	NP	SM, ML	---
S33-DM1-7U-A	5.12	83 (82 - 85)	2.37 (2.27 - 2.43)	83	37	n/a	NP	ML	2.68
S33-DM1-8U-A	5.72	80 (74 - 88)	2.53 (2.39 - 2.66)	100	10	39	10	ML	2.67
S33-DM1-8U-B	5.875	82 (80 - 87)	2.62 (2.48 - 2.71)	100	7	38	10	ML	---
EQC4-DM1B-6U-A	6.17	109 (107 - 115)	1.64 (1.62 - 1.65)	1	201	---	---	SP	---
EQC4-DM1B-6U-B	6.325	115 (115 - 116)	1.64 (1.63 - 1.64)	1	213	---	---	SP	2.68
EQC4-DM1B-7U-A	6.87	125 (125 - 126)	1.65 (1.64 - 1.66)	9	168	---	---	SP-SM	---
EQC4-DM2-3U-A	2.27	75 (73 - 78)	2.30 (2.21 - 2.41)	34	88	---	---	SM	2.68
EQC4-DM2-3U-B	2.425	85 (78 - 94)	2.36 (2.06 - 2.58)	34	96	---	---	SM	---
EQC4-DM2-4U-A	2.72	81 (76 - 88)	2.07 (2.03 - 2.14)	22	122	---	---	SM	---

Notes: Specimen naming notation = "Site-Boring-Sample-Specimen". Geometric mean, min, and max values of $q_{tLN,cs}$ and I_c estimated over specimen interval of 14 cm. In-situ water contents not available (samples allowed to drain in laboratory prior to extrusion). Specimens S33-DM1-5U-B and S33-DM1-6U-B showed clear layering and were separated into portions for particle size analysis. Values shown for S33-DM1-5U-B are for the top, middle, and bottom portions of the specimen, while the values shown for S33-DM1-6U-B are for the ends and middle portions of the specimen. LL of "n/a" indicates that liquid limit could not be obtained with Casagrande cup. Multiple LL values indicate multiple Casagrande cup tests.

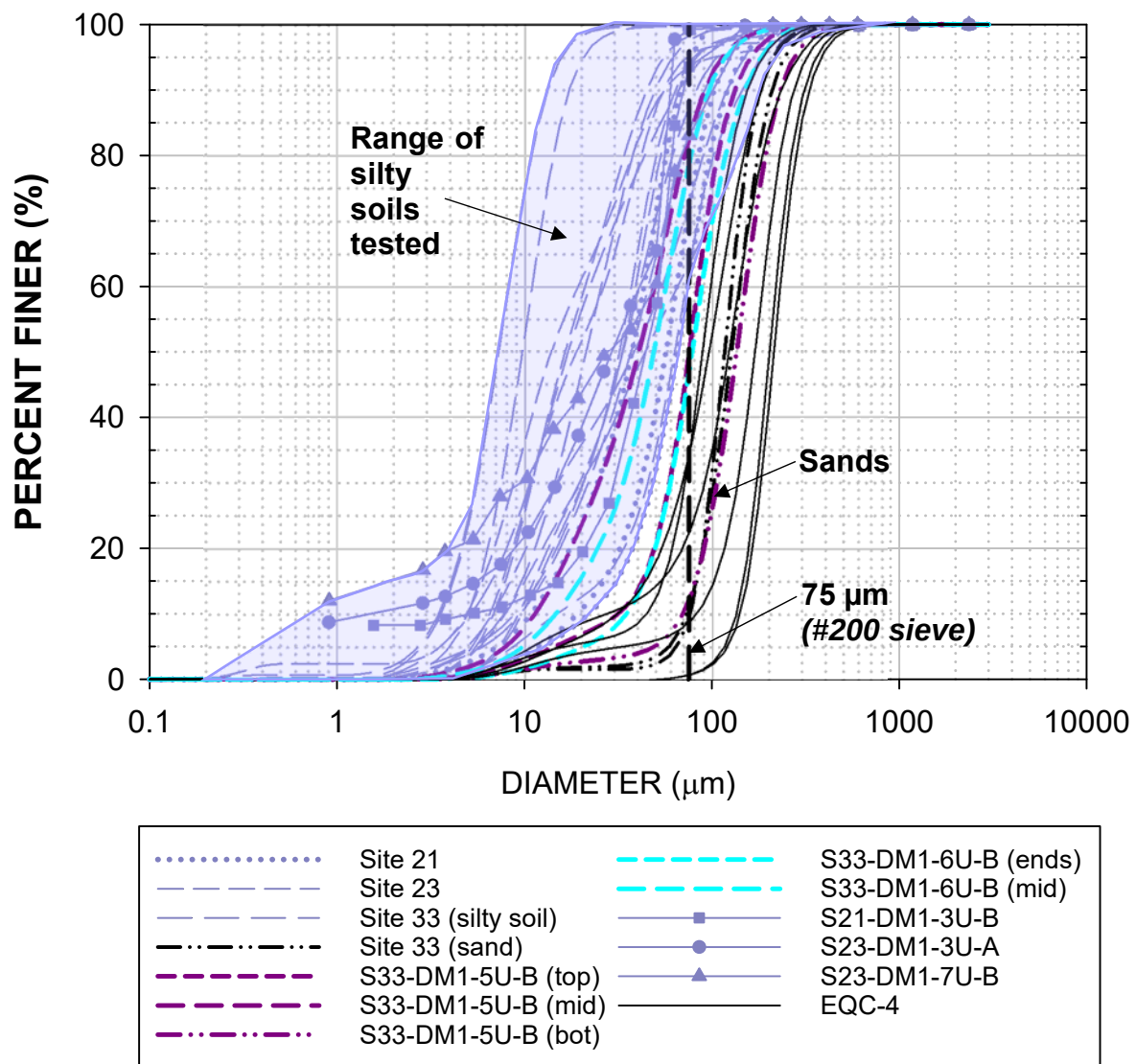


Figure 4.7: Particle size distributions. Lines with discrete points represent hydrometer tests.

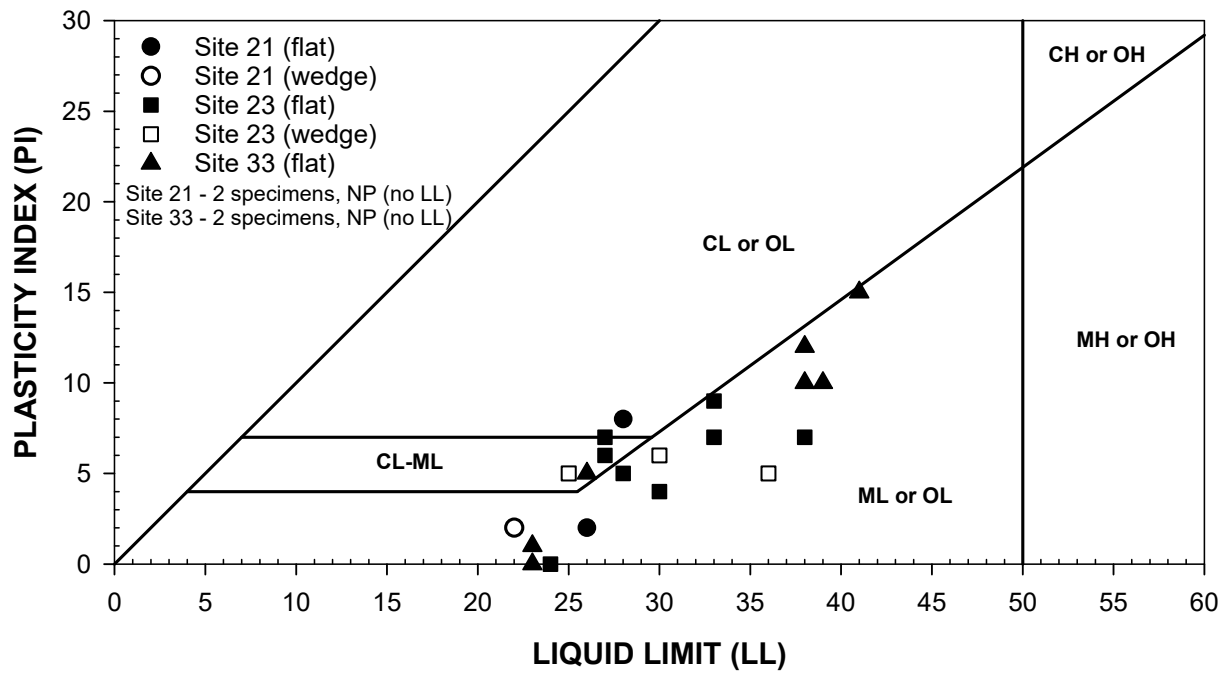


Figure 4.8: Plasticity chart. Liquid limit obtained using Casagrande cup with either flat or wedge-shaped grooving tools.

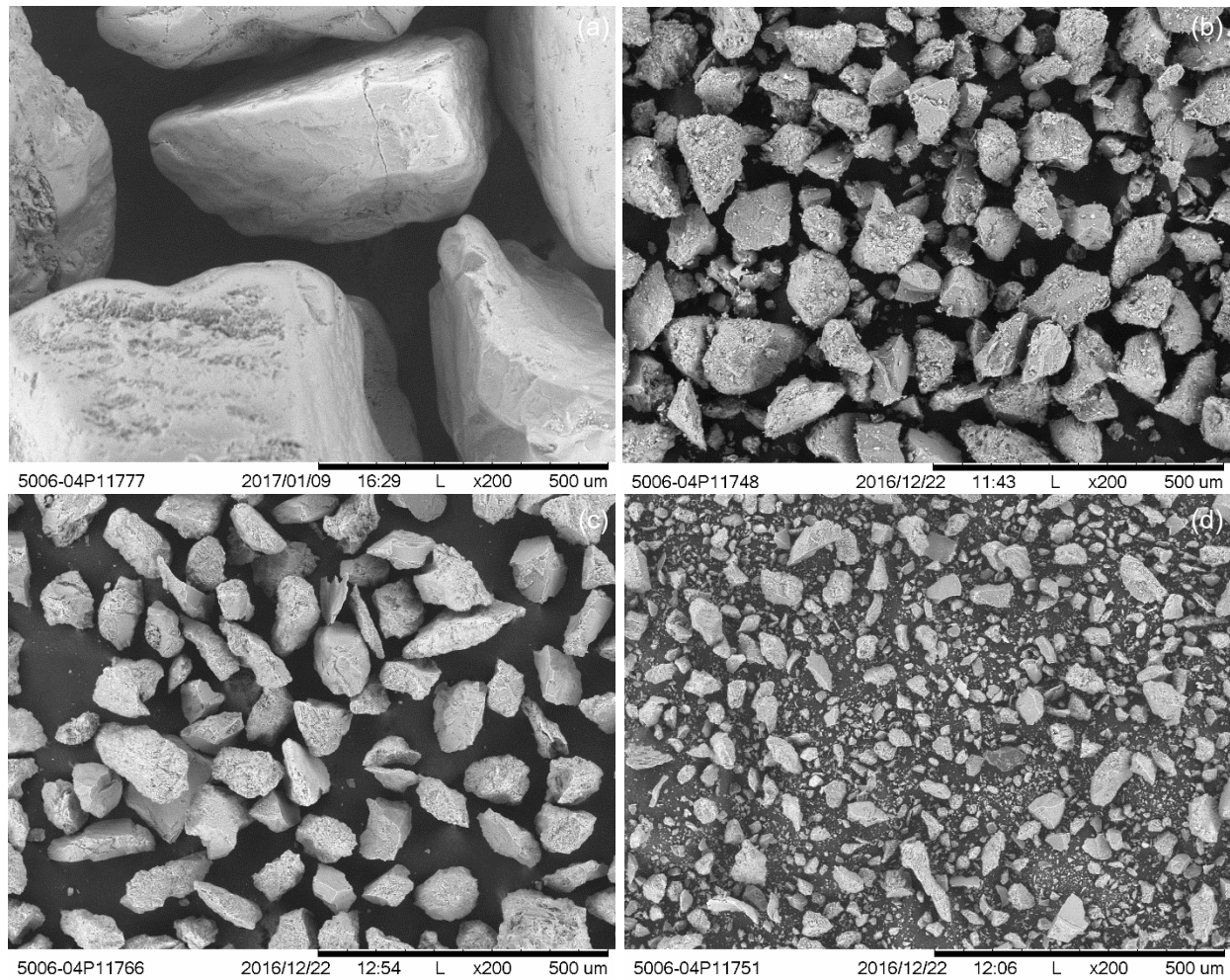


Figure 4.9: Scanning electron microscope (SEM) photographs at 200x magnification. (a) Monterey 0/30 sand, FC = 0%; (b) S33-DM1-5U-A sand, FC=10%; (c,d) S23-DM1-8Ub-A silt, FC=63%: coarse fraction ($> 75 \mu\text{m}$) and fines fraction ($< 75 \mu\text{m}$), respectively.

Table 4.2: CTX test results and specimen parameters for Site 21, Site 23, Site 33, and EQC-4 specimens.

Specimen	B_c	p'_c (kPa)	ρ_c (kg/m ³)	e_c	f (Hz)	CSR	$N_{3\%,SA}$	$N_{5\%,DA}$	$\epsilon_{a,max}$ (%)	$\epsilon_{v,recon}$ (%)
S21-DM1-2U-A	0.98	35	1467	0.85	1	0.25	67	75	-6.4	3.1
S21-DM1-3U-A	0.97	46	1481	0.82	1	0.43	4	7.5	-6.2	2.25
S21-DM1-3U-B	0.98	47	1463	0.84	1	0.30	19	23	-7.1	2.9
S23-DM1-3U-A	0.97	52	1362	1.00	1	0.40	5	8	-7.1	2.2
S23-DM1-3U-B	0.97	53	1310	1.08	1	0.30	12	16	-6.1	2.35
S23-DM1-4U-B	0.99	58	1366	0.98	1	0.35	6	10	-8.1	2.7
S23-DM1-5U-A	0.99	68	1289	1.11	1	0.25	36	43	-7.7	3.1
S23-DM1-7U-A	0.92	79	1574	0.71	1	0.32	5	7	-8.0	3.1
S23-DM1-7U-B	0.97	80	1597	0.68	1	0.40	4	6	-8.0	3.15
S23-DM1-8U-B-A	0.97	99	1518	0.76	1	0.25	18	25	-6.9	2.5
S33-DM1-2U-B	1.00	42	1382	0.93	1	0.42	16	24	-5.6	1.1
S33-DM1-3U-A	0.99	47	1454	0.86	1	0.35	5	8	-8.1	2.95
S33-DM1-3U-B	0.97	48	1435	0.88	1	0.25	27	29	-6.2	2.5
S33-DM1-4U-A	0.96	52	1546	0.73	1	0.35	52	48	-3.7	1.75
S33-DM1-5U-A	0.98	58	1439	0.87	1	0.43	2	3	-8.1	2.3
S33-DM1-5U-B	0.98	60	1436	0.87	1	0.39	3	5	-8.0	2.45
S33-DM1-6U-A	0.98	64	1363	0.97	1	0.47	1	1	-6.0	2
S33-DM1-6U-B	0.98	66	1369	0.96	1	0.25	11	13	-8.5	3.4
S33-DM1-7U-A	0.98	70	1361	0.97	1	0.42	1	2	-8.1	2.4
S33-DM1-8U-A	0.99	75	1390	0.92	1	0.35	5	7.5	-6.1	2.4
S33-DM1-8U-B	0.99	77	1333	1.00	1	0.30	9	12	-6.1	1.8
EQC4-DM1B-6U-A	0.98	80	1535	0.75	0.1	0.50	4	6.5	-5.7	2.05
EQC4-DM1B-6U-B	0.98	82	1549	0.73	0.1	0.38	13	18	-4.7	1.5
EQC4-DM1B-7U-A	0.98	88	1496	0.79	0.1	0.34	5	7.5	-6.0	1.9
EQC4-DM2-3U-A	0.98	43	1377	0.95	1	0.35	12	14	-6.1	2.2
EQC4-DM2-3U-B	0.96	45	1426	0.88	1	0.48	5	7	-6.0	1.75
EQC4-DM2-4U-A	0.99	48	1169	1.26	1	0.28	87	95	-6.0	3.5

Notes: Subscript "c" indicates value after consolidation to testing stress, $p' = 1.1$ *in-situ vertical effective stress, immediately prior to cyclic testing.

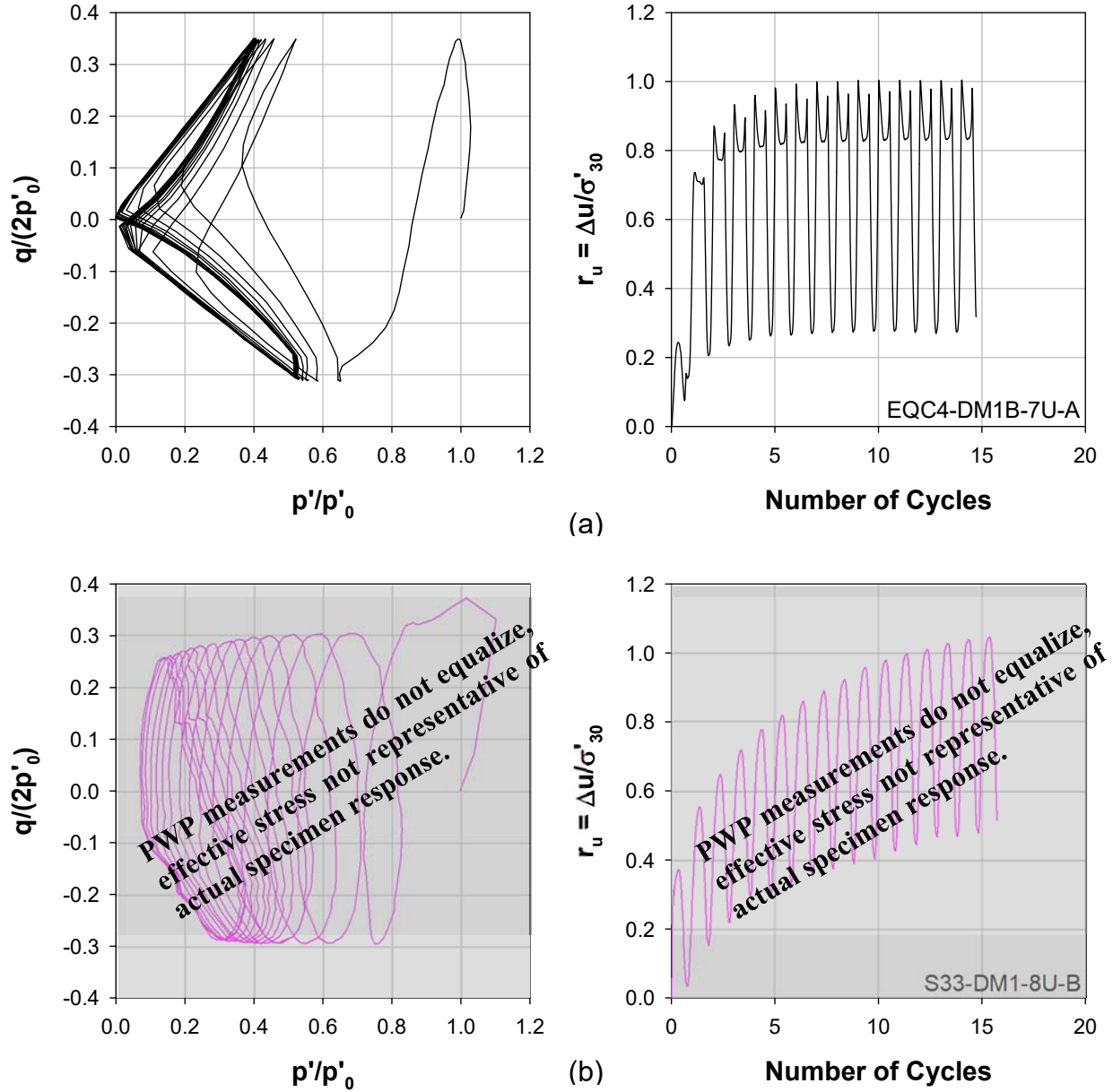


Figure 4.10: CTX results demonstrating un-equalized PWP measurements in silt as compared with equalized PWP measurements in sand. Stress path (q vs. p') and excess pore water pressure ratio (r_u) for: (a) EQC4-DM1B-7U-A (Clean Sand, $f = 0.1$ Hz loading) and (b) S33-DM1-8U-B (PI=10 Silt, $f = 1$ Hz loading).

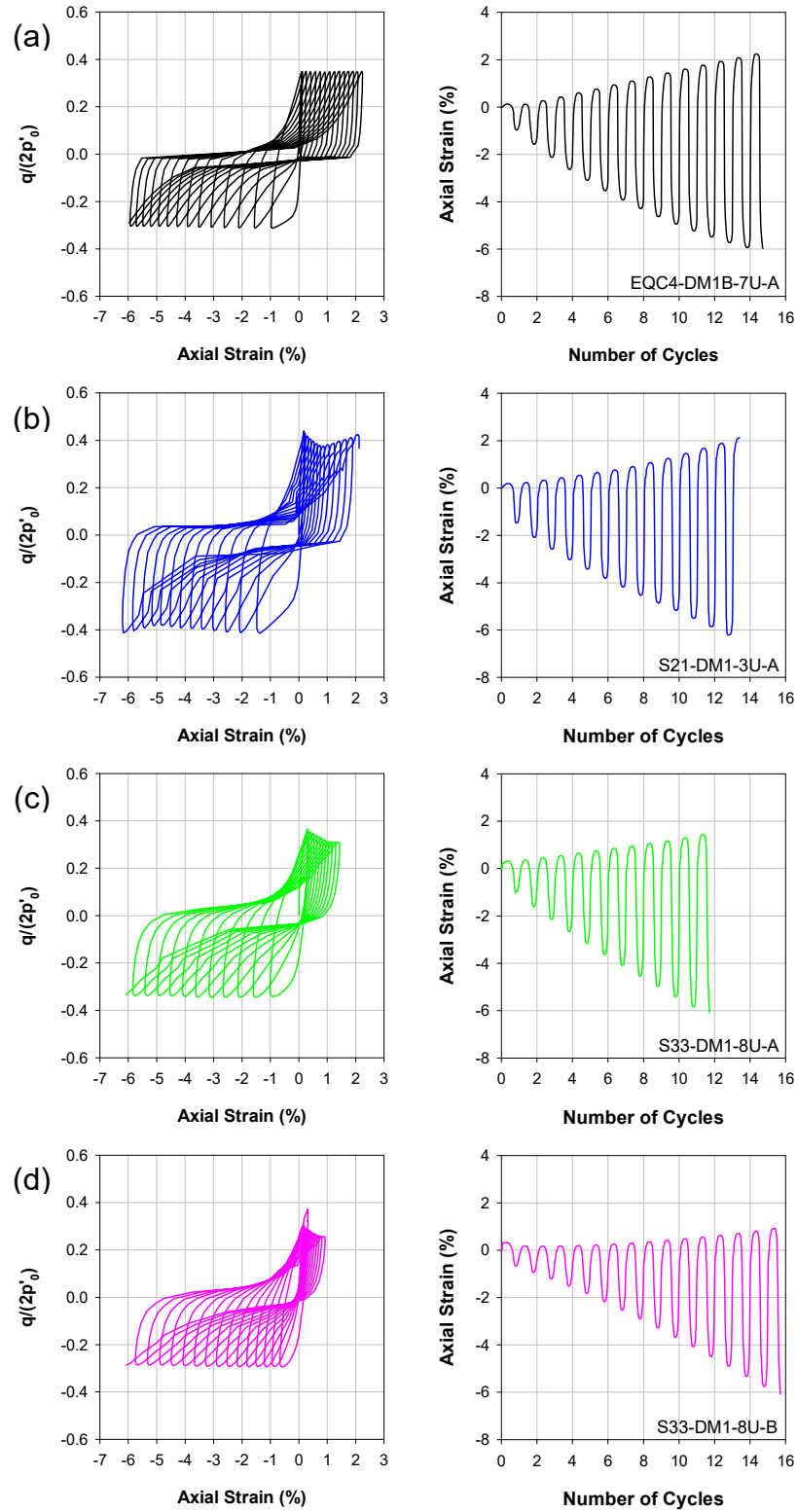


Figure 4.11: Representative CTX stress-strain and axial strain accumulation results for: (a) Clean Sand, $f=0.1$ Hz; (b) PI=0 Silt, $f=1$ Hz, (c) PI=10 Silt, $f=1$ Hz, and (d) PI=10 Silt, $f=1$ Hz.

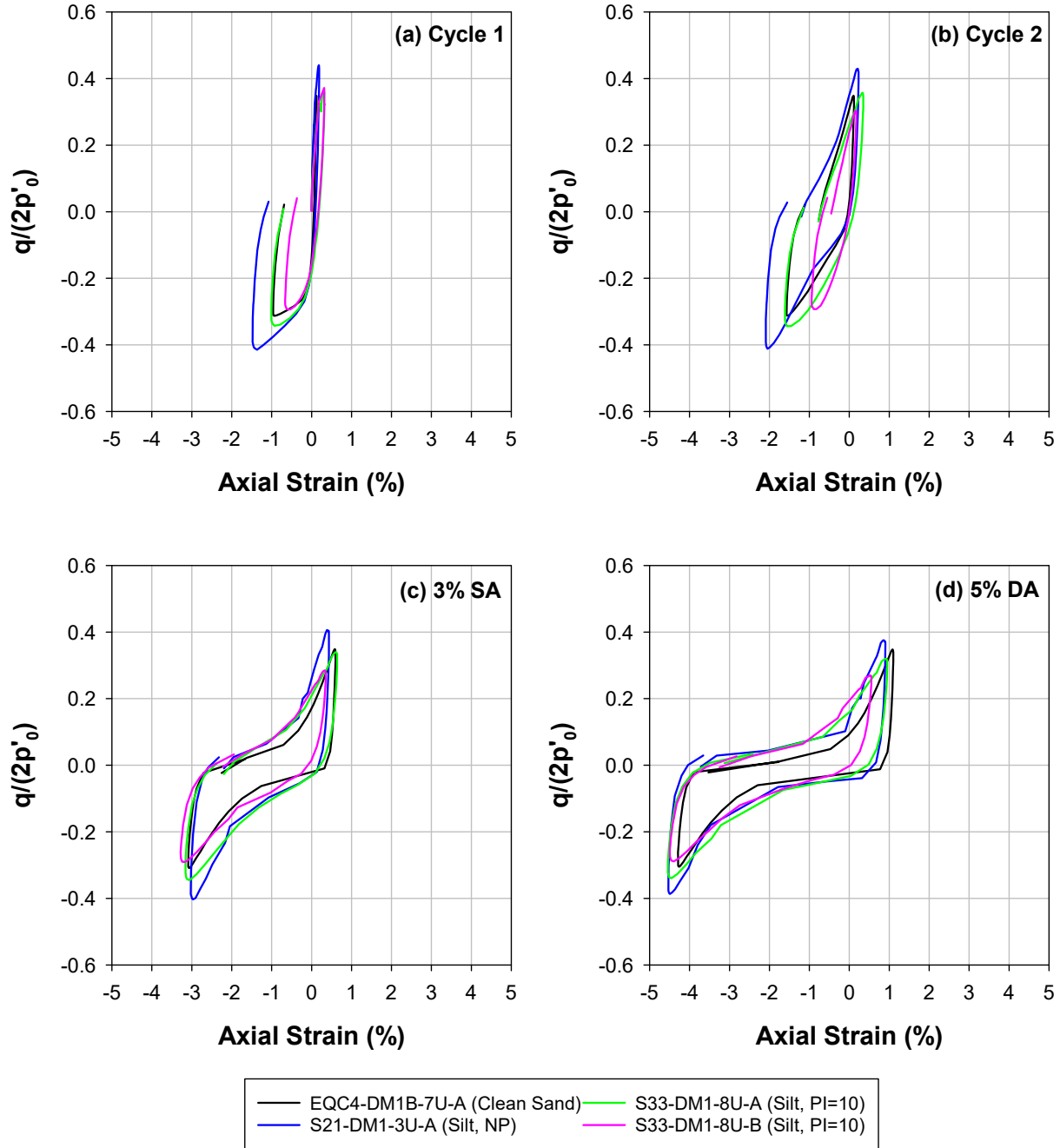


Figure 4.12: Stress-strain response for: a) Cycle 1, b) Cycle 2, c) 3% single-amplitude (SA) axial strain, and d) 5% double-amplitude (DA) axial strain. Specimens reach 3% SA at 5 cycles, 4 cycles, 5 cycles, and 9 cycles for EQC4-DM1B-7U-A, S21-DM1-3U-A, S33-DM1-8U-A, and S33-DM1-8U-B, respectively. Specimens reach 5% DA at 7.5 cycles, 7.5 cycles, 7.5 cycles, and 12 cycles, respectively.

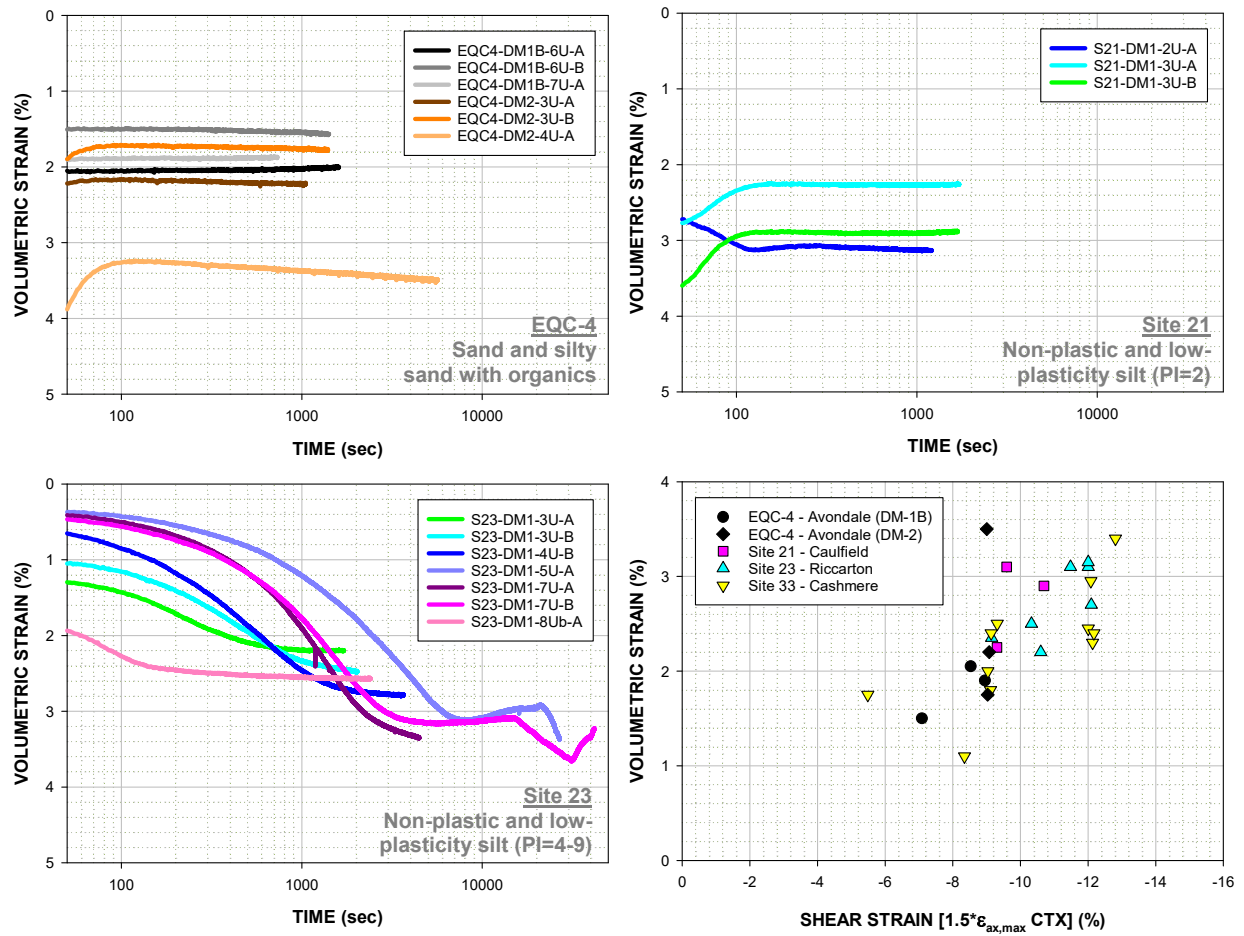


Figure 4.13: Post-liquefaction reconsolidation data: volumetric strain vs. time, volumetric strain vs. shear strain [1.5*maximum axial strain from CTX testing]. Representative responses for sand, non-plastic silt, and low-plasticity silt.

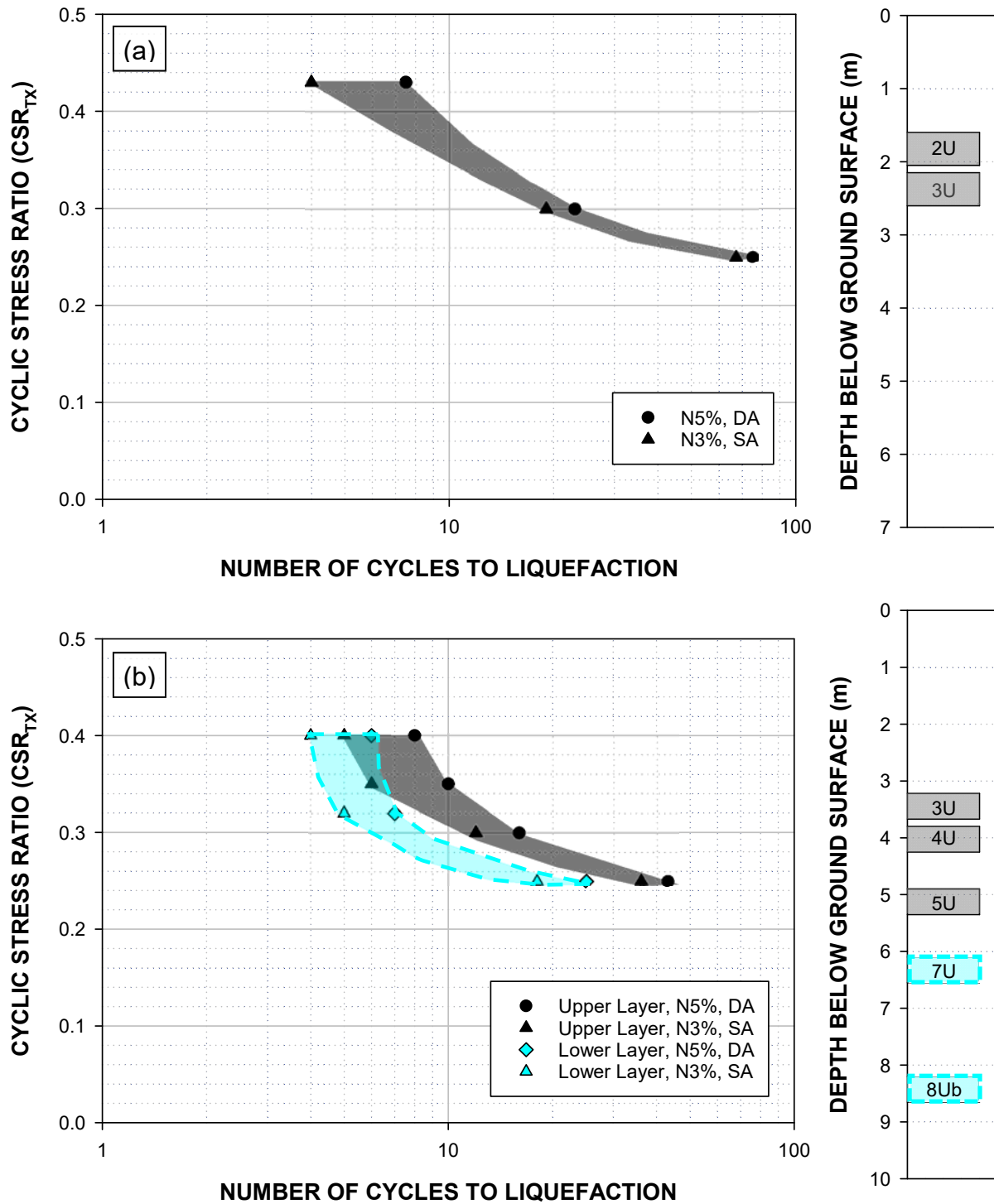


Figure 4.14: Representative CTX liquefaction resistance data: (a) Site 21 and (b) Site 23. CRR bands drawn using both axial strain criteria. Laboratory data not corrected to field conditions. Strain criteria indicated as: “N5%, DA” = 5% double-amplitude, and “N3%, SA” = 3% single-amplitude.

CHAPTER 5: CONCLUSIONS

5.1 SUMMARY

The liquefaction response of silty soils remains an area of geotechnical earthquake engineering where further understanding is needed. Liquefaction case histories and laboratory research have focused primarily on sandy soils and the current state-of-practice liquefaction assessment procedures were developed from those databases of field and laboratory data. However, these procedures are often applied at sites with subsurface conditions that differ from those of the case histories upon which the liquefaction procedures are based. This can result in a liquefaction assessment which contains significant uncertainty by extending the state-of-practice liquefaction assessment procedures well beyond the data on which they were based.

Field case histories provide the opportunity to evaluate our understanding of liquefaction response and the efficacy of our current liquefaction assessment procedures. The 2010-2011 Canterbury earthquake sequence in Christchurch, New Zealand provides an unprecedented opportunity in this regard. It provides a dataset of extensive, well-documented post-earthquake observations and subsurface investigations over a large geographic region subjected to multiple earthquake events. This research focuses on silty soil sites located in southwest Christchurch. State-of-practice methods indicate that these silty soil sites would be expected to liquefy during the Canterbury earthquake sequence, but post-earthquake observations showed no surface manifestations of liquefaction. This discrepancy between post-earthquake liquefaction field observations and state-of-practice liquefaction estimations led to development of the research program presented in this dissertation. The primary goals of this research were to further our understanding on liquefaction response of silty soils and assess the applicability of current state-of-practice methods at silty soil sites. This study has approached the investigation of liquefaction performance at silty soil sites through consideration of depositional environment effects, site characterization, and laboratory testing to evaluate liquefaction response of silty soils.

Depositional environment has been recognized as an important factor affecting liquefaction susceptibility, but its effect has typically been considered qualitatively. The 2010-2011 Canterbury earthquake sequence data set provides the opportunity for a more quantitative assessment. Regional analysis of CPT data from the New Zealand Geotechnical Database (NZGD) was conducted to examine depositional environment effects on observed liquefaction performance, focusing on the southwest region of Christchurch where there was a significant discrepancy between state-of-practice liquefaction estimations and post-earthquake observations. Historical maps, geologic maps, and geomorphology were considered to evaluate the differing depositional environments throughout Christchurch. The study focused on the shallow soils governing liquefaction response and manifestations at the ground surface.

Silt-dominant back-swamps were identified as a key feature that allowed for differentiation of observed liquefaction performance. Site-specific comparisons were conducted between two similar silty soil sites, one of which showed surface manifestations of liquefaction (outside a swamp) and one of which did not (within a swamp), for the 22 FEB 2011 Christchurch earthquake. Interbedded thin layers of silt and sand were identified as important characteristics of these swamp deposits in southwest Christchurch. This thin layering has implications for liquefaction response of a site due to pore water pressure dissipation effects and hydraulic connectivity of the liquefiable layers. Unfortunately, it was not identified through conventional site investigation techniques for liquefaction assessment, which as mentioned previously, were developed largely for

characterization of sandy sites. Both regional and site-specific analysis indicate that depositional environment captures aspects of liquefaction performance missed by state-of-practice methods and can be considered on a more quantitative basis through new data sets.

Conventional site investigation techniques, such as CPTs and borings, are employed in research and practice to obtain data used for subsurface characterization. However, these conventional site investigation techniques may not capture some details of subsurface conditions that are important for liquefaction assessment at silty soil sites, such as thin layering and fluctuating groundwater conditions. Extensive site investigations were conducted at several silty soil sites as part of the larger UC-UCB-UT-TT silty soils project, consisting of sonic borings, piezometers, CPTs and mini-CPTs, high-quality sampling for advanced laboratory testing and detailed logging, and direct-push crosshole seismic testing. The investigation of site characterization at silty soil sites focused on a dense array of in-situ tests aimed at capturing detailed actual subsurface conditions, rather than spatial variability. The site investigation techniques were compared with the actual in-situ layering profile, established using detailed logging of continuous high-quality samples, to evaluate the level of detail captured by each site investigation technique. Multiple groundwater measurement methods were compared to better understand the dynamic groundwater regime at the silty soil sites in Christchurch. Fluctuating ground water conditions are of importance in liquefaction assessment as they determine the part of the soil profile that is likely to liquefy (i.e., susceptible soil below the groundwater table that is saturated). Multiple methods are needed for the most robust assessment, with each method providing insight on a different aspect of groundwater conditions. Recommendations for improved site investigation techniques for silty soil sites were presented.

Field case histories and site investigations provide important data and allow for comparisons with observed earthquake performance. However, complex subsurface conditions and three-dimensional response make it difficult to identify and to quantify trends in the liquefaction response of specific soils. Laboratory testing is used to investigate trends and establish the framework used to describe and assess liquefaction response. High-quality soil samples were obtained at the silty soil sites for laboratory-based characterization of silty soil liquefaction response at the element scale. These natural silty soil specimens contained heterogeneities, but they enabled understanding of the liquefaction response of the in-situ soil deposits in terms of cyclic resistance, axial strain development, and post-liquefaction reconsolidation. Cyclic triaxial (CTX) testing was performed on specimens from five silty soil sites. Specimens from two sand sites were also tested to provide a point of comparison with the better understood liquefaction response of sands. Index testing was conducted on the CTX specimens (e.g., particle size distributions, specific gravity, $e_{\max}$, and $e_{\min}$). The insights provided by element-scale testing inform the field case histories and provide data about silty soil liquefaction response that can be used to better understand in-situ performance.

This dissertation focuses on a thorough investigation of a relatively small sample size of no-liquefaction case history sites located primarily in southwest Christchurch. Importantly, the findings presented herein are only applicable for free-field or light construction sites. Trends also indicate that liquefaction may have manifested at the ground surface at the no-liquefaction silty soil sites had earthquake ground shaking been higher or longer at each site. The research presented in this dissertation has direct implications for liquefaction assessment in geotechnical earthquake engineering practice. Although additional work is required on the cyclic response of silty soils and the system response of interbedded silty soil sites, the results of this research project advance current understanding and identify several opportunities for developing additional insights.

5.2 FINDINGS

Key findings from this study are delineated in this section in the order in which they were developed. Chapter 2 investigates depositional environment effects on observed liquefaction performance, with these key findings:

- Interbedded silty soil sites differ from typical clean-sand case histories upon which liquefaction methodologies are based. Silt and stratified silt/sand deposits are not well represented in the case history databases used to develop the simplified liquefaction assessment procedures.
- Depositional environment effects are difficult to capture using the state-of-practice simplified liquefaction assessment methods, which do not take into account the effects of stratification on hydraulic connectivity and pore water pressure movement through a stratum.
- Depositional environment distinguishes between sites that did or did not liquefy, whereas CPT-based simplified procedures did not. Differing depositional environments were found to explain in part the limitations of simplified liquefaction triggering procedures at silty soil sites in southwest Christchurch.
- Depositional environment is important and its effects on liquefaction performance can be quantified. Given the variability of natural deposits, as noted by Youd & Perkins (1978), a straightforward incorporation of depositional environment effects can be challenging. However, consideration of these issues through a geologic/historical study of the region and through detailed site-specific investigations will afford the engineer the information required to employ judgment in the overall assessment.
- Site-specific comparisons between a swamp site and a non-swamp site identified stratigraphy differences in the likely critical layer at each site, resulting from differences in the depositional environment, with thin layers of silt and organics being present in the sand critical layer at the swamp site.
- Regional CPT-based analyses provide evidence that silt swamp deposits have a mitigating effect on liquefaction manifestation at silty soil sites during the Canterbury earthquake sequence, beyond what can be currently characterized and quantified by simplified liquefaction assessment procedures. Swamp zones were identified through examination of historical maps and confirmed by CPT profiles. These Christchurch back-swamp environments lead to sites with defined silt layers and stratified silt/sand deposits. Regional CPT analyses indicate that eastern swamps have a sandier soil profile signature, as compared with the silt-dominant or interlayered silty soil profile signature found in the western swamps.
- Depositional environment in Christchurch manifests as stratigraphy differences that can impact liquefaction manifestations. These differences were not discerned with the CPT, but were identified through detailed evaluations of in-situ layering obtained using high-quality sampling and careful logging of samples. Depositional environment should be explicitly considered in liquefaction assessments. Historical maps, geologic studies, and continuous sampling can provide key information.

Chapter 3 explores characterization of silty soil sites with thin layers and fluctuating groundwater conditions for the purpose of liquefaction assessment. The key findings from this part of the study are:

- Christchurch silty soils can vary over depth intervals as thin as a few millimeters or a few centimeters.
- CPTs smear across thin layers, because of the large size of the cone diameter relative to the layer thickness. The cones measure average properties over zones of influence too large to capture accurately in-situ layering at the scale necessary to discern the silty soil layering that impacts liquefaction manifestations at the studied sites. The 5-cm² mini-CPT does not significantly improve thin layer characterization over the conventional 10-cm² or 15-cm² CPT, but it does show slightly increased q_c estimates in some thin sand layers relative to the conventional CPT.
- Conventional sonic borings are useful for evaluating general soil type transitions, but they do not adequately preserve thin layering for detailed characterization purposes.
- Continuous high-quality sampling with detailed logging of samples revealed that the scale of thin-layering at these silty soil sites can be on the order of millimeters and centimeters, with interbedded silts, silty sands, sandy silts, and sands. High-quality samples preserve in-situ features that may impact liquefaction assessment and provide the opportunity for detailed characterization of those features, such as scale and soil type of layering. Only high-quality continuous sampling and detailed logging can capture currently the actual ground conditions that impact seismic performance at these silty soil sites.
- The required level of detail at interbedded silty soils sites in Christchurch is not captured by conventional site investigation techniques such as the CPT. Key features at silty soil sites that are not characterized adequately by conventional methods include the apparent critical layer, interbedded soils (noting variations affecting hydraulic conductivity and plasticity), and thickness and soil type of the potentially non-liquefiable crust (noting features that may affect crust integrity or indicating zone of groundwater fluctuation).
- Preliminary site investigations using conventional methods and simplified liquefaction assessment methods can be used with a thorough knowledge of geology and depositional environment to assess the need for more detailed site investigations. CPT profiles may indicate the need for detailed logging of high-quality samples, when the profile indicates silty soil conditions that differ from better understood thick sand deposits. Continuous high-quality sampling, detailed logging, and index testing can be performed in the potential critical layer identified by the CPT when some thin-layer stratification is suspected. Detailed logs can be used to calibrate CPT profiles to characterize layering in complex subsurface conditions, enable targeted sampling for advanced laboratory testing, if desired, and can provide the information required to perform nonlinear effective stress analyses that may provide further insight.
- When state-of-practice liquefaction assessment methods do not capture adequately the subsurface characteristics of a site, continuous sampling with detailed soil logging through visual evaluation and conventional lab testing may provide a sufficient basis for evaluating the likelihood of liquefaction triggering at the site. A major difficulty in interlayered silty

soil deposits is defining what constitutes a discrete layer; it will depend on the purpose and type of analysis. The level of detail in characterization also depends on nature of project.

- Using data from widely spaced soil samples and CPT locations is also problematic in an area with spatially variable subsurface conditions such as Christchurch, where subsurface conditions can vary on the order of 5 m distance. Maintaining close spacing between in-situ tests (often less than 1.5-2 m) provided consistent profiles for direct comparison between different site investigation techniques.
- Estimating fines content with a $FC-I_c$ correlation is unreliable in thinly interbedded silty soils because of the limited level of detail obtained with the CPT and the typical practice of bulk sampling that may mix several discrete thin soil layers. For liquefaction assessment at silty soil sites, the focus should be on variations in hydraulic conductivity and plasticity and not on fines content.
- Groundwater conditions are difficult to capture at sites with significant GWT fluctuation and possible partial saturation effects. Multiple investigation techniques, such as piezometers, sampling, and compression wave (V_p) testing, measure different aspects of groundwater conditions at a site and should be employed to characterize complex groundwater conditions. However, depending on the project and site conditions, a sensitivity study during preliminary liquefaction assessment may indicate that a detailed investigation of groundwater conditions is not necessarily warranted.
- The recommended approach to characterize sites with thin soil layers and groundwater fluctuations is:
 - 1) Consider depositional environment to assess if interbedded deposits are likely to be present.
 - 2) Conduct preliminary site investigations using conventional methods and perform simplified liquefaction assessment procedures. Assess the need through sensitivity analyses and judgment for more detailed site investigations to characterize adequately the apparent critical layer, interbedded layers, and non-liquefiable crust.
 - 3) Conduct high-quality continuous sampling and detailed logging at locations adjacent to the most representative CPTs if thinly interbedded materials are suspected.
 - 4) Implement multiple methods to characterize complex groundwater conditions, if warranted.
 - 5) Develop soil profiles from detailed logs to characterize interbedded soils, the apparent critical layer, and thickness and soil type of the potentially non-liquefiable crust.
 - 6) Interpret site investigations considering the issues discussed in this thesis for liquefaction assessment.
 - 7) Recognize this is an ongoing area of research and communicate the uncertainties to the client, considering the specific project and site conditions in developing a path forward toward design. It is premature to formalize recommendations for liquefaction assessment at interbedded silty soil sites with groundwater fluctuations, but the enhanced characterization of these sites enables the engineer

to employ judgement with a more complete understanding of actual in-situ conditions.

- The limitations of current site characterization and liquefaction assessment methods at silty soil sites require reconsideration of the current approaches to liquefaction assessment. A more holistic approach is needed, rather than interpreting these interbedded silty soils with equivalent-clean sand properties.

Chapter 4 presents data and insights on the cyclic response of Christchurch silty soils through cyclic triaxial testing of high-quality soil specimens. The key findings of this laboratory testing program are:

- Specimen variability and heterogeneity should be considered when interpreting the cyclic response of natural silty soil specimens. Natural soils have heterogeneities and soil structure that are difficult, if not impossible, to replicate with laboratory-prepared specimens. Consideration of relative scale effects and overall stratum characterization enables more effective testing programs that move towards better understanding of in-situ silty soil cyclic response.
- Cyclic triaxial testing of natural silty soil specimens showed a range of transitional soil responses for the intermediate soils tested. Cyclic response and axial strain development of the silty soil test specimens demonstrate only subtle differences between the cyclic responses of fine sand, non-plastic silt, and $PI=10$ silt. Intermediate silty soils exhibit transitional responses that are difficult to characterize with parameters developed for a “sand” vs. “clay” framework for evaluating soil liquefaction.
- State-of-practice simplified liquefaction evaluation procedures indicate that the silty soil sites should have expressed surface manifestations of liquefaction during the intense Christchurch earthquake shaking. Yet, no manifestations were observed. Cyclic resistance and strain development data from CTX testing also indicate that the silty soils tested should have liquefied for the Christchurch event.
- CTX test strain data indicate these low penetration resistance silty soils exhibit cyclic mobility with limited strain response, even when characterized with low CRR values due to low equivalent-clean sand penetration resistances.
- Post-liquefaction reconsolidation time curves exhibit easily identifiable differences. Fine sands and non-plastic silts exhibit “sand-like” reconsolidation volumetric responses wherein the specimen rapidly reaches the final volumetric strain (i.e., the response is nearly instantaneous). Low- PI silts exhibit time-dependent reconsolidation volumetric responses before reaching a point at which final volumetric strain can be estimated.
- Slow pore water pressure dissipation response during post-liquefaction reconsolidation tests indicate that those silty soils would not likely accumulate a large amount of water or the flow velocity necessary to form ejecta, especially considering the fine layering of the silty soil deposits and their relatively low vertical hydraulic conductivities. The differences in post-liquefaction reconsolidation response have implications for pore water pressure movement and ejecta development, especially when considered with the layered nature of the silty soil sites. The impacts of these laboratory-based differences can be extrapolated

using engineering judgement to post-liquefaction field manifestations and settlement potential, considering adjustments from element-scale to site-scale and site stratigraphy effects.

- The CTX test data and post-liquefaction reconsolidation data complement the detailed post-earthquake observations and site investigations at the case history sites for incorporation in the global dataset and development of the next generation of liquefaction assessment methods. This combination of laboratory testing and field observations provides robust “no-liquefaction” case histories that can enable model refinements to reduce the discrepancies between liquefaction assessment procedures and post-earthquake observations at silty soil sites. Insights for developing effective laboratory testing programs, guiding liquefaction assessments, and calibrating numerical models are provided.

In summary, currently established simplified liquefaction evaluation procedures are not applicable at all sites. Liquefaction assessments at sites that differ from the majority of case histories underlying the current simplified procedures should consider depositional environment at the regional scale, site scale, and specimen scale. Where historical or geologic maps and preliminary subsurface investigations indicate a complex depositional environment or a depositional environment that differs from a majority of the liquefaction case history dataset, high-quality continuous sampling is beneficial for enhanced characterization of stratigraphy impacting liquefaction potential and to assess the most appropriate methods for evaluating those strata. Improved site characterization and understanding of the actual in-situ deposits at interbedded silty soil sites should go hand-in-hand with research through laboratory testing and numerical simulations, so that the evaluation framework and the representation of the actual characteristics of the silty soil deposit can be advanced. Free-field silty soil sites could potentially show liquefaction manifestations if large buildings were present or if shaken harder. Understanding in-situ “system” response of the layered soil deposit is key to evaluating its seismic performance.

The results of this study identified several factors that impact the liquefaction response at silty soil sites. To address the various aspects of silty soil liquefaction response, there may need to be a reconsideration of what is important in liquefaction assessment of silty and interbedded soil sites, such as the sand-like vs. clay-like framework, cyclic resistance, time-dependent post-liquefaction settlement, ejecta potential, saturation effects, permeability and plasticity, and non-liquefiable crust. All of these aspects should be considered for the in-situ system response. Field investigations and laboratory testing will inform the assessment, and perhaps allow for identifying the key aspects governing system response at a site, but it is clear for these sites and liquefaction assessment moving forward, in-situ system response should be considered.

5.3 FUTURE RESEARCH

The research presented in this dissertation advances our understanding of the liquefaction response of fine-grained soils through investigation of case histories at silty soil sites from the 2010-2011 Canterbury earthquake sequence. However, it has also demonstrated that additional work is warranted. Further research on the following topics is recommended:

- Depositional environment and geologic effects on liquefaction performance
- Cyclic response of stratified silty soil deposits

- Site characterization techniques for highly stratified silty soils
- System response and characterization
- Liquefaction performance of interlayered silty soil sites with heavy buildings present

The data available in the NZGD provides the opportunity for further analysis of depositional environment effects on observed liquefaction performance during the Canterbury earthquake sequence. The work presented in this dissertation focused on swamp zones as a key feature in comparing simplified method estimations with post-earthquake observations, but the quantitative analysis could be extended to an analysis of CPT properties themselves throughout the geospatial region. For example, considering the sand-dominant vs. silt-dominant or silt-layered CPT profiles seen in the different environments across southwest Christchurch, further analysis could extend this work and examine the change in CPT profile signatures over transitional distances between differing depositional environments. If consistent layers are identified over a spatial region or line, analysis could investigate how q_c changes over lateral distance as a sand or silt layer pinches out with distance or how q_c varies in a soil type that occurs at varying thicknesses with depth. This may provide some understanding of the CPT properties of thin layers affected by the zone of influence based on where a similar sand layer is thick enough to fully develop q_c .

The laboratory testing of natural silty soil specimens presented in this dissertation has highlighted the difference between natural vs. laboratory-prepared specimens, but further testing is needed to understand the effects of these differences on cyclic response of element-scale specimens. Additional research is also needed on translating laboratory-scale findings to field-scale understanding, particularly for: reconsolidation response and effects, cyclic resistance correction factors for triaxial-to-simple shear (C_r) and multidirectional shaking, and specimen heterogeneity as representative of the overall stratum.

Further research on site characterization at silty soil sites should focus on characterization of the actual in-situ profile and translating that profile into meaningful properties for liquefaction assessment. The geotechnical parameters developed for liquefaction assessment and modeling of sandy soils, such as relative density (D_r) and minimum and maximum void ratio (e_{min} and e_{max}), are not well-suited to silty soils and interlayered silty and sandy soils. Further research on appropriate constitutive models for silty soils, as well as interbedded deposits, would be highly beneficial. Working with the constitutive models currently available, cyclic testing can be used to calibrate the controlling parameters for various effects (such as cyclic resistance and reconsolidation) to capture observed specimen response, rather than estimating the D_r of a silty soil and directly applying that as the input parameter. A rational approach may be to characterize the scale and type of soil layering at a silty soil site, and conduct parametric analysis wherein those characteristic soil properties are assigned to thin layers through stochastic analysis (e.g., similar to the approach used in Boulanger & Montgomery 2015). Assessing the frequency, thickness, and type of layers through detailed logging at a site could be used as starting point for assigning those layering properties in a stochastic analysis. Additional research on the comparison of the results of 1D analyses with those of 2D and 3D analysis would be beneficial. Importantly, the system response of the soil deposit should be investigated further.

The effects of partial saturation on cyclic resistance and hydraulic conductivity require further research to better understand the implications for non-liquefiable crust and ejecta flow. Saturation is typically considered in terms of its impact on cyclic resistance, but the effect on permeability and flow through a partially saturated medium may also be of importance when considering pore water pressure dissipation and ejecta flow. Along with partial saturation effects,

further research is needed on the non-liquefiable crust and how non-liquefiable it has to be to prevent surface manifestations.

For these interlayered silty soils, with profiles that vary over depth and distance, the CPT is a better tool than the SPT for characterization across a site, but as demonstrated, the CPT and currently established thin layer corrections do not fully capture the level of detail needed for the depositional setting at the silty soil sites and the scale of layering in these deposits. The highly variable, interlayered nature of subsurface profiles at these silty soil sites and the relative lack of contrast among the range of silty soils (e.g., as compared with sand vs. clay layering) makes it unlikely that a single correction factor that could be applied to CPT data which would capture the various system effects at play. The thin layering seen at the silty soil sites is at a scale smaller than that typically investigated in previous work, where thin layers and corrections were considered down to 0.3-0.4 m. Detailed logging and CPT data could be used to develop site-specific corrections for CPT data for thinner layers (i.e., for density and hydraulic conductivity).

A significant effort has been made to investigate and characterize the case history sites presented in this dissertation. The field and laboratory data for these case history sites will be made available in the Next Generation Liquefaction project database currently under development (Stewart et al. 2016), toward developing the next generation of liquefaction assessment models. Additional silty soil case histories, and no-liquefaction case histories, should be developed to improve database representation of different subsurface conditions and liquefaction performance. Downhole arrays and instrumentation to better understand what is happening below ground surface during earthquake events would be useful in moving beyond the implicit pairing of surface manifestations and liquefaction triggering, and helpful in understanding system response.

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Appendix A

Site Investigations

- A.1 Subsurface Investigation Overview
- A.2 Boring Logs for Dames & Moore Sampling
- A.3 Mini-CPT ConeTec Data Report

Appendix A.1

Subsurface Investigation Overview

APPENDIX A.1: SUBSURFACE INVESTIGATION OVERVIEW

The case history sites presented in this dissertation were investigated through a joint research effort by the University of Canterbury (UC), University of California – Berkeley (UCB), Tonkin + Taylor (TT), and University of Texas at Austin (UT), referred to as the “silty soils project.”

The appendices to this dissertation provide supporting data and information relevant to the doctoral research activities undertaken directly by the dissertation author. Subsurface investigation data have been made publically available through the New Zealand Geotechnical Database (NZGD, www.nzgd.org.nz).

Additional information is available in a series of geotechnical data reports prepared for the New Zealand Ministry of Business, Innovation, and Employment (MBIE) and several publications resulting from the silty soils project research effort (refer to References section of this dissertation).

Appendix A.1 provides site overviews and a summary of subsurface investigations conducted at each site. Investigation data is available in the NZGD. Appendix A.2 provides boring logs prepared by the dissertation author. Appendix A.3 provides the ConeTec mini-CPT data report for CPTs that are not yet available in the NZGD.

These case histories will also be made available in the Next Generation Liquefaction project database, currently under development, toward developing the next generation of liquefaction assessment models (Stewart et al. 2016).

Important Notice: Several figures presented in this dissertation were created from maps or data extracted from the NZGD, formerly the Canterbury Geotechnical Database, which were prepared or compiled for the Earthquake Commission (EQC) to assist in assessing insurance claims made under the Earthquake Commission Act 1993. The source maps and data were not intended for any other purpose. EQC and its engineers, Tonkin & Taylor, have no liability for any use of the maps and data or for the consequences of any person relying on them in any way.

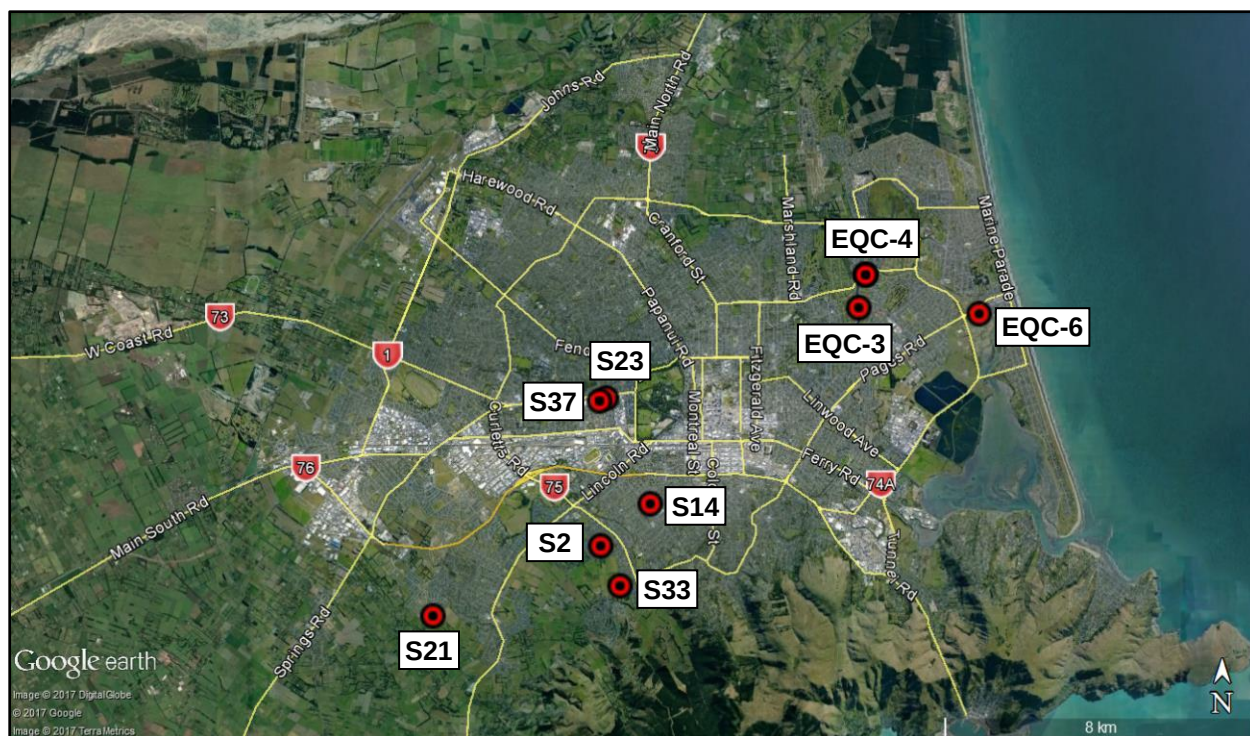


Figure A.1-1: Location of sites 2, 14, 21, 23, 33, 37, EQC-3, EQC-4, and EQC-6 in the greater Christchurch area (modified from Google Earth™).



Figure A.1-2: Aerial view of Site 2 – Gainsborough. Modified from NZGD and Google Earth™.



Figure A.1-3: Aerial view of Site 14 – Barrington. Modified from NZGD and Google Earth™.



Figure A.1-4: Aerial view of Site 21 – Caulfield. Modified from NZGD and Google Earth™.

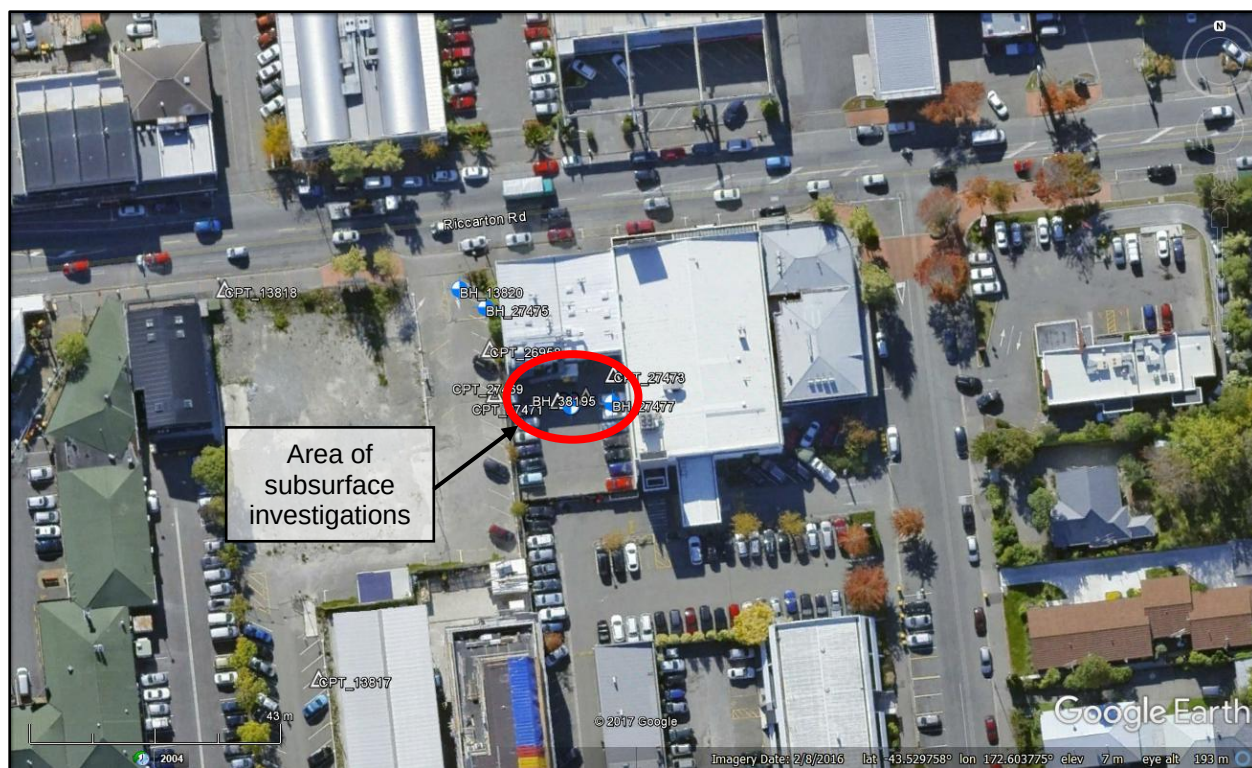


Figure A.1-5: Aerial view of Site 23 – Riccarton. Modified from NZGD and Google Earth™.



Figure A.1-6: Aerial view of Site 33 – Cashmere. Modified from NZGD and Google Earth™.

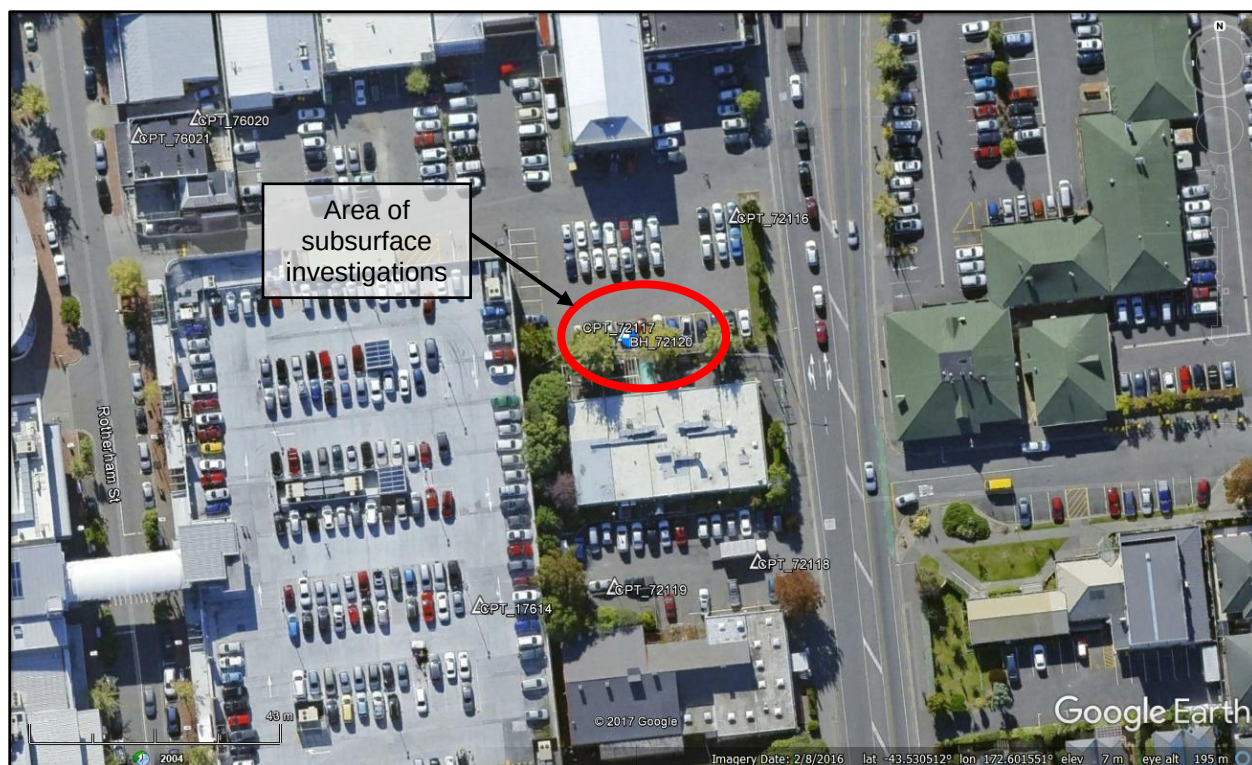


Figure A.1-7: Aerial view of Site 37 – Clarence. Modified from NZGD and Google Earth™.



Figure A.1-8: Aerial view of EQC-3 – Avondale. Modified from NZGD and Google Earth™.

Area of subsurface investigations

Quincey St

Walnut St

30 m

© 2017 Google

Imagery Date: 2/8/2016 lat: 43.510438° lon: 172.721600° elev: 4 m

Figure A.1-10: Aerial view of EQC-6 – Bexley. Modified from NZGD and Google Earth™.

Table A.1-1: Summary of Site Investigations

Site Name	Latitude, Longitude	Investigation Type ^a and NZGD Location ID ^b				
		Sonic Boring ^c	Mud- Rotary Boring	CPT	Mini-CPT	Direct Push Crosshole Seismic ^g
Site 2 Gainsborough	-43.5634, 172.6016	38196	DM-1 ^d , GP-1 ^e , GP- 2 ^e , GP-3 ^e	36417	---	38176, 38177
Site 14 Barrington	-43.5553, 172.6180	38193	BH-1 ^{d,e} , BH-2 ^d , 73103 (BH-3 ^f)	37818	Mini-CPT_04	38172
Site 21 Caulfield	-43.5800, 172.5489	38194	DM-1 ^d	36419	---	38174, 38175
Site 23 Riccarton	-43.5299, 172.6036	38195	DM-1 ^d	36420	---	38170
Site 33 Cashmere	-43.5725, 172.6082	38197	DM-1 ^d , 73104 (DM-2 ^f)	36421	Mini-CPT_01, Mini-CPT_02	38171
Site 37 ^h Clarence	-43.5305, 172.6016	---	72120 (DM-1 ^f)	72117	Mini-CPT_08, Mini-CPT_09, Mini-CPT_10	---
EQC-3 ⁱ Avondale	-43.5090, 172.6836	21494	BH-1 ^{d,e} , BH-2 ^e	21509	---	36465
EQC-4 ⁱ Avondale	-43.5014, 172.6857	21495	DM-1A, DM-1B ^d , DM-2 ^d	21511, 55399	---	36460
EQC-6 ⁱ Bexley	-43.5102, 172.7215	21490	BH-1 ^e to BH-4 ^e , BH-5 ^{d,e}	21506	---	36462

^a In-situ tests listed in this table comprise the dense test array from this study. Additional in-situ tests may be available further from the dense array at each site.

^b NZGD Location ID is the identifier used in the NZGD. Each in-situ test uploaded to the NZGD is assigned a unique location ID number (e.g., “38195”), with preceding letters that identify the type of in-situ test (e.g., “BH” = borehole, “CPT” = cone penetration test, “VsVp” = shear and compression wave velocity testing - typically direct-push crosshole seismic testing).

^c Sonic borings logged by Tonkin + Taylor, Ltd.

^d Mud-rotary boring, Dames & Moore (DM) high-quality sampling for cyclic triaxial testing

^e Mud-rotary boring, Gel-Push (GP) high-quality sampling for cyclic triaxial testing

^f Mud-rotary boring, Dames & Moore (DM) high-quality continuous sampling for detailed logging

^g Direct push crosshole seismic testing conducted by Univ. of Texas at Austin researchers (Stokoe, Cox et al.)

^h Approximately 200 m west of Site 23 – Riccarton

ⁱ Sites EQC-3, EQC-4, and EQC-6 were part of the EQC Ground Improvement Trials Project; investigations for pre-improvement conditions are listed (<https://www.nzgd.org.nz/ReportFiles/EQC/GroundImprovementTrials.htm>).

Appendix A.2

Boring Logs for Dames & Moore Sampling

		SOIL BORING LOG				
		Project Number n/a			Boring Number DM-1	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		Gainsborough Reserve ("Site 2"), Hoon Hay, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish: 18 March 2014 (Tuesday) - 19 March 2014 (Wednesday)		
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1	0.80- 1.25 m	1U (DM)	91%	400 kPa	<i>Not extruded for 2014 CTX testing</i>	Casing at 0.42 m.
2						
3	2.68- 3.13 m	2U (DM)	87%	600 kPa	<i>Not extruded for 2014 CTX testing</i>	Casing at 2.21 m.
4	3.76- 4.21 m	3U (DM)	100%	500 kPa	Gray silt	Casing at 3.46 m.
5	4.60- 5.05 m	4U (DM)	60%	700 kPa	Gray sandy silt	Casing at 4.185 m.
6	5.40- 5.85 m	5U (DM)	84%	700 kPa (issues)	Gray silty sand	Casing at 5.10 m.
7	6.90- 7.35 m	6U (DM)	98%	(issues)	<i>Not extruded for 2014 CTX testing</i>	(pg. 1 of 2)

		SOIL BORING LOG				
		Project Number n/a			Boring Number DM-1	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		Gainsborough Reserve ("Site 2"), Hoon Hay, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish: 18 March 2014 (Tuesday) - 19 March 2014 (Wednesday)		
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
6.90- 7.35 m	6U (DM)	98%	(issues)	<i>Not extruded for 2014 CTX testing</i>		
7.90- 8.35 m	7U (DM)	98%	900 kPa	Gray silty sand	Casing at 7.24 m.	
8.68- 9.13 m	8U (DM)	---	900 kPa (issues)	Gray sand, some silt (void in sample tube below top portion used for CTX testing)	Casing at 8.30 m.	
10						
11						
12						
13						
14						<i>End of boring at 9.13 m (pg. 2 of 2)</i>

					SOIL BORING LOG	
					Project Number n/a	Boring Number BH-2*
					General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.	
Project Name: Silty Soils Project			Location: Barrington Park ("Site 14"), Barrington, Christchurch, NZ			
Elevation: ---			Drilling Contractor: McMillan Drilling Services			
Drilling Method and Equipment: Mud-rotary, Track rig (Geoprobe 8140LS)						
Mud Level: ---			Start/Finish: 24 March 2014 (Monday) - 25 March 2014 (Tuesday)			
Logger: Christine Z. Beyzaei (UC Berkeley) / Mark Stringer (Univ. of Canterbury)						
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1	Sample 1U (DM) obtained in boring BH-1.					BH-2 started as a gel-push (GP) boring; issues encountered with GP sampler so boring was changed to a DM boring. Sample 1U was obtained in BH-1 since BH-2 had been drilled past that depth.
1.55-2.00 m	2U (DM)	99%	140 psi	Gray silt	Casing at 1.00 m.	
2.30-2.75 m	3U (DM)	72%	400 kPa	Wood	Casing at 2.00 m.	
3.50-3.95 m	4U (DM)	100%	300 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 2.645 m.	
5.00-5.45 m	5U (DM)	100%	300 psi	Gray silty sand	Casing at 4.175 m.	
6.50-6.95 m	6U (DM)	100%	200 psi	Gray sandy silt	Casing at 5.695 m.	
7	*Note: "BH-2" originally named "DM-1." Full sampler advancement = 45 cm.					End of boring at 6.95 m

		SOIL BORING LOG				
		Project Number n/a			Boring Number BH-1*	
		General Comments: Dames & Moore (DM) and Gel-Push (GP) sampling for cyclic triaxial testing program.				
Project Name:		Silty Soils Project		Location:		Barrington Park ("Site 14"), Barrington, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish: 25 March 2014 (Tuesday) - 26 March 2014 (Wednesday)		
Logger:		Christine Z. Beyzaei (UC Berkeley) / Mark Stringer (Univ. of Canterbury)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
0.40- 0.85 m	1U (DM)	91%	400 psi	Not extruded for 2014 CTX testing	No casing.	
1.00- 2.00 m	2U (GP)	95%	1 bar	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1	Casing at 0.700 m.	
2.00- 3.00 m	3U (GP)	87%	1 bar	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1	Casing at 1.150 m.	
3.20- 4.20 m	4U (GP)	93%	5 bar	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1	Casing at 2.670 m.	
4.60- 5.60 m	5U (GP)	92%	1-3 bar	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1	Casing at 4.195 m.	
6.00- 7.00 m	6U (GP)	88%	1-3 bar	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1	Casing at 5.26 m.	
					*Note: "BH-1" originally named "DM-2." Full sampler advancement = 45 cm.	
					End of boring at 7.00 m	

		SOIL BORING LOG				
		Project Number n/a			Boring Number DM-1	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		Caulfield Avenue ("Site 21"), Halswell, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish:		24 June 2014 (Tuesday)
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1	1.00- 1.45 m	1U (DM)	99%	250 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 0.65 m.
2	1.60- 2.05 m	2U (DM)	99%	150 psi	Gray silt	Casing at 1.135 m.
	2.15- 2.60 m	3U (DM)	101%	150 psi	Gray sandy silt	Casing at 1.135 m.
3	2.75- 3.20 m	4U (DM)	100%	130 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 2.18 m.
	3.20- 3.65 m	5U (DM)	100%	175 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 2.635 m.
4	4.00- 4.45 m	6U (DM)	52%	150 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 2.635 m.
5						
6						
7						<i>End of boring at 4.45 m</i>

*Note: Full sampler advancement = 45 cm.

		SOIL BORING LOG				
		Project Number n/a			Boring Number DM-1	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		85 Riccarton Road ("Site 23"), Riccarton, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish: 21 June 2014 (Saturday)		
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1						
1.35- 1.80 m	1U (DM)	91%	300 psi	Not extruded for 2014 CTX testing	Casing at 0.69 m.	
2						
2.05- 2.50 m	2U (DM)	100%	200 psi	Not extruded for 2014 CTX testing	Casing at 1.145 m.	
3						
3.22- 3.67 m	3U (DM)	101%	150 psi	Gray silt	Casing at 2.665 m.	
4						
3.80- 4.25 m	4U (DM)	101%	150 psi	Gray silt	Casing at 2.665 m.	
5						
4.90- 5.35 m	5U (DM)	101%	175 psi	Top portion: Gray silt (Bottom portion not extruded for 2014 CTX testing)	Casing at 4.185 m.	
6						
5.50- 5.95 m	6U (DM)	98%	225 psi	Not extruded for 2014 CTX testing	Casing at 5.150 m.	
7						
6.10- 6.55 m	7U (DM)	101%	250 psi	Gray sandy silt	Casing at 5.705 m.	
*Note: Full sampler advancement = 45 cm.						(pg. 1 of 2)

		SOIL BORING LOG			
		Project Number n/a		Boring Number DM-1	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.			

Project Name:	Silty Soils Project	Location:	85 Riccarton Road ("Site 23"), Riccarton, Christchurch, NZ		
Elevation:	---	Drilling Contractor:	McMillan Drilling Services		
Drilling Method and Equipment:	Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:	---	Start/Finish:	21 June 2014 (Saturday)		
Logger:	Christine Z. Beyzaei (UC Berkeley)				

Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
7.60- 8.05 m	8Ua (DM)	100%	350 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 7.225 m.	
8.20- 8.65 m	8Ub (DM)	102%	200 psi	Top portion: Gray sandy silt (Bottom portion not extruded for 2014 CTX testing)	Casing at 7.225 m.	
14	*Note: Full sampler advancement = 45 cm.					End of boring at 8.65 m (pg. 2 of 2)

		SOIL BORING LOG				
		Project Number n/a			Boring Number DM-1	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		200 Cashmere Road ("Site 33"), Cashmere, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish:		21 October 2014 (Tuesday)
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1	0.65- 1.10 m	1U (DM)	97%	225 psi	<i>Not extruded for 2014 CTX testing</i>	No casing.
2	1.80- 2.25 m	2U (DM)	101%	175 psi	Gray silt	Casing at 1.15 m.
	2.40- 2.85 m	3U (DM)	102%	150 psi	Gray silt	Casing at 2.10 m.
3	3.05- 3.50 m	4U (DM)	103%	220 psi	Top portion: Gray sand (Bottom portion not extruded for 2014 CTX testing)	Casing at 2.67 m.
4	3.65- 4.10 m	5U (DM)	102%	200 psi	Gray sand with silt and organic layers	Casing at 2.67 m.
	4.35- 4.80 m	6U (DM)	102%	120 psi	Gray sandy silt with silt, sand, and organic layers	Casing at 4.05 m.
5	4.95- 5.40 m	7U (DM)	89%	120 psi	Top portion: Gray sandy silt, silt, sand, and organic layers (Bottom portion not extruded for 2014 CTX testing)	Casing at 4.19 m.
6	5.55- 6.00 m	8U (DM)	101%	160 psi	Gray silt	Casing at 5.25 m.
7	*Note: Full sampler advancement = 45 cm.					<i>End of boring at 6.00 m</i>

		SOIL BORING LOG					
		Project Number n/a		Boring Number DM-1A			
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.					
Project Name:		Silty Soils Project		Location:		19 Ardrossan Street ("EQC-4"), Avondale, Christchurch, NZ	
Elevation:		---		Drilling Contractor:		McMillan Drilling Services	
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)					
Mud Level:		---		Start/Finish:		22 October 2014 (Wednesday)	
Logger:		Christine Z. Beyzaei (UC Berkeley)					
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments	
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation	
1							
2	(No DM samples obtained.)					Hand-augered to 1.3 m, encountered gravel and cobbles. At ~1.3 m, hand-auger sounded like it was hitting a pipe or large cobble that could not be retrieved with the hand-auger. Boring DM-1A abandoned and drill rig shifted to boring DM-1B location.	
3							
4							
5							
6							
7	*Note: Full sampler advancement = 45 cm.					End of boring at ~1.3 m	

	SOIL BORING LOG	
	Project Number n/a	Boring Number DM-1B
	General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.	

Project Name: Silty Soils Project	Location: 19 Ardrossan Street ("EQC-4"), Avondale, Christchurch, NZ
Elevation: ---	Drilling Contractor: McMillan Drilling Services
Drilling Method and Equipment: Mud-rotary, Track rig (Geoprobe 8140LS)	
Mud Level: ---	Start/Finish: 22 October 2014 (Wednesday) - 23 October 2014 (Thursday)
Logger: Christine Z. Beyzaei (UC Berkeley)	

Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1						
1.05- 1.50 m	1U (DM)	---	300 psi		<i>Not extruded for 2014 CTX testing</i>	No casing.
2						
1.95- 2.40 m	2U (DM)	96%	260 psi		<i>Not extruded for 2014 CTX testing</i>	Casing at 1.15 m.
3						
3.10- 3.55 m	3U (DM)	83%	400 psi, then 240 psi		<i>Not extruded for 2014 CTX testing</i>	Casing at 2.67 m.
4						
4.10- 4.55 m	4U (DM)	98%	240-260 psi		<i>Not extruded for 2014 CTX testing</i>	Casing at 3.74 m.
5						
4.70- 5.15 m	5U (DM)	100%	220 psi		<i>Not extruded for 2014 CTX testing</i>	Casing at 4.19 m.
6						
6.00- 6.45 m	6U (DM)	100%	280-300 psi		Gray sand, trace silt	Casing at 5.70 m.
7						
6.70- 7.15 m	7U (DM)	100%	400 psi		Gray sand, some silt	(pg. 1 of 2)

		SOIL BORING LOG			
		Project Number n/a		Boring Number DM-1B	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.			

Project Name:	Silty Soils Project	Location:	19 Ardrossan Street ("EQC-4"), Avondale, Christchurch, NZ
Elevation:	---	Drilling Contractor:	McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)	
Mud Level:	---	Start/Finish: 22 October 2014 (Wednesday) - 23 October 2014 (Thursday)	
Logger:	Christine Z. Beyzaei (UC Berkeley)		

Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
		7U (DM)	100%	400 psi	Gray sand, some silt	Casing at 5.70 m.
7.40- 7.85 m		8U (DM)	98%	300 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 6.80 m.
8						
9						
10						
11						
12						
13						
14						<i>End of boring at 7.85 m (pg. 2 of 2)</i>

		SOIL BORING LOG				
		Project Number n/a			Boring Number DM-2	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		1134 Avonside Drive ("EQC-4"), Avondale, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish:		24 October 2014 (Friday)
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1 2 3 4 5 6 7						Continuous sampling to obtain samples in the upper silty sand.
	1.20-1.65 m	1U (DM)	100%	200 psi	Not extruded for 2014 CTX testing	Casing at 1.15 m.
	1.65-2.10 m	2U (DM)	102%	100 psi	Not extruded for 2014 CTX testing	Casing at 1.15 m.
	2.10-2.55 m	3U (DM)	102%	110 psi	Gray silty sand, trace organics	Casing at 1.15 m.
	2.55-3.00 m	4U (DM)	101%	140 psi	Gray silty sand with organics	Casing at 2.22 m.
	3.00-3.45 m	5U (DM)	98%	200 psi	Not extruded for 2014 CTX testing	Casing at 2.22 m.
	3.60-4.05 m	6U (DM)	100%	240 psi	Not extruded for 2014 CTX testing	Casing at 2.67 m.
						End of boring at 4.05 m

	SOIL BORING LOG	
	Project Number n/a	Boring Number BH-1*
	General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.	

Project Name: Silty Soils Project	Location: 1046 Avonside Drive ("EQC-3"), Avondale, Christchurch, NZ
Elevation: ---	Drilling Contractor: McMillan Drilling Services
Drilling Method and Equipment: Mud-rotary, Track rig (Geoprobe 8140LS)	
Mud Level: ---	Start/Finish: 20 May 2014 (Tuesday) - 21 May 2014 (Wednesday)
Logger: Christine Z. Beyzaei (UC Berkeley)	

Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
<						

		SOIL BORING LOG				
		Project Number n/a			Boring Number BH-1*	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		1046 Avonside Drive ("EQC-3"), Avondale, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish: 20 May 2014 (Tuesday) - 21 May 2014 (Wednesday)		
Logger: Christine Z. Beyzaei (UC Berkeley) / Mark Stringer (Univ. of Canterbury)						
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
6.90- 7.35 m	7U (DM)	94%	325 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 5.745 m.	
8						
8.35- 8.80 m	8U (DM)	100%	450 psi	<i>Not extruded for 2014 CTX testing</i>	Casing at 7.265 m.	
9						
10						
11						
12						
13						
13.30- 14.30 m	9U (GP)	74%	4-6 MPa	Dark gray sand; Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1.	Casing at 11.795 m. Core catcher did not activate during sampling.	
14						

		SOIL BORING LOG			
		Project Number n/a		Boring Number BH-1*	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.			

Project Name:	Silty Soils Project	Location:	1046 Avonside Drive ("EQC-3"), Avondale, Christchurch, NZ
Elevation:	---	Drilling Contractor:	McMillan Drilling Services
Drilling Method and Equipment:	Mud-rotary, Track rig (Geoprobe 8140LS)		
Mud Level:	---	Start/Finish:	20 May 2014 (Tuesday) - 21 May 2014 (Wednesday)
Logger:	Christine Z. Beyzaei (UC Berkeley) / Mark Stringer (Univ. of Canterbury)		

Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
13.3- 14.3 m	9U (GP)	74%	4-6 MPa	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1.	Casing at 11.795 m. Core catcher did not activate during sampling.	
15						
16						
16.00- 17.00 m	10U (GP)	18%	4-6 MPa	Dark gray sand; Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-1.	Casing at 14.38 m. Sample abandoned due to low recovery. Core catcher did not activate during sampling.	
17						
18						
19						
20						
21						
						*Note: "BH-1" originally named "DM-1."
						End of boring at 17.0 m (pg. 3 of 3)

		SOIL BORING LOG				
		Project Number n/a			Boring Number BH-5*	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		18-20 Wairoa Street ("EQC-6"), Bexley, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish: 18 June 2014 (Wednesday) - 19 June 2014 (Thursday)		
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
1	1.00-1.45 m	1U (DM)	99%	75 psi	Not extruded for 2014 CTX testing	Casing at 0.64 m.
2						
3	2.80-3.25 m	2U (DM)	99%	275 psi	Not extruded for 2014 CTX testing; Tube slightly dented during sampling	Casing at 2.33 m.
4	3.60-4.05 m	3U (DM)	97%	0 kPa	Not extruded for 2014 CTX testing; Tube significantly dented during sampling	Casing at 2.33 m. Pressure gauge read 0 kPa, but drilling mud return observed at surface.
	4.20-4.65 m	4U (DM)	100%	225-275 psi	Not extruded for 2014 CTX testing	Casing at 3.78 m.
5	4.80-5.25 m	5U (DM)	100%	275 psi	Not extruded for 2014 CTX testing	Casing at 3.78 m.
	5.50-5.95 m	6U (DM)	---	400-600 psi	Not extruded for 2014 CTX testing; Tube crushed during sampling (sample bagged)	Casing at 3.78 m.
6	6.20-6.65 m	7U (DM)	100%	300 psi	Not extruded for 2014 CTX testing; Wood at top surface of sample	Casing at 5.755 m.
7						(pg. 1 of 2)

		SOIL BORING LOG				
		Project Number n/a			Boring Number BH-5*	
		General Comments: Dames & Moore (DM) sampling for cyclic triaxial (CTX) testing program.				
Project Name:		Silty Soils Project		Location:		18-20 Wairoa Street ("EQC-6"), Bexley, Christchurch, NZ
Elevation:		---		Drilling Contractor:		McMillan Drilling Services
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level:		---		Start/Finish:		18 June 2014 (Wednesday) - 19 June 2014 (Thursday)
Logger:		Christine Z. Beyzaei (UC Berkeley)				
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
						*Note: "BH-5" originally named "DM-1."
7.51- 7.96 m	8U (DM)	101%	300-500 psi	Not extruded for 2014 CTX testing	Casing at 6.82 m.	
8						
9						
10						
11	11.00- 11.45 m	9U (DM)	68%	300-325 psi	Not extruded for 2014 CTX testing; Tube slightly dented during sampling	Casing at 10.315 m.
12						
12.11- 12.56 m	10U (DM)	101%	400 psi	Not extruded for 2014 CTX testing	Casing at 11.765 m.	
13						
12.80- 13.25 m	11U (DM)	102%	500 psi	Not extruded for 2014 CTX testing	Casing at 11.835 m.	
14						
13.7- 14.7 m	12U (GP)	49%	not recorded	Gel-Push sample obtained by Mark Stringer (Univ. of Canterbury) after completion of DM sampling in BH-5.	End of boring at 14.7 m (pg. 2 of 2)	

		SOIL BORING LOG				
		Project Number n/a		Boring Number DM-1		
		General Comments: Dames & Moore Continuous Sampling <i>(This is a simplified log. Detailed logging will be provided.)</i>				
Project Name: Mini-Cone/Continuous D&M		Location: 201 Clarence Street ("Site 37"), Riccarton, Christchurch, NZ				
Elevation: ---		Drilling Contractor: McMillan Drilling Services				
Drilling Method and Equipment:		Mud-rotary, Track rig (Geoprobe 8140LS)				
Mud Level: 0.25 m BGS* (10 June 2016, 8:15AM)		Start/Finish: 9 June 2016 (Thursday) - 10 June 2016 (Friday)				
Logger: Christine Z. Beyzaei (UC Berkeley)						
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
						<i>Hand-augered (0 - 0.5m)</i>
1	0.5- 0.89 m	1U (DM)	100%	400+ psi	Gray silt	No casing. Sampler not fully advanced* (estimated advancement approx. 39 cm).
	0.95- 1.38 m	2U (DM)	100%	275 psi	Gray silt	No casing. Sampler not fully advanced* (estimated advancement approx. 43 cm).
	1.40- 1.84 m	3U (DM)	100%	125 psi	Gray silt	Casing at 0.78 m. Sampler not fully advanced* (estimated advancement approx. 44 cm).
2	1.85- 2.30 m	4U (DM)	103%	75 psi	Gray silt grading into silty sand	Casing at 0.78 m.
	2.30- 2.75 m	5U (DM)	100%	50 psi	Gray silty sand and sandy silt	Casing at 1.85 m.
3	2.75- 3.20 m	6U (DM)	101%	75 psi	Gray silty sand and sandy silt	Casing at 1.85 m.
	3.20- 3.65 m	7U (DM)	99%	125 psi	Gray silty sand and sandy silt	Casing at 2.90 m.
4	3.65- 4.10 m	8U (DM)	99%	125 psi	Gray silty sand and sandy silt	Casing at 2.90 m.
	4.10- 4.55 m	9U (DM)	100%	75 psi	Gray silty sand and sandy silt	Casing at 3.36 m.
	4.55- 5.00 m	10U (DM)	101%	75 psi	Gray sandy silt	Casing at 4.25 m.
5	5.00- 5.45 m	11U (DM)	101%	100 psi	Gray silt	Casing at 4.25 m.
	5.45- 5.90 m	12U (DM)	101%	125 psi	Gray silt	Casing at 4.25 m.
6	5.90- 6.35 m	13U (DM)	99%	100 psi	Gray silty sand and sandy silt	Casing at 5.34 m.
	6.35- 6.80 m	14U (DM)	100%	100 psi	Gray silty sand and silt	Casing at 5.34 m.
7	*Note: BGS = Below Ground Surface. Full sampler advancement = 45 cm.					<i>End of boring at 6.80 m</i>

	SOIL BORING LOG	
	Project Number n/a	Boring Number BH-3
	General Comments: Dames & Moore Continuous Sampling <i>(This is a simplified log. Detailed logging will be provided.)</i>	

Project Name: Mini-Cone/Continuous D&M	Location: Barrington Park ("Site 14"), Christchurch, NZ
Elevation: ---	Drilling Contractor: McMillan Drilling Services
Drilling Method and Equipment: Mud-rotary, Track rig (Geoprobe 8140LS)	
Mud Level: Above ground surface (8 June 2016, 8:30AM)	Start/Finish: 7 June 2016 (Tuesday) - 8 June 2016 (Wednesday)
Logger: Christine Z. Beyzaei (UC Berkeley)	

Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
						<i>Hand-augered (0 - 0.5m)</i>
1	0.50- 0.90 m	1U (DM)	100%	350+ psi	Gray silt	No casing. Sampler not fully advanced* (estimated advancement approx. 40 cm).
	0.95- 1.40 m	2U (DM)	103%	150 psi	Gray silt and silty sand	No casing.
	1.40- 1.85 m	3U (DM)	98%	125 psi	Gray silt and silty sand	Casing at 0.78 m.
2	1.85- 2.30 m	4U (DM)	101%	75 psi	Gray silt and sandy silt	Casing at 0.78 m.
	2.30- 2.75 m	5U (DM)	101%	75 psi	Gray silt	Casing at 1.85 m.
3	2.75- 3.20 m	6U (DM)	100%	200 psi	Gray silt and silty sand	Casing at 1.85 m.
	3.20- 3.65 m	7U (DM)	100%	200 psi	Gray silty sand	Casing at 2.90 m.
4	3.65- 4.10 m	8U (DM)	99%	150 psi	Gray silty sand	Casing at 2.90 m.
	4.10- 4.55 m	9U (DM)	101%	175 psi	Gray silty sand	Casing at 2.90 m.
	4.55- 5.00 m	10U (DM)	99%	150 psi	Gray silty sand	Casing at 4.25 m.
5	5.00- 5.45 m	11U (DM)	98%	200 psi	Gray silty sand, sand, and silt	Casing at 4.25 m.
	5.45- 5.90 m	12U (DM)	99%	150 psi	Gray sand, some-trace silt	Casing at 4.25 m.
6	5.90- 6.35 m	13U (DM)	99%	250 psi	Gray silty sand and sand, some-trace silt	Casing at 5.34 m.
	6.35- 6.80 m	14U (DM)	98%	150 psi	Gray sand and silt	Casing at 5.34 m.
7						<i>End of boring at 6.80 m</i>

*Note: Full sampler advancement = 45 cm.

				SOIL BORING LOG		
				Project Number n/a	Boring Number DM-2	
				General Comments: Dames & Moore Continuous Sampling <i>(This is a simplified log. Detailed logging will be provided.)</i>		
Project Name: Mini-Cone/Continuous D&M				Location: 200 Cashmere Road ("Site 33"), Cashmere, Christchurch, NZ		
Elevation: ---				Drilling Contractor: McMillan Drilling Services		
Drilling Method and Equipment:				Mud-rotary, Track rig (Geoprobe 8140LS)		
Mud Level: Above ground surface (7 June 2016, 8:30AM)				Start/Finish: 3 June 2016 (Friday) - 7 June 2016 (Tuesday)		
Logger: Christine Z. Beyzaei (UC Berkeley)						
Depth below Surface (m)	Sample			D&M Sampling Pressure	Soil Description	Comments
	Interval	Number and Type	Recovery (%)	(psi)	(from extrusion of sample in the lab)	Depth of Casing, Drilling Rate, Drilling Fluid Loss, Tests and Instrumentation
						<i>Hand-augered (0 - 0.5m)</i>
0.5- 0.89 m	1U (DM)	100%	350-400 psi	Gray sandy silt	No casing. Sampler not fully advanced* (estimated advancement approx. 39 cm).	
0.95- 1.40 m	2U (DM)	100%	200 psi	Gray sandy silt	No casing.	
1.40- 1.85 m	3U (DM)	100%	100 psi	Gray sandy silt	Casing at 0.78 m.	
1.85- 2.30 m	4U (DM)	99%	100 psi	Gray clayey silt	Casing at 0.78 m.	
2.30- 2.75 m	5U (DM)	101%	100 psi	Gray clayey silt	Casing at 1.85 m.	
2.75- 3.20 m	6U (DM)	101%	100 psi	Gray sandy silt to silty sand	Casing at 1.85 m.	
3.20- 3.65 m	7U (DM)	100%	150-250 psi	Gray fine sand, some silt	Casing at 2.90 m.	
3.65- 4.10 m	8U (DM)	101%	150-250 psi	Gray silty fine sand (silt/organic bands and laminations)	Casing at 2.90 m.	
4.10- 4.55 m	9U (DM)	95%	75 psi	Gray fine sand, some silt & Gray silt with laminations	Casing at 3.80 m.	
4.55- 5.00 m	10U (DM)	101%	75 psi	Gray silt & silty fine sand (organic/sand laminations and partings)	Casing at 4.25 m.	
5.00- 5.45 m	11U (DM)	102%	50 psi	Layered silty sand and silt	Casing at 4.25 m.	
5.45- 5.90 m	12U (DM)	98%	100 psi	Layered silty sand and silt	Casing at 4.25 m.	
5.90- 6.35 m	13U (DM)	100%	50 psi	Layered silt	Casing at 5.34 m.	
6.35- 6.80 m	14U (DM)	101%	75 psi	Layered silt	Casing at 5.34 m.	
						<i>End of boring at 6.80 m</i>
*Note: Full sampler advancement = 45 cm.						

Appendix A.3

Mini-CPT ConeTec Data Report

PRESENTATION OF SITE INVESTIGATION RESULTS

Mini CPT Research, Christchurch, New Zealand

Prepared for:

Tonkin + Taylor

ConeTec Job No: 16-02040

Project Start Date: 31-May-2016

Project End Date: 07-Jul-2016

Revised Report Date: 08-Jul-2016



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Mini CPT Research, Christchurch, New Zealand

Introduction

The enclosed report presents the results of the site investigation program conducted by ConeTec Investigations Ltd. for Tonkin + Taylor at three locations in Christchurch, New Zealand. The program consisted of ten cone penetration tests (CPT). Results for six of the CPT soundings are presented (CPT16-01, CPT16-02, CPT16-04, CPT16-08, CPT16-09, and CPT16-10). The other four CPT sounding results (CPT16-03, CPT16-05, CPT16-06, and CPT16-07) are not presented due to equipment issues.

Project Information

Project	
Client	Tonkin + Taylor
Project	Mini CPT Research
ConeTec project number	16-02040

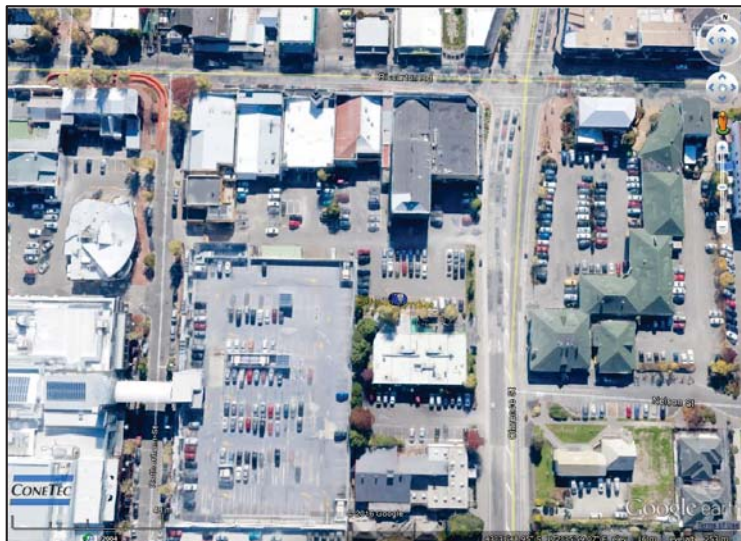
A map from Google earth including CPT test locations (CPT16-01 and CPT16-02) at 200 Cashmere Rd. is presented below.



A map from Google earth including CPT test location (CPT16-04) at Barrington Park is presented below.



A map from Google earth including CPT test locations (CPT16-08, CPT16-09, and CPT16-10) at 201 Clarence St. is presented below.



Mini CPT Research, Christchurch, New Zealand

Rig Description	Deployment System	Test Type
Geotechnics- Geoprobe	Drill Head	CPT

Coordinates		
Test Type	Collection Method	EPSG Reference
CPT	Consumer-grade GPS	32759

Cone Penetration Test (CPT)	
Depth reference	Depths are referenced to the existing ground surface at the time of each test.
Tip and sleeve data offset	0.05 meter This has been accounted for in the CPT data files.
Additional plots	Advanced CPT plots with Q_{tn} , c_s , I_c , $N1(60)$, and SBT Q_{tn} .

Cone Penetrometers Used for this Project						
Cone Description	Cone Number	Cross Sectional Area (cm ²)	Sleeve Area (cm ²)	Tip Capacity (bar)	Sleeve Capacity (bar)	Pore Pressure Capacity (psi)
362:T500F10U500	AD362	5	75	500	10	500
284:T500F15U500	AD284	5	75	500	10	500
Cone 362 was used for CPT16-01, CPT16-02, CPT16-07, CPT16-08, CPT16-09, and CPT16-10 soundings.						
Cone 284 was used for CPT16-03, CPT16-04, CPT16-05, and CPT16-06 soundings.						

Interpretation Tables	
Additional information	The Soil Behaviour Type (SBT) classification chart (Robertson et al., 1986) was used to classify the soil for this project. A detailed set of CPT interpretations were generated and are provided in Excel format files in the release folder. The CPT interpretations are based on values of corrected tip (q_t), sleeve friction (f_s) and pore pressure (u_2). Soils were classified as either drained or undrained based on the Soil Behaviour Type (SBT) classification chart (Robertson et al., 1986). Calculations for both drained and undrained parameters were included for materials that classified as silt (zone 6).

Limitations

This report has been prepared for the exclusive use of Tonkin + Taylor (Client) for the project titled “Mini CPT Research”. The report’s contents may not be relied upon by any other party without the express written permission of ConeTec Investigations Ltd. (ConeTec). ConeTec has provided site investigation services, prepared the factual data reporting, and provided geotechnical parameter calculations consistent with current best practices. No other warranty, expressed or implied, is made.

The information presented in the report document and the accompanying data set pertain to the specific project, site conditions and objectives described to ConeTec by the Client. In order to properly understand the factual data, assumptions and calculations, reference must be made to the documents provided and their accompanying data sets, in their entirety.

CONE PENETRATION TEST

The cone penetration tests (CPTu) are conducted using an integrated electronic piezocone penetrometer and data acquisition system manufactured by Adara Systems Ltd. of Richmond, British Columbia, Canada.

ConeTec's piezocone penetrometers are compression type designs in which the tip and friction sleeve load cells are independent and have separate load capacities. The piezocones use strain gauged load cells for tip and sleeve friction and a strain gauged diaphragm type transducer for recording pore pressure. The piezocones also have a platinum resistive temperature device (RTD) for monitoring the temperature of the sensors, an accelerometer type dual axis inclinometer and a geophone sensor for recording seismic signals. All signals are amplified down hole within the cone body and the analog signals are sent to the surface through a shielded cable.

ConeTec penetrometers are manufactured with various tip, friction and pore pressure capacities in 5 cm², 10 cm² and 15 cm² tip base area configurations in order to maximize signal resolution for various soil conditions. The specific piezocone used for each test is described in the CPT summary table presented in the first appendix. The 15 cm² penetrometers do not require friction reducers as they have a diameter larger than the deployment rods. The 5 cm² and 10 cm² piezocones use a friction reducer consisting of a rod adapter extension behind the main cone body with an enlarged cross sectional area (typically 44 mm diameter over a length of 32 mm with tapered leading and trailing edges) located at a distance of 585 mm above the cone tip.

The penetrometers are designed with equal end area friction sleeves, a net end area ratio of 0.8 and cone tips with a 60 degree apex angle.

All ConeTec piezocones can record pore pressure at various locations. Unless otherwise noted, the pore pressure filter is located directly behind the cone tip in the "u₂" position (ASTM Type 2). The filter is 6 mm thick, made of porous plastic (polyethylene) having an average pore size of 125 microns (90-160 microns). The function of the filter is to allow rapid movements of extremely small volumes of water needed to activate the pressure transducer while preventing soil ingress or blockage.

The piezocone penetrometers are manufactured with dimensions, tolerances and sensor characteristics that are in general accordance with the current ASTM D5778 standard. ConeTec's calibration criteria also meets or exceeds those of the current ASTM D5778 standard. An illustration of the piezocone penetrometer is presented in Figure CPTu.



CONE PENETRATION TEST

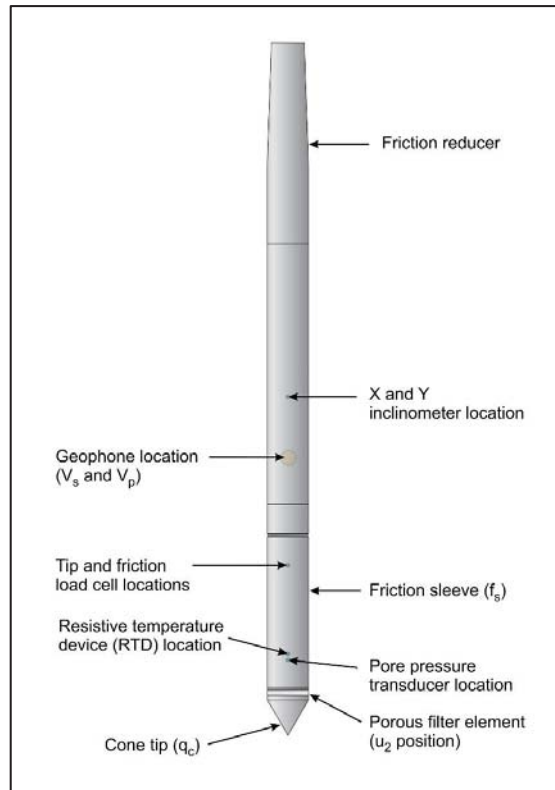


Figure CPTu. Piezocone Penetrometer (15 cm²)

The ConeTec data acquisition systems consist of a Windows based computer and a signal conditioner and power supply interface box with a 16 bit (or greater) analog to digital (A/D) converter. The data is recorded at fixed depth increments using a depth wheel attached to the push cylinders or by using a spring loaded rubber depth wheel that is held against the cone rods. The typical recording intervals are either 2.5 cm or 5.0 cm depending on project requirements; custom recording intervals are possible. The system displays the CPTu data in real time and records the following parameters to a storage media during penetration:

- Depth
- Uncorrected tip resistance (q_c)
- Sleeve friction (f_s)
- Dynamic pore pressure (u)
- Additional sensors such as resistivity, passive gamma, ultra violet induced fluorescence, if applicable

All testing is performed in accordance to ConeTec's CPT operating procedures which are in general accordance with the current ASTM D5778 standard.



CONE PENETRATION TEST

Prior to the start of a CPTu sounding a suitable cone is selected, the cone and data acquisition system are powered on, the pore pressure system is saturated with either glycerine or silicone oil and the baseline readings are recorded with the cone hanging freely in a vertical position.

The CPTu is conducted at a steady rate of 2 cm/s, within acceptable tolerances. Typically one meter length rods with an outer diameter of 1.5 inches are added to advance the cone to the sounding termination depth. After cone retraction final baselines are recorded.

Additional information pertaining to ConeTec's cone penetration testing procedures:

- Each filter is saturated in silicone oil or glycerine under vacuum pressure prior to use
- Recorded baselines are checked with an independent multi-meter
- Baseline readings are compared to previous readings
- Soundings are terminated at the client's target depth or at a depth where an obstruction is encountered, excessive rod flex occurs, excessive inclination occurs, equipment damage is likely to take place, or a dangerous working environment arises
- Differences between initial and final baselines are calculated to ensure zero load offsets have not occurred and to ensure compliance with ASTM standards

The interpretation of piezocone data for this report is based on the corrected tip resistance (q_t), sleeve friction (f_s) and pore water pressure (u). The interpretation of soil type is based on the correlations developed by Robertson (1990) and Robertson (2009). It should be noted that it is not always possible to accurately identify a soil type based on these parameters. In these situations, experience, judgment and an assessment of other parameters may be used to infer soil behaviour type.

The recorded tip resistance (q_c) is the total force acting on the piezocone tip divided by its base area. The tip resistance is corrected for pore pressure effects and termed corrected tip resistance (q_t) according to the following expression presented in Robertson et al, 1986:

$$q_t = q_c + (1-a) \cdot u_2$$

where: q_t is the corrected tip resistance

q_c is the recorded tip resistance

u_2 is the recorded dynamic pore pressure behind the tip (u_2 position)

a is the Net Area Ratio for the piezocone (0.8 for ConeTec probes)

The sleeve friction (f_s) is the frictional force on the sleeve divided by its surface area. As all ConeTec piezocones have equal end area friction sleeves, pore pressure corrections to the sleeve data are not required.

The dynamic pore pressure (u) is a measure of the pore pressures generated during cone penetration. To record equilibrium pore pressure, the penetration must be stopped to allow the dynamic pore pressures to stabilize. The rate at which this occurs is predominantly a function of the permeability of the soil and the diameter of the cone.



CONE PENETRATION TEST

The friction ratio (R_f) is a calculated parameter. It is defined as the ratio of sleeve friction to the tip resistance expressed as a percentage. Generally, saturated cohesive soils have low tip resistance, high friction ratios and generate large excess pore water pressures. Cohesionless soils have higher tip resistances, lower friction ratios and do not generate significant excess pore water pressure.

A summary of the CPTu soundings along with test details and individual plots are provided in the appendices. A set of files with calculated geotechnical parameters were generated for each sounding based on published correlations and are provided in Excel format in the data release folder. Information regarding the methods used is also included in the data release folder.

For additional information on CPTu interpretations and calculated geotechnical parameters, refer to Robertson et al. (1986), Lunne et al. (1997), Robertson (2009), Mayne (2013, 2014) and Mayne and Peuchen (2012).

References

ASTM D5778-12, 2012, "Standard Test Method for Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils", ASTM, West Conshohocken, US.

Lunne, T., Robertson, P.K. and Powell, J. J. M., 1997, "Cone Penetration Testing in Geotechnical Practice", Blackie Academic and Professional.

Mayne, P.W., 2013, "Evaluating yield stress of soils from laboratory consolidation and in-situ cone penetration tests", Sound Geotechnical Research to Practice (Holtz Volume) GSP 230, ASCE, Reston/VA: 406-420.

Mayne, P.W. and Peuchen, J., 2012, "Unit weight trends with cone resistance in soft to firm clays", Geotechnical and Geophysical Site Characterization 4, Vol. 1 (Proc. ISC-4, Pernambuco), CRC Press, London: 903-910.

Mayne, P.W., 2014, "Interpretation of geotechnical parameters from seismic piezocone tests", CPT'14 Keynote Address, Las Vegas, NV, May 2014.

Robertson, P.K., Campanella, R.G., Gillespie, D. and Greig, J., 1986, "Use of Piezometer Cone Data", Proceedings of InSitu 86, ASCE Specialty Conference, Blacksburg, Virginia.

Robertson, P.K., 1990, "Soil Classification Using the Cone Penetration Test", Canadian Geotechnical Journal, Volume 27: 151-158.

Robertson, P.K., 2009, "Interpretation of cone penetration tests – a unified approach", Canadian Geotechnical Journal, Volume 46: 1337-1355.

PORE PRESSURE DISSIPATION TEST

The cone penetration test is halted at specific depths to carry out pore pressure dissipation (PPD) tests, shown in Figure PPD-1. For each dissipation test the cone and rods are decoupled from the rig and the data acquisition system measures and records the variation of the pore pressure (u) with time (t).

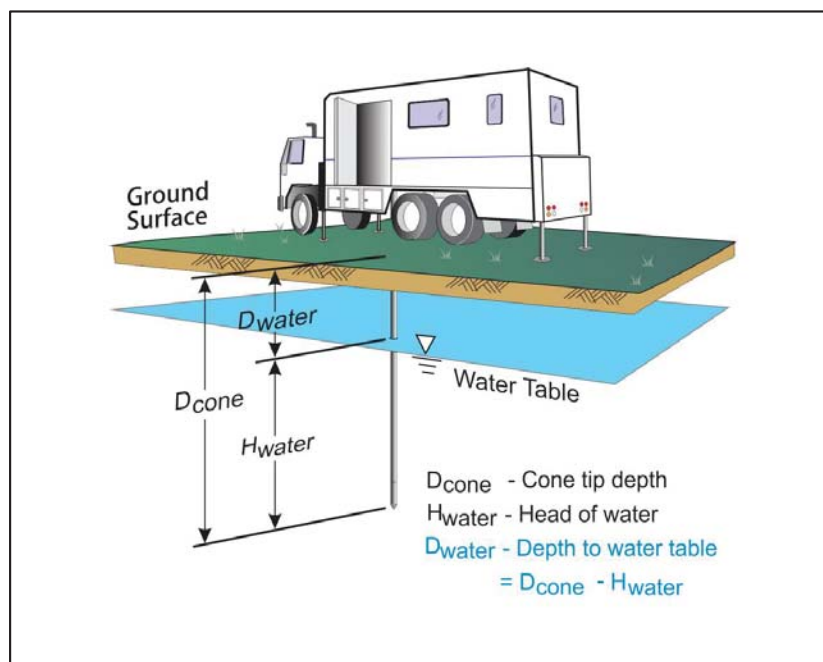


Figure PPD-1. Pore pressure dissipation test setup

Pore pressure dissipation data can be interpreted to provide estimates of ground water conditions, permeability, consolidation characteristics and soil behaviour.

The typical shapes of dissipation curves shown in Figure PPD-2 are very useful in assessing soil type, drainage, in situ pore pressure and soil properties. A flat curve that stabilizes quickly is typical of a freely draining sand. Undrained soils such as clays will typically show positive excess pore pressure and have long dissipation times. Dilative soils will often exhibit dynamic pore pressures below equilibrium that then rise over time. Overconsolidated fine-grained soils will often exhibit an initial dilatatory response where there is an initial rise in pore pressure before reaching a peak and dissipating.

PORE PRESSURE DISSIPATION TEST

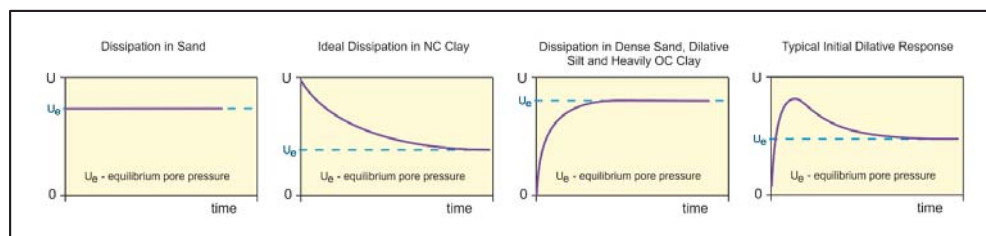


Figure PPD-2. Pore pressure dissipation curve examples

In order to interpret the equilibrium pore pressure (u_{eq}) and the apparent phreatic surface, the pore pressure should be monitored until such time as there is no variation in pore pressure with time as shown for each curve of Figure PPD-2.

In fine grained deposits the point at which 100% of the excess pore pressure has dissipated is known as t_{100} . In some cases this can take an excessive amount of time and it may be impractical to take the dissipation to t_{100} . A theoretical analysis of pore pressure dissipations by Teh and Houlsby (1991) showed that a single curve relating degree of dissipation versus theoretical time factor (T^*) may be used to calculate the coefficient of consolidation (c_h) at various degrees of dissipation resulting in the expression for c_h shown below.

$$c_h = \frac{T^* \cdot a^2 \cdot \sqrt{I_r}}{t}$$

Where:

- T^* is the dimensionless time factor (Table Time Factor)
- a is the radius of the cone
- I_r is the rigidity index
- t is the time at the degree of consolidation

Table Time Factor. T^* versus degree of dissipation (Teh and Houlsby, 1991)

Degree of Dissipation (%)	20	30	40	50	60	70	80
$T^* (u_z)$	0.038	0.078	0.142	0.245	0.439	0.804	1.60

The coefficient of consolidation is typically analyzed using the time (t_{50}) corresponding to a degree of dissipation of 50% (u_{50}). In order to determine t_{50} , dissipation tests must be taken to a pressure less than u_{50} . The u_{50} value is half way between the initial maximum pore pressure and the equilibrium pore pressure value, known as u_{100} . To estimate u_{50} , both the initial maximum pore pressure and u_{100} must be known or estimated. Other degrees of dissipations may be considered, particularly for extremely long dissipations.

At any specific degree of dissipation the equilibrium pore pressure (u at t_{100}) must be estimated at the depth of interest. The equilibrium value may be determined from one or more sources such as measuring the value directly (u_{100}), estimating it from other dissipations in the same profile, estimating the phreatic surface and assuming hydrostatic conditions, from nearby soundings, from client provided information, from site observations and/or past experience, or from other site instrumentation.

PORE PRESSURE DISSIPATION TEST

For calculations of c_h (Teh and Houlsby, 1991), t_{50} values are estimated from the corresponding pore pressure dissipation curve and a rigidity index (I_r) is assumed. For curves having an initial dilatory response in which an initial rise in pore pressure occurs before reaching a peak, the relative time from the peak value is used in determining t_{50} . In cases where the time to peak is excessive, t_{50} values are not calculated.

Due to possible inherent uncertainties in estimating I_r , the equilibrium pore pressure and the effect of an initial dilatory response on calculating t_{50} , other methods should be applied to confirm the results for c_h .

Additional published methods for estimating the coefficient of consolidation from a piezocone test are described in Burns and Mayne (1998, 2002), Jones and Van Zyl (1981), Robertson et al. (1992) and Sully et al. (1999).

A summary of the pore pressure dissipation tests and dissipation plots are presented in the relevant appendix.

REFERENCES

- ASTM D5778-12, 2012, "Standard Test Method for Performing Electronic Friction Cone and Piezocone Penetration Testing of Soils", ASTM, West Conshohocken, US.
- Burns, S.E. and Mayne, P.W., 1998, "Monotonic and dilatatory pore pressure decay during piezocone tests", *Canadian Geotechnical Journal* 26 (4): 1063-1073.
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- Robertson, P.K., 2009, "Interpretation of cone penetration tests – a unified approach", *Canadian Geotechnical Journal*, Volume 46: 1337-1355.
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- Sully, J.P., Robertson, P.K., Campanella, R.G. and Woeller, D.J., 1999, "An approach to evaluation of field CPTU dissipation data in overconsolidated fine-grained soils", *Canadian Geotechnical Journal*, 36(2): 369-381.
- Teh, C.I., and Houlsby, G.T., 1991, "An analytical study of the cone penetration test in clay", *Geotechnique*, 41(1): 17-34.

APPENDICES

The appendices listed below are included in the report:

- Cone Penetration Test Summary and Standard Cone Penetration Test Plots
- Advanced Cone Penetration Test Plots with $Q_{tn,cs}$, I_c , $N1(60)$, and SBT Q_{tn}
- Pore Pressure Dissipation Summary and Pore Pressure Dissipation Plots

Cone Penetration Test Summary and
Standard Cone Penetration Test Plots





Job No: 16-02040
Client: Tonkin + Taylor
Project: Mini CPT Research
Start Date: 31-May-2016
End Date: 07-Jul-2016

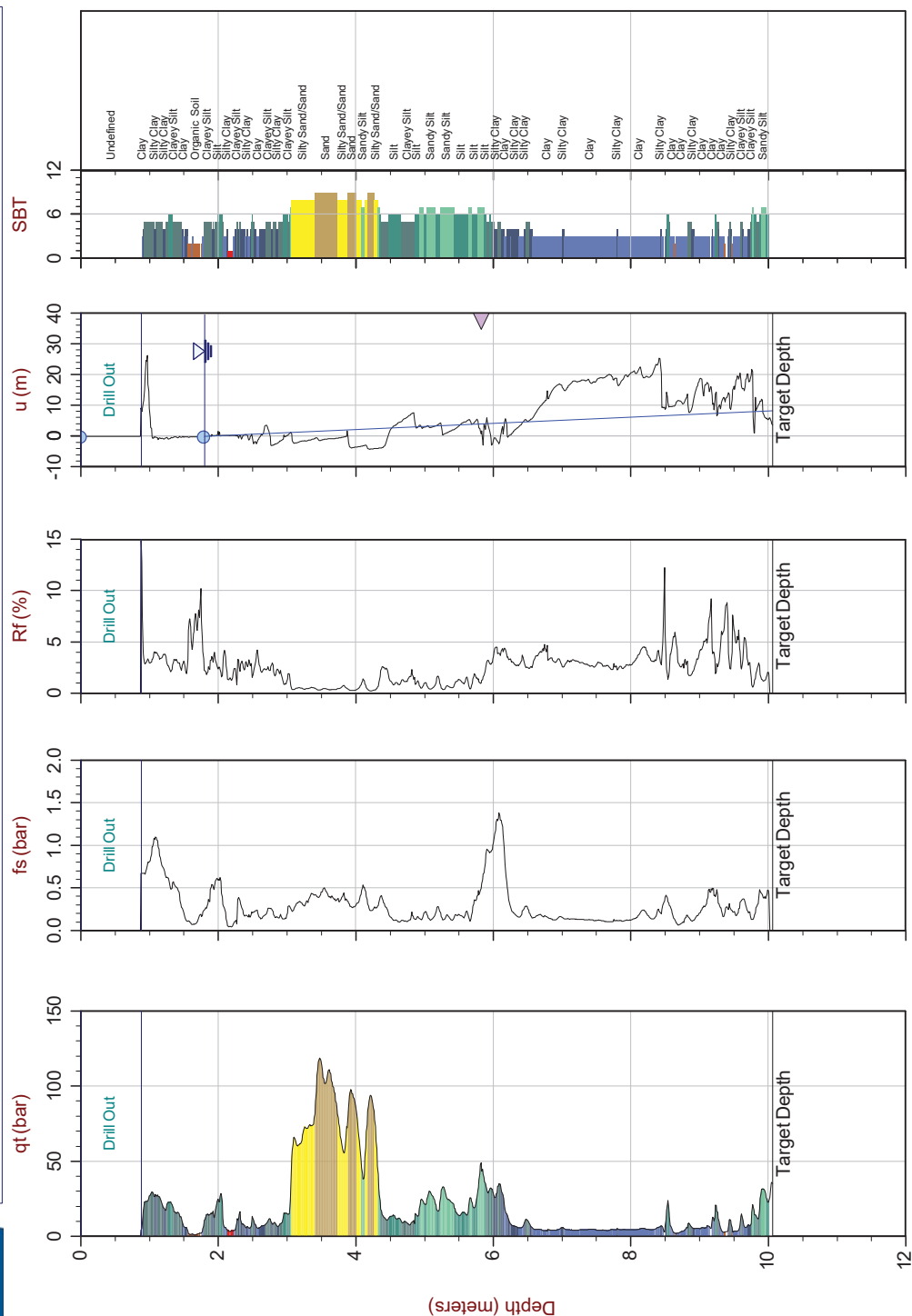
CONE PENETRATION TEST SUMMARY								
Sounding ID	File Name	Date	Cone	Assumed Phreatic Surface ¹ (m)	Final Depth (m)	Northing ² (m)	Easting (m)	Refer to Notation Number
CPT16-01	16-02040_CP01a	31-May-2016	362:T500F10U500	1.8	10.07	5174334	629850	3
CPT16-02	16-02040_CP02	31-May-2016	362:T500F10U500	1.8	10.07	5174334	629851	
CPT16-04	16-02040_CP04	01-Jun-2016	284:T500F10U500	0.0	7.06	5176392	630652	4
CPT16-08	16-02040_CP08	07-Jul-2016	362:T500F10U500	0.0	8.10	5179033	629406	
CPT16-09	16-02040_CP09	07-Jul-2016	362:T500F10U500	0.0	8.33	5179033	629407	
CPT16-10	16-02040_CP10	07-Jul-2016	362:T500F10U500	0.0	8.19	5179033	629408	

1. The assumed phreatic surfaces were based on pore pressure dissipation tests. Hydrostatic conditions were assumed for the interpretation tables.
2. The coordinates were obtained using consumer-grade GPS device with datum: WGS84/UTM South.
3. The assumed phreatic surface was based on equilibrium achieved from the adjacent sounding.
4. The assumed phreatic surface was estimated from dynamic pore pressure response.

Tonkin + Taylor

Job No: 16-02040
Date: 05:31:16 17:47
Site: 200 Cashmere Rd

Sounding: CPT16-01
Cone: 362:T500F10U500



Max Depth: 10.070 m / 33.04 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
Overplot Item:  Assumed Use  Ueq

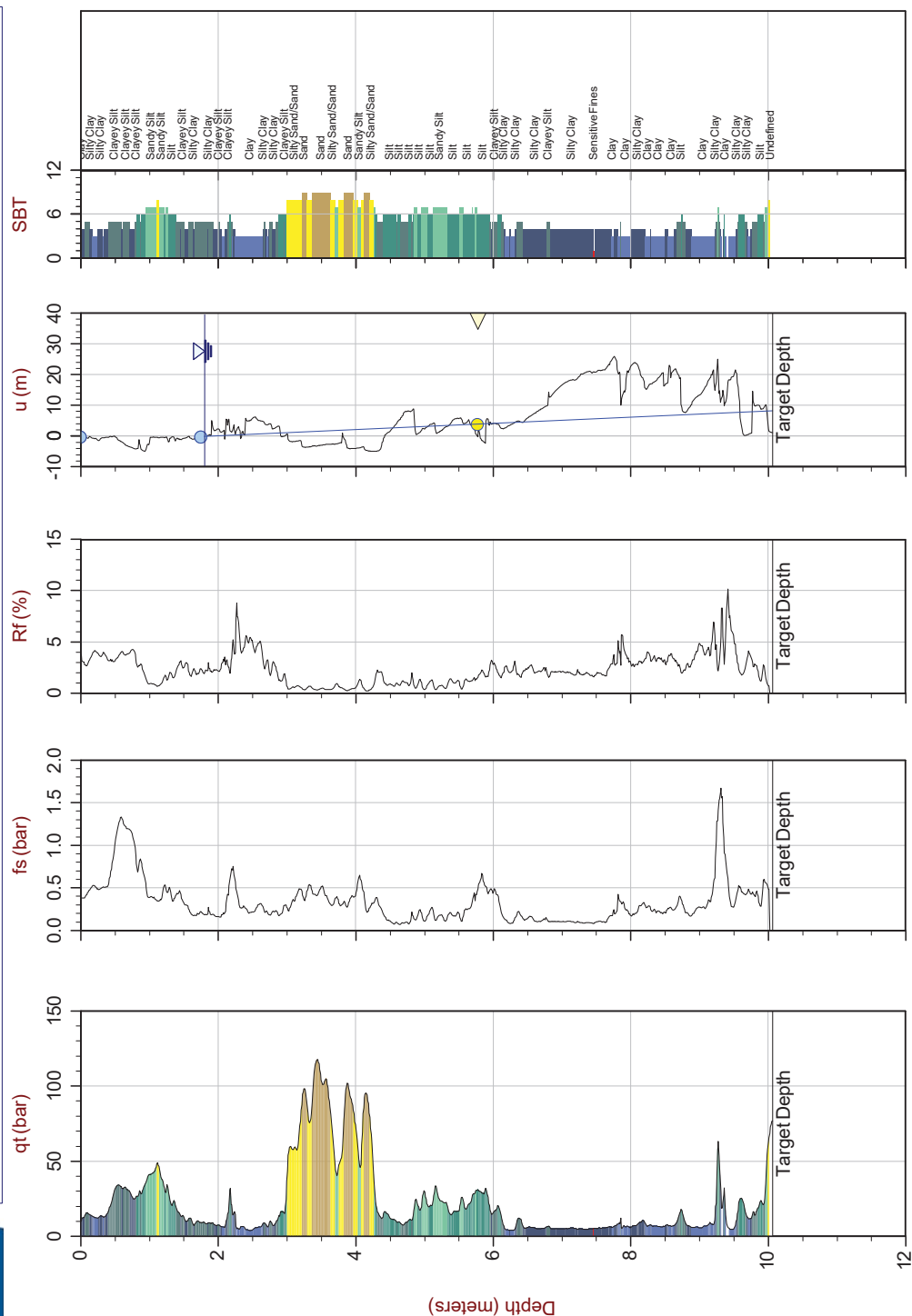
File: 16-02040_CP01A.COR
Unit Wt: SBT_Zones

SBT: Robertson and Campanella, 1986
 Coords: UTM South Zone 59G N: 5174334 E: 629850
 Page No: 1 of 1

Tonkin + Taylor

Job No: 16-02040
Date: 05:31:16 19:31
Site: 200 Cashmere Rd

Sounding: CPT16-02
Cone: 362:T500F10U500



SBT: Robertson and Campanella, 1986
 Coords: UTM South Zone 59G N: 5174334 E: 629851
 Page No: 1 of 1

File: 16-02040_CP02.COR
Unit Wt: SBT_Zones

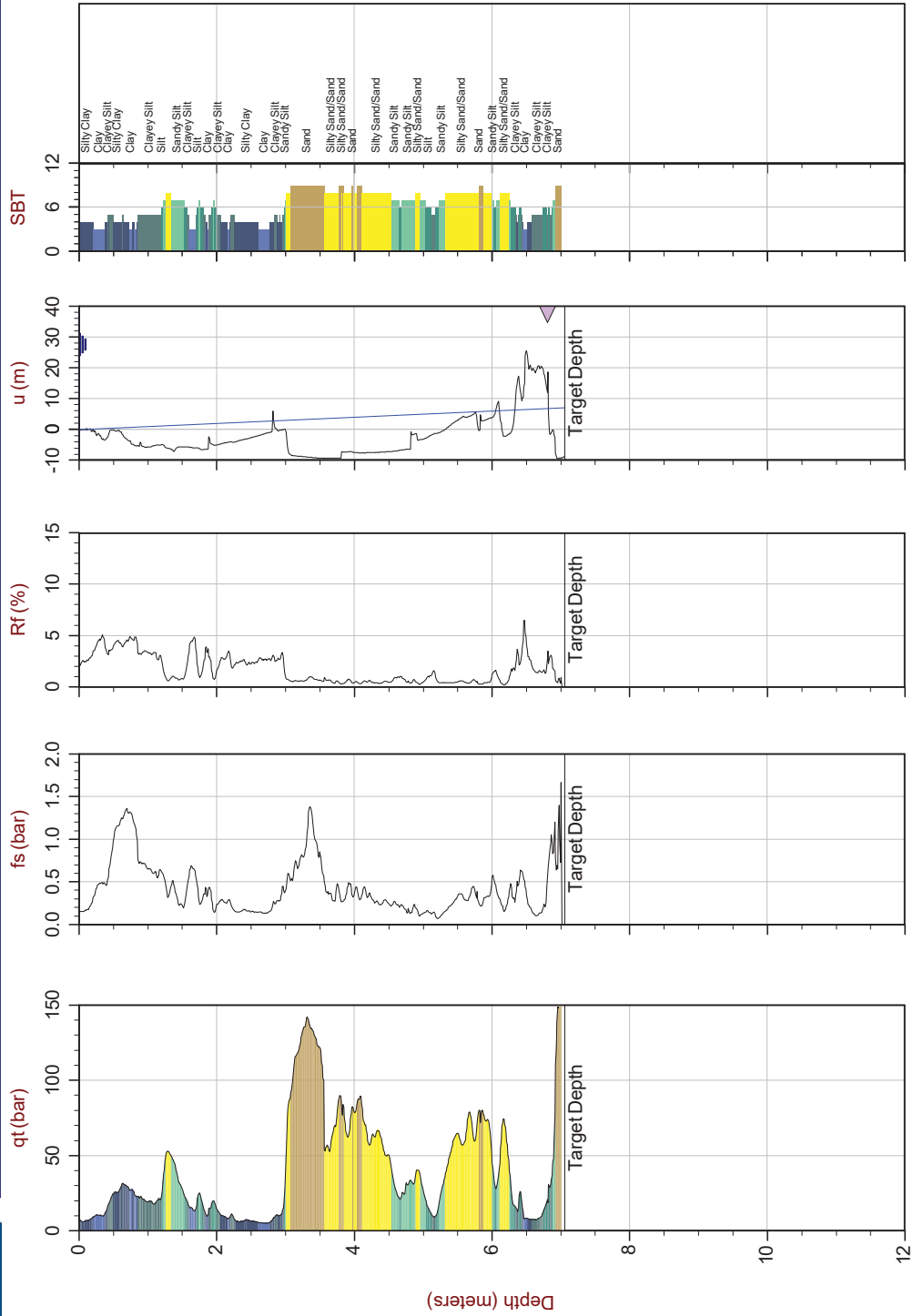
Max Depth: 10.070 m / 33.04 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
Overplot Item:  Assumed Ueq  Ueq



Tonkin + Taylor

Job No: 16-02040
Date: 06/01/16 16:36
Site: Barrington Park

Sounding: CPT16-04
Cone: 284:T500F10U500



Max Depth: 7.060 m / 23.16 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
Overplot Item: ● Assumed Ueq ● Ueq

File: 16-02040_CP04.COR
Unit Wt: SBT Zones

▼ Dissipation, equilibrium achieved
▲ Dissipation, equilibrium not achieved

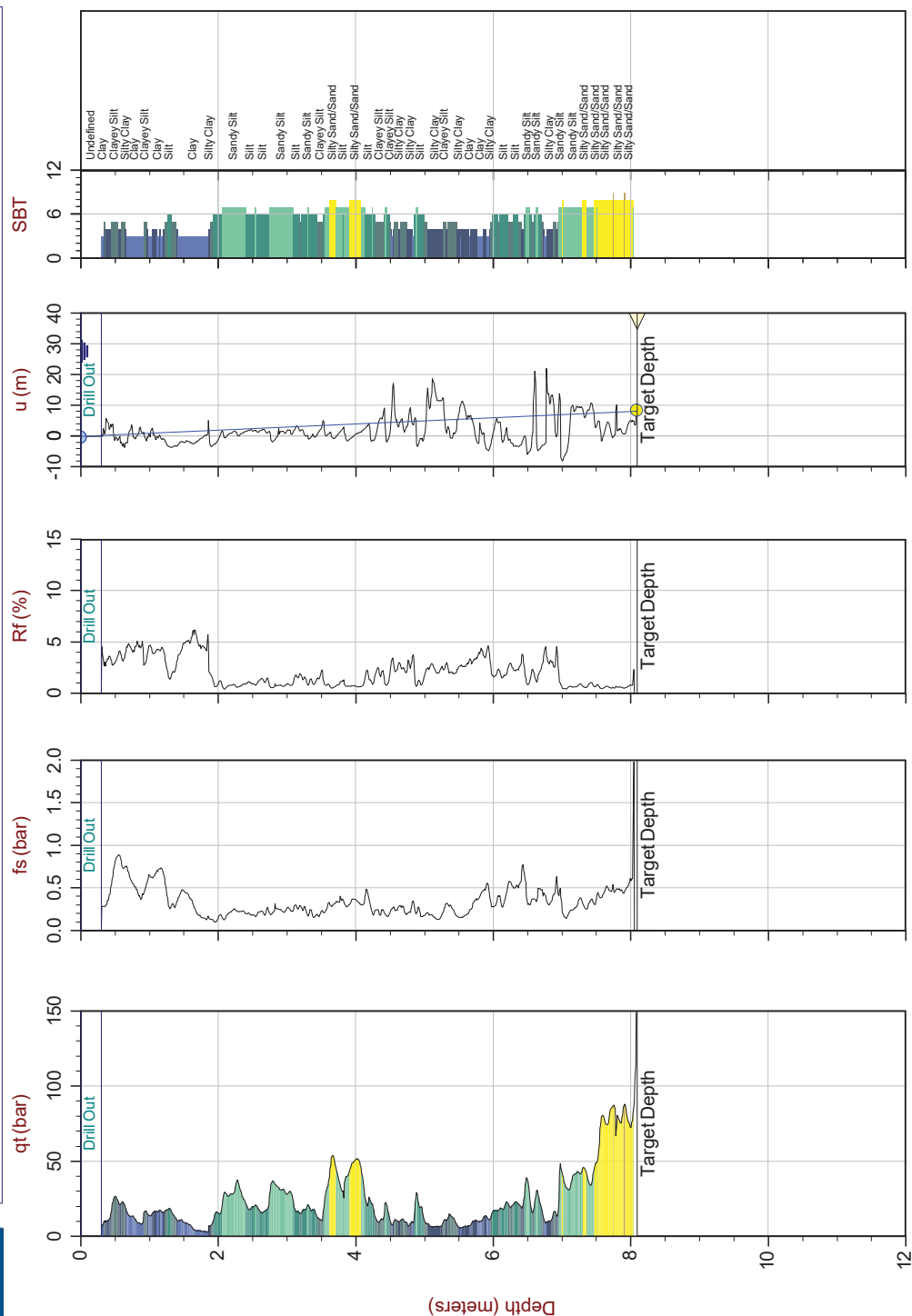
— Hydrostatic Line

SBT: Robertson and Campanella, 1986
Coords: UTM South Zone 59G N: 5176392 E: 630652
Page No: 1 of 1

Tonkin + Taylor

Job No: 16-02040
Date: 07:07:16 12:11
Site: 201 Clarence St

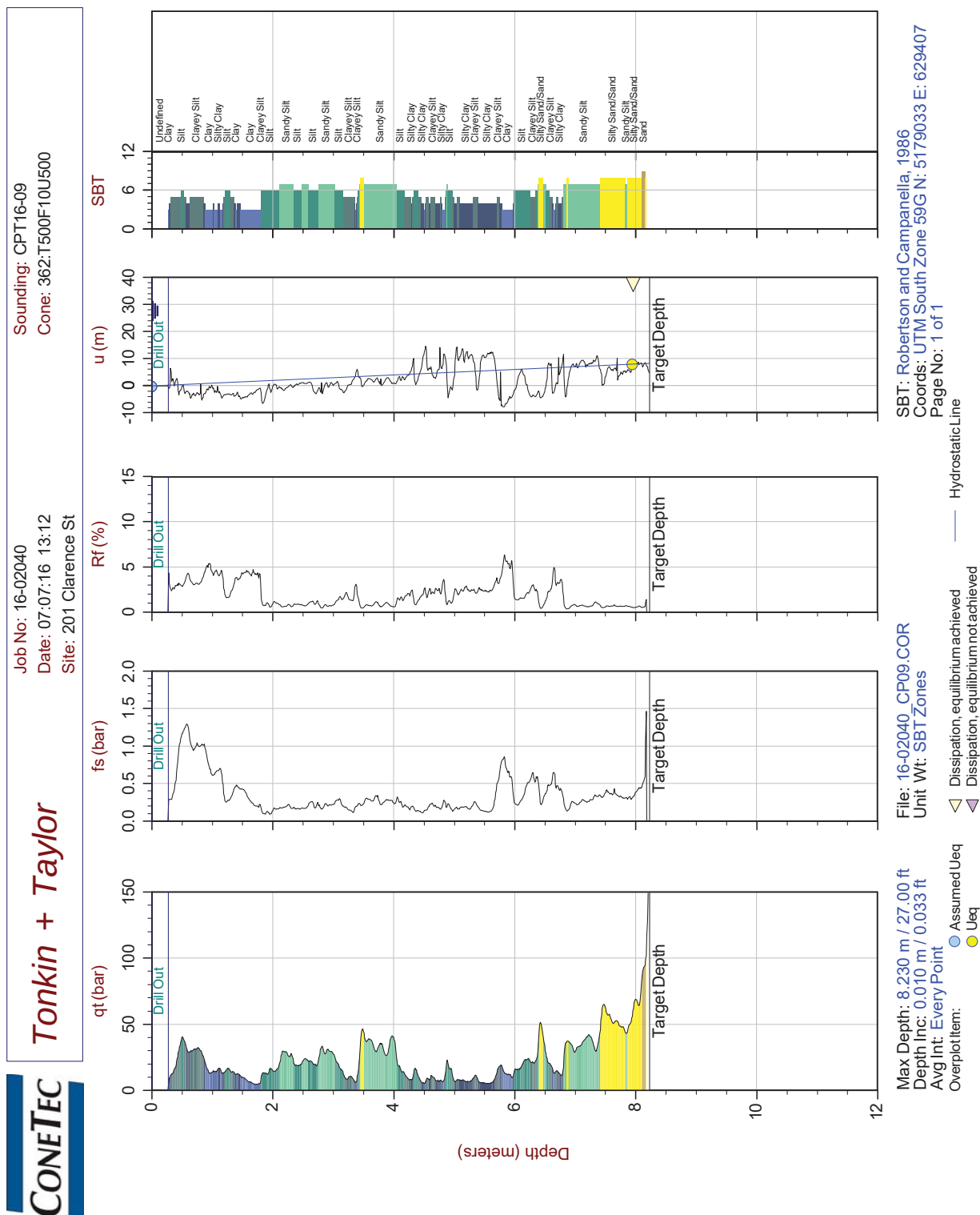
Sounding: CPT16-08
Cone: 362:T500F10U500



SBT: Robertson and Campanella, 1986
 Coords: UTM South Zone 59G N: 5179033 E: 629406
 Page No: 1 of 1

File: 16-02040_CP08.COR
Unit Wt: SBT_Zones

Max Depth: 8.100 m / 26.57 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
Overplot Item: ● Assumed U ● Ueq

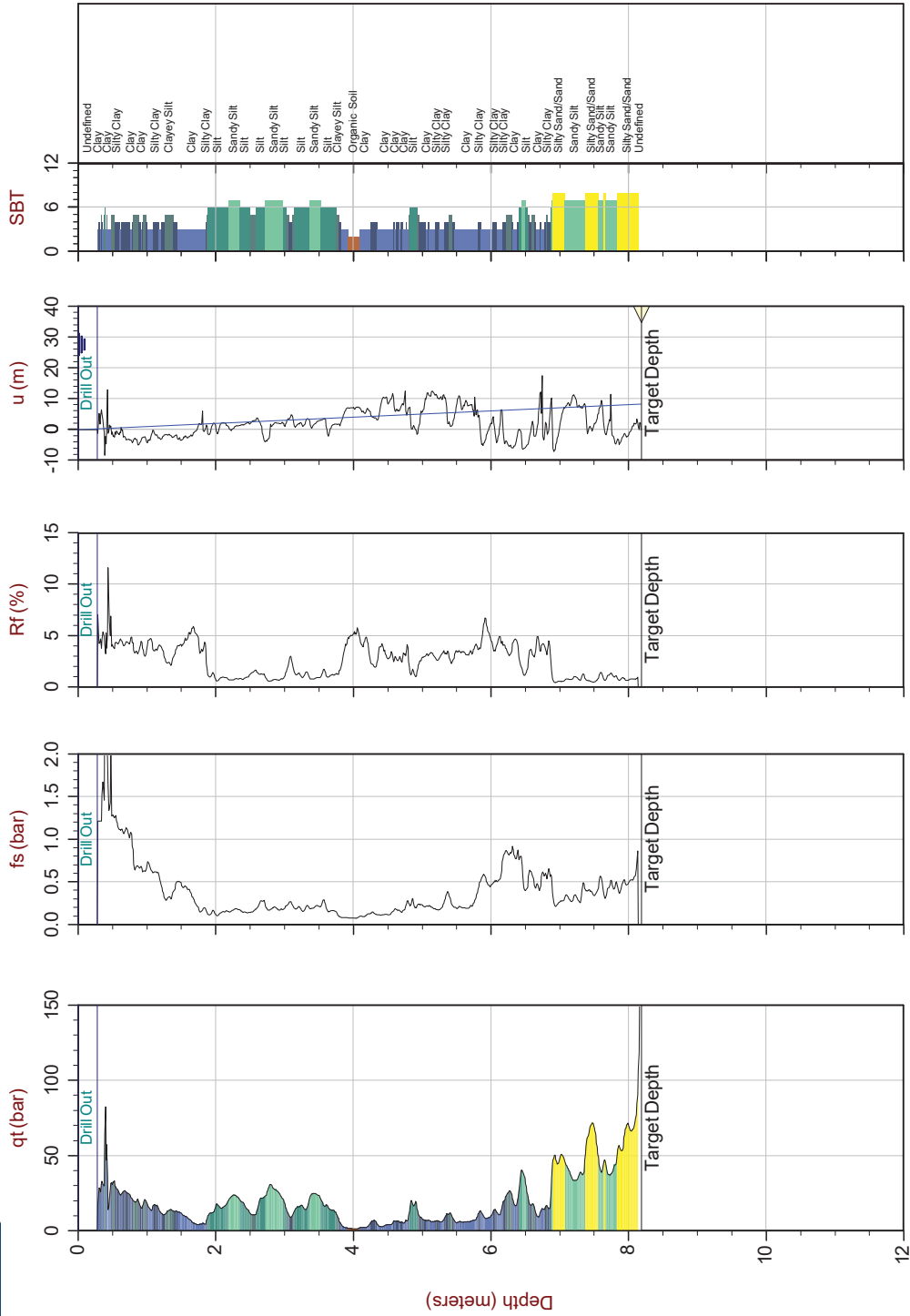




Tonkin + Taylor

Job No: 16-02040
Date: 07:07:16 15:19
Site: 201 Clarence St

Sounding: CPT16-10
Cone: 362:T500F10U500



Max Depth: 8.190 m / 26.87 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
Overplot Item: ● Assumed Ueq ● Ueq

File: 16-02040 CP10.COR
Unit Wt: SBT Zones

▼ Dissipation, equilibrium achieved
▼ Dissipation, equilibrium not achieved

— Hydrostatic Line

SBT: Robertson and Campanella, 1986
Coords: UTM South Zone 59G N: 5179033 E: 629408
Page No: 1 of 1

Advanced Cone Penetration Test Plots with $Q_{tn,cs}$, I_c , $N1(60)$, and SBT
 Q_{tn}

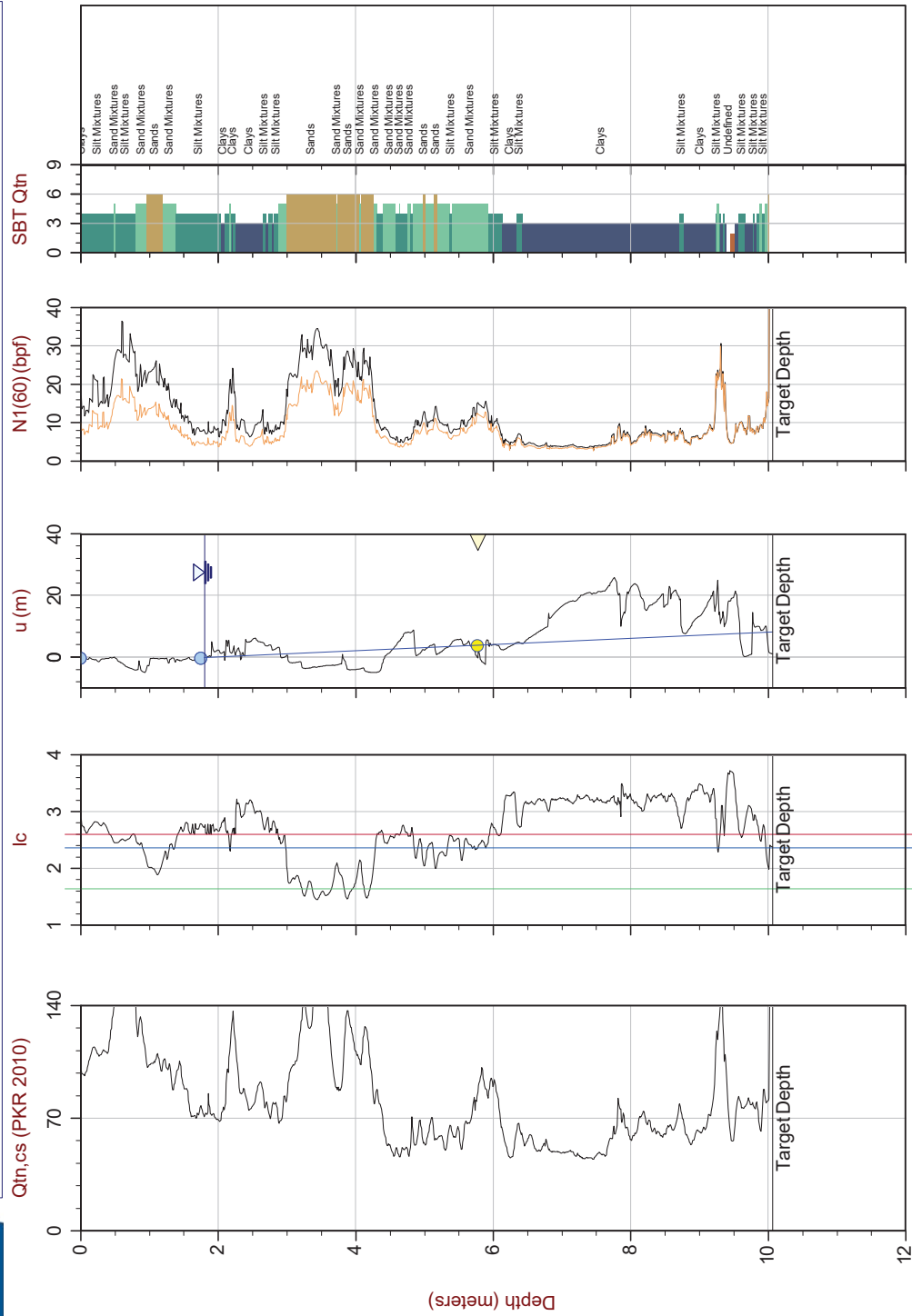
SBT: Robertson, 2009 and 2010
 Coords: UTM South Zone 59G N: 5174334 E: 629850
 Page No: 1 of 1



Tonkin + Taylor

Job No: 16-02040
Date: 05:31:16 19:31
Site: 200 Cashmere Rd

Sounding: CPT16-02
Cone: 362:T500F10U500



Max Depth: 10.070 m / 33.04 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
N(60) (bpf)

File: 16-02040_CP02.COR
Unit Wt: SBT Zones

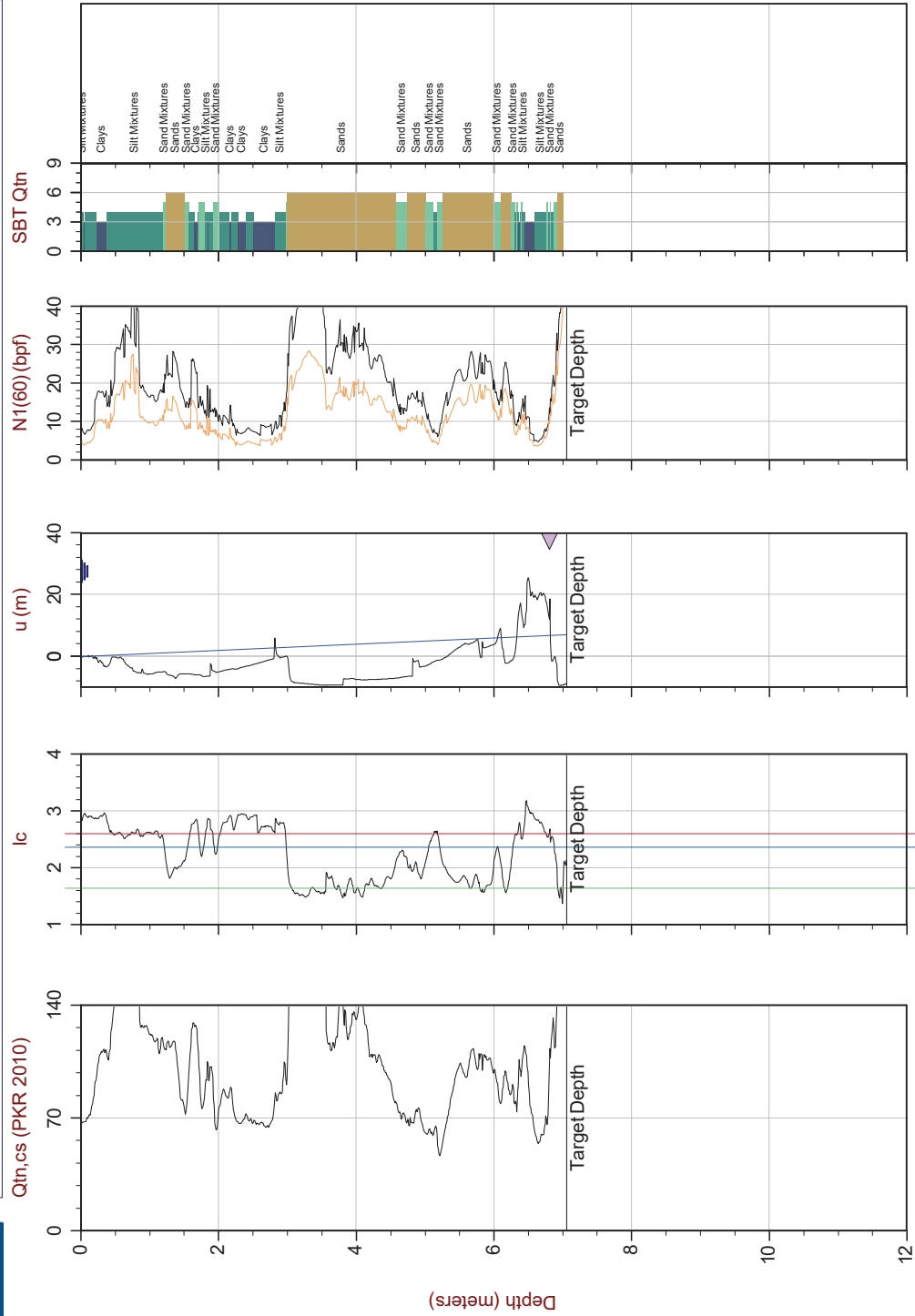
SBT: Robertson, 2009 and 2010
Coords: UTM South Zone 59G N: 5174334 E: 629851
Page No: 1 of 1



Tonkin + Taylor

Job No: 16-02040
Date: 06/01/16 16:36
Site: Barrington Park

Sounding: CPT16-04
Cone: 284:T500F10U500



Max Depth: 7.060 m / 23.16 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
N(60) (bpf)

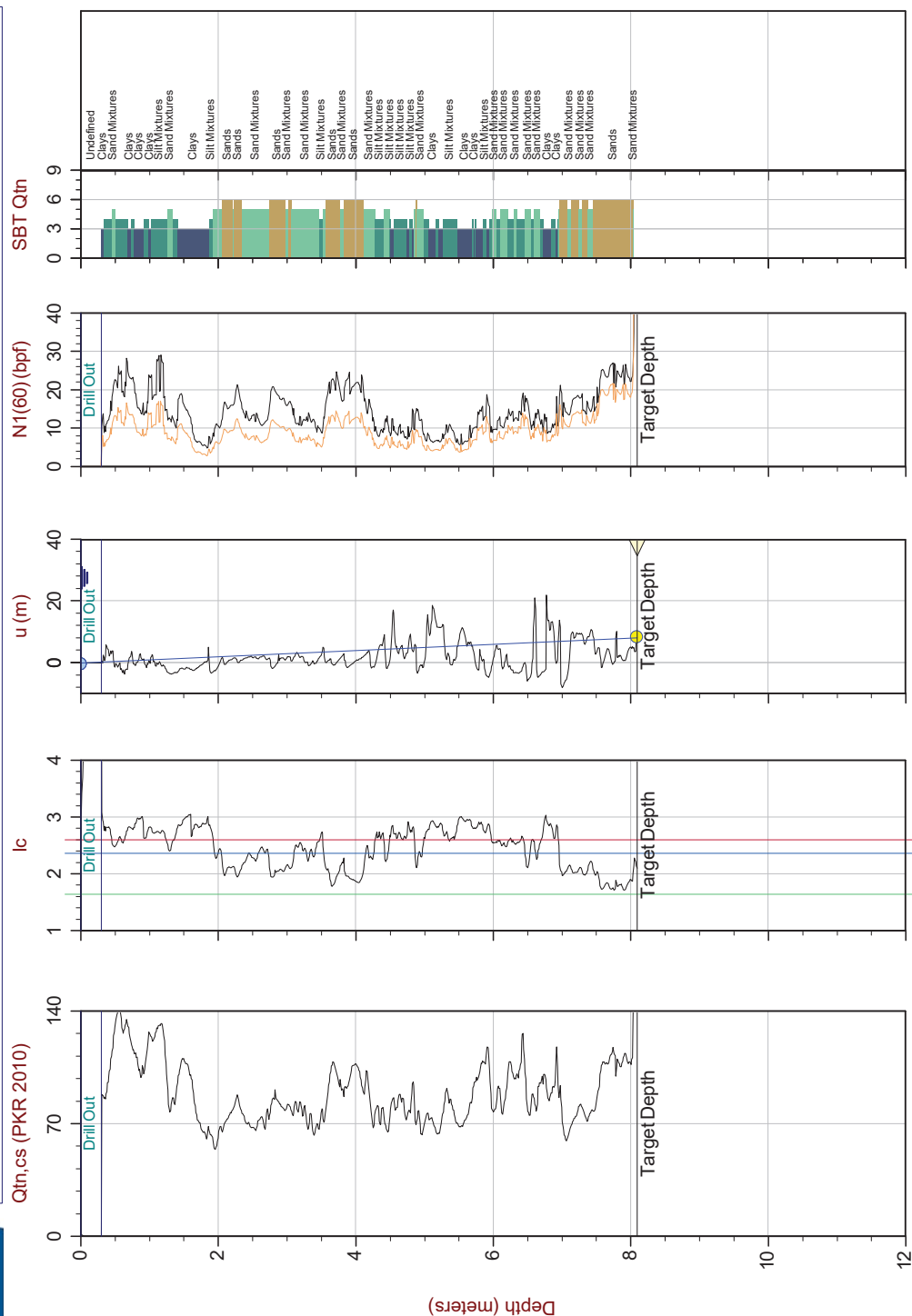
File: 16-02040_CP04.COR
Unit Wt: SBT Zones

SBT: Robertson, 2009 and 2010
Coords: UTM South Zone 59G N: 5176392 E: 630652
Page No: 1 of 1

Tonkin + Taylor

Job No: 16-02040
Date: 07:07:16 12:11
Site: 201 Clarence St

Sounding: CPT16-08
Cone: 362:T500F10U500



Max Depth: 8.100 m / 26.57 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
N(60) (bpf)

File: 16-02040_CP08.COR
Unit Wt: SBT Zones

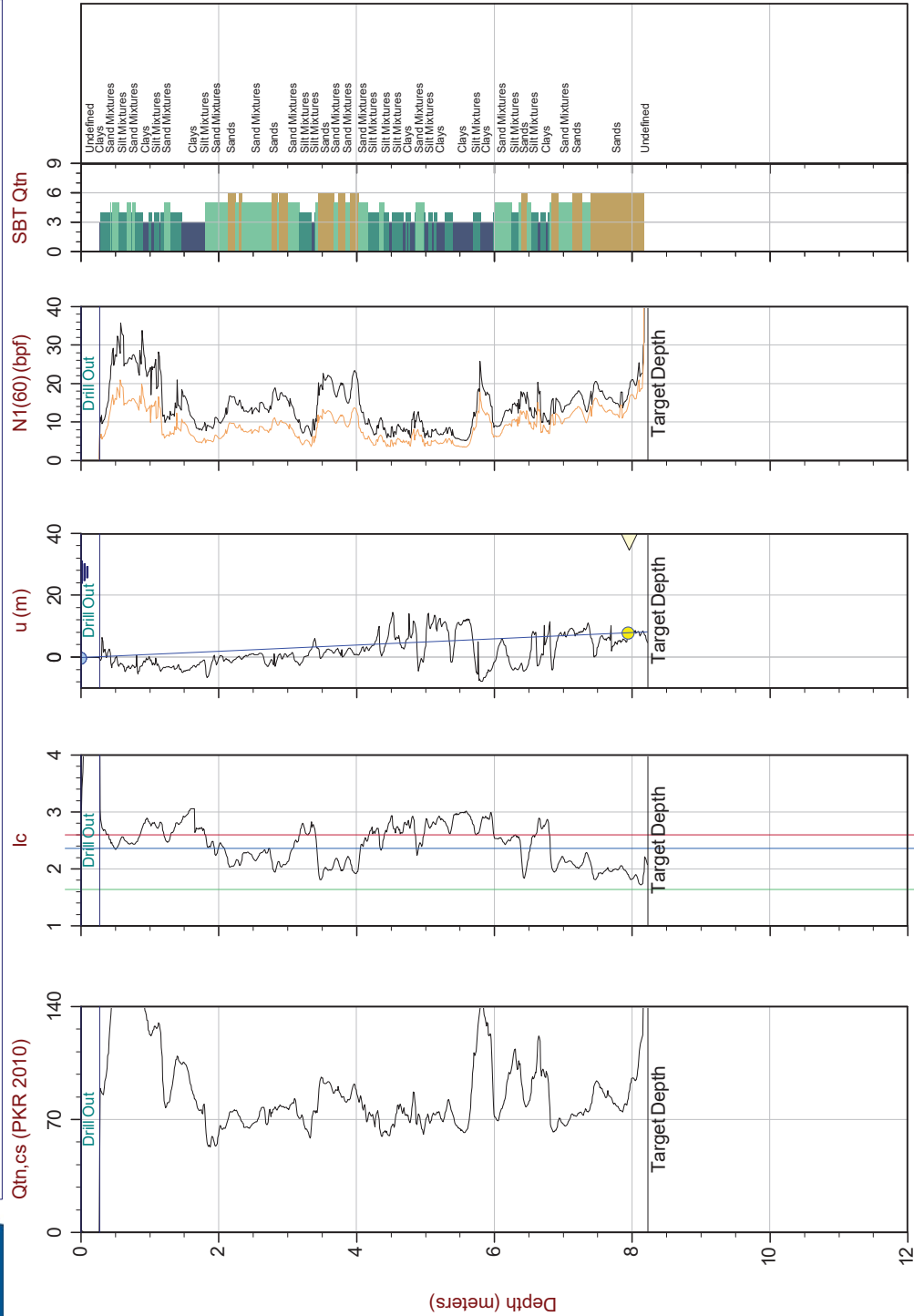
SBT: Robertson, 2009 and 2010
 Coords: UTM South Zone 59G N: 5179033 E: 629406
 Page No: 1 of 1



Tonkin + Taylor

Job No: 16-02040
Date: 07:07:16 13:12
Site: 201 Clarence St

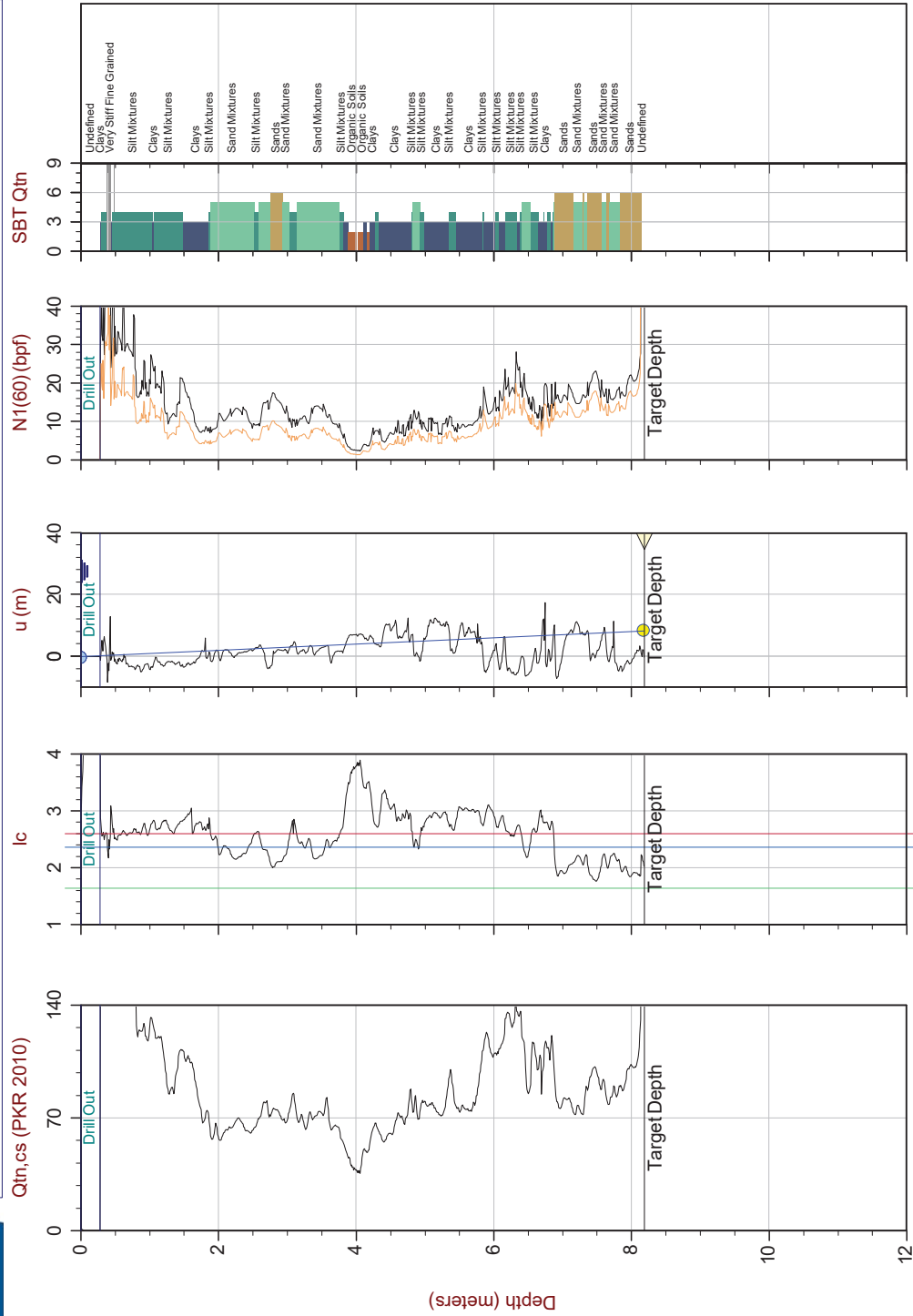
Sounding: CPT16-09
Cone: 362:T500F10U500



Max Depth: 8.230 m / 27.00 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
N(60) (bpf)

File: 16-02040_CP09.COR
Unit Wt: SBT Zones

SBT: Robertson, 2009 and 2010
Coords: UTM South Zone 59G N: 5179033 E: 629407
Page No: 1 of 1



Max Depth: 8.190 m / 26.87 ft
Depth Inc: 0.010 m / 0.033 ft
Avg Int: Every Point
N(60) (bpf)

File: 16-02040_CP10.COR
Unit Wt: SBT Zones

SBT: Robertson, 2009 and 2010
Coords: UTM South Zone 59G N: 5179033 E: 629408
Page No: 1 of 1

Pore Pressure Dissipation Summary and
Pore Pressure Dissipation Plots



Job No: 16-02040
 Client: Tonkin + Taylor
 Project: Mini CPT Research
 Start Date: 31-May-2016
 End Date: 07-Jul-2016

<i>CPT_u PORE PRESSURE DISSIPATION SUMMARY</i>						
Sounding ID	File Name	Cone Area (cm ²)	Duration (s)	Test Depth (m)	Estimated Equilibrium Pore Pressure U _{eq} (m)	Calculated Phreatic Surface (m)
CPT16-01	16-02040_CP01a	5	515	5.83	Not Achieved	
CPT16-02	16-02040_CP02	5	970	5.78	4.0	1.8
CPT16-04	16-02040_CP04	5	70	6.81	Not Achieved	
CPT16-08	16-02040_CP08	5	305	8.10	8.7	-0.6
CPT16-09	16-02040_CP09	5	260	8.23	8.1	-0.2
CPT16-10	16-02040_CP10	5	300	8.19	8.7	-0.5



Tonkin + Taylor

Job No: 16-02040

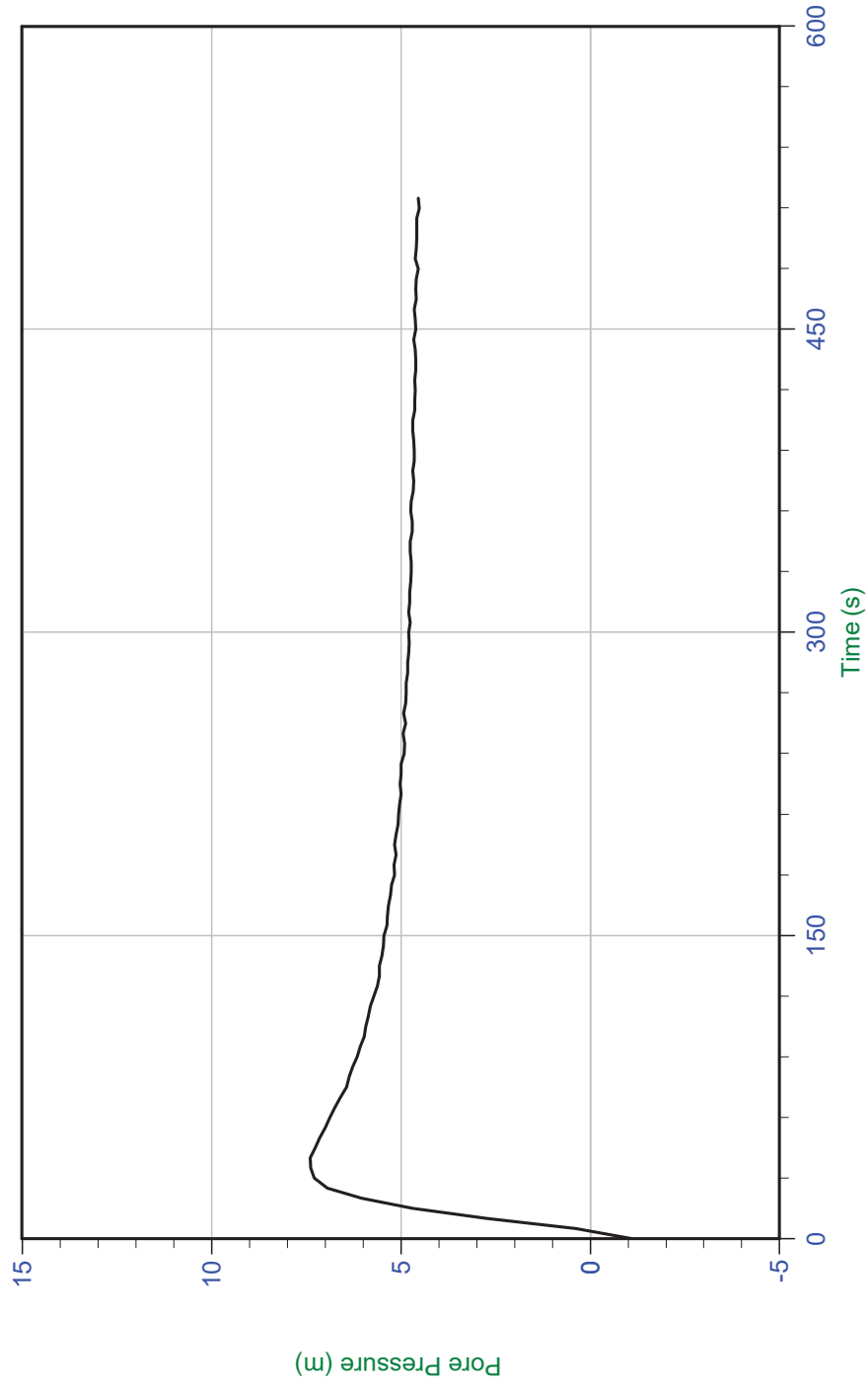
Date: 05/31/2016 17:47

Site: 200 Cashmere Rd

Sounding: CPT16-01

Cone: 362.T500F10U500

Cone Area: 5 sq cm



Filename: 16-02040_CP01a.PPF

U Min: -1.1 m

U Max: 7.4 m

Trace Summary: Depth: 5.830 m / 19.127 ft

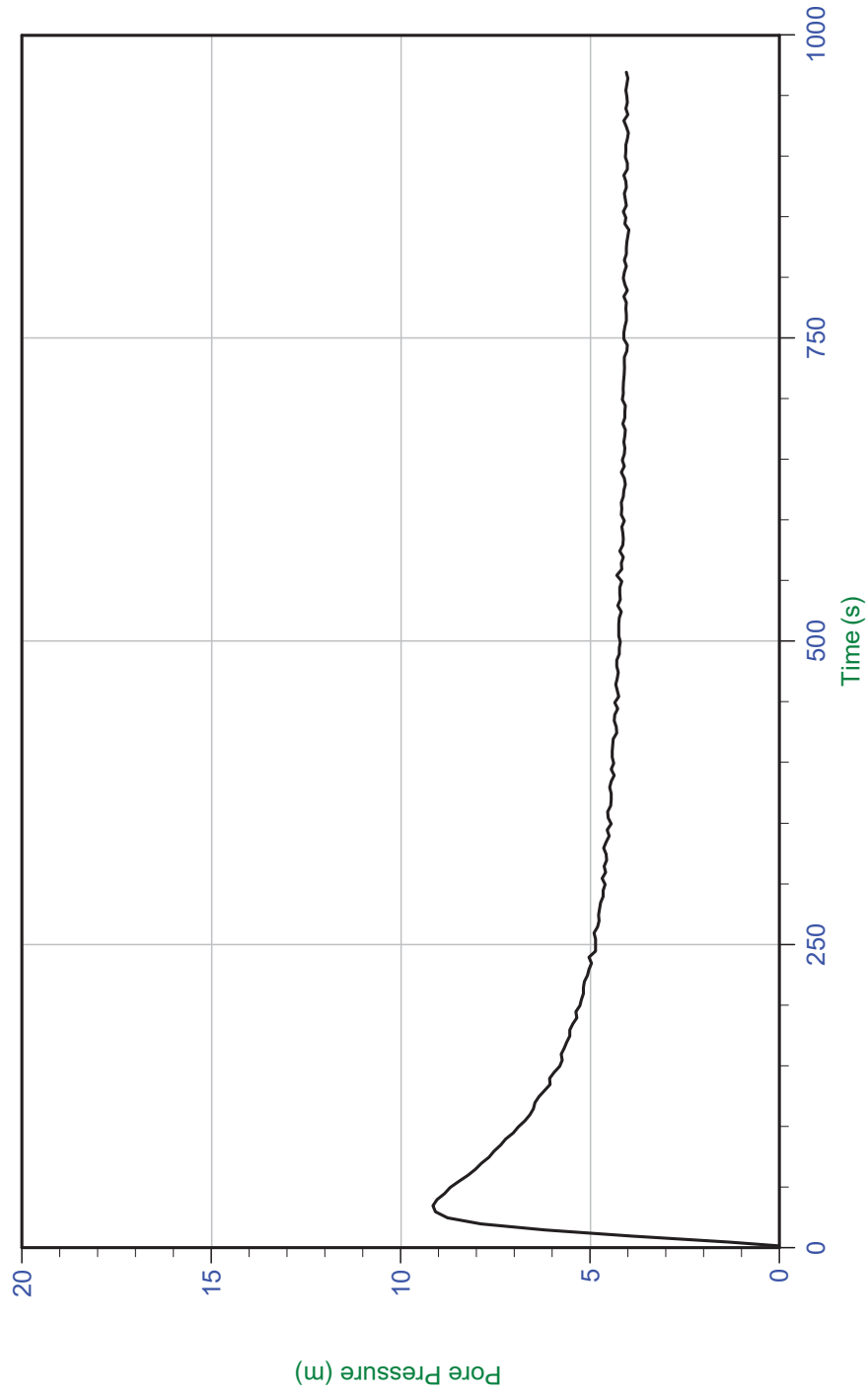
Duration: 515.0 s



Tonkin + Taylor

Job No: 16-02040
Date: 05/31/2016 19:31
Site: 200 Cashmere Rd

Sounding: CPT16-02
Cone: 362.T500F10U500
Cone Area: 5 sq cm



Trace Summary: Filename: 16-02040_CP02.PPF
Depth: 5.780 m / 18.963 ft
Duration: 970.0 s
WT: 1.755 m / 5.758 ft
U Min: -0.6 m
U Max: 9.2 m
Ueq: 4.0 m



Tonkin + Taylor

Job No: 16-02040

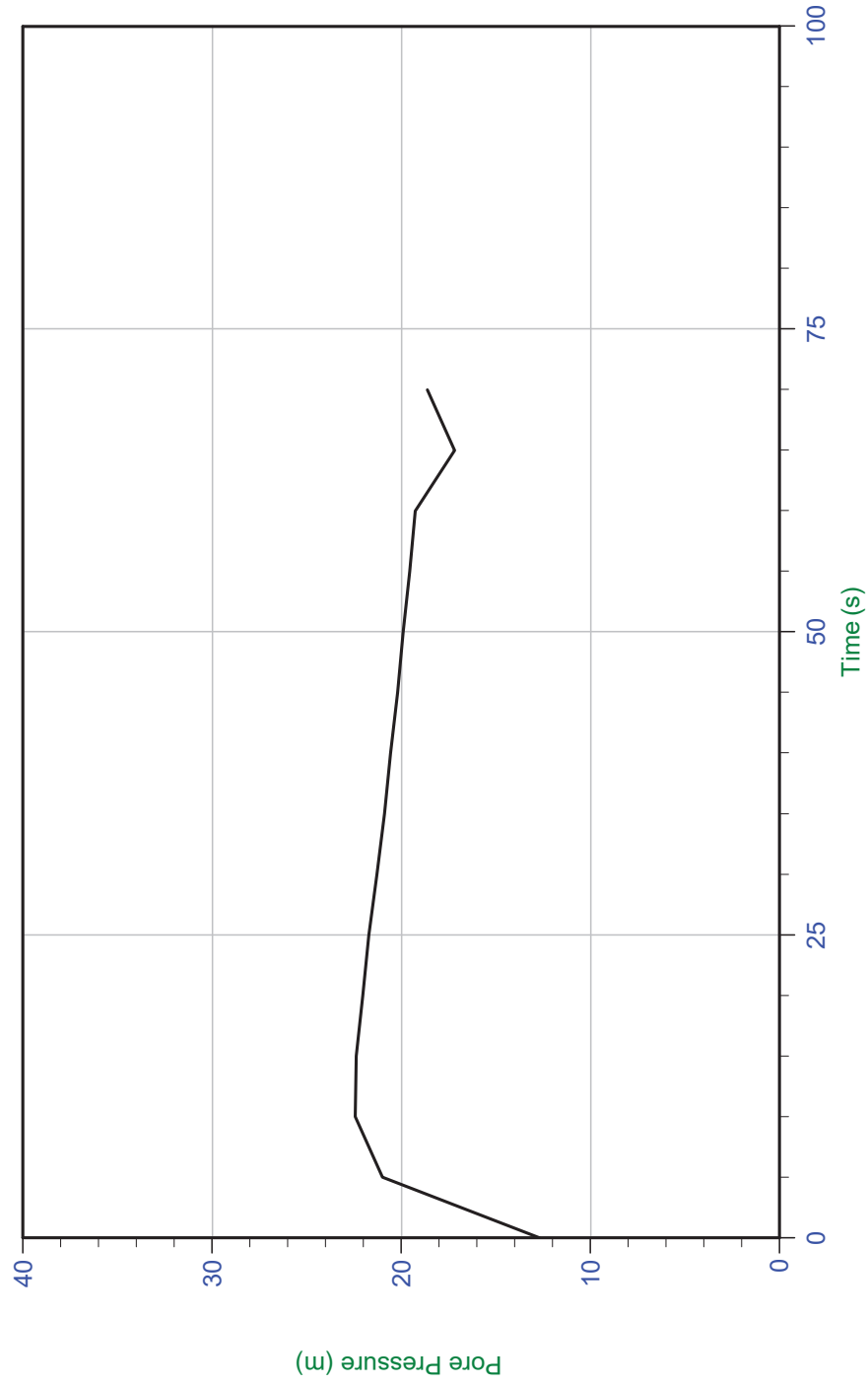
Date: 06/01/2016 16:36

Site: Barrington Park

Sounding: CPT16-04

Cone: 284:T500F10U500

Cone Area: 5 sq cm



Filename: 16-02040_CP04.PPF

Depth: 6.810 m / 22.342 ft

Duration: 70.0 s

U Min: 12.7 m

U Max: 22.4 m

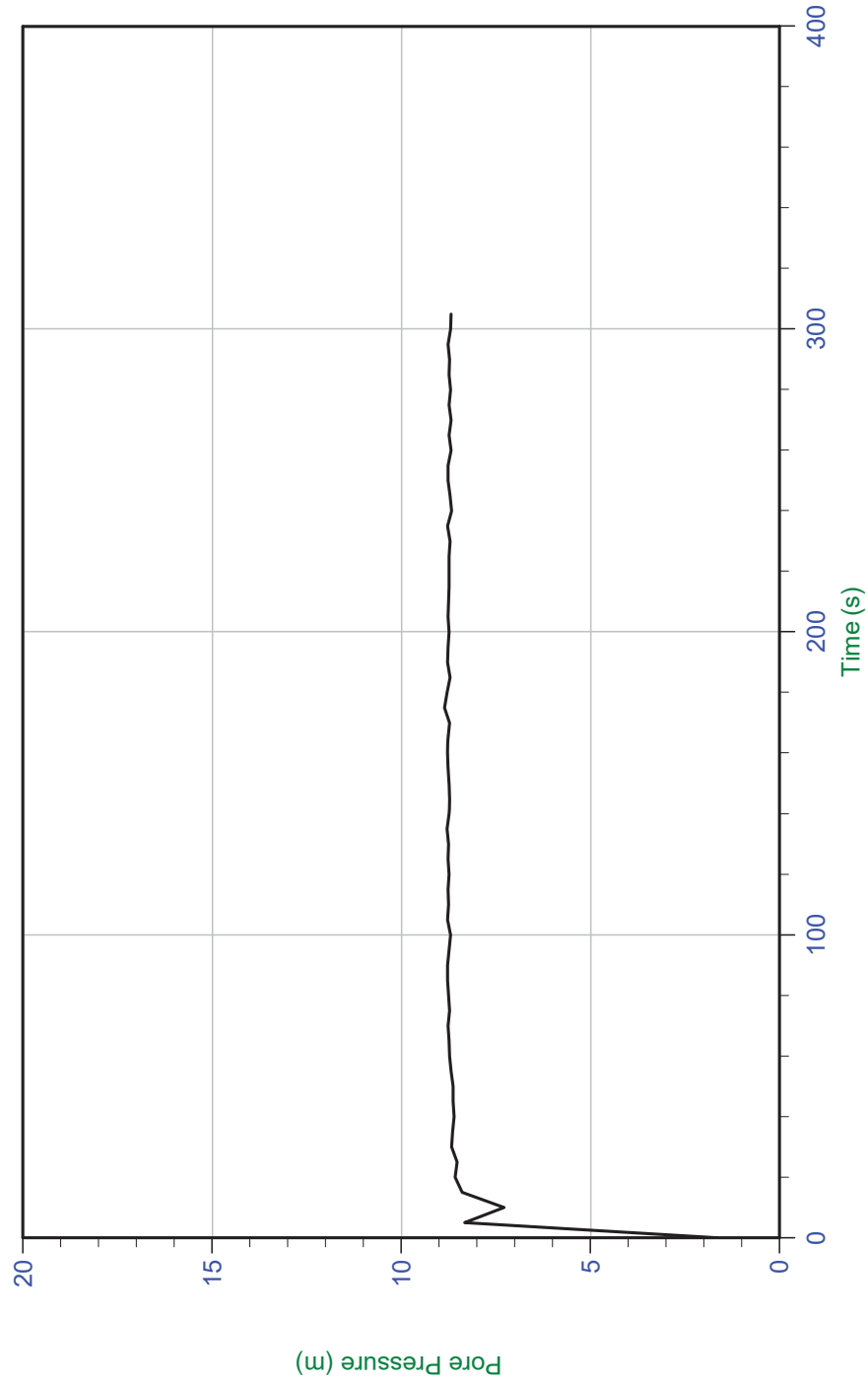
Trace Summary:



Tonkin + Taylor

Job No: 16-02040
Date: 07/07/2016 12:11
Site: 201 Clarence St

Sounding: CPT16-08
Cone: 362.T500F10U500
Cone Area: 5 sq cm



Trace Summary: Filename: 16-02040_CP08.PPF
Depth: 8.100 m / 26.574 ft
Duration: 305.0 s
U Min: 1.7 m
U Max: 8.9 m
WT: -0.627 m / -2.057 ft
Ueq: 8.7 m



Tonkin + Taylor

Job No: 16-02040

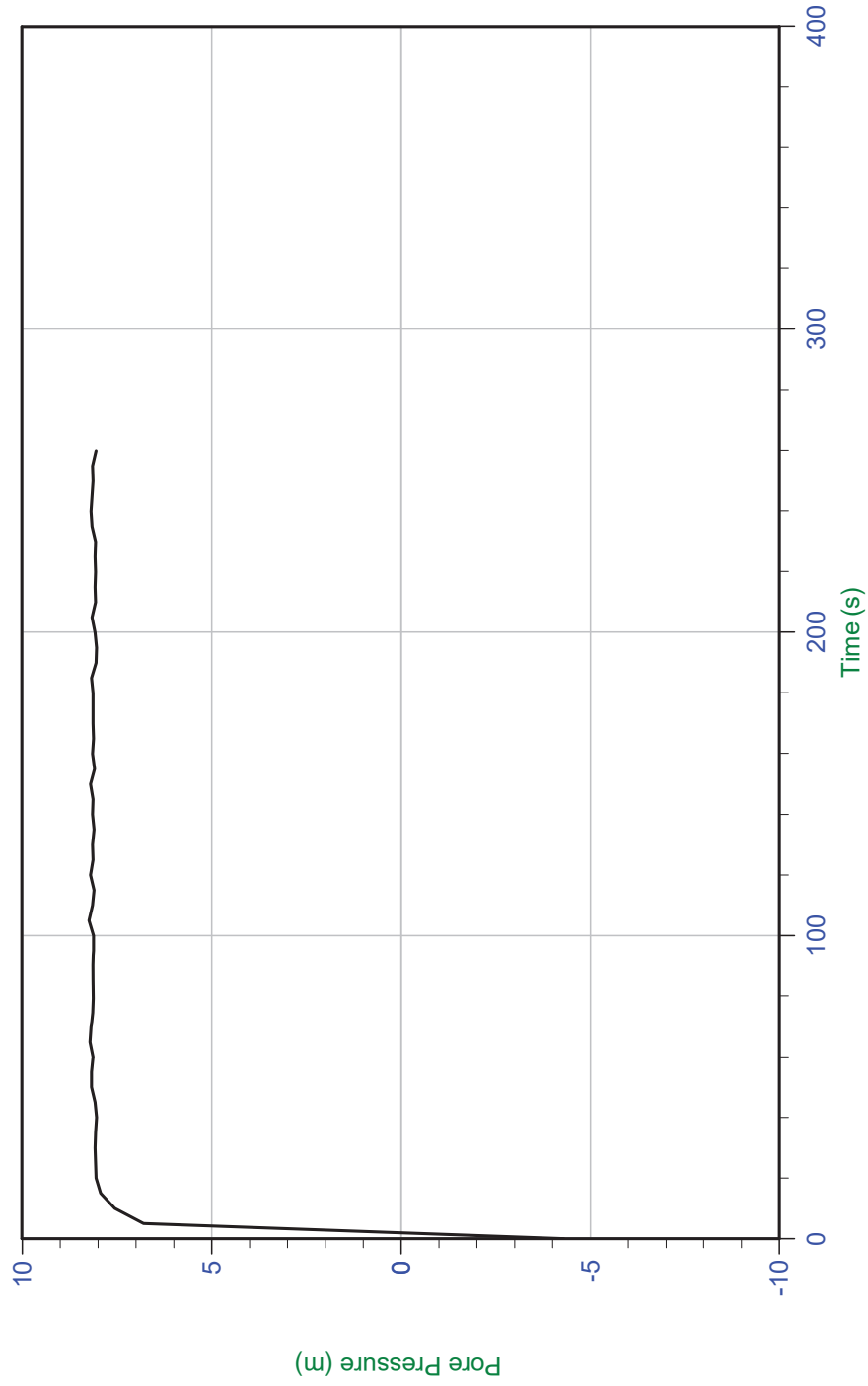
Date: 07/07/2016 13:12

Site: 201 Clarence St

Sounding: CPT16-09

Cone: 362:T500F10U500

Cone Area: 5 sq cm



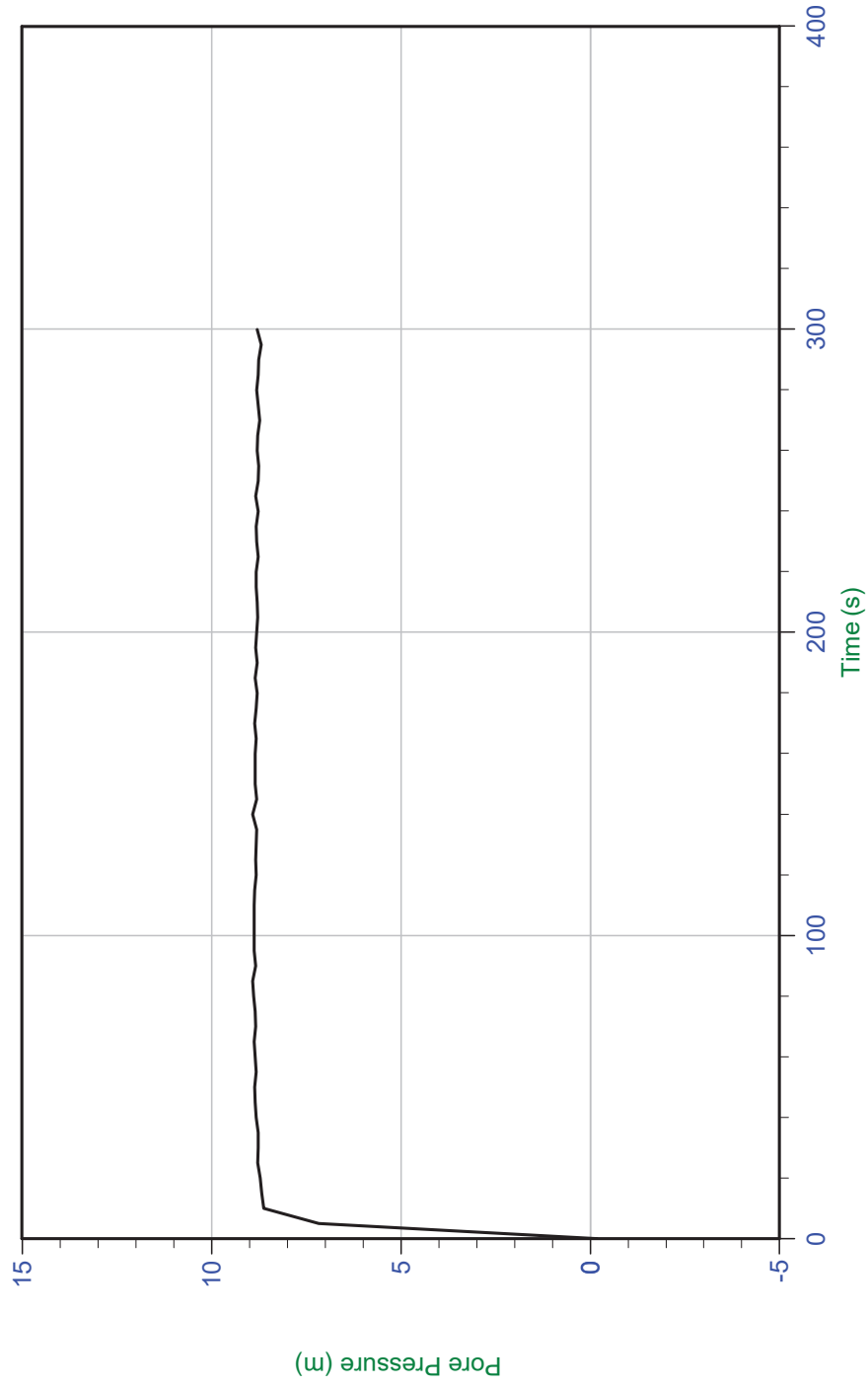
Trace Summary: Filename: 16-02040_CP09.PPF
Depth: 7.960 m / 26.115 ft
Duration: 260.0 s
WT: -0.181 m / -0.594 ft
Ueq: 8.1 m
U Min: -4.3 m
U Max: 8.2 m



Tonkin + Taylor

Job No: 16-02040
Date: 07/07/2016 15:19
Site: 201 Clarence St

Sounding: CPT16-10
Cone: 362.T500F10U500
Cone Area: 5 sq cm



Trace Summary: Filename: 16-02040_CP10.PPF
Depth: 8.190 m / 26.870 ft
Duration: 300.0 s
WT: -0.507 m / -1.663 ft
Ueq: 8.7 m
U Min: -0.2 m
U Max: 8.9 m

Appendix B

Supporting Data and Information for Detailed Logging of High-Quality Samples

- B.1 Dames & Moore Sample Photographs
- B.2 Detailed Logs
- B.3 Laboratory Testing

Appendix B.1

Dames & Moore Sample Photographs

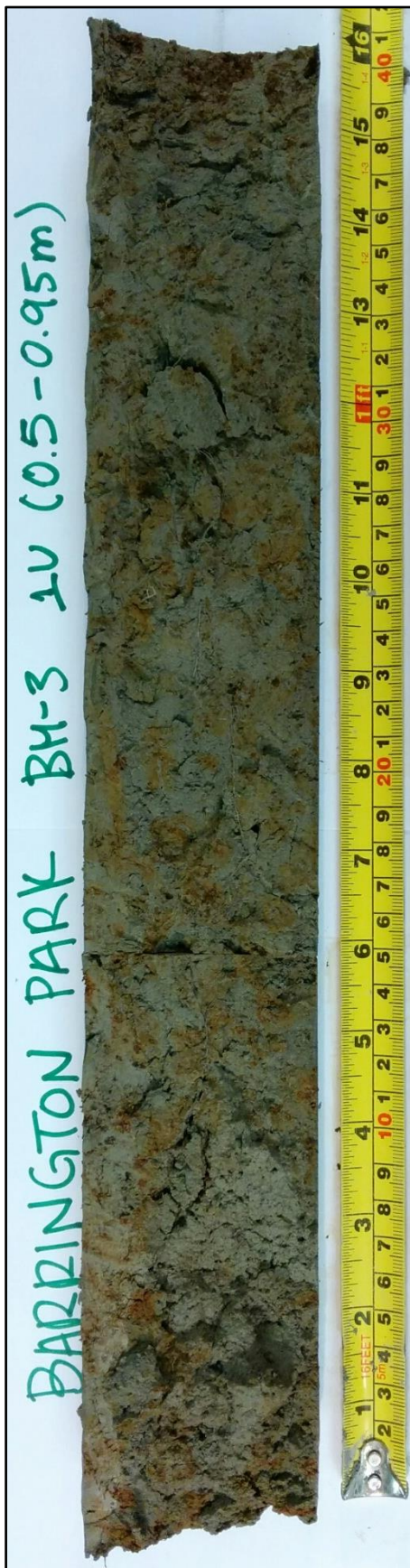


Figure B.1-1: S14-BH3-1U (0.5-0.90 m BGS)



Figure B.1-2: S14-BH3-2U (0.95-1.40 m BGS)



Figure B.1-3: S14-BH3-3U (1.40-1.85 m BGS)

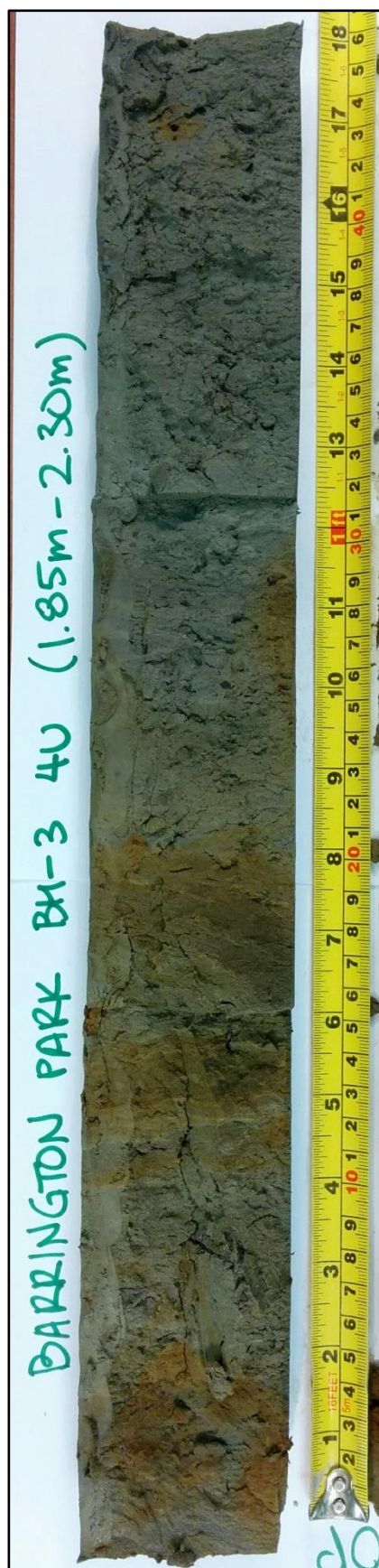


Figure B.1-4: S14-BH3-4U (1.85-2.30 m BGS)



Figure B.1-5: S14-BH3-5U (2.30-2.75 m BGS)



Figure B.1-6: S14-BH3-6U (2.75-3.20 m BGS)



Figure B.1-7: S14-BH3-7U (3.20-3.65 m BGS)



Figure B.1-8: S14-BH3-8U (3.65-4.10 m BGS)



Figure B.1-9: S14-BH3-9U (4.10-4.55 m BGS)



Figure B.1-10: S14-BH3-10U (4.55-5.00 m BGS)



Figure B.1-11: S14-BH3-11U (5.00-5.45 m BGS)



Figure B.1-12: S14-BH3-12U (5.45-5.90 m BGS)



Figure B.1-13: S14-BH3-13U (5.90-6.35 m BGS)



Figure B.1-14: S14-BH3-14U (6.35-6.80 m BGS)



Figure B.1-15: S33-DM2-1U (0.5-0.89 m BGS)



Figure B.1-16: S33-DM2-2U (0.95-1.40 m BGS)



Figure B.1-17: S33-DM2-3U (1.40-1.85 m BGS)



Figure B.1-18: S33-DM2-4U (1.85-2.30 m BGS) – void at ~ 37 cm is from large piece of wood in other half of sample



Figure B.1-19: S33-DM2-5U (2.30-2.75 m BGS)



Figure B.1-20: S33-DM2-6U (2.75-3.20 m BGS)



Figure B.1-21: S33-DM2-7U (3.20-3.65 m BGS)



Figure B.1-22: S33-DM2-8U (3.65-4.10 m BGS)



Figure B.1-23: S33-DM2-9U (4.10-4.55 m BGS)



Figure B.1-24: S33-DM2-10U (4.55-5.00 m BGS)



Figure B.1-25: S33-DM2-11U (5.00-5.45 m BGS)



Figure B.1-26: S33-DM2-12U (5.45-5.90 m BGS)



Figure B.1-27: S33-DM2-13U (5.90-6.35 m BGS)



Figure B.1-28: S33-DM2-14U (6.35-6.80 m BGS)



Figure B.1-29: S37-DM1-1U (0.5-0.89 m BGS)



Figure B.1-30: S37-DM1-2U (0.95-1.38 m BGS)

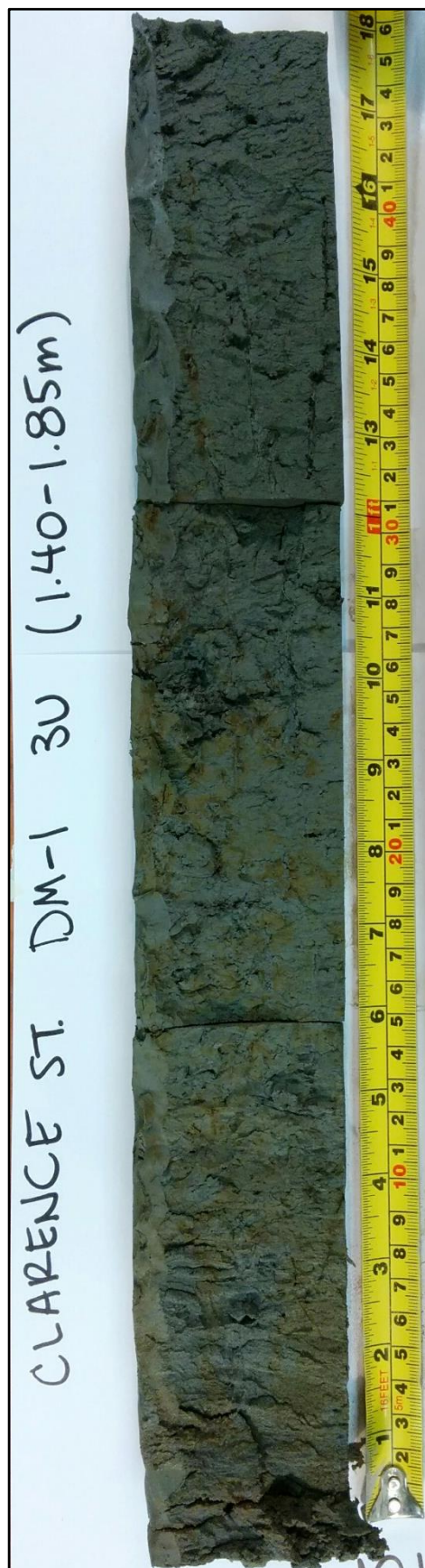


Figure B.1-31: S37-DM1-3U (1.40-1.84 m BGS)

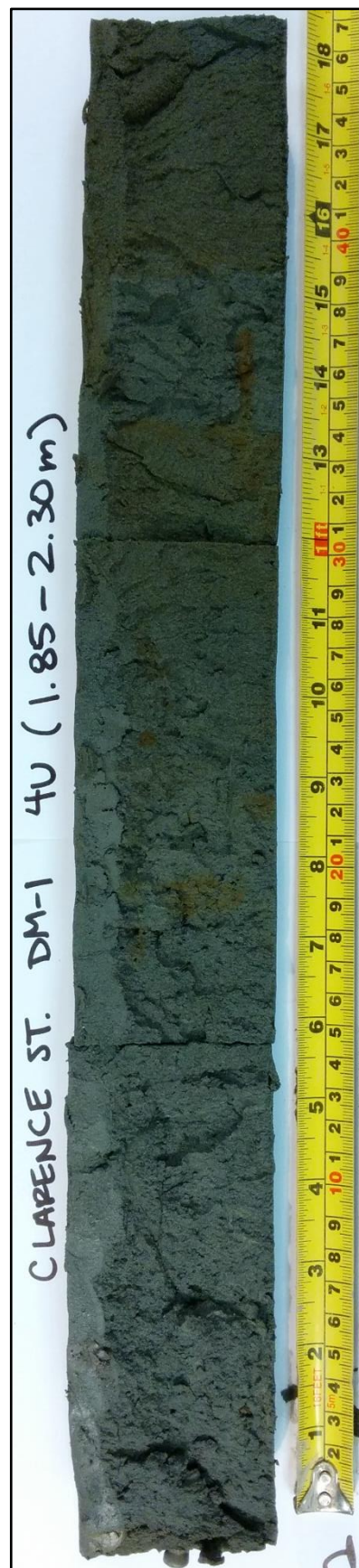


Figure B.1-32: S37-DM1-4U (1.85-2.30 m BGS)



Figure B.1-33: S37-DM1-5U (2.30-2.75 m BGS)



Figure B.1-34: S37-DM1-6U (2.75-3.20 m BGS)



Figure B.1-35: S37-DM1-7U (3.20-3.65 m BGS)



Figure B.1-36: S37-DM1-8U (3.65-4.10 m BGS)



Figure B.1-37: S37-DM1-9U (4.10-4.55 m BGS)



Figure B.1-38: S37-DM1-10U (4.55-5.00 m BGS)



Figure B.1-39: S37-DM1-11U (5.00-5.45 m BGS)



Figure B.1-40: S37-DM1-12U (5.45-5.90 m BGS)



Figure B.1-41: S37-DM1-13U (5.90-6.35 m BGS)



Figure B.1-42: S37-DM1-14U (6.35-6.80 m BGS)

Appendix B.2

Detailed Logs

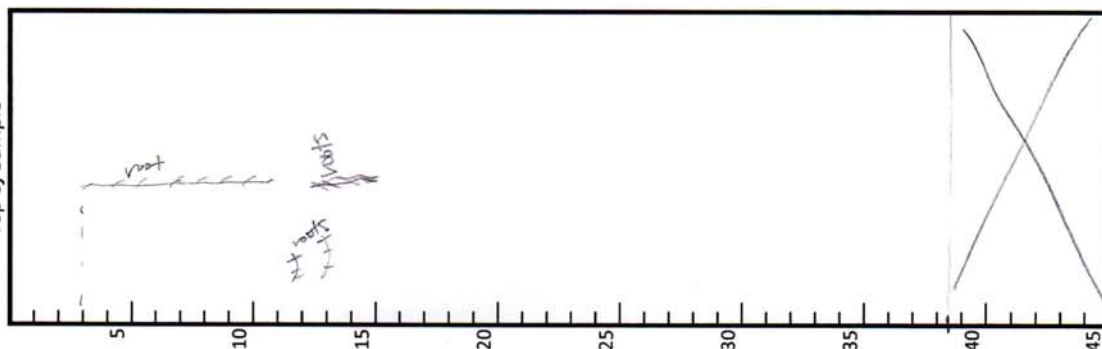
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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 1UStart Depth 0.5mEnd Depth 0.88mSampling Date June 3, 2016Extrusion Date June 6, 2016Weight 3156.5g (soil + tube)Top Empty 12.2cmBottom Empty 0cm

- * v. Difficult to extrude; hard/dry
- * Top feels sandy/coarse cutting in to split it
- * Mid feels sandy @ top, gets clayier at the bottom of mid
- * feels coarse/crumbly to cut through

Top of Sample

Description:

relatively uniform, w/ sandier pockets
clayey sandy silt - JDB

iron stained throughout
gy silty f. sand/sandy silt

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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 2VStart Depth 0.95mEnd Depth 1.40mSampling Date June 3, 2016Extrusion Date June 6, 2016
(silt + tube)Weight 3237.5gTop Empty 5.4cmBottom Empty 0.6cm*Scraped out a little @ bottom to
have flush bottom surface*v. difficult to extrude, tried using
pneum. extender to get it going,
compressed BOT, moved top up a little.

Top Empty = 4.5cm

Bot empty = 6.3 - 6.7cm

*Punched through plastic cap used as foot.

June 7th, 2016

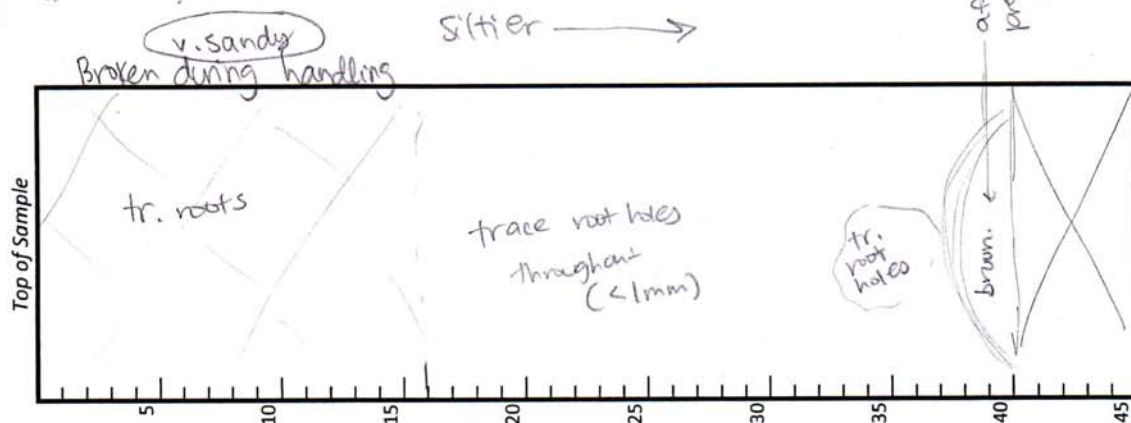
Description:

*Scraping out affected portion of
tube from yesterday

Bot Empty = 6.8cm

Top Empty = 4.5 - 4.6cm

Weight = 3059.5g

*Had to cut tube
into 3 portions
to be able to extrudeTop / Bot, then cut
Bot into 2 halves

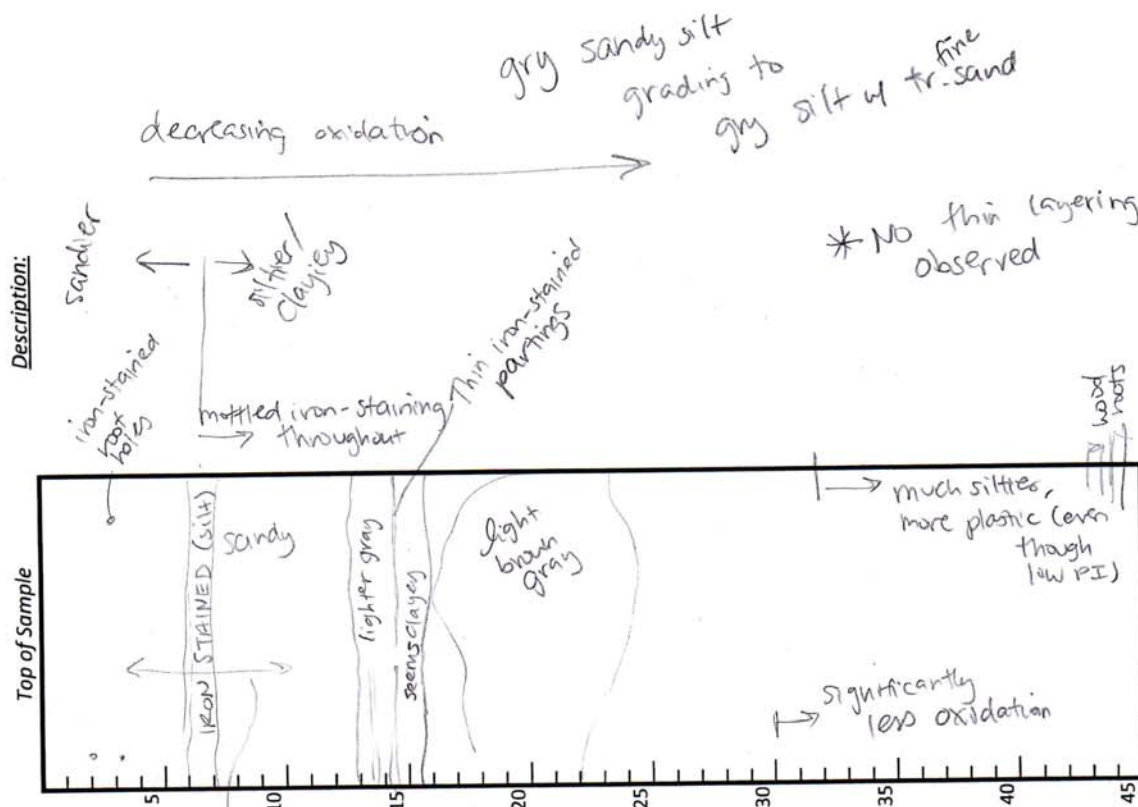
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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 3UStart Depth 1.40mEnd Depth 1.85mSampling Date June 3, 2016Extrusion Date June 8, 2016
soil + tube
+ scraped out portionWeight 3329.0gTop Empty 5.6cmBottom Empty 0cm - 0.5cm

* A little soil removed to have smooth bottom surface

* Some free water coming out-top holes during extrusion (@ 7-8cm from top of sample) on one side of sample



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Mini-Cone and DM Project - Lab Extrusion

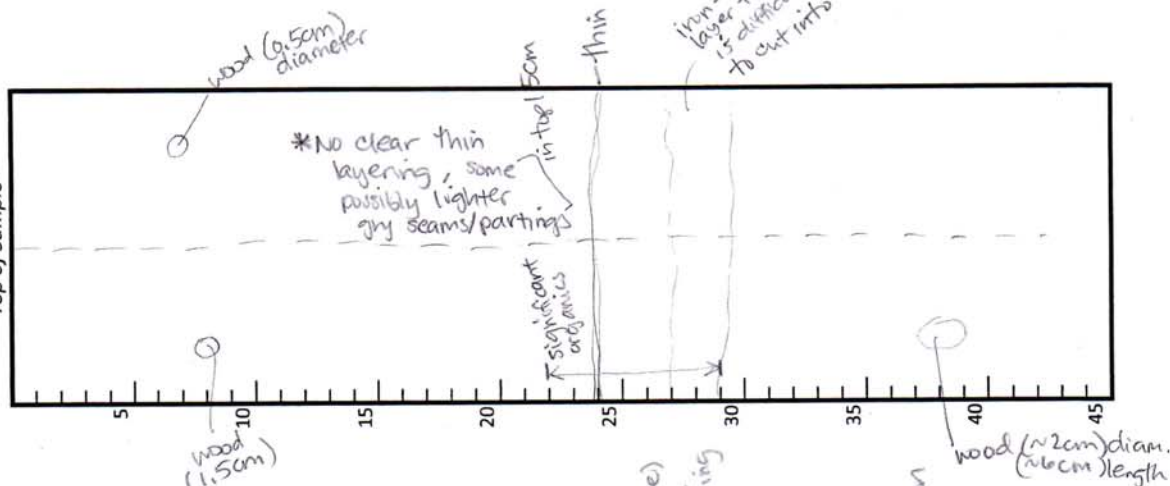
Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 4UStart Depth 1.85mEnd Depth 2.30mSampling Date JUNE 3, 2016Extrusion Date JUNE 13, 2016Weight 3238.5g (soil + tube) before scrapingTop Empty 6.1 - 6.2cmBottom Empty 0 - 0.5cm (uneven)

* Bot. surface: scraped out some soil to even the surface for extrusion
 ↳ moist, clayey, easily rolled

* V. Easy to extrude

* Wood + organics visible in exterior of sample (~mm - 2cm x 1.5cm)

Top of Sample

Description:

* Entire length feels clayey to cut into
 ↳ some pockets w/ organics feel like cutting into wood or through roots

* wood, organics, roots throughout interior

* iron-staining / mottling down to ~33cm

* Clayey silt, tr. f. sand (v. easily rolled) + balled (mod. plasticity)

* 0-15cm: some iron-staining
 15-29cm: more iron-staining
 29-33cm: trace iron-staining
 33-44cm: no iron-staining

* Shallower wood = brown-red, fresh
 Deeper wood = black, stains boards like charcoal, cannot break w/ hands

* Grey w/ iron-stained mottles

Munsell: 7.5 YR
 5/0, 5/6

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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE ST. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 5UStart Depth 2.30mEnd Depth 2.75mSampling Date June 3, 2016Extrusion Date June 13, 2016Weight 3432.0g (soil + tube)Top Empty 3.1-3.4cmBottom Empty 2.0-2.3cm

* Bot. surface: relatively even

* Extruded v. easily

* No wood/organics visible on exterior, some at top surface of 3rd portion

* Feels clayey to cut into, some minor pockets feel a little sandier, or like cutting through roots

Description:

* Relatively homogeneous:

Clayey silt, tr. sand (mod. plasticity)

L roots, root pores, thin wood/twigs throughout (top to bot.)

* No visible iron-staining (some red-brown wood at bottom)

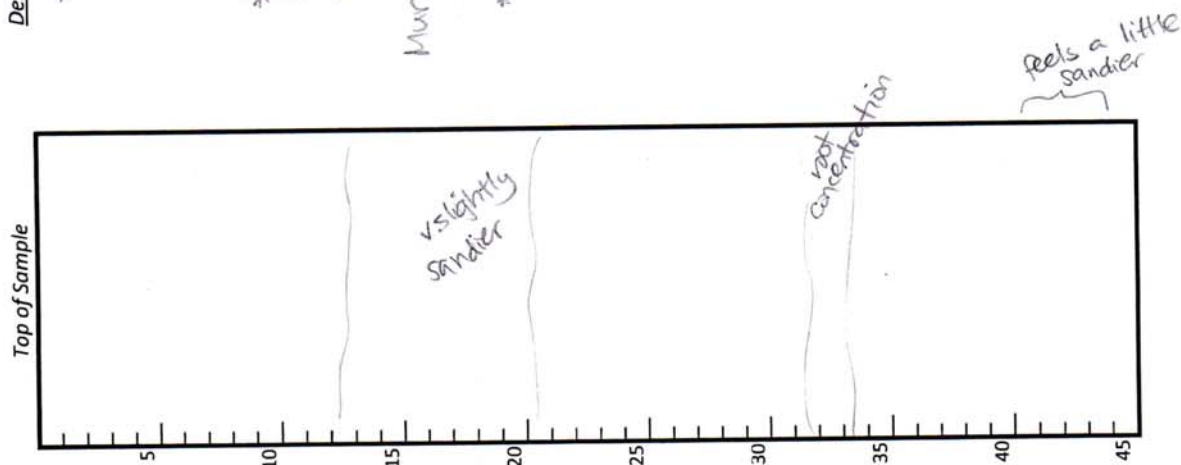
* No visible thin-layers

* Smells a bit organic

Munsell: 7.5YR 5/0

* trace iron-staining at top surface, under drilling mud layer that was cut off

* bagged remainder of sample



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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 6UStart Depth 2.75mEnd Depth 3.20mSampling Date June 3, 2016Extrusion Date June 13, 2016Weight 3455.5g (soil + tube)Top Empty 3.3 - 3.5cmBottom Empty 1.2 - 1.5cm

* Bot. surface relatively even

* Sample is very wet

* Some wood/organics visible from sample exterior

Ref: silty clay @ 1.2m to 1.5m sand to 1.5m sand f. silty

Description:

Top: f. sandy silt, tr. clayey

Bot: silty f. sand

* Some wood/twig/rocks throughout to trace

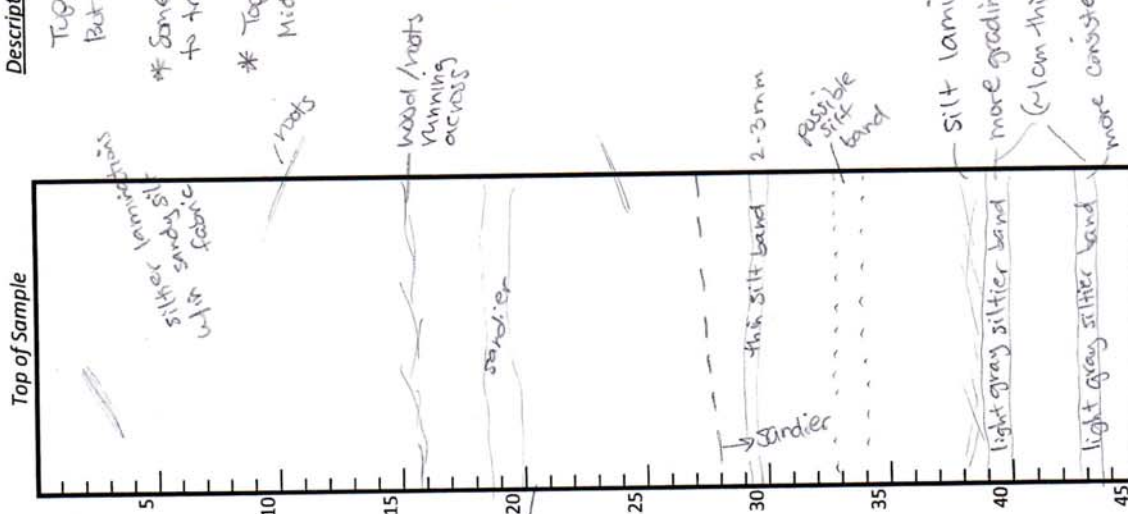
* Top = clayier to cut into
Mid-Bot = sandier to cut into

* Roots/organics gone by ~26cm

* NO iron-staining

* Munsell: 7.5YR 5/0

* bagged in 2 parts (homogeneous parts)



silt laminations grading into silt band
more grading into silt/thinner (~1cm thick)
more consistently silt/mixer

v. little
can this year!
the top part was
sampled
were so hard to
extrude

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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD (SITE 33)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-2

Sample 7U

Start Depth 3.20m

End Depth 3.65

Sampling Date June 3, 2016

Extrusion Date June 13, 2016

Weight 3.3915 kg 3374.5g

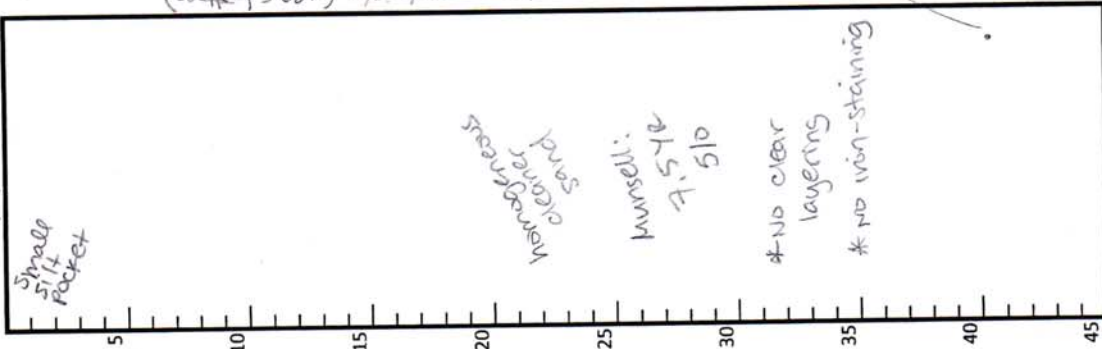
Top Empty 4.9 - 5.0cm

Bottom Empty 0.3 - 0.6cm

(still)

* Free-draining, letting sit
on paper w/o bottom cap on.
(3:15pm - 3:35pm) → not really
free-draining anymore, going to
try extruding again

Top of Sample



Description:

* Tried extruding, bottom compressing, top not coming up, going to cut the @ 1/2 way pt. (22cm from top of tube)
↳ top surface not settling at all, tube

* NO free-draining water at cut location

* 1. difficult to extrude bottom cut portion, f-m. sand, skipping. as it comes up (extruder w/o the functioning smoothly though)

↳ bottom portion of bottom cut portion is siltier/finer + comes out much more easily (last 8cm, f. sand w/ some silt) above that f-m. sand, tr. silt

* Top cut portion coming out much more easily

* Relatively clean f. sand, some parts grading to siltier or medium sand

There organic smeared on outside (near bottom)
- trace organics throughout sample (v. small pieces, v. trace)
- silt pocket present in sample

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Mini-Cone and DM Project - Lab Extrusion

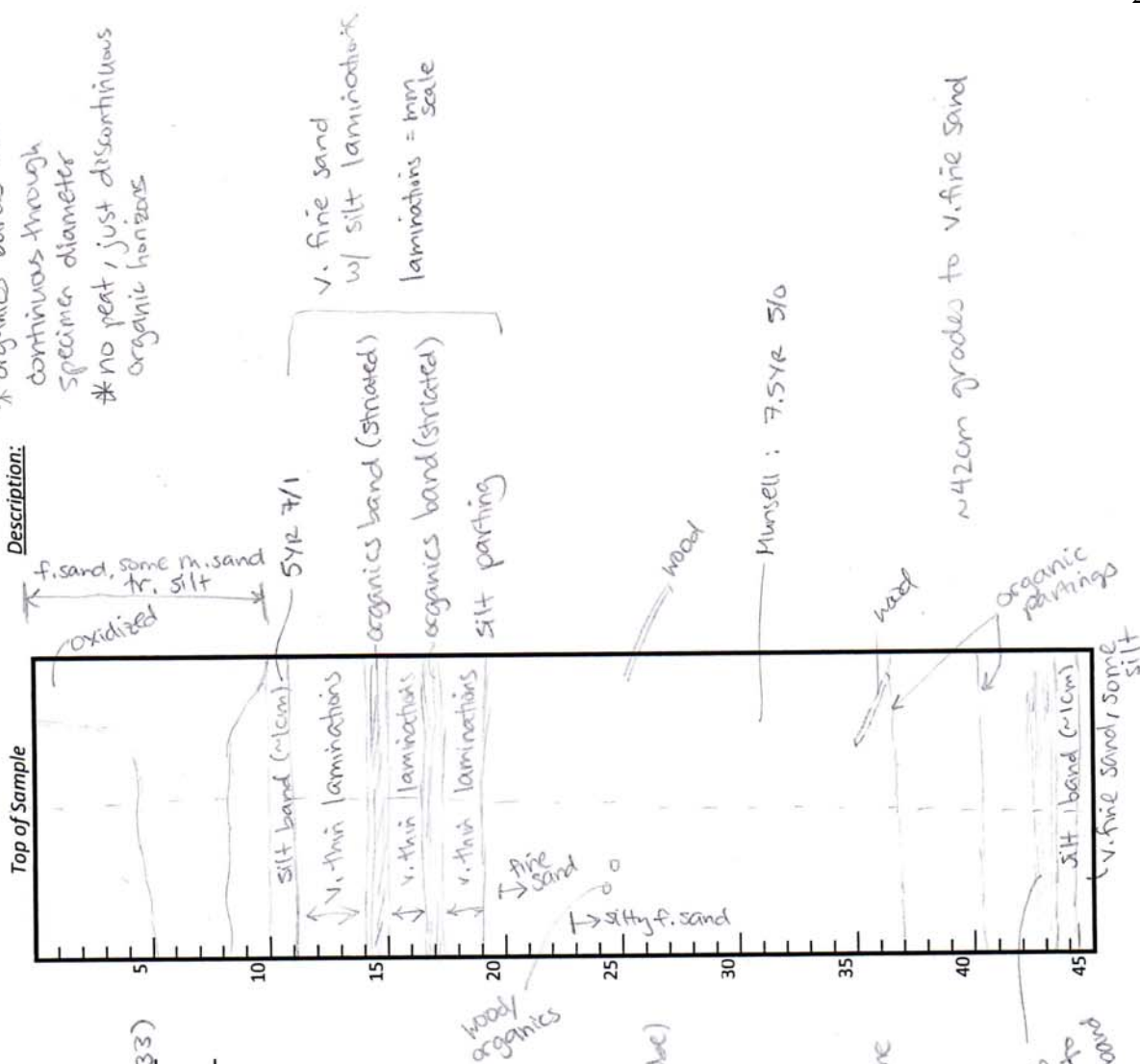
Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample BUStart Depth 3.65mEnd Depth 4.10mSampling Date June 3, 2016Extrusion Date June 10, 2016Weight 3392.5g (silt+tube)Top Empty 5.5-5.6cmBottom Empty 0cm (uneven)

* Minimal water coming out bottom for 1st push w/ extruder, then more

* No silt scraped off bottom

* Sands sandy as extruding

* organics bands not continuous through specimen diameter
 * no peat, just discontinuous organic horizons

Description:

v. fine sand
 laminations
 of organic
 silt

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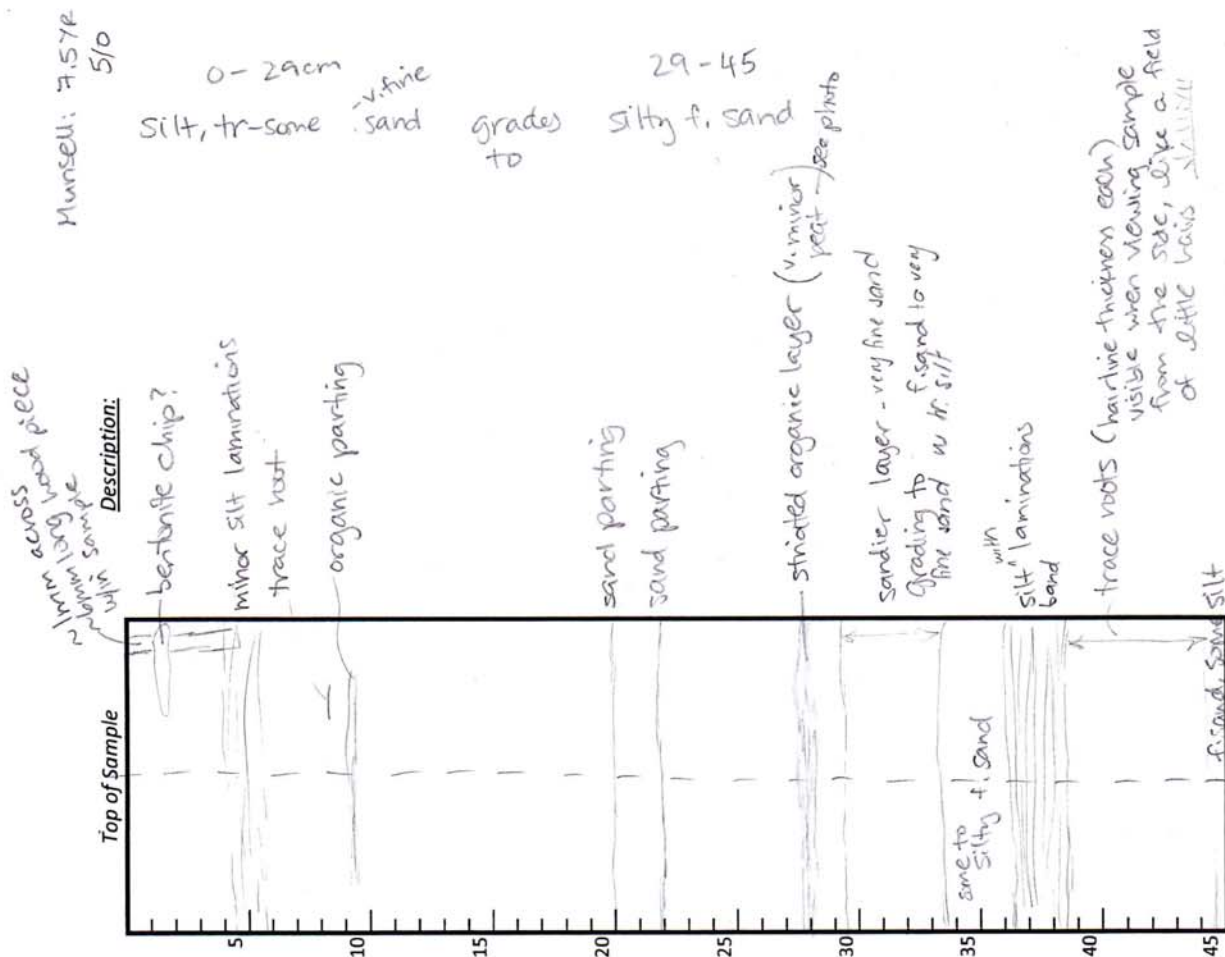
Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 10UStart Depth 4.55mEnd Depth 5.00mSampling Date June 7, 2016Extrusion Date June 14, 2016Weight 3316.5g (soil + tube)Top Empty 3.3-3.5cmBottom Empty 2.1-2.4cm

* Allowed to free-drain w/o bot. cap before extruding

* Slides out of tube very easily (no bot. soil scraped out)

* Some soil squeezed out bottom as liquidity silty sand during extrusion



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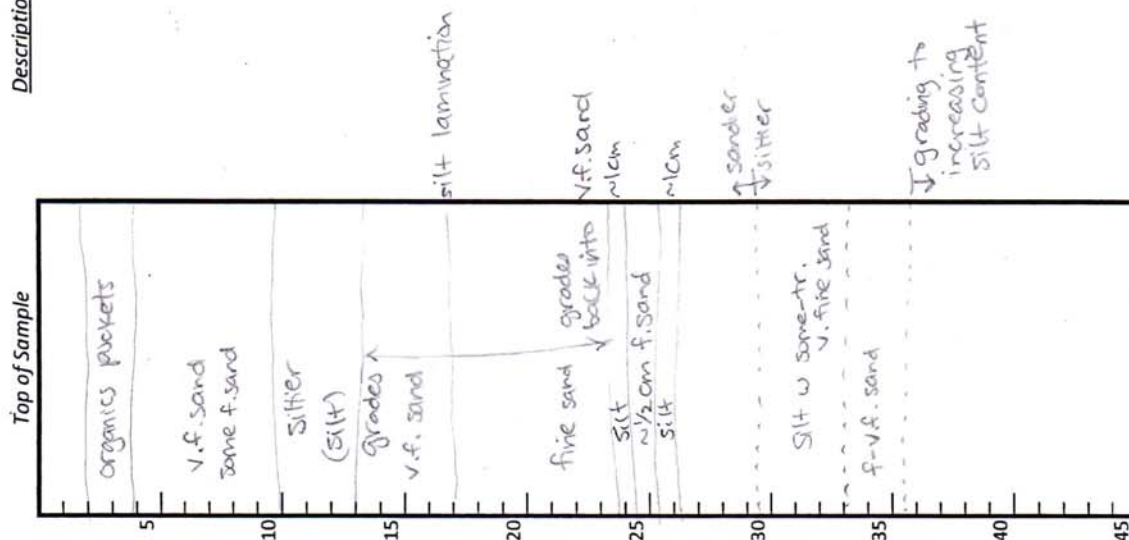
Mini-Cone and DM Project - Lab Extrusion

Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 11UStart Depth 5.00mEnd Depth 5.45mSampling Date June 7, 2016Extrusion Date June 14, 2016Weight 3.3915 kg (silt + tube)Top Empty ~ 3.5cm (top surface broken up during sample removal)Bottom Empty 1.70cm - 2.0cm

* Extrudes relatively easily, feels sandier further in tube

* Free-water releasing at ~12cm, silt (sticky) at cut surface — used paper towels to take water, not boating on next pump push, but feels like getting stiffer

* Much easier to extrude after mid 15cm removed
 * Some silt oozed out bottom but not much

Description:

(same gray as before)

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Mini-Cone and DM Project - Lab Extrusion

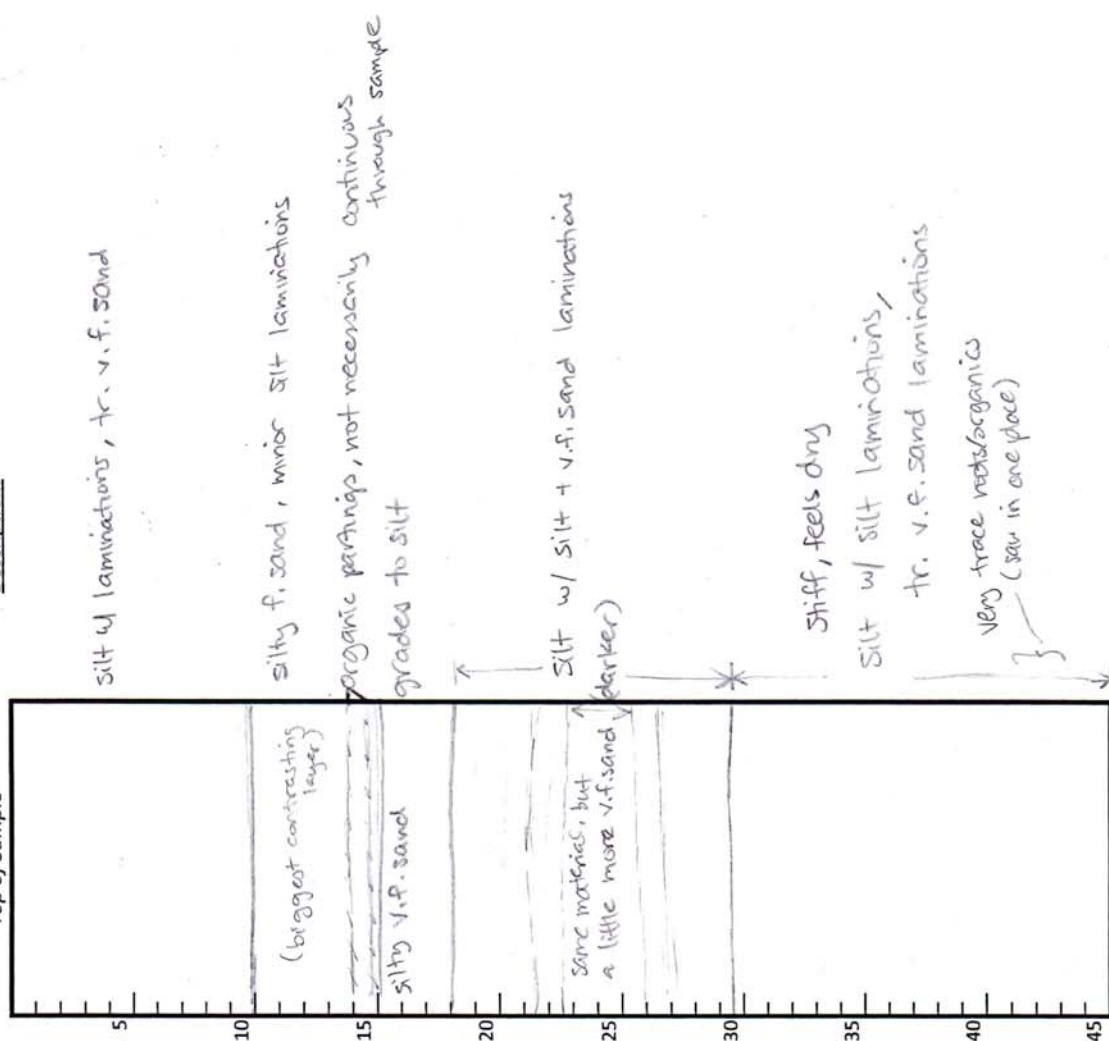
Location 200 CASHMERE RD. (SITE 33)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-2Sample 12UStart Depth 5.45mEnd Depth 5.90mSampling Date June 7, 2016Extrusion Date June 14, 2016Weight 3310.0g (soil + tube)
before
scrapingsTop Empty 4.8 - 5.0cmBottom Empty 1.4 - 2.1cm* Scraped out some soil at bottom
to make surface even

* Slides out v. easily during extrusion

* No free-draining water

* Cut at 30cm = v. adhesive, difficult
to pull wire saw
through at one
sideDescription:

Top of Sample



Significant construction
vibration in lab today from
ride's
w/ frame
silt to
vibrate

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Mini-Cone and DM Project - Lab Extrusion

Location 200 CASIMERE RD. (SITE 33)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-2

Sample 13U

Start Depth 5.90m

End Depth 6.35m

Sampling Date June 7, 2016

Extrusion Date June 14, 2016

Weight 3255.0g

Top Empty 5.3-6.1cm

Bottom Empty 0-0.4cm

* Extrudes out pretty easily

* Stiff to cut through w/ wire saw

* very stiff & seems dry.

* no caving out of bottom during
extrusion

Description:

0-25 cm: v. stiff/dry, difficult to
break open
25-45cm: softer, easier to break open, feels
a little wetter

Silt w/ silt + v.f. sand laminations. Partings to
(tr. v.f. sand) 2mm thick.

Silt w/ silt laminations (tr. v.f. sand)

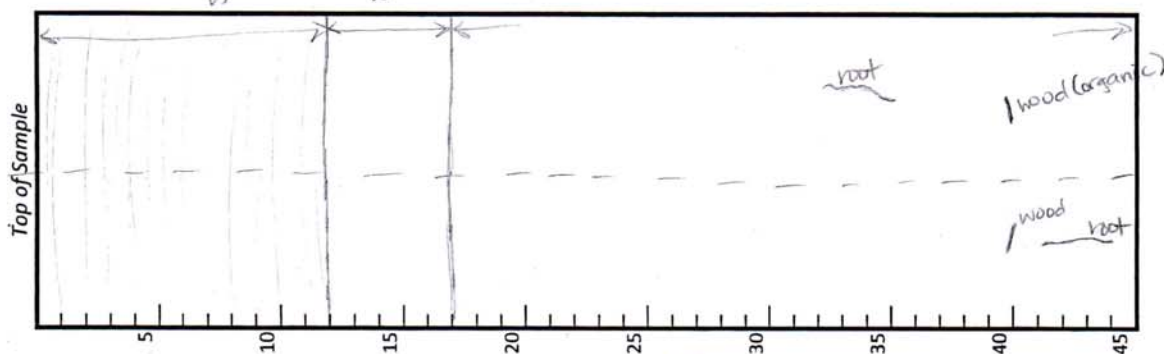
(maybe very trace)

silt, tr. v.f. sand

maybe trace silt
laminations/partings
~ 22cm-26cm

tr. organics/roots

(v. easily
rolled)



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Mini-Cone and DM Project - Lab Extrusion

Location ZOO CASHMERE RD. (SITE 33)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-2

Sample 14U

Start Depth 6.35m

End Depth 6.80m

Sampling Date June 7, 2016

Extrusion Date June 14, 2016

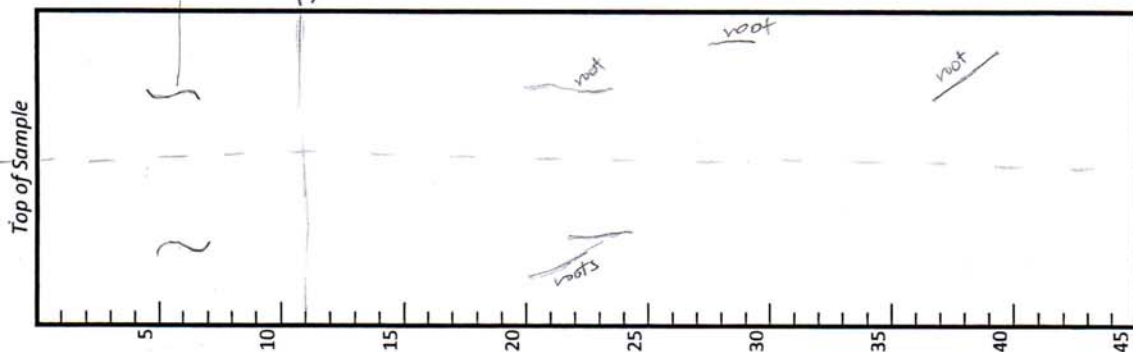
Weight 3056.0g

Top Empty 5.4cm (unseen)

Bottom Empty 0cm

* Comes out of tube very easily

Description:



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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (PACAPARTON)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-1

Sample 1U

Start Depth 0.50m

End Depth 0.95m

Sampling Date June 9, 2016

Extrusion Date June 14, 2016

Weight 3146.0g (soil + tube)

Top Empty 11.5-11.7cm

Bottom Empty 0cm

* Difficult to extrude. Some soil
cored out bottom at beginning of
extrusion; difficult to cut through
with wire saw

Description:

- * v. stiff, feels dry, crunchy
to cut into
- * bluish tint
- * iron-staining / mottles throughout
- * trace roots / root pores throughout

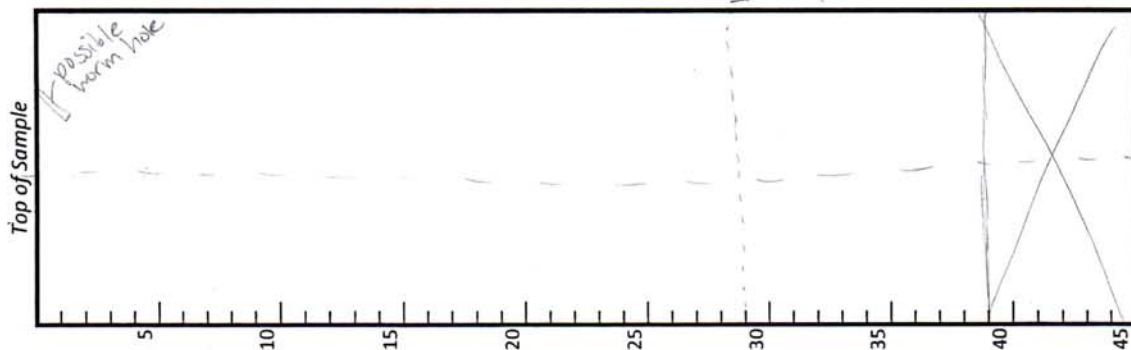
to some f.
silt, tr. f. sand

possibly bioturbated, holes that
seem larger than visible roots

no obvious structure/layering
below 29cm has faint silt
laminations

GLEYS 1: 4/10GY after soil has
dried out a bit

GLEYS 1: 4/N] first estimate of color
GLEYS 2: 4/10BG] before it dried out a
bit



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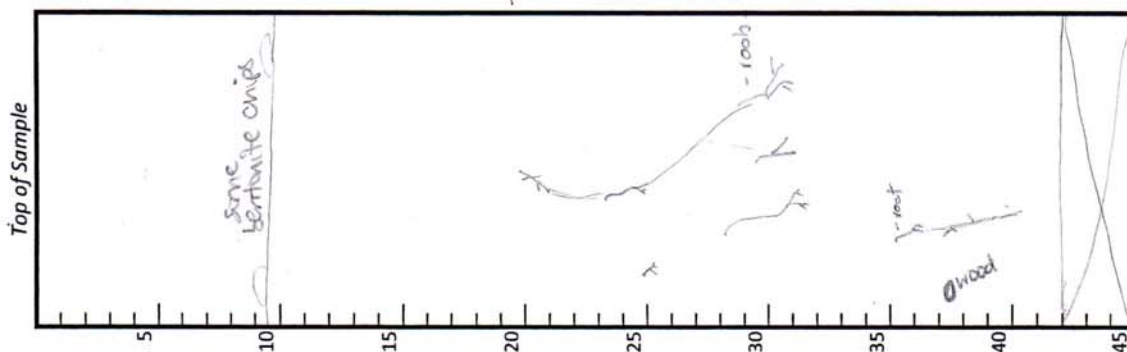
Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCAFTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 20Start Depth 0.95mEnd Depth 1.40mSampling Date June 9, 2016Extrusion Date June 14, 2016Weight 3224.5g (soil+tube)Top Empty 8.1-8.3cmBottom Empty 0cmDescription:

- Top 5cm oozing
- Next 5cm oozing to intact to 7cm

* Bottom 28.7cm intact/good sample

Munsell: 5YR 6/1

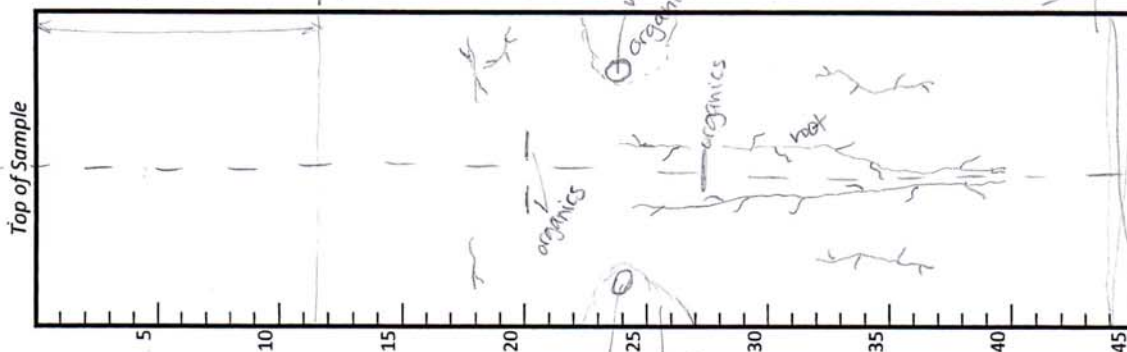
- silt, fr. v. fine sand
trace faint silt laminations- Non staining & mottling
throughoutv. fine (how-like) * roots + root-pores
throughout* Sample was
sitting out for
a bit while
talking w/ Mike
b4 taking water
contents

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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 3UStart Depth 1.40mEnd Depth 1.85mSampling Date June 9, 2016Extrusion Date June 14, 2016Weight 3.3585 kgTop Empty 6.4 cm - 6.7 cmBottom Empty 0.0 cm

* Coming out of tube very easily during extrusion

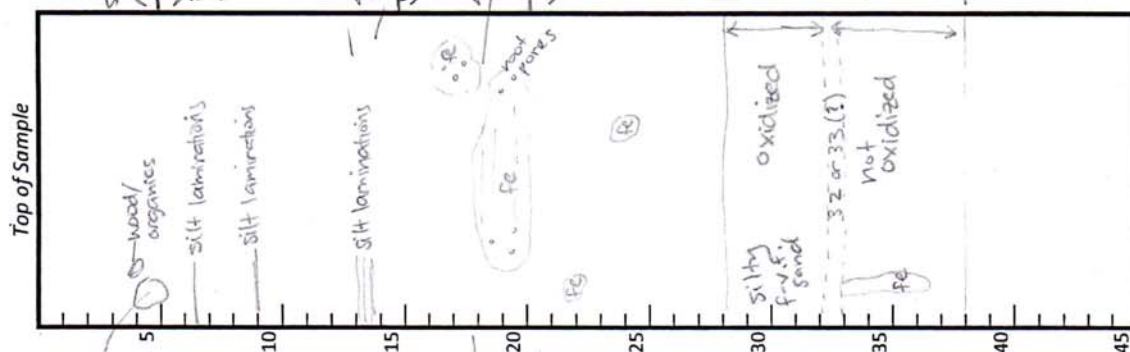
Description:silt, some v.f. sand
silt laminations visiblesome parts
feel a little
clayey↓ silt, tr. v.f. sand
no laminations visible* iron-staining throughout (0-28cm)
trace iron-staining (28-40cm)
no iron-staining (40-44cm)* tr. organics throughout
+ wood + roots + root poresgrades to silt, some v.f. sand, tr. f. sand
(can still roll a bit)

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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 4UStart Depth 1.85mEnd Depth 2.30mSampling Date June 9, 2016Extrusion Date June 14, 2016Weight 3528.0g (Soil + tube)Top Empty 3.3-3.6cmBottom Empty 1.1-1.6cm

* Extruded out pretty easily, makes sandy noise as extruding
 * A little bit of soil/water coaxed out the bottom when extruding

Description:

Fe = iron - staining mottles
 silty, some v.f. sand
 grades into trace roots/organics/root pores into silty v.f. sand throughout sample

roots
 grades into silty f. sand

grades into oxidation

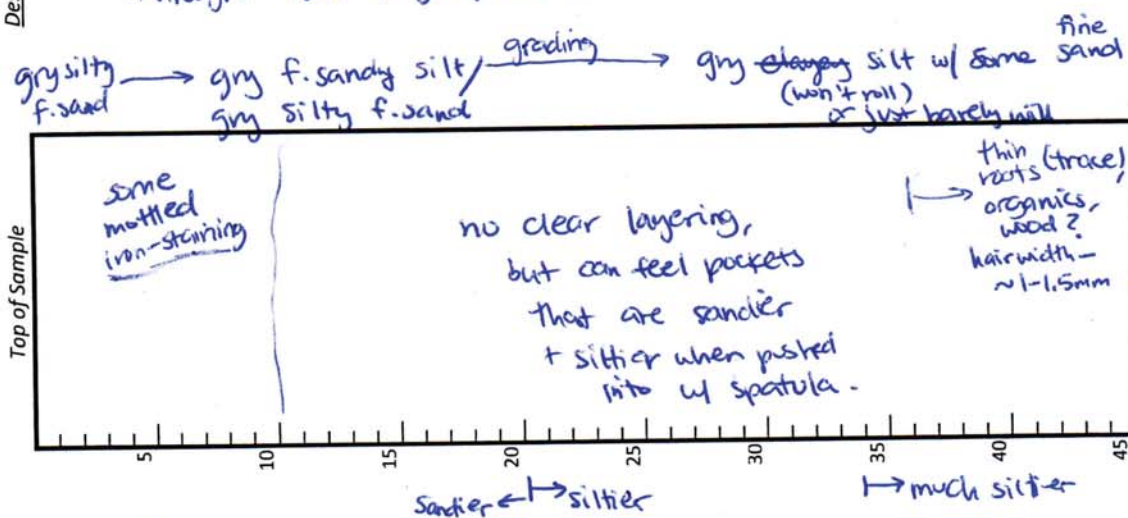
Some depths have slightly more silt content

silty f. sand

oxidized, grades into silty f. sand, lens silt content than above (maybe same silt)

Description:

squeezing w/ fingers makes surface water go back into sample
throughout full length, even in sandier top portion



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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-1Sample 5UStart Depth 2.30mEnd Depth 2.75mSampling Date June 9, 2016Extrusion Date June 9, 2016

Weight

Top Empty

Bottom Empty

slid out
of tube
while
on site

wood content/organics at Kiccarton
Contributing to CPT showing stratification?

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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (KICCARTON)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-1

Sample 6U

Start Depth 2.75m

End Depth 3.20m

Sampling Date June 9, 2016

Extrusion Date June 15, 2016

Weight 3391.0g (soil + tube)

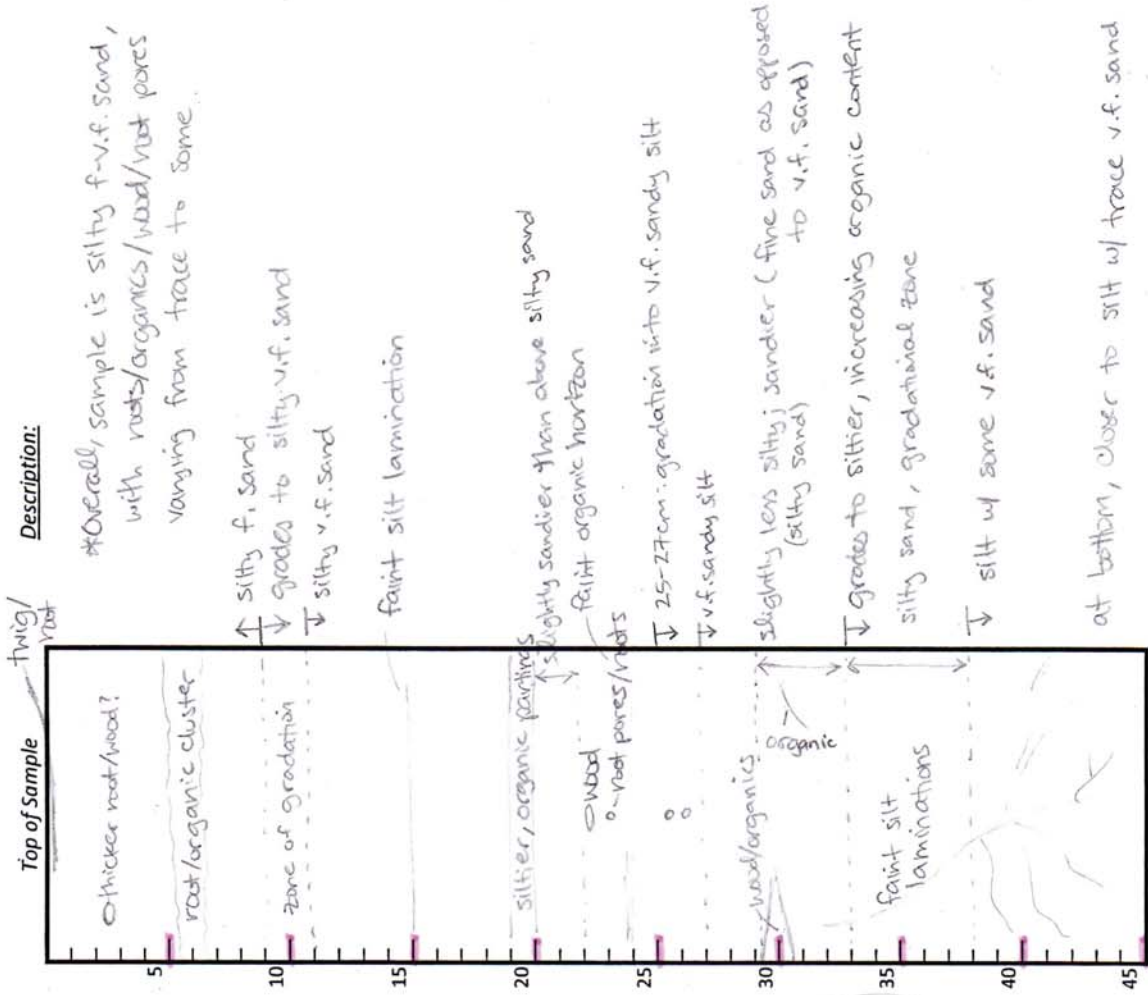
Top Empty 5.2-5.5cm (twig/wood at top)

Bottom Empty 0cm (organics/roots sticking out at bottom of tube)

- * Extrudes easily
- * Sounds sandy coming out of tube
- * Middle portion is wetter / siltier than top portion
- * Bottom portion sounds smoother / less sandy while extruding

* appears fine
allowing sample
to air-dry

* NO soil oozed out of bottom during
Extrusion



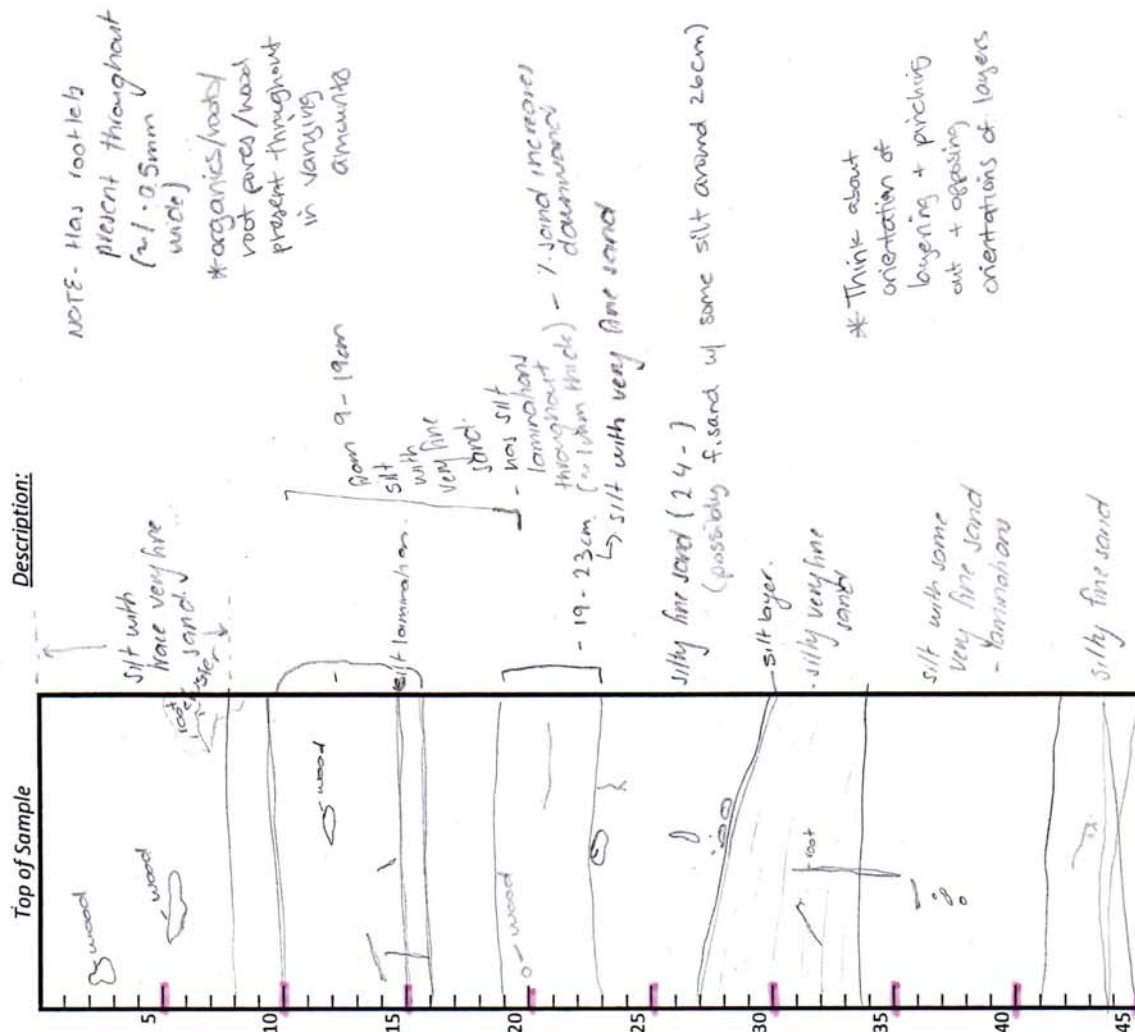
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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 7UStart Depth 3.20mEnd Depth 3.65mSampling Date JUNE 9, 2016Extrusion Date JUNE 15, 2016Weight 3336.5g (soil+tube before scraping)Top Empty 3.7-3.8cmBottom Empty 2-3.2cm

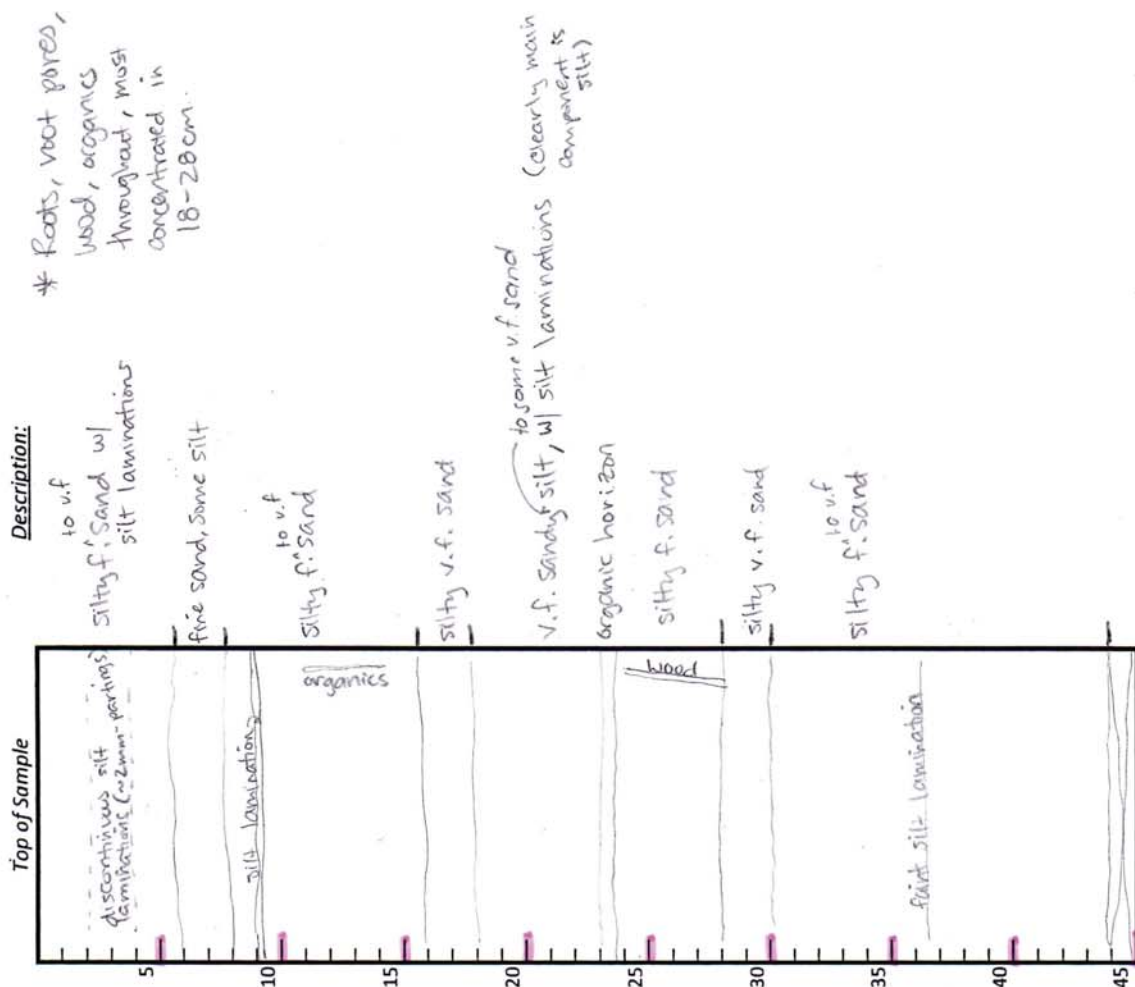
* A little soil scraped out of bottom

* Somewhat difficult to extrude.



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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 80Start Depth 3.65mEnd Depth 4.10mSampling Date June 9, 2016Extrusion Date June 15, 2016Weight 3.3530 kg (Silt+tube)
before
scrapingTop Empty 3.5 - 3.7cmBottom Empty 2.4 - 3.2cm* Some bottom soil scraped out
before extruding* Extrudes pretty easily, sounds sandy
coming out* A little soil/water came out at bottom
while extruding

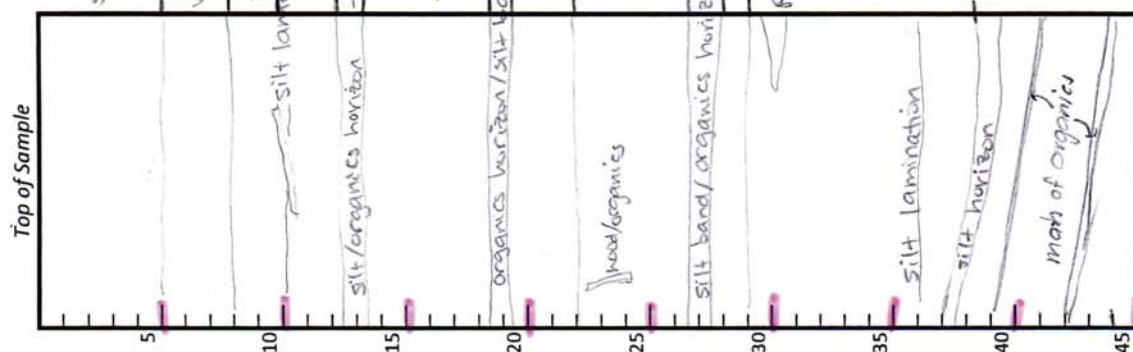
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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RACCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 90Start Depth 4.1mEnd Depth 4.55mSampling Date June 10, 2016Extrusion Date June 15, 2016 (silt tube)Weight 3.3005kg before scrapingTop Empty 4.6-4.8cmBottom Empty 1.3-1.6cm

* A little soil scraped out of bottom
 + Easy to get out of tube

Description:



* roots/organics/wet pores
 present throughout.

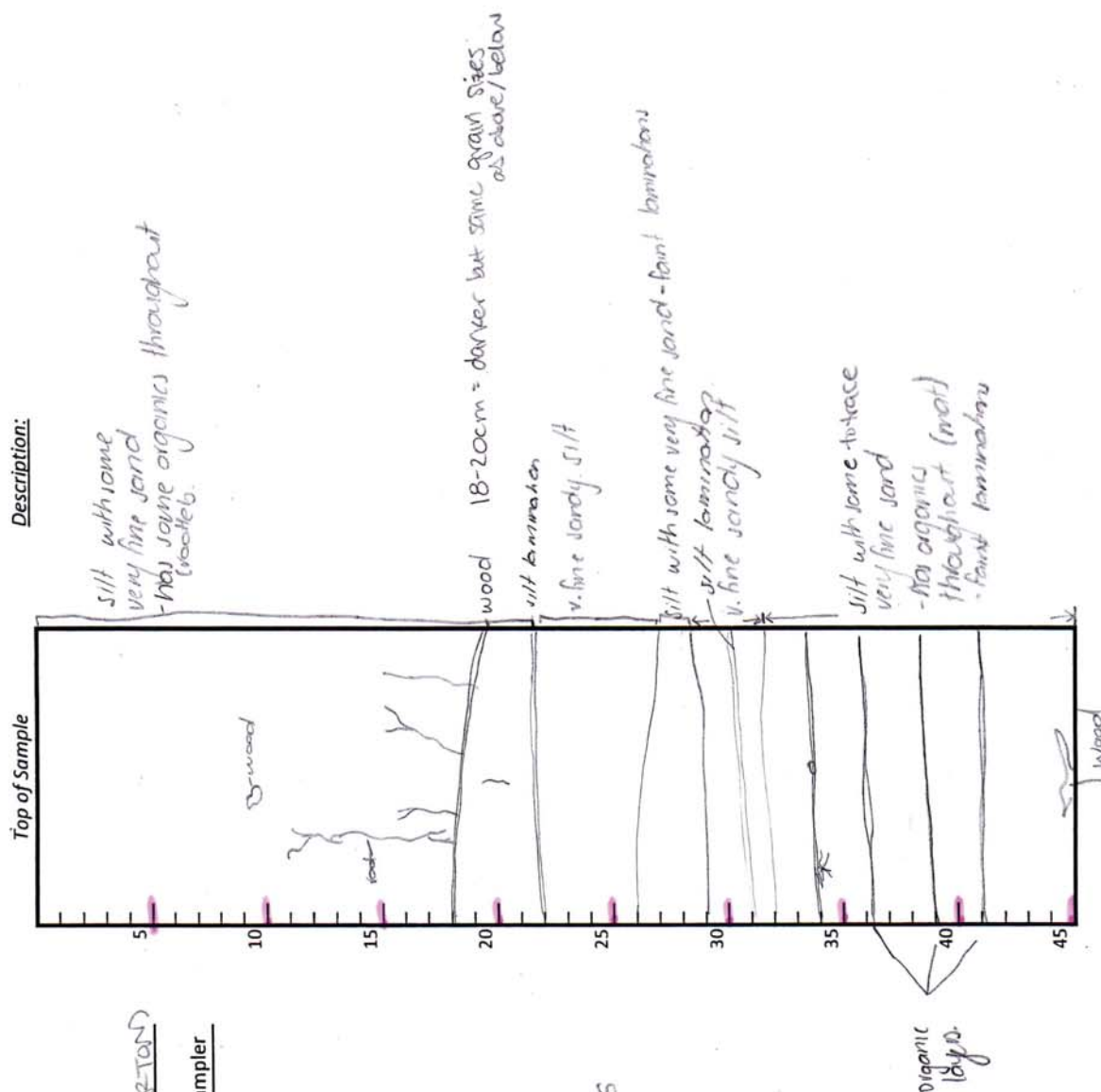
39-43cm: almost all organic fabric, continuous mat of previously visible layers on surface

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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 1DUStart Depth 4.55mEnd Depth 5.0mSampling Date June 10, 2016Extrusion Date June 15, 2016Weight 3.3180kgTop Empty 5.4 - 5.5cmBottom Empty 0cm

*Extrudes out easily



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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARTON)

Sampler Dames & Moore Hydraulic Piston Sampler

Tube Brass (2.5" O.D.)

Boring DM-1

Sample 11V

Start Depth 5.00 m

End Depth 5.45 m

Sampling Date June 10, 2016

Extrusion Date June 15, 2016

Weight 3408.5 g (Soil+tube)

Top Empty 5.2-5.36 m

Bottom Empty 0 cm

*Extrudes v. easily

Description:

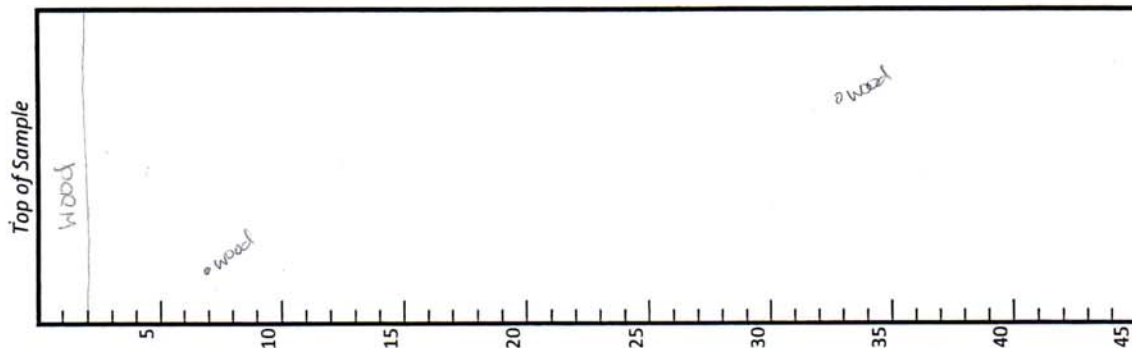
Homogeneous sample

Slightly clayey silt, tr. v.f. sand

Around 28-30 cm, possibly
tr. v.f. sand to
tr. f. sand

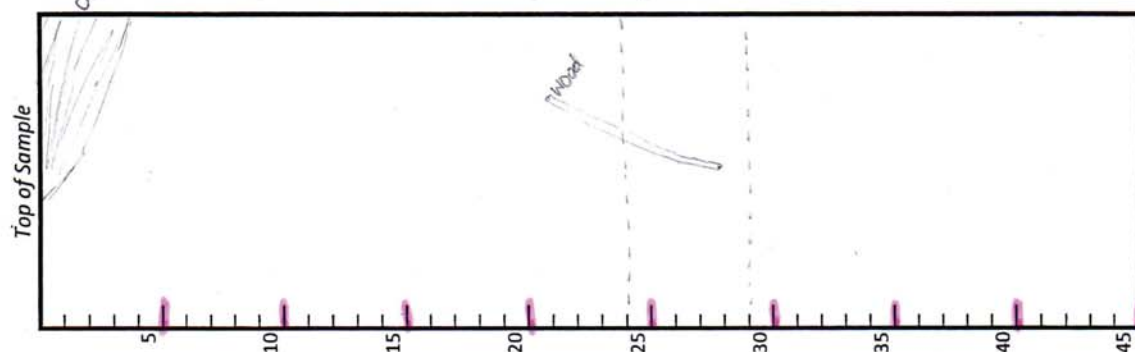
tr. roots, organics throughout

Munsell: 7.5YR 5/0



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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCARION)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 12UStart Depth 5.45mEnd Depth 5.90Sampling Date June 10, 2016Extrusion Date June 15, 2016Weight 3.5535 kgTop Empty 5.1 - 5.2cmBottom Empty 0cmDescription:

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Mini-Cone and DM Project - Lab Extrusion

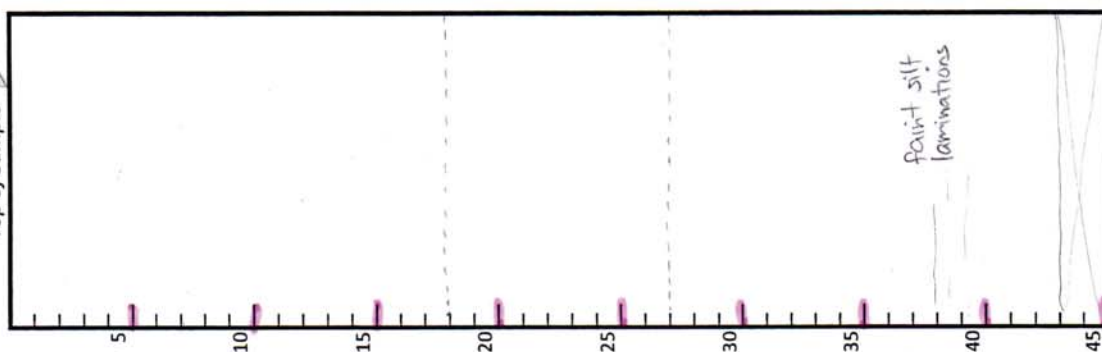
Location CLARENCE ST. (RACCARTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 13UStart Depth 5.90End Depth 6.35Sampling Date June 10, 2016Extrusion Date June 15, 2016Weight 3.4295 kgTop Empty 3.2-3.5 cmBottom Empty 1.7-3.7 cm

- Top may be broken during sample tube removal from sampler

- A small amount of soil/water coaxed out bottom during extrusion

- Slightly difficult to extrude

Top of Sample



Description:

- Grey with blue-ish tinge.

v.f. sandy silt, tr. f. sand

* Trace roots throughout, fewer roots 28cm-end

silt and v.f. sand

silty to some silt, fine sand

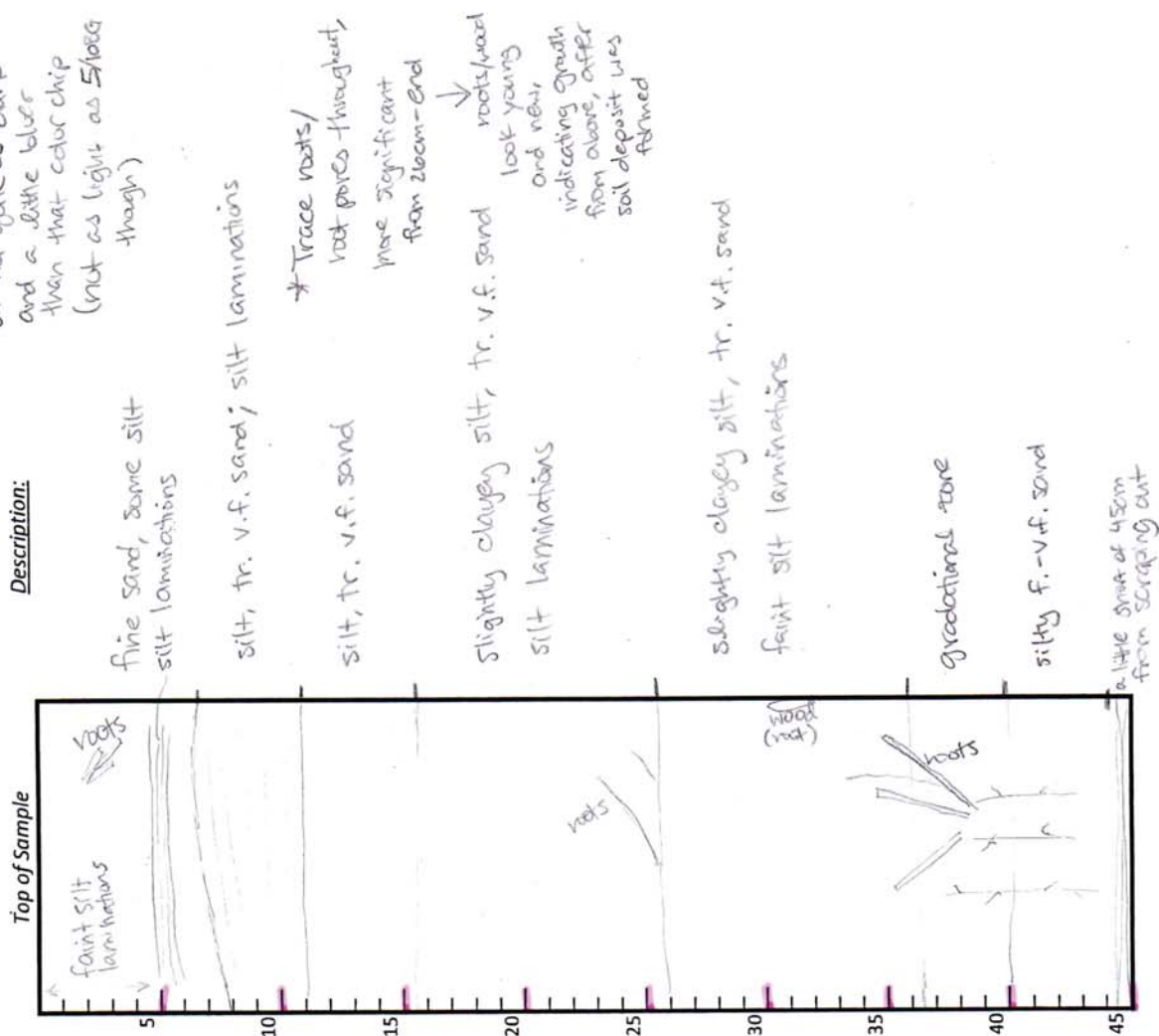
twig/organics fall-in or mud re-circulation
top likely borehole

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Mini-Cone and DM Project - Lab Extrusion

Location CLARENCE ST. (RICCAPTON)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring DM-1Sample 140Start Depth 6.35mEnd Depth 6.80mSampling Date June 10, 2016Extrusion Date June 16, 2016Weight 2459.0g (soil + tube)
(before
extrusion)Top Empty 3.2-3.4cmBottom Empty 1.7-3.8cm* Extrudes out easily, top part
feels sandy- foot retaining water at ~ 30cm depth
in core* Some soil scraped out of bottom to
create even surface

* Bluish tint when 1st cut open,
closest to Russell:
GLEYS 4/10BG
but not quite as dark
and a little bluer
than that color chip
(not as light as 5/10BG
though)

Description:

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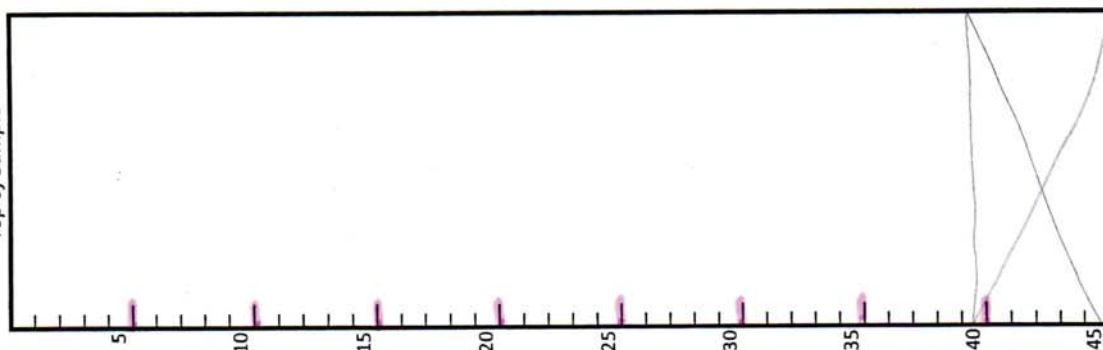
Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 1UStart Depth 0.5mEnd Depth 0.93

Sampling Date _____

Extrusion Date June 16, 2016Weight 3.20kgTop Empty 11.2 - 11.3 cmBottom Empty 0cm

Top of Sample

Description:

Munsell: 10YR 5/2 grey-olive green
 7.5YR 5/6 mottles
 7.5YR 4/4 mottles (lost 2cm)

Slightly clayey silt,
 fr. v.f. sand

* iron-staining + mottles
 throughout (~25%)

* Thin roots / root pores
 throughout

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Mini-Cone and DM Project - Lab Extrusion

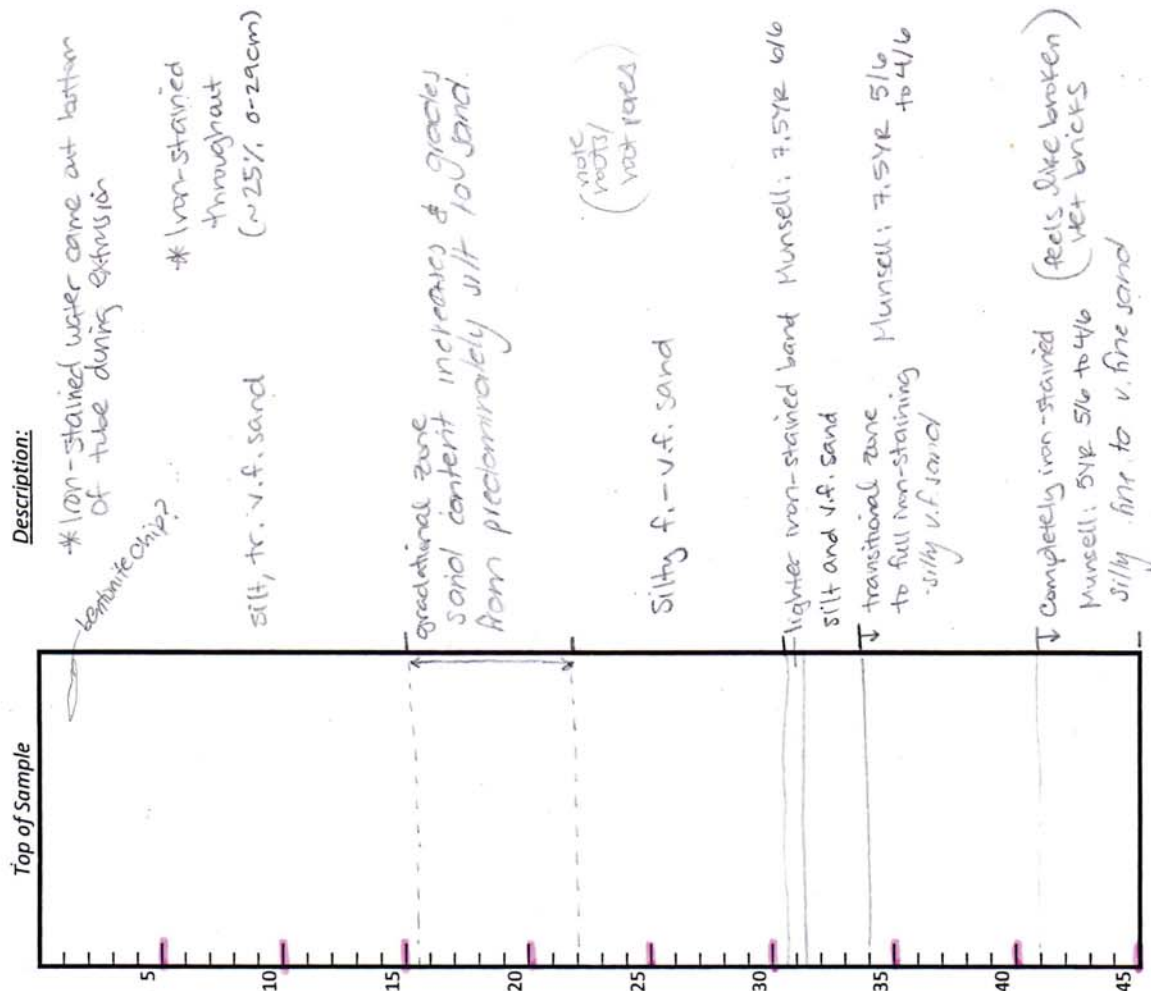
Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 2L1Start Depth 0.95End Depth 1.4m

Sampling Date _____

Extrusion Date June 16, 2016Weight 3.4290kgTop Empty 4.5cm - 4.7cmBottom Empty DM (extends out bottom)

* Bottom extended part scraped off before weighing + extruding (v. iron-stained)

* Extends out v. easily
 * 15cm from top of sample, v. soft layer, coming out side wds, sample above tilting

Description:

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Mini-Cone and DM Project - Lab Extrusion

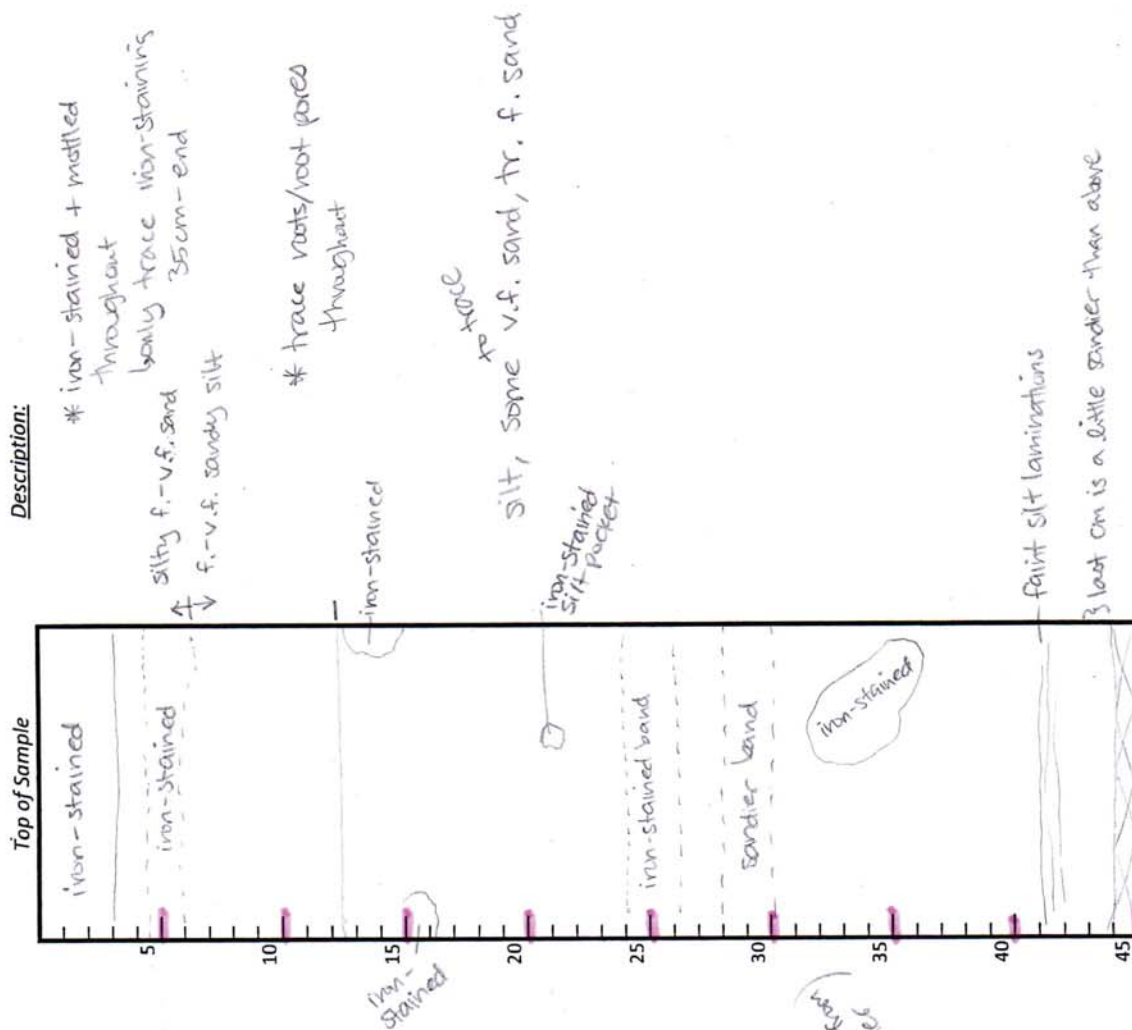
Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 3UStart Depth 1.40 mEnd Depth 1.85 m

Sampling Date _____

Extrusion Date June 16, 2016Weight 3.4110 kgTop Empty 4.0 m - 4.2 mBottom Empty 1.7 - 1.8 m

- Top broken during sampling

- Top 7cm softer & free-water draining out sides.

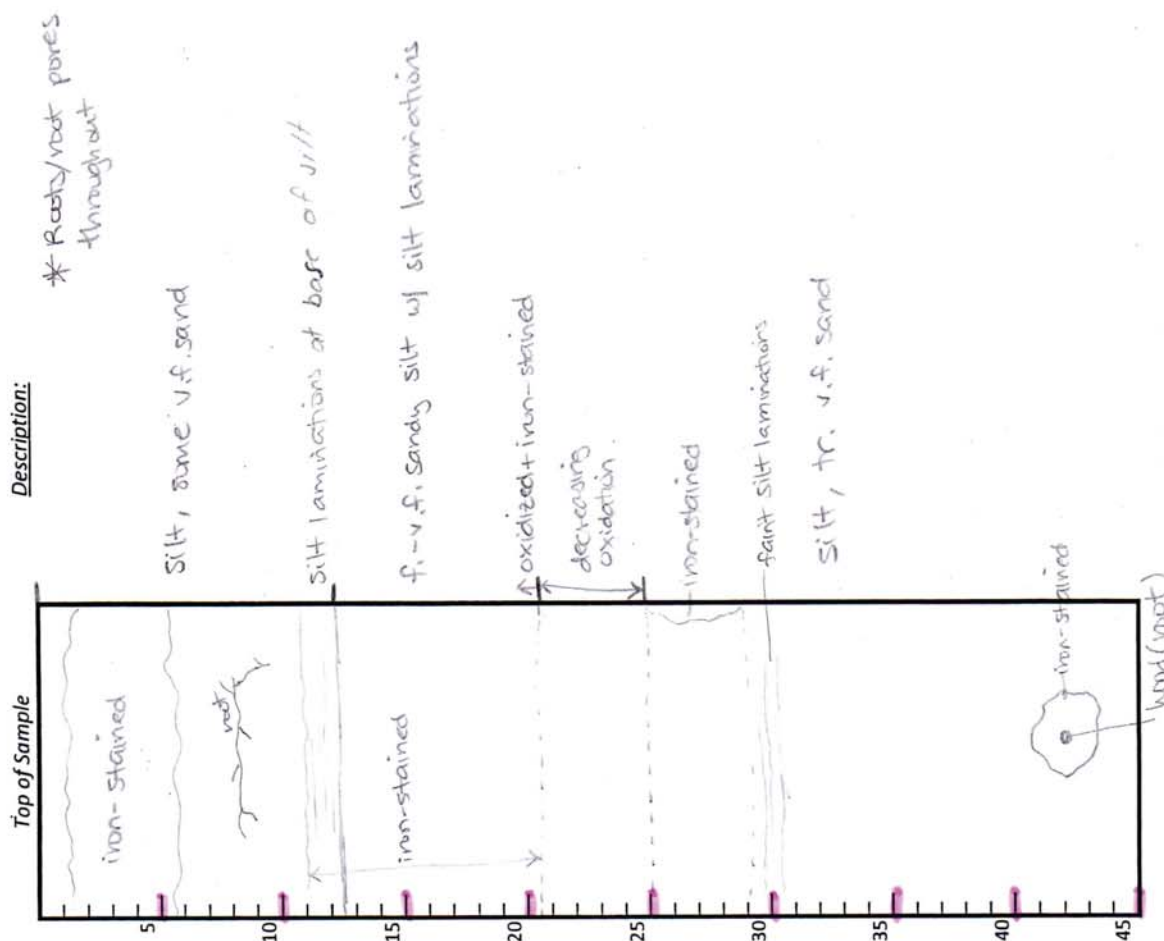


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Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BK-3Sample 4UStart Depth 1.85mEnd Depth 2.30m

Sampling Date _____

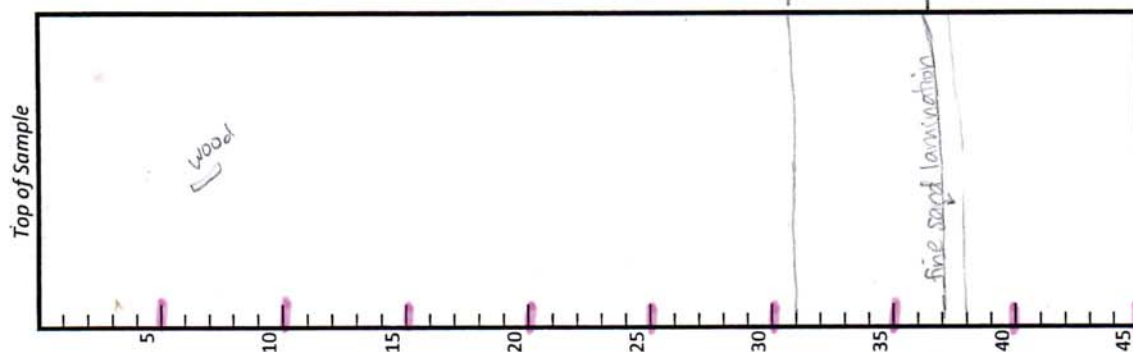
Extrusion Date June 16, 2016Weight 3387.0g (Soil + tube)Top Empty 3.2 - 3.3cmBottom Empty 2.4 - 2.5cm

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Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample GUStart Depth 2.75mEnd Depth 3.20m

Sampling Date _____

Extrusion Date June 16, 2016Weight 3.4880 kgTop Empty 3.2 cm - 3.3 cmBottom Empty 2.4 - 2.6 cmGLE71 4/10GY - Munsell
Gk10

Description:

* Some roots/wood pores/
wood/organics throughout
(less present 33cm - end)

clayey silt, fr. v.f. sand
(slightly increasing sand content
with depth)

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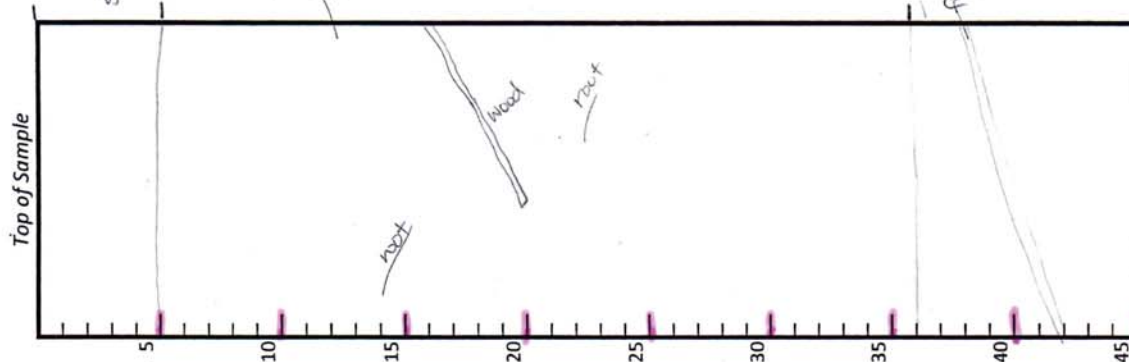
Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample FUStart Depth 3.20mEnd Depth 3.65m

Sampling Date _____

Extrusion Date June 16, 2016Weight 3581.5gTop Empty 5.9 - 5.6cmBottom Empty 0cm (extending out
bottom a bit,
scraped off
before weighing)

- pretty hard to extrude
↳ small amount of water &
sand came out the bottom

Description:

* Trace voids/wood/root pores
Silty v. f. to fine sand
NOTE: v. f. sand grades downwards into fine sand v. f. to fine sand
to some silt
Silty f. v. f. sand (predom. f. sand)

* Note: no visible silt laminations

* Bagged 5-45cm

silty v. fine sand horizon - possible liquefaction feature
tr. f. sand

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Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 80Start Depth 3.65mEnd Depth 4.10m

Sampling Date _____

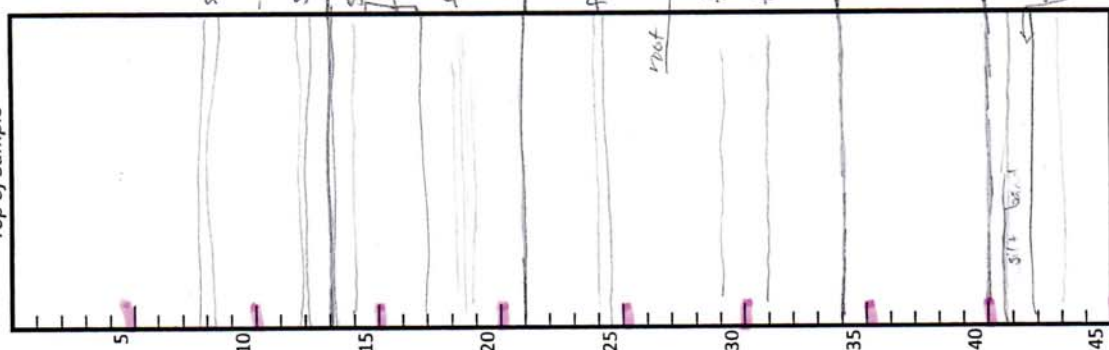
Extrusion Date June 16, 2016Weight 3.4875 kgTop Empty 5.6 - 6.1cmBottom Empty 0 - 0.4cm

*Tried to extrude, leaking water/sand
out of bottom of tube, tube moving
up in extruder rather than sample
in tube

⇒ cutting tube in half
(now extrudes OK)

Description:

Top of Sample



Silty f. sand, then fine - v. f. sand below (13-34cm)
→ lower silt content

* Series of 5-6
flood deposits

siltier band - v. fine sandy silt

- silty fine sand (10-15cm)

siltier band - v. fine sandy silt

Silt lamination

Silty v.f. sand (from 15-17cm)

faint silt laminations, increased f. sand content

↳ silty fine sand (17-21cm)

← contact between silty fine sand & silty f. sand

fine sand band

Silty v.f. sand, tr. f. sand (from 21-34cm)

faint silt lamination

faint silt lamination

to some silt

silty f. sand (34-40cm)

silty v.f. sand, tr. f. sand (40-45cm)

silt lamination

v. fine sandy silt from 40.5-42cm

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Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 90Start Depth 4.10mEnd Depth 4.55m

Sampling Date _____

Extrusion Date _____

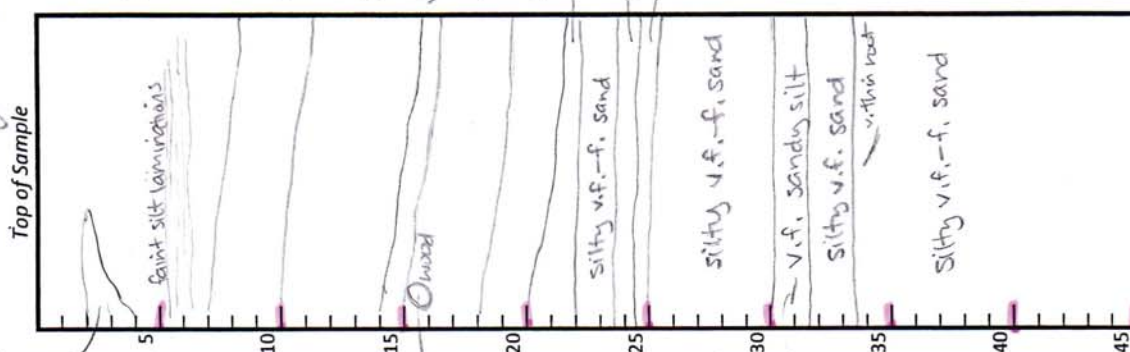
Weight 3439.0g (soil + tube)
before
scrapingTop Empty 3.4-3.6cmBottom Empty 1.7-2.3cm* A little soil scraped out at bottom
surface* Tube was draining for several days,
1st push still pushed up tube not
soil, a lot of water came out
bottom on 1st push → cutting tube
in half

- Extrudes easily once cut in half - no water squeezing out

(v.v. trace)
* Almost no organic /
wood/roots throughout
specimen

Description:

fine sand - discontinuous
lens in silty v.f. sand



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Mini-Cone and DM Project - Lab Extrusion

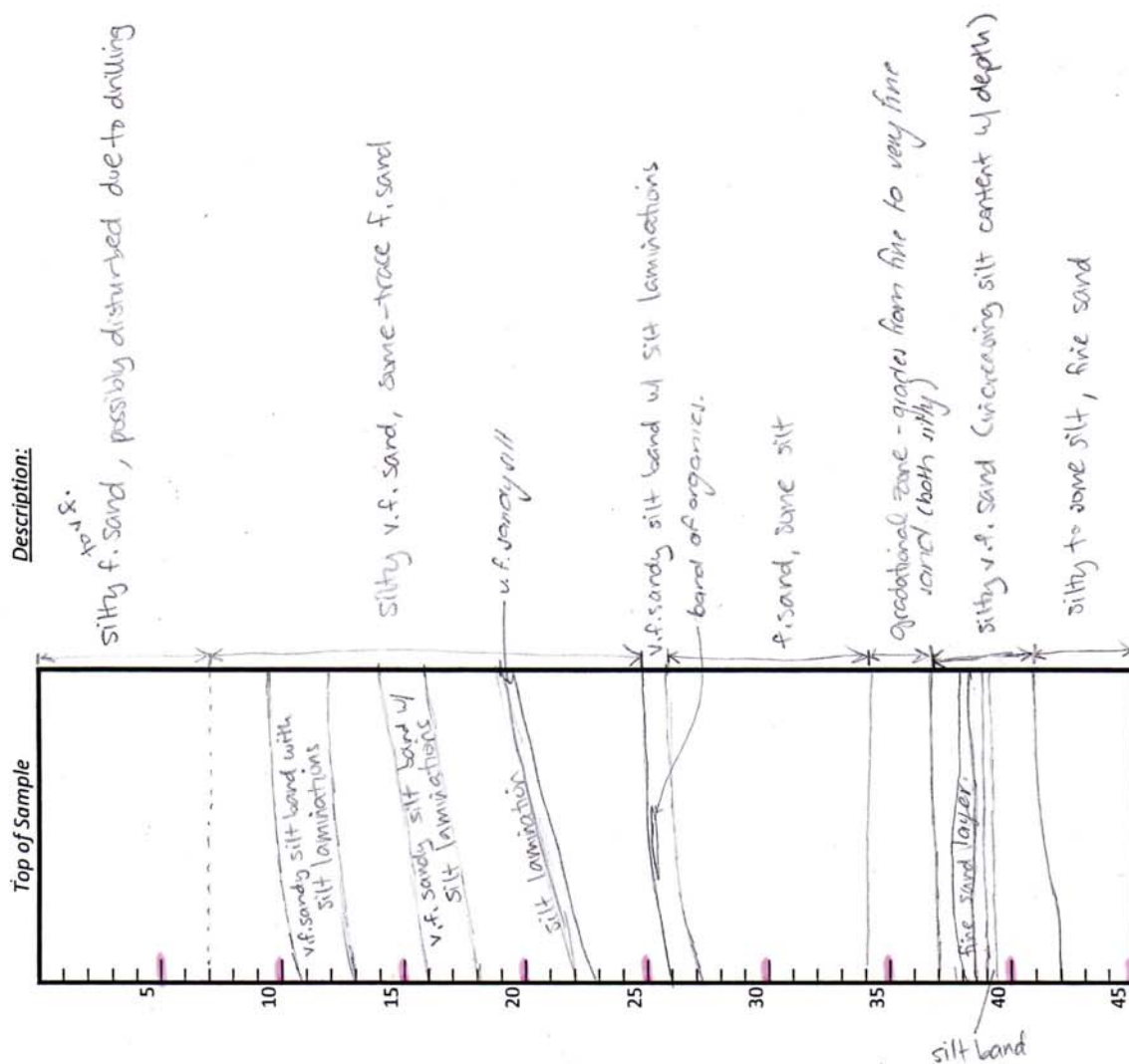
Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 10UStart Depth 4.55mEnd Depth 5.00m

Sampling Date _____

Extrusion Date June 17, 2016Weight 3392.0gTop Empty 5.7-6.1cmBottom Empty 0-0.3cm

* Cut tube in half from beginning, extrudes v. easily

* Top surface of portion # 2/4 seems like possible L10 feature



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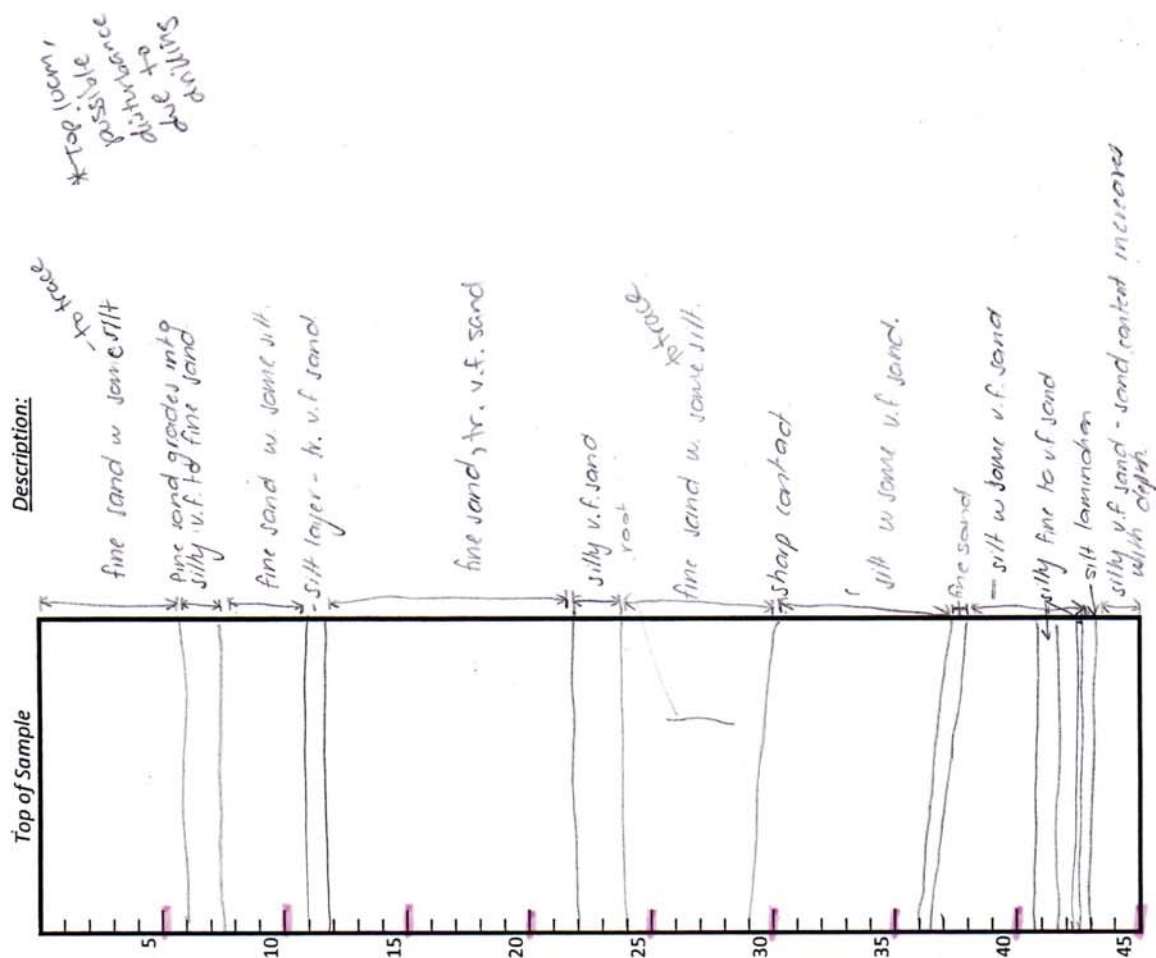
Mini-Cone and DM Project - Lab Extrusion

Location BARKINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 11UStart Depth 5.00mEnd Depth 5.45m

Sampling Date _____

Extrusion Date June 17, 2016Weight 3.3095 kgTop Empty 6.6 - 6.7 cmBottom Empty 0 cm (was extending out)

- Bottom scraped off before weighing.
 - Won't extrude w/o cutting tube,
 water/sand coming out bottom

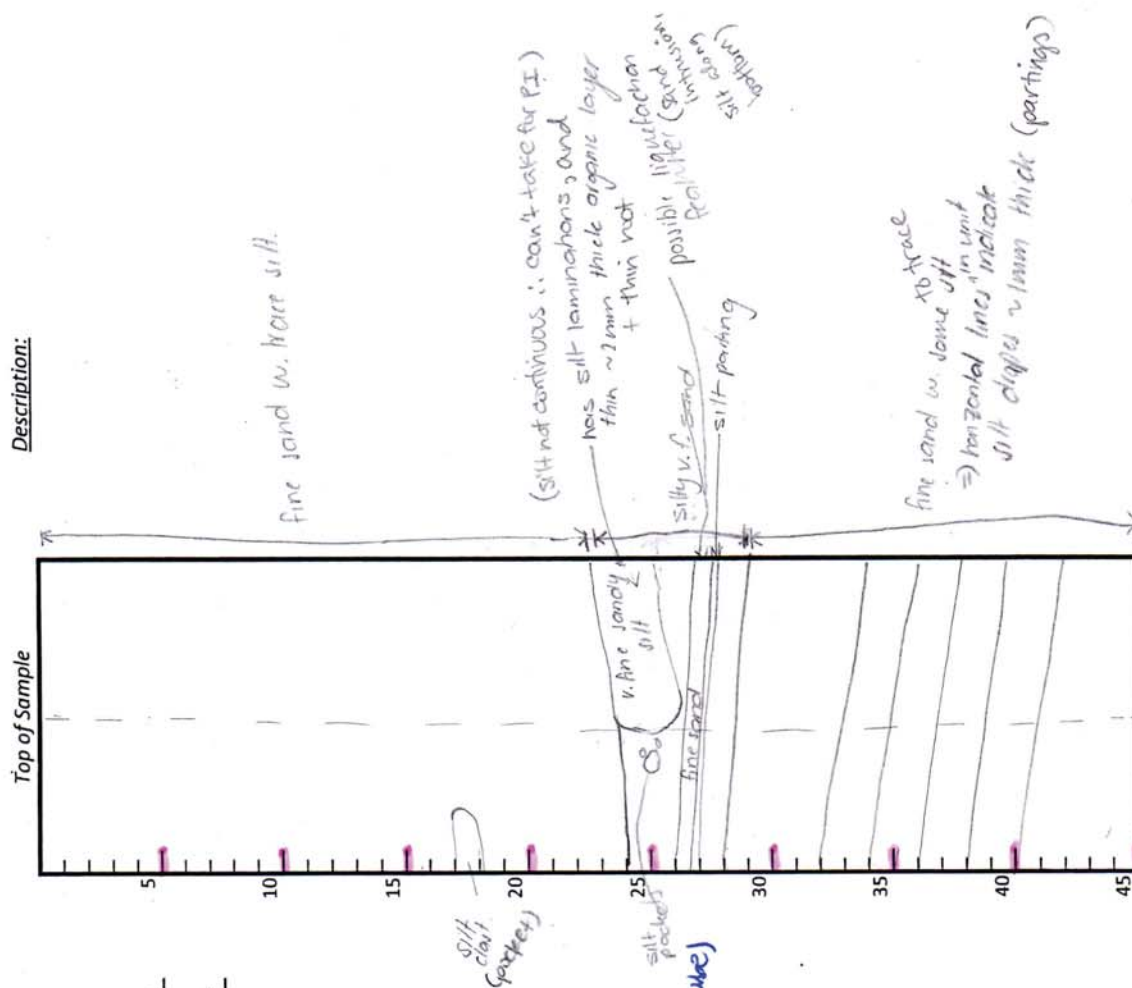


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Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 120Start Depth 5.45mEnd Depth 5.90m

Sampling Date _____

Extrusion Date June 17th, 2016Weight 3257.0g (soil + tube)Top Empty 6.0-6.1cmBottom Empty 0cmDescription:

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Mini-Cone and DM Project - Lab Extrusion

Location BARRINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 13UStart Depth 5.90mEnd Depth 6.35m

Sampling Date _____

Extrusion Date June 17, 2016Weight 3.3930 kg (silt + wood)Top Empty 6-6.2cmBottom Empty 0cmDescription:

Top of Sample

*Top 11cm seems
disturbed due to
drilling

fine sand, tr. silt

f.-v.f. sand, some-tr. silt
v.f. sandy silt band

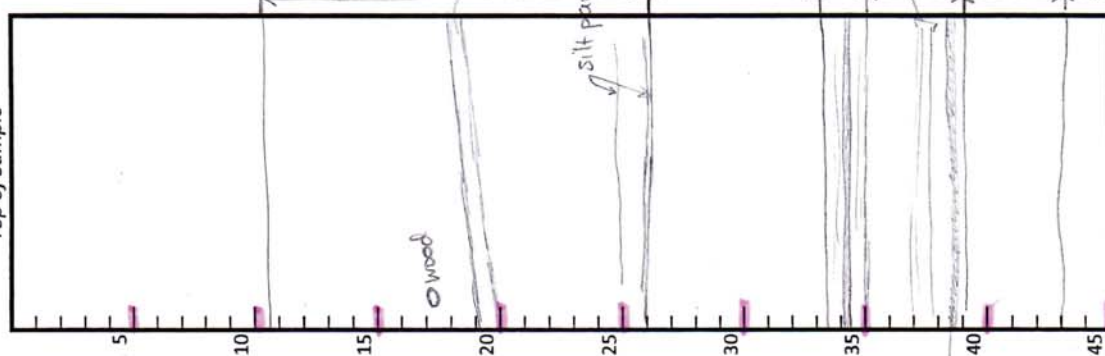
silt partings

fine sand, tr. silt

silt band; silt laminations, fine sand seam (~2mm)

silt laminations
v.f. sandy silt with silt laminations

silty v.f. sand

-silt parting along contact
f.-v.f. sand, some-tr. siltsilty
f. sand
seam

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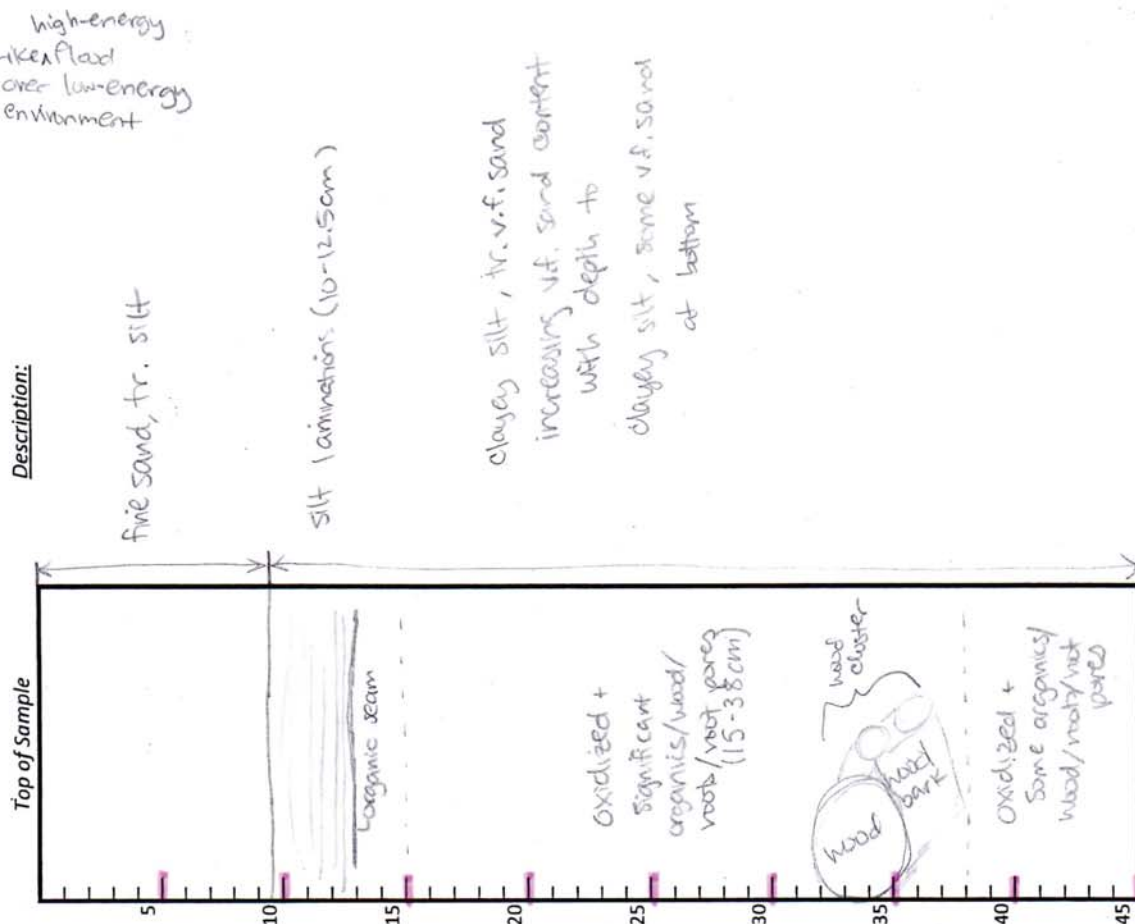
Mini-Cone and DM Project - Lab Extrusion

Location BARKINGTON PARK (SITE 14)Sampler Dames & Moore Hydraulic Piston SamplerTube Brass (2.5" O.D.)Boring BH-3Sample 140Start Depth 6.35mEnd Depth 6.80m

Sampling Date _____

Extrusion Date June 17, 2016Weight 3.0255kgTop Empty 6.3 - 6.5cmBottom Empty 0 - 0.5cm

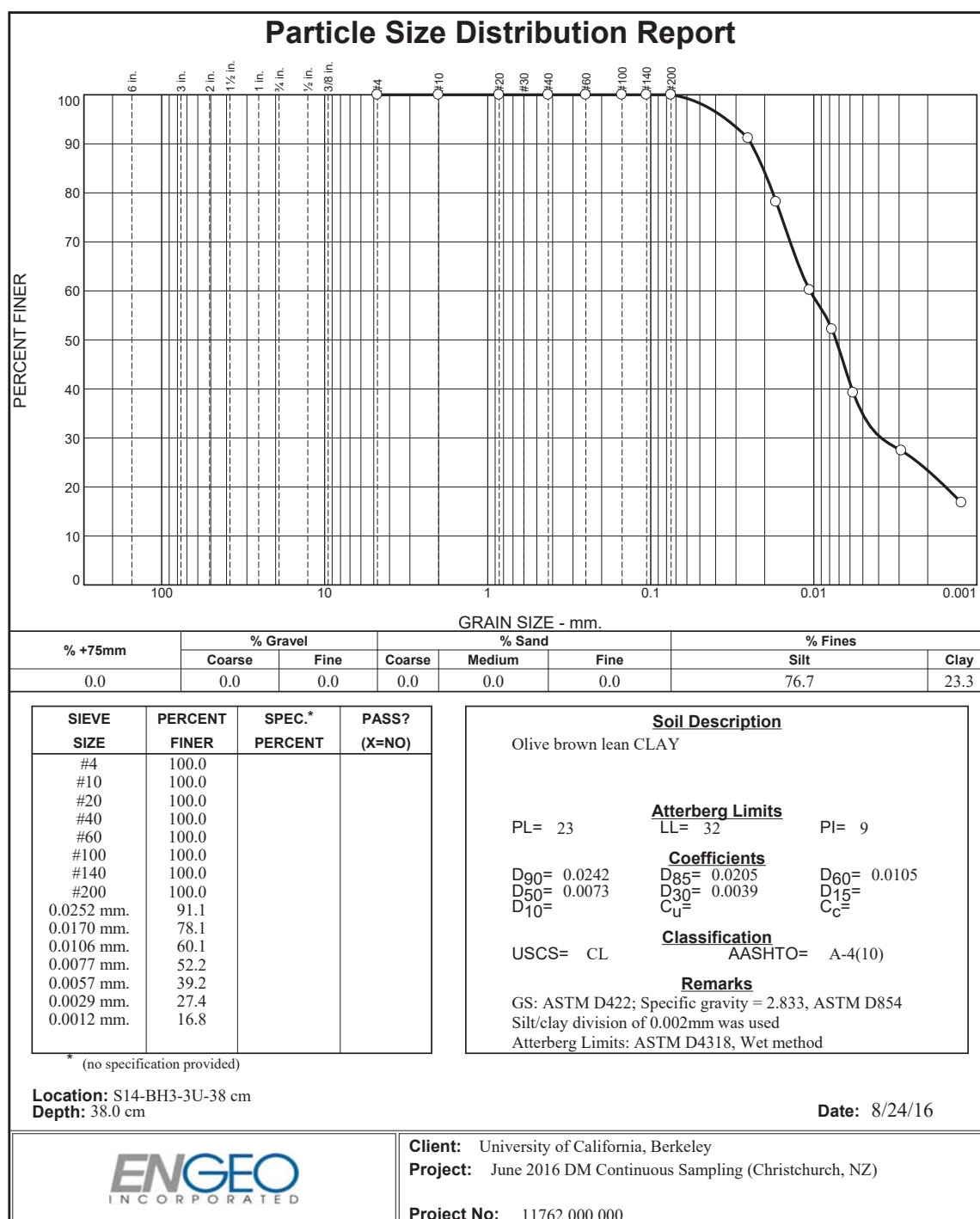
- Sample easy to extrude
 ↳ lubr was not cut.

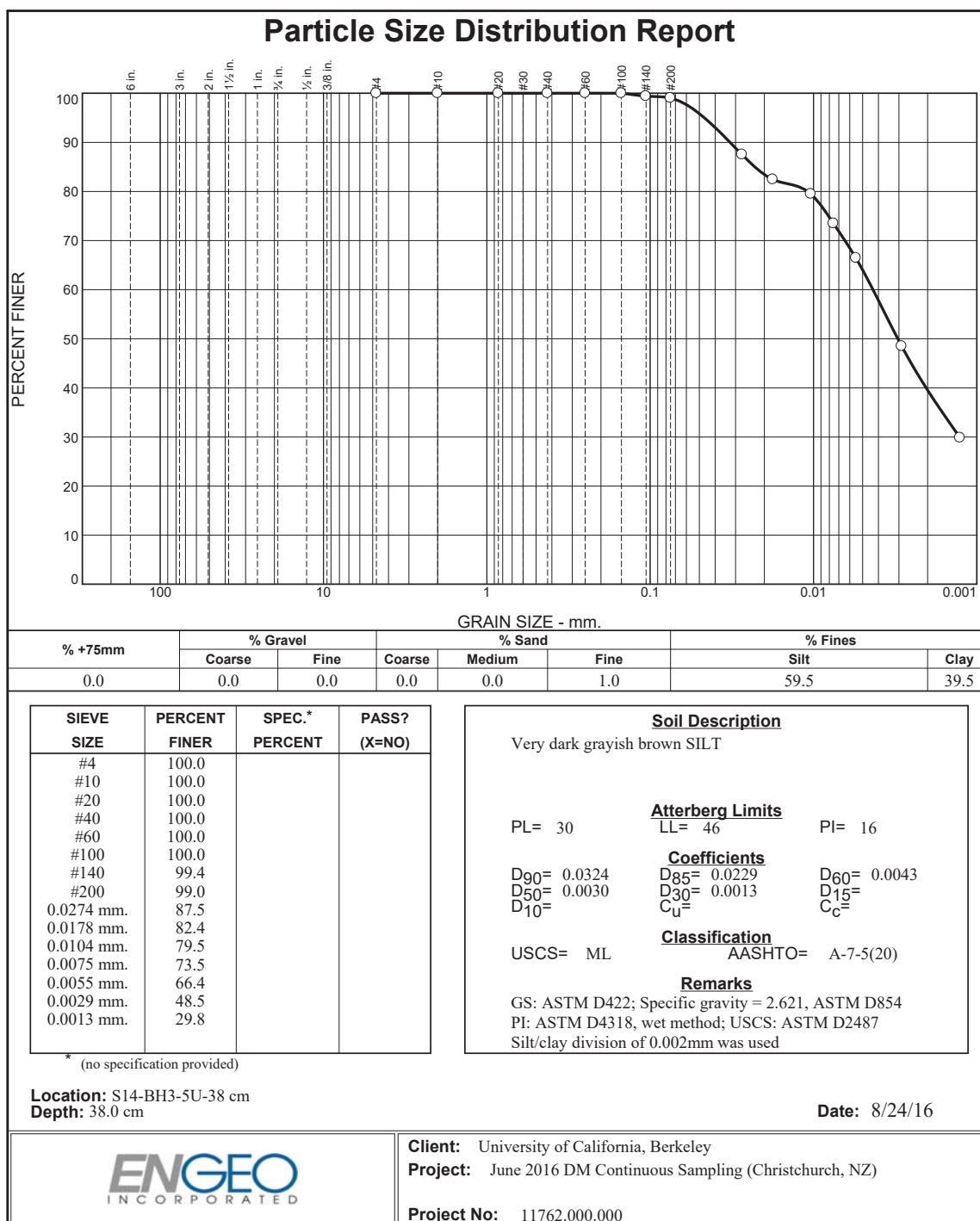


high-energy
 * Like a flood
 over low-energy
 environment

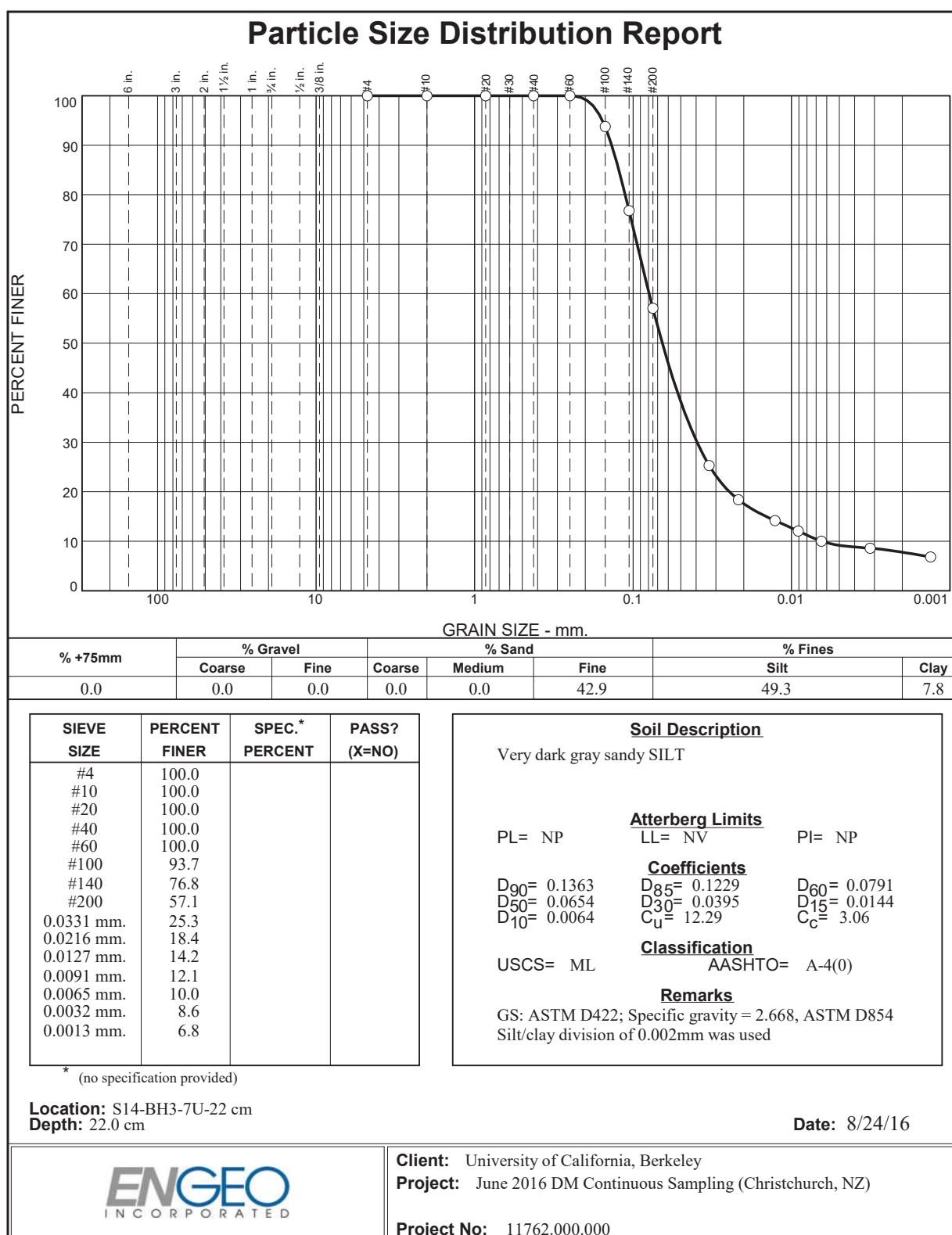
Appendix B.3

Laboratory Testing





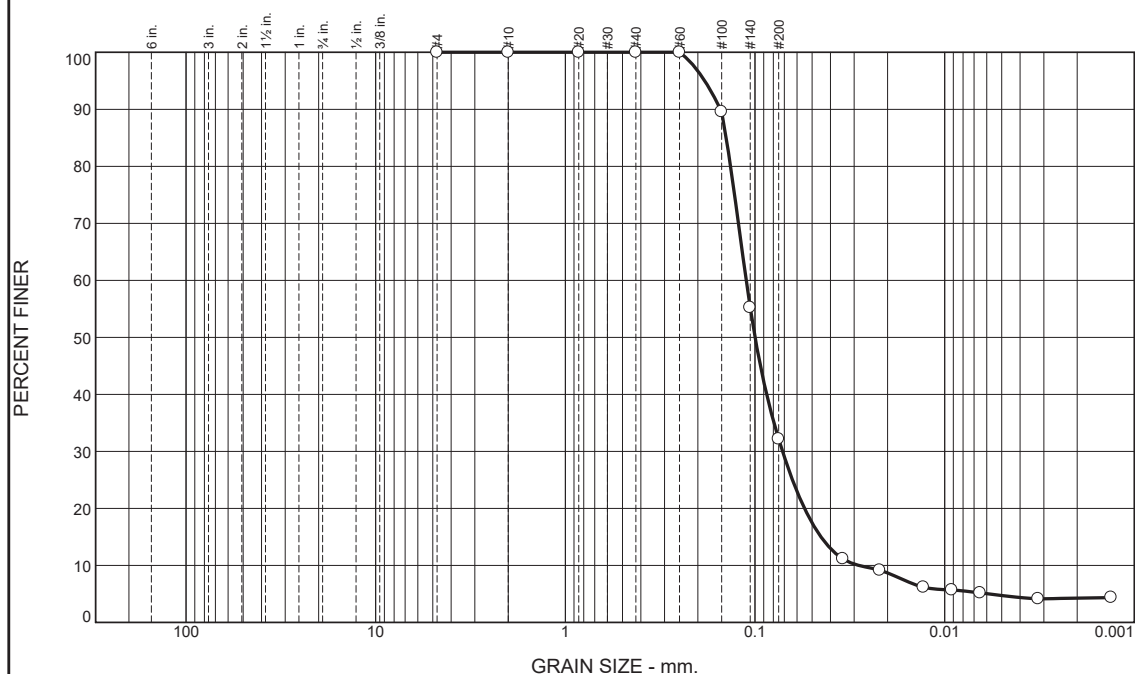
Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem

Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	67.8	27.9	4.3

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	100.0		
#100	89.6		
#140	55.2		
#200	32.2		
0.0344 mm.	11.1		
0.0220 mm.	9.2		
0.0129 mm.	6.2		
0.0092 mm.	5.7		
0.0065 mm.	5.2		
0.0032 mm.	4.1		
0.0013 mm.	4.4		

* (no specification provided)

Location: S14-BH3-8U-37 cm
Depth: 37.0 cm

Date: 8/24/16

Soil Description

Very dark gray silty SAND

Atterberg Limits

PL= LL= PI=

Coefficients

D₉₀= 0.1521 D₈₅= 0.1418 D₆₀= 0.1113
D₅₀= 0.0999 D₃₀= 0.0716 D₁₅= 0.0449
D₁₀= 0.0283 C_u= 3.93 C_c= 1.62

Classification

USCS= AASHTO=

Remarks

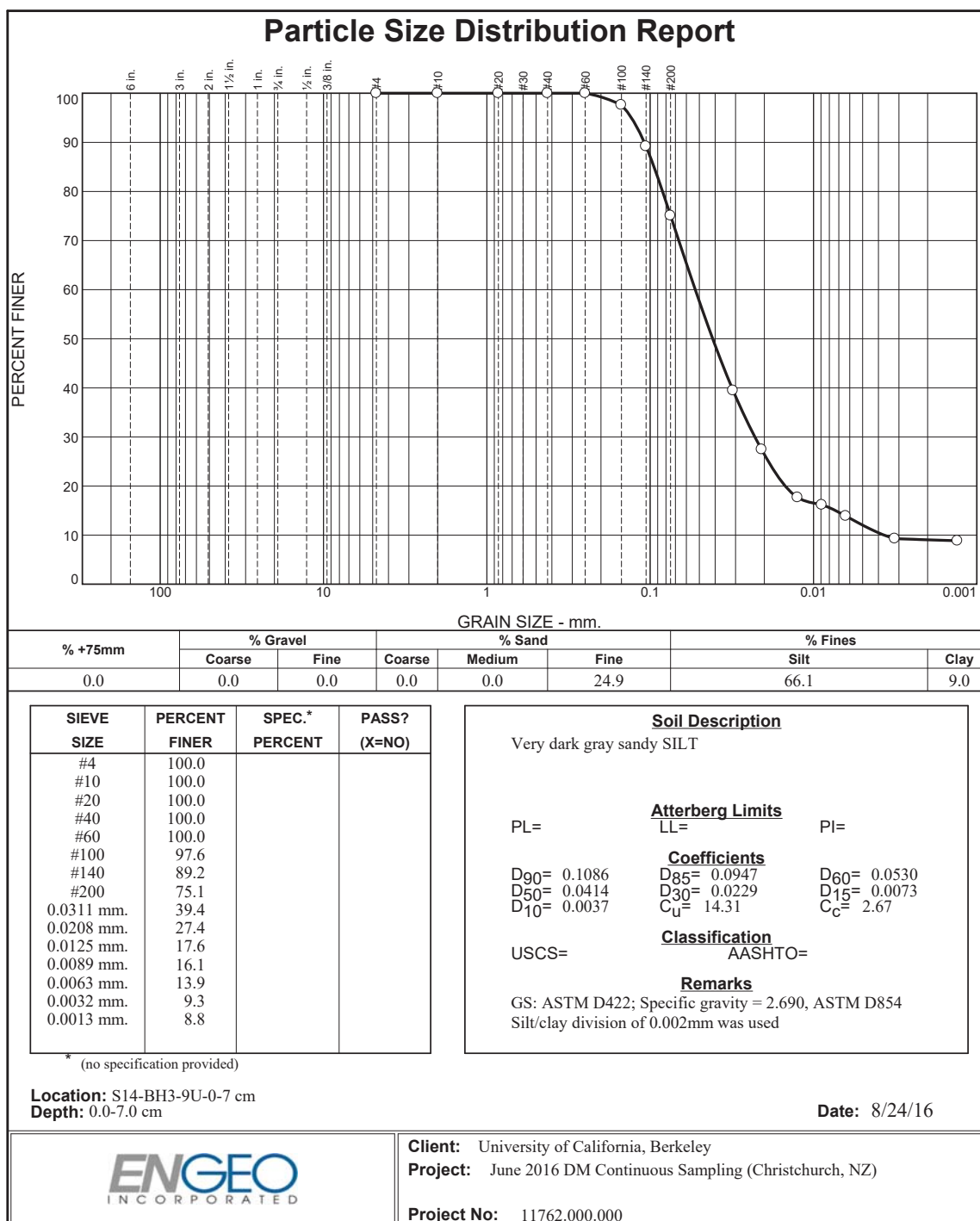
GS: ASTM D422; Specific gravity = 2.689, ASTM D854
Silt/clay division of 0.002mm was used



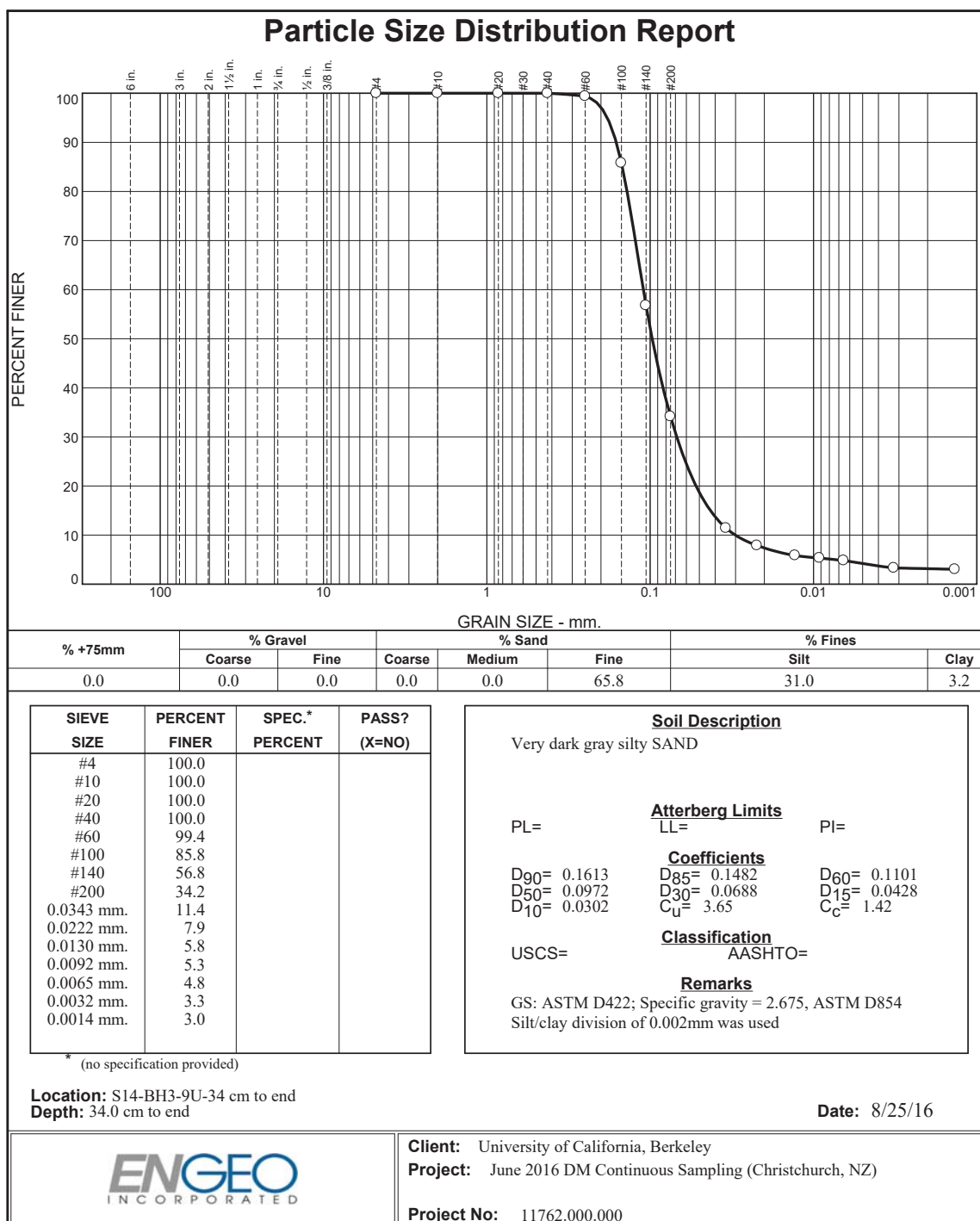
Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)

Project No: 11762.000.000

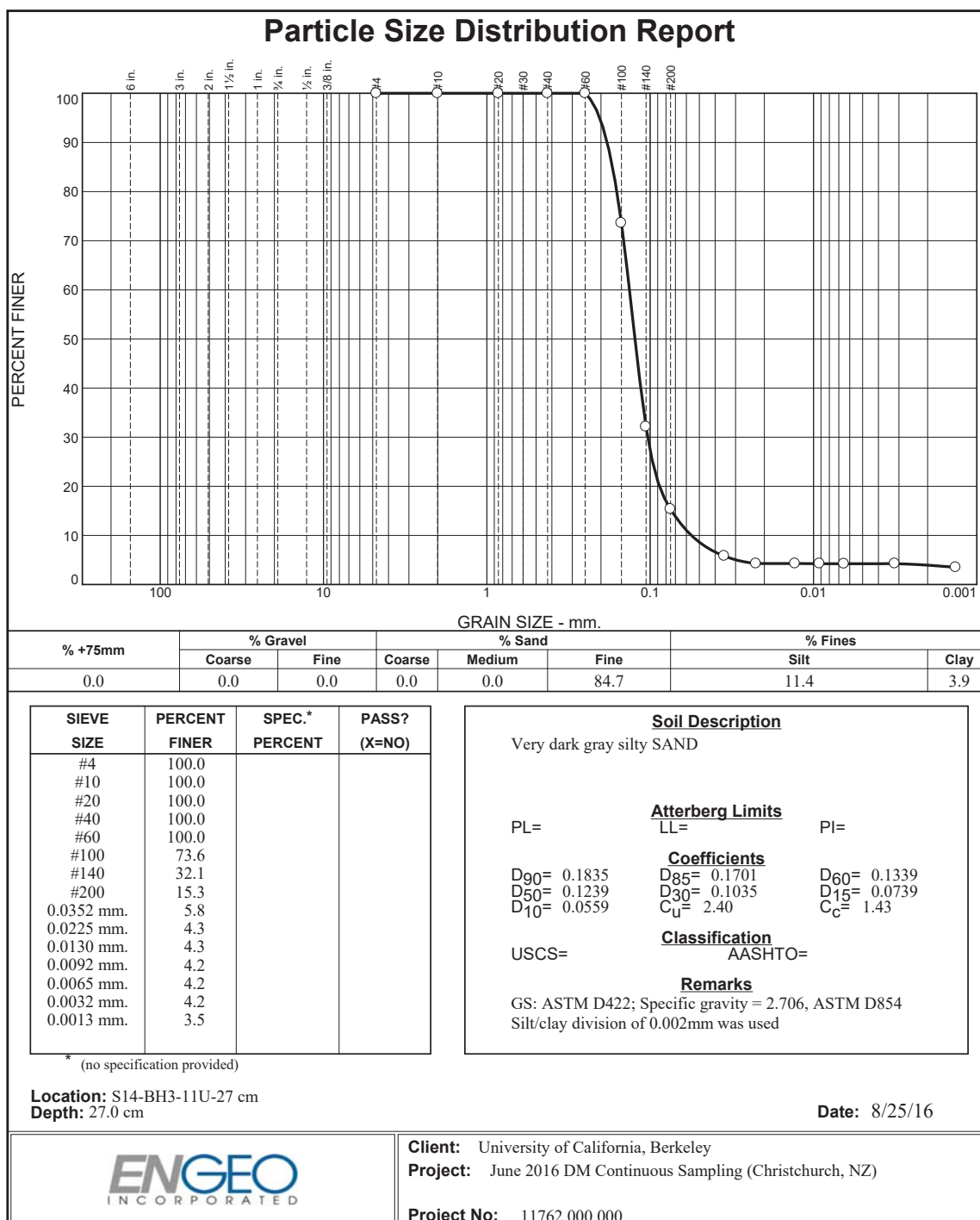
Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

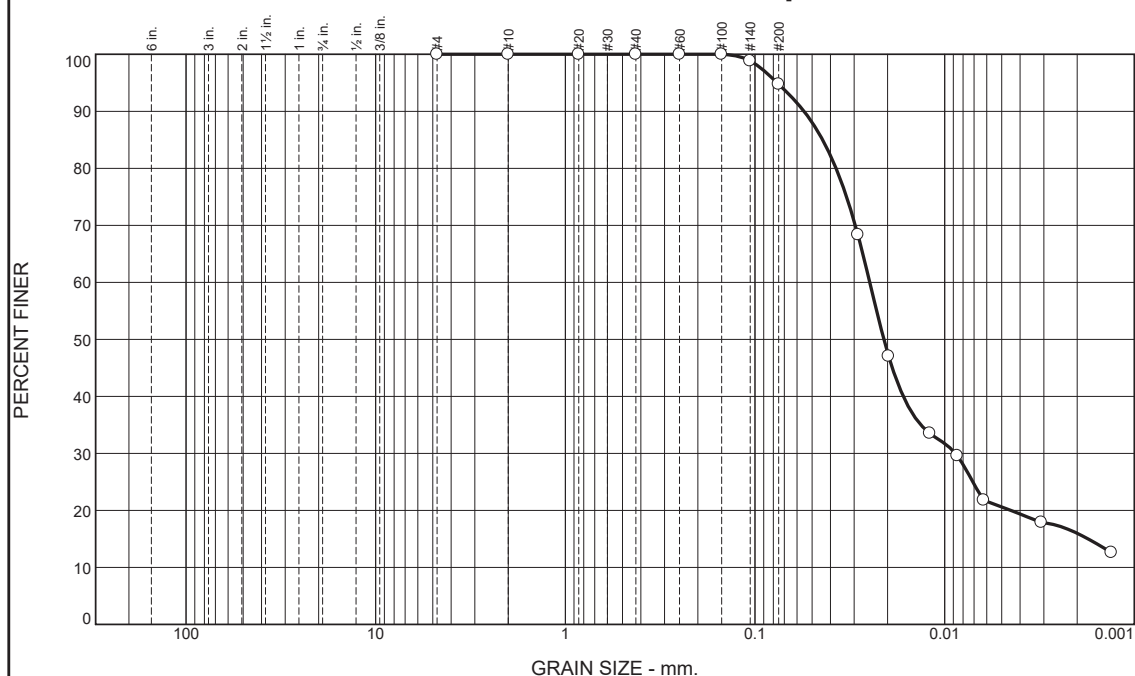


Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	5.2	78.8	16.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	100.0		
#100	100.0		
#140	98.8		
#200	94.8		
0.0287 mm.	68.3		
0.0198 mm.	47.0		
0.0120 mm.	33.5		
0.0086 mm.	29.6		
0.0062 mm.	21.8		
0.0031 mm.	17.9		
0.0013 mm.	12.6		

* (no specification provided)

Location: S14-BH3-11U-32 cm
Depth: 32.0 cm

Date: 8/25/16

Soil Description

Very dark gray SILT

Atterberg Limits

PL= LL= PI=

Coefficients

D₉₀= 0.0552 D₈₅= 0.0440 D₆₀= 0.0248
D₅₀= 0.0209 D₃₀= 0.0088 D₁₅= 0.0018
D₁₀= C_u= C_c=

Classification

USCS= AASHTO=

Remarks

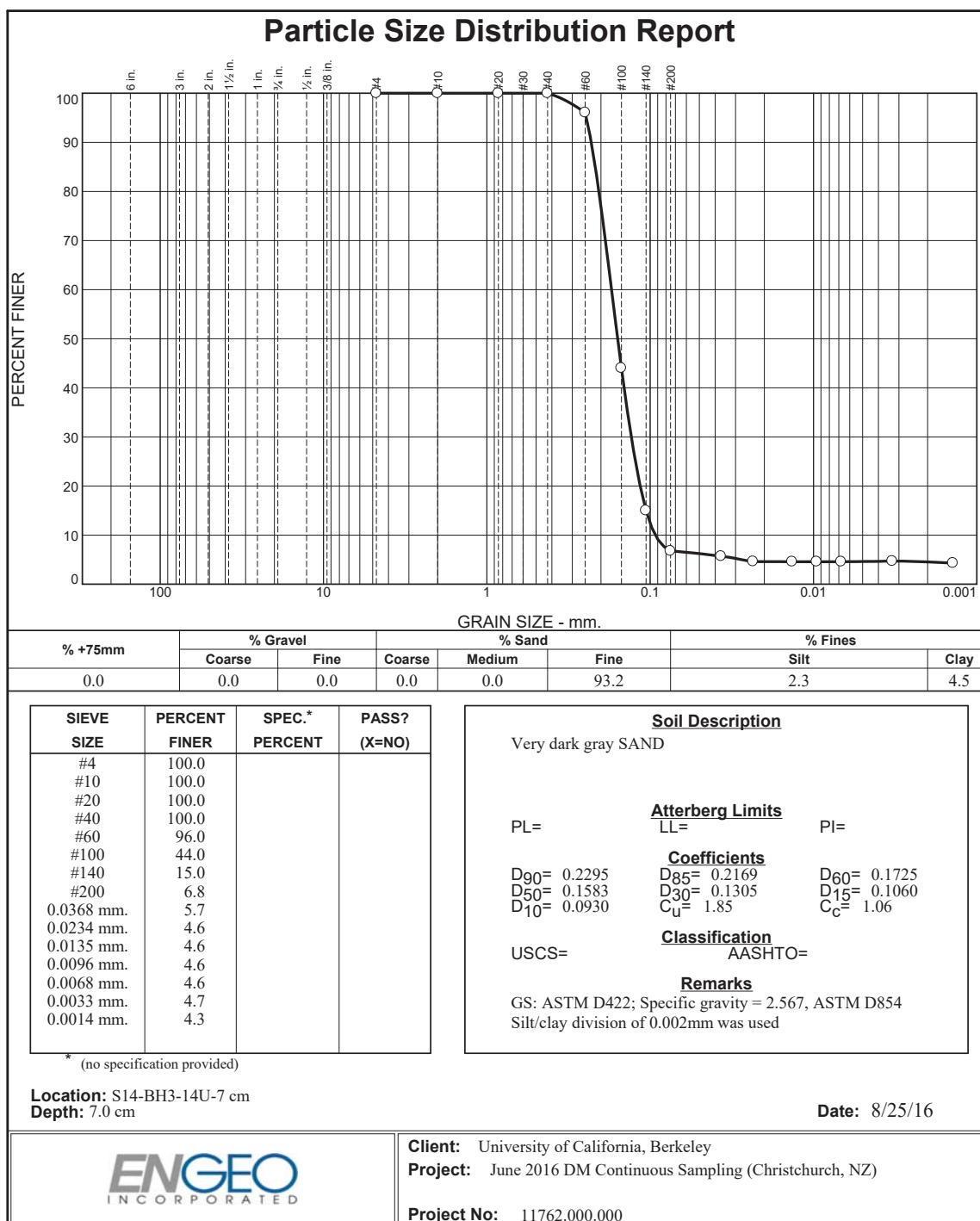
GS: ASTM D422; Specific gravity = 2.709, ASTM D854
Silt/clay division of 0.002mm was used



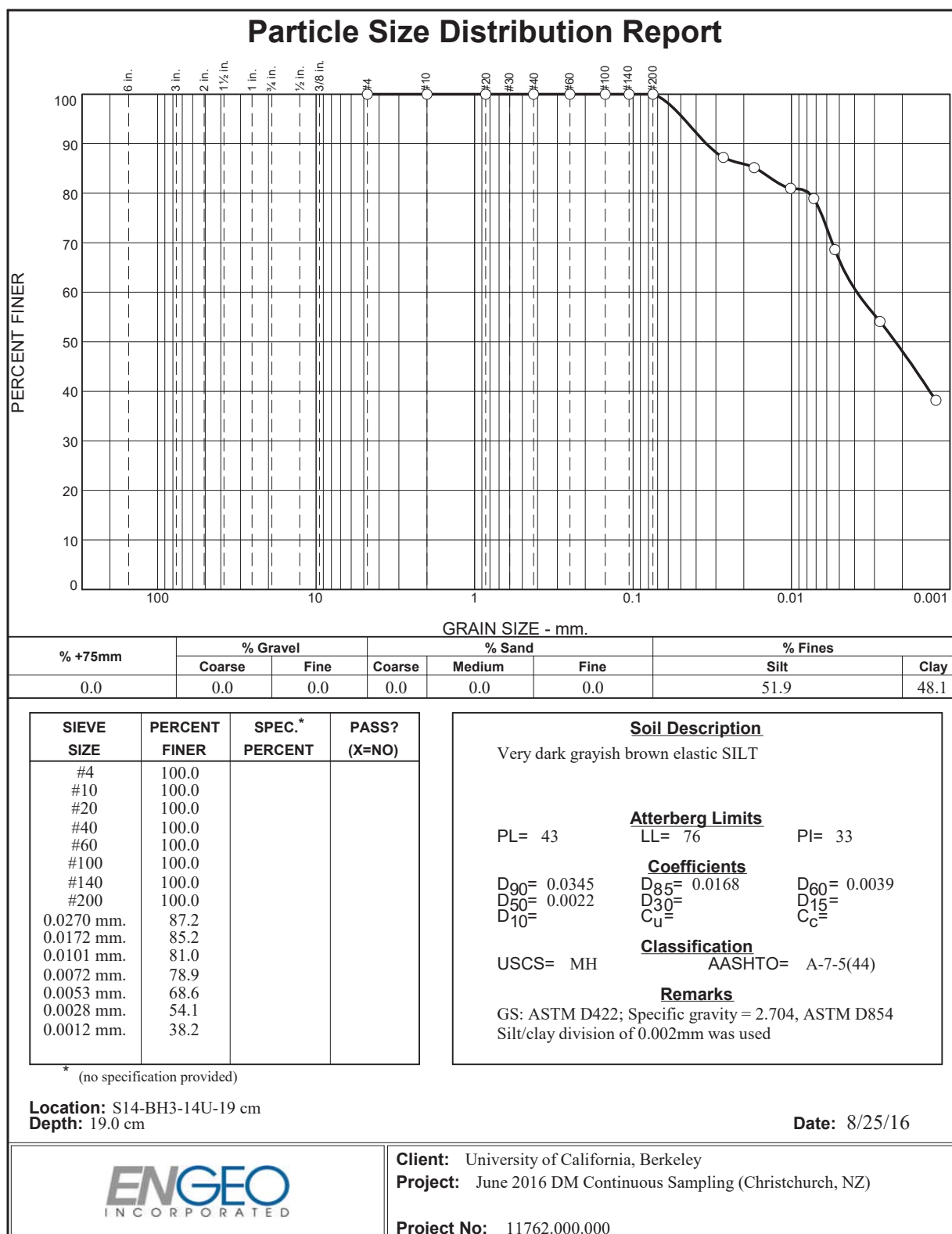
Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)

Project No: 11762.000.000

Tested By: M. Quasem Checked By: M. Tong

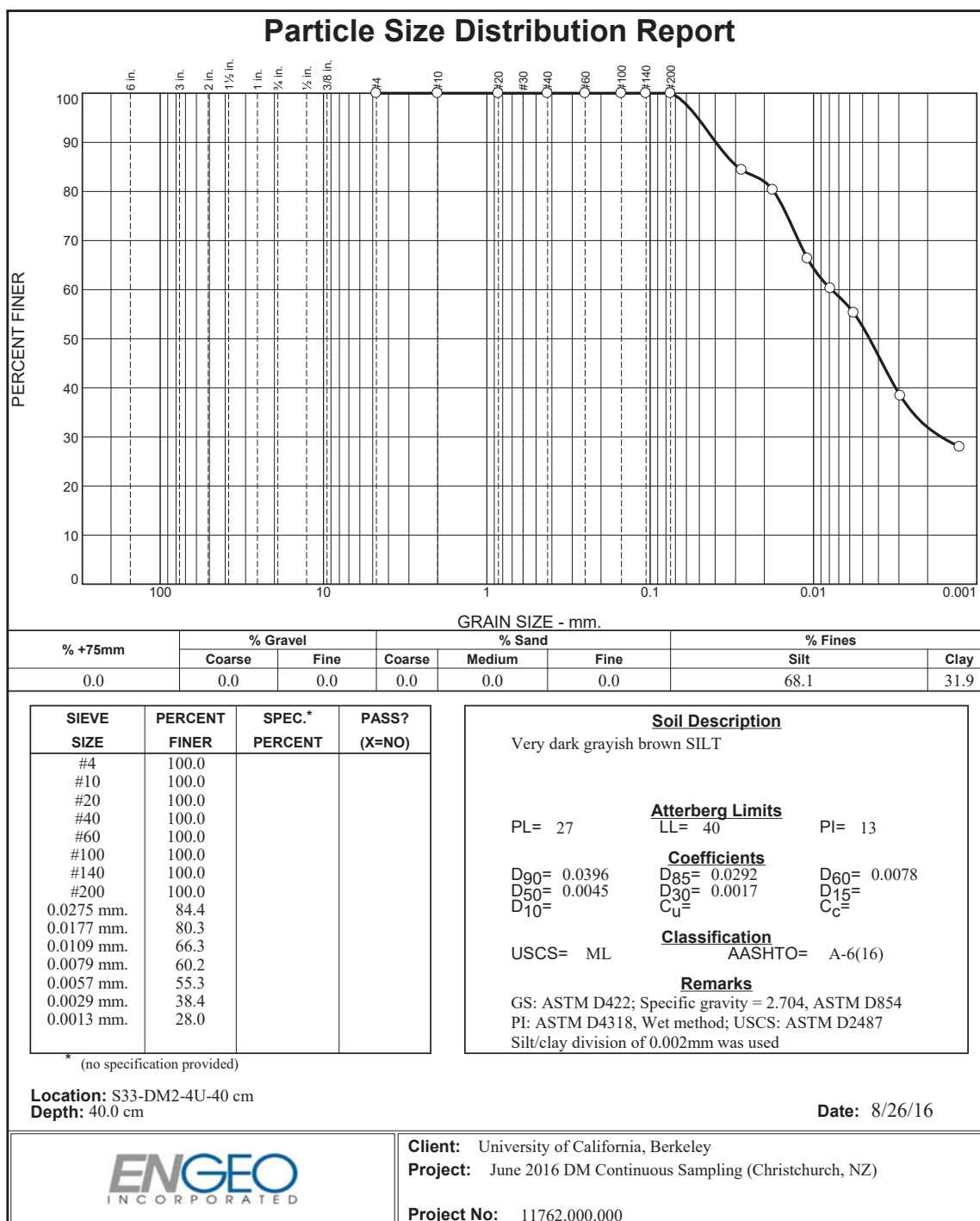


Tested By: M. Quasem Checked By: M. Tong

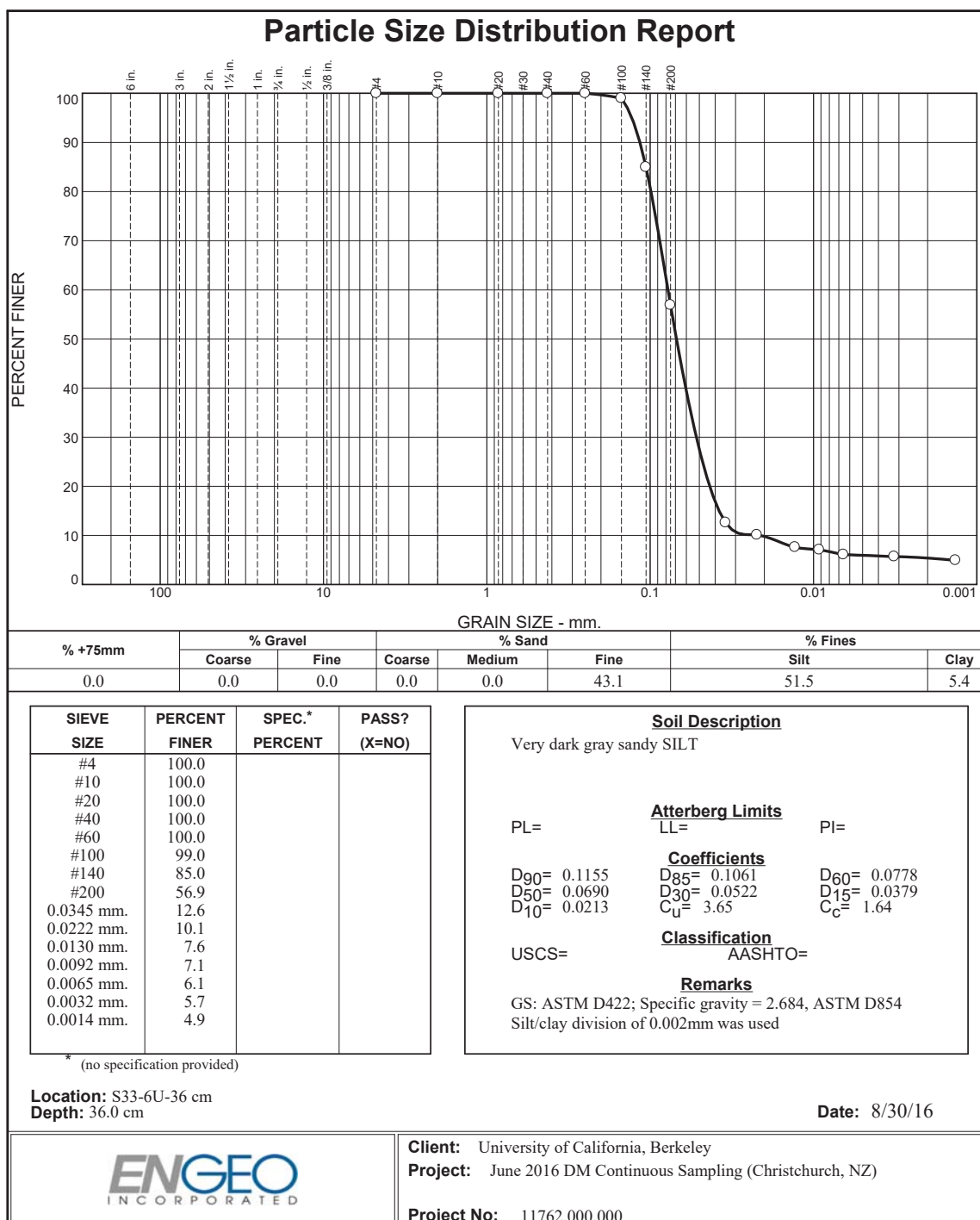


Tested By: M. Quasem

Checked By: M. Tong

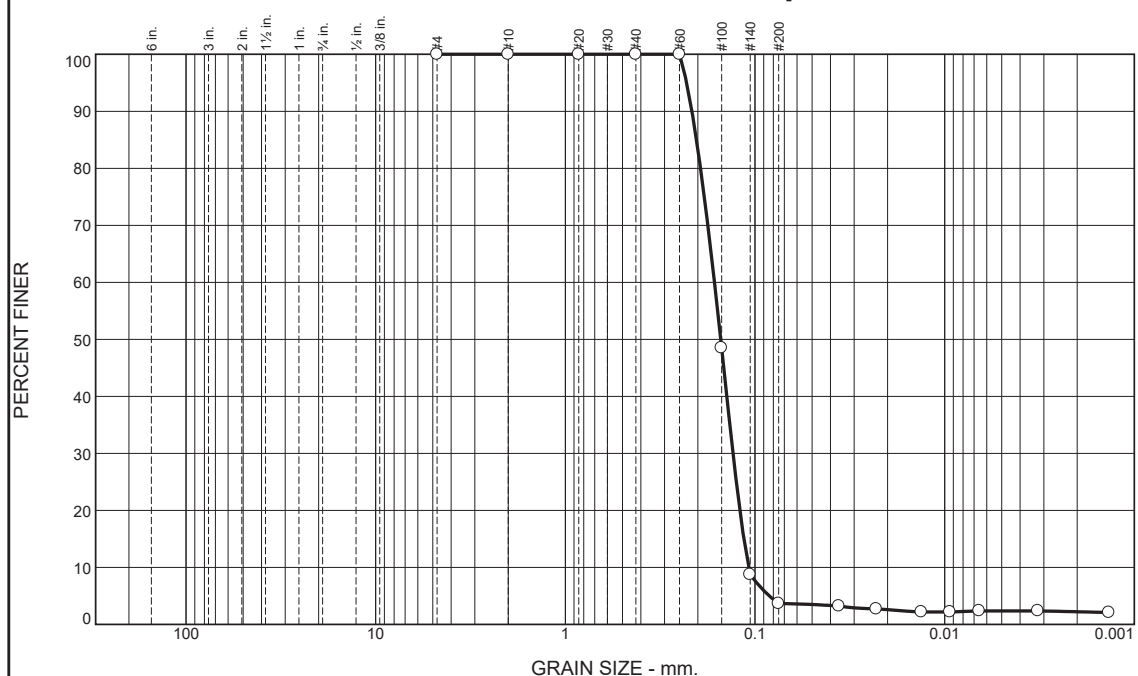


Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	96.3	1.5	2.2

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	100.0		
#100	48.5		
#140	8.7		
#200	3.2		
0.0361 mm.	3.2		
0.0229 mm.	2.7		
0.0133 mm.	2.2		
0.0094 mm.	2.2		
0.0066 mm.	2.4		
0.0032 mm.	2.4		
0.0014 mm.	2.1		

* (no specification provided)

Location: S33-DM2-7U-28 cm
Depth: 28.0 cm

Date: 8/31/16

Soil Description

Very dark gray poorly graded SAND

Atterberg Limits

PL= LL= PI=

Coefficients

D₉₀= 0.2151 D₈₅= 0.2036 D₆₀= 0.1636
D₅₀= 0.1517 D₃₀= 0.1306 D₁₅= 0.1145
D₁₀= 0.1080 C_u= 1.52 C_c= 0.97

Classification

USCS= SP AASHTO=

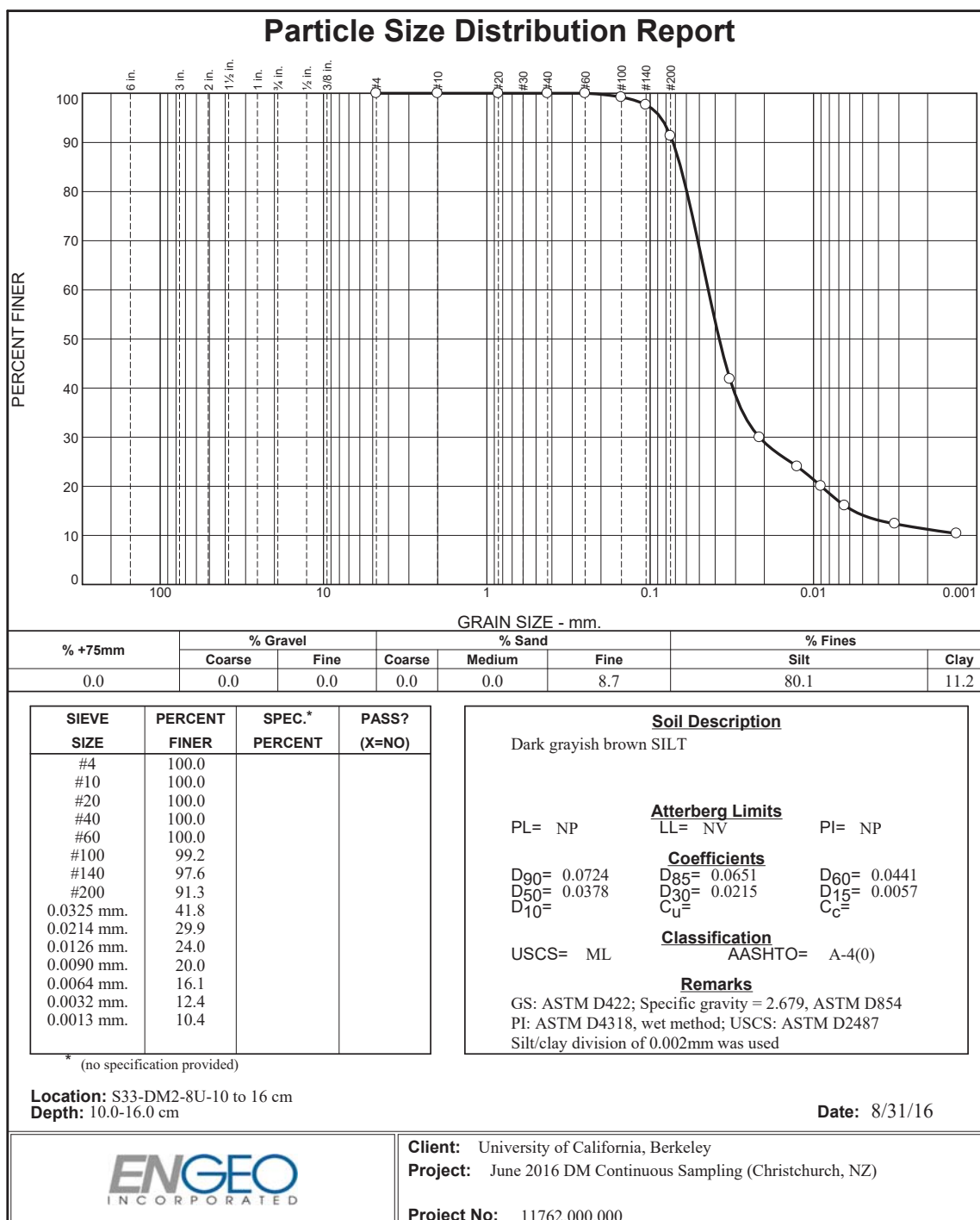
Remarks

GS: ASTM D422; Specific gravity = 2.701, ASTM D854
Silt/clay division of 0.002mm was used



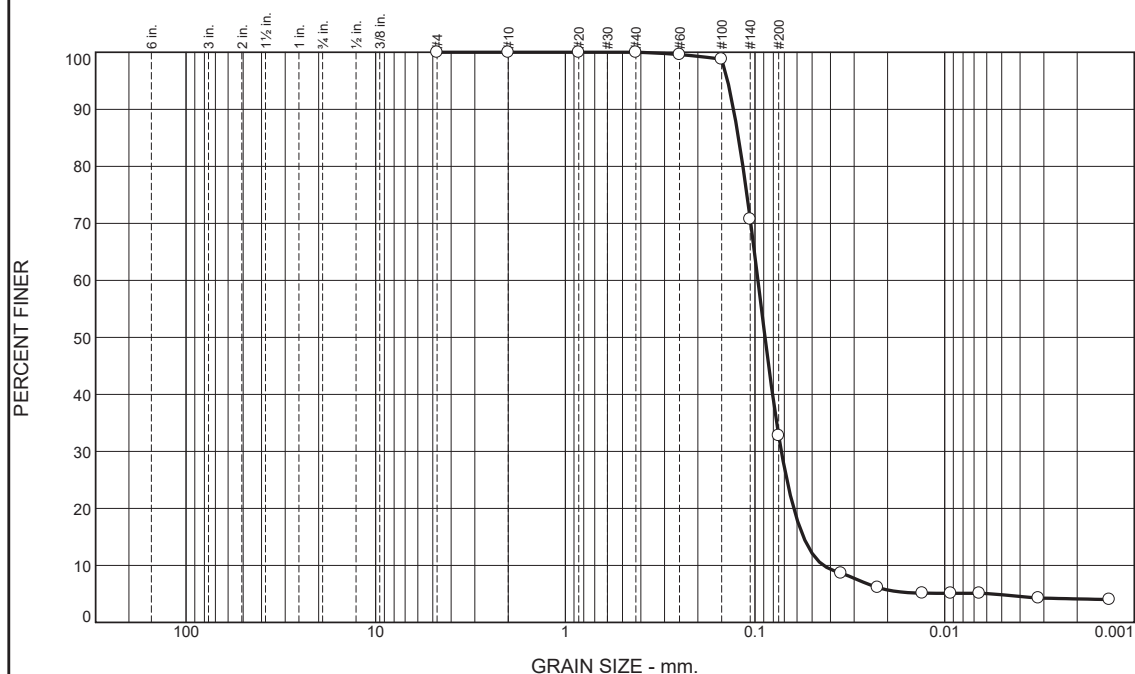
Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)
Project No: 11762.000.000

Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	67.2	28.7	4.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	99.6		
#100	98.8		
#140	70.7		
#200	32.8		
0.0352 mm.	8.6		
0.0226 mm.	6.1		
0.0131 mm.	5.1		
0.0093 mm.	5.1		
0.0066 mm.	5.1		
0.0032 mm.	4.3		
0.0014 mm.	4.0		

* (no specification provided)

Location: S33-DM2-8U-23 to 40 cm
Depth: 23.0-40.0 cm

Soil Description

Very dark gray silty SAND

Atterberg Limits

PL=

LL=

PI=

Coefficients

D₉₀= 0.1298

D₈₅= 0.1222

D₆₀= 0.0965

D₅₀= 0.0885

D₃₀= 0.0726

D₁₅= 0.0556

D₁₀= 0.0435

C_u= 2.22

C_c= 1.26

Classification

USCS=

AASHTO=

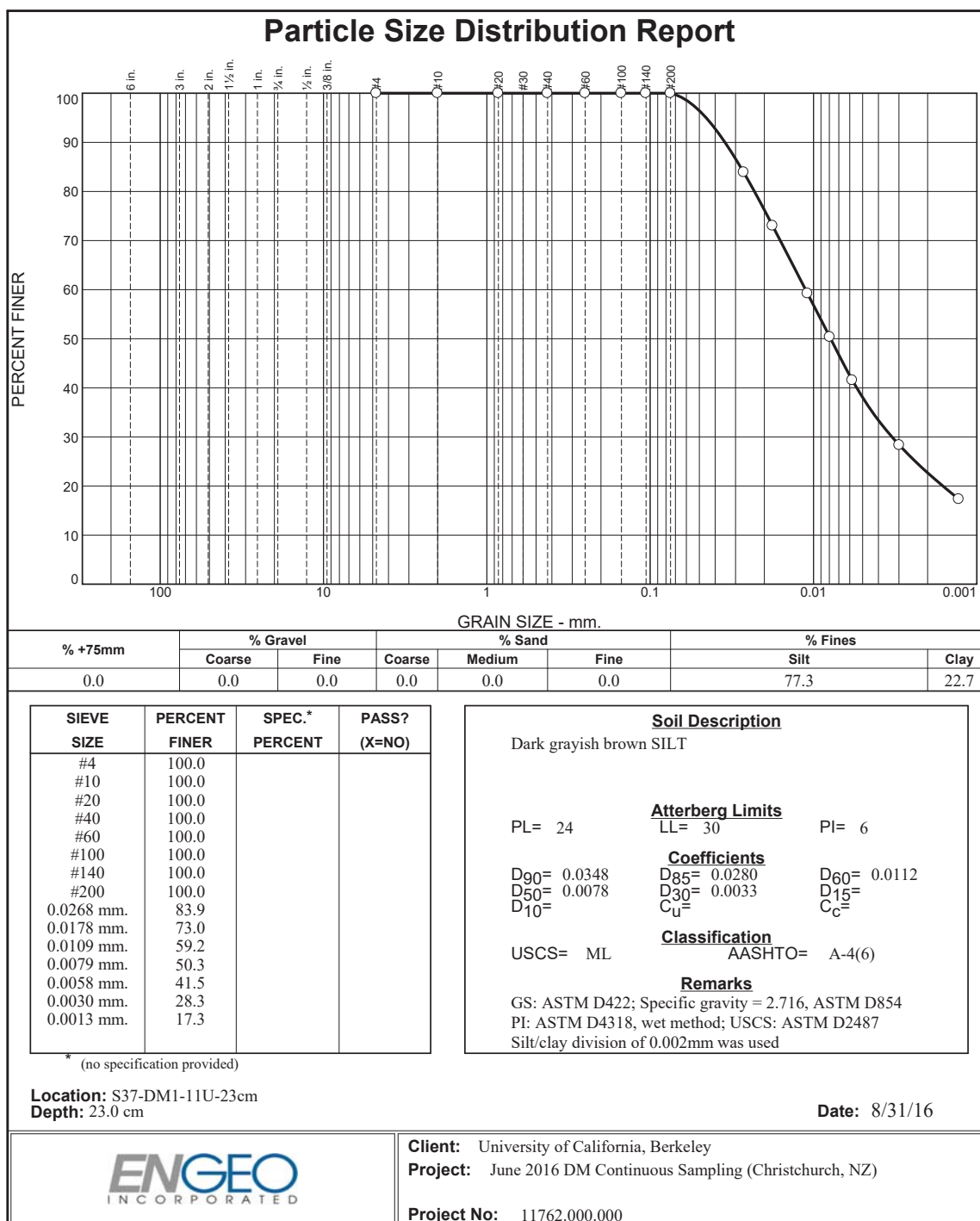
Remarks

GS: ASTM D422; Specific gravity = 2.679, ASTM D854
Silt/clay division of 0.002mm was used

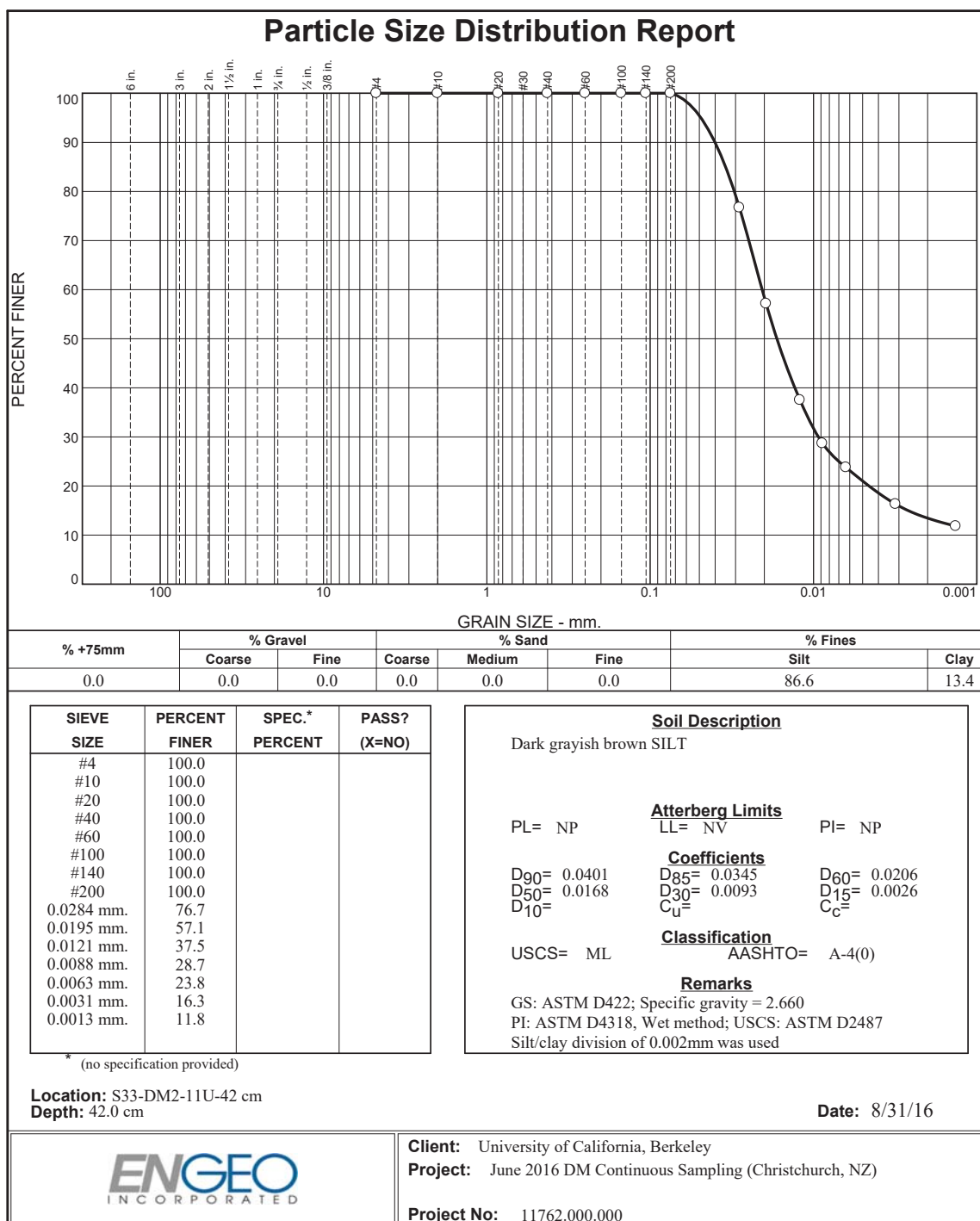


Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)
Project No: 11762.000.000

Tested By: M. Quasem **Checked By:** M. Tong

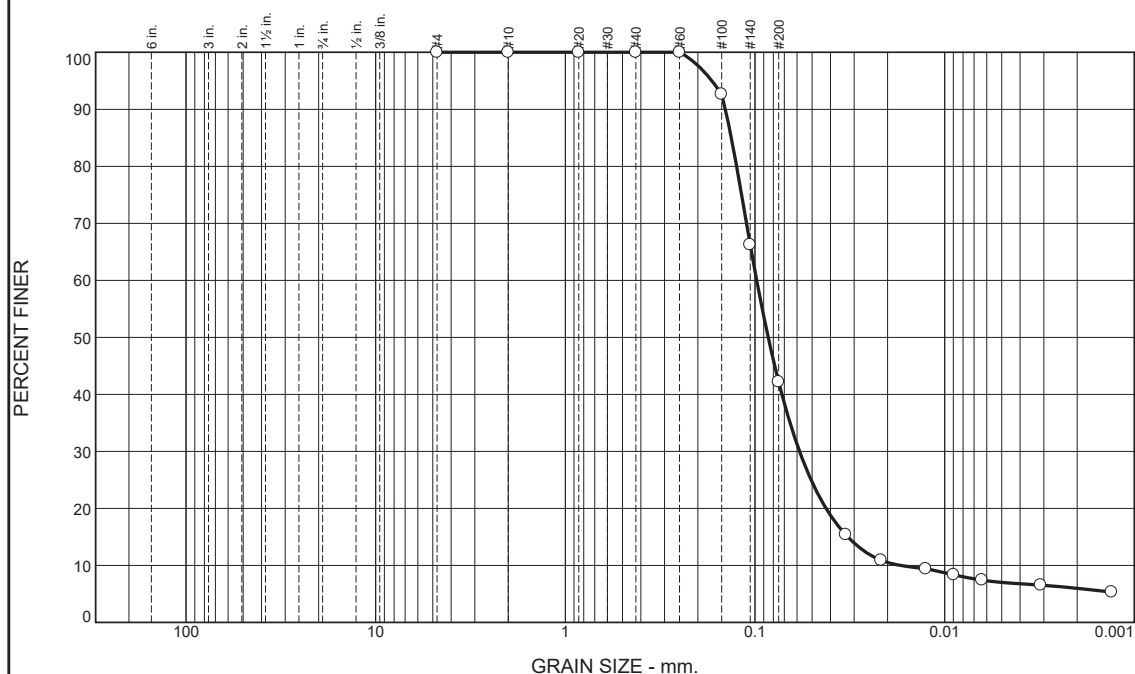


Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	57.8	36.2	6.0

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	100.0		
#100	92.6		
#140	66.2		
#200	42.2		
0.0332 mm.	15.4		
0.0216 mm.	10.9		
0.0126 mm.	9.4		
0.0090 mm.	8.4		
0.0064 mm.	7.4		
0.0031 mm.	6.5		
0.0013 mm.	5.3		

* (no specification provided)

Location: S37-DM1-4U-38cm to end
Depth: 38.0 cm to end

Date: 8/30/16

Soil Description

Light olive brown silty SAND

Atterberg Limits

PL= LL= PI=

Coefficients

D₉₀= 0.1433 D₈₅= 0.1333 D₆₀= 0.0979
D₅₀= 0.0851 D₃₀= 0.0582 D₁₅= 0.0324
D₁₀= 0.0172 C_u= 5.71 C_c= 2.02

Classification

USCS= AASHTO=

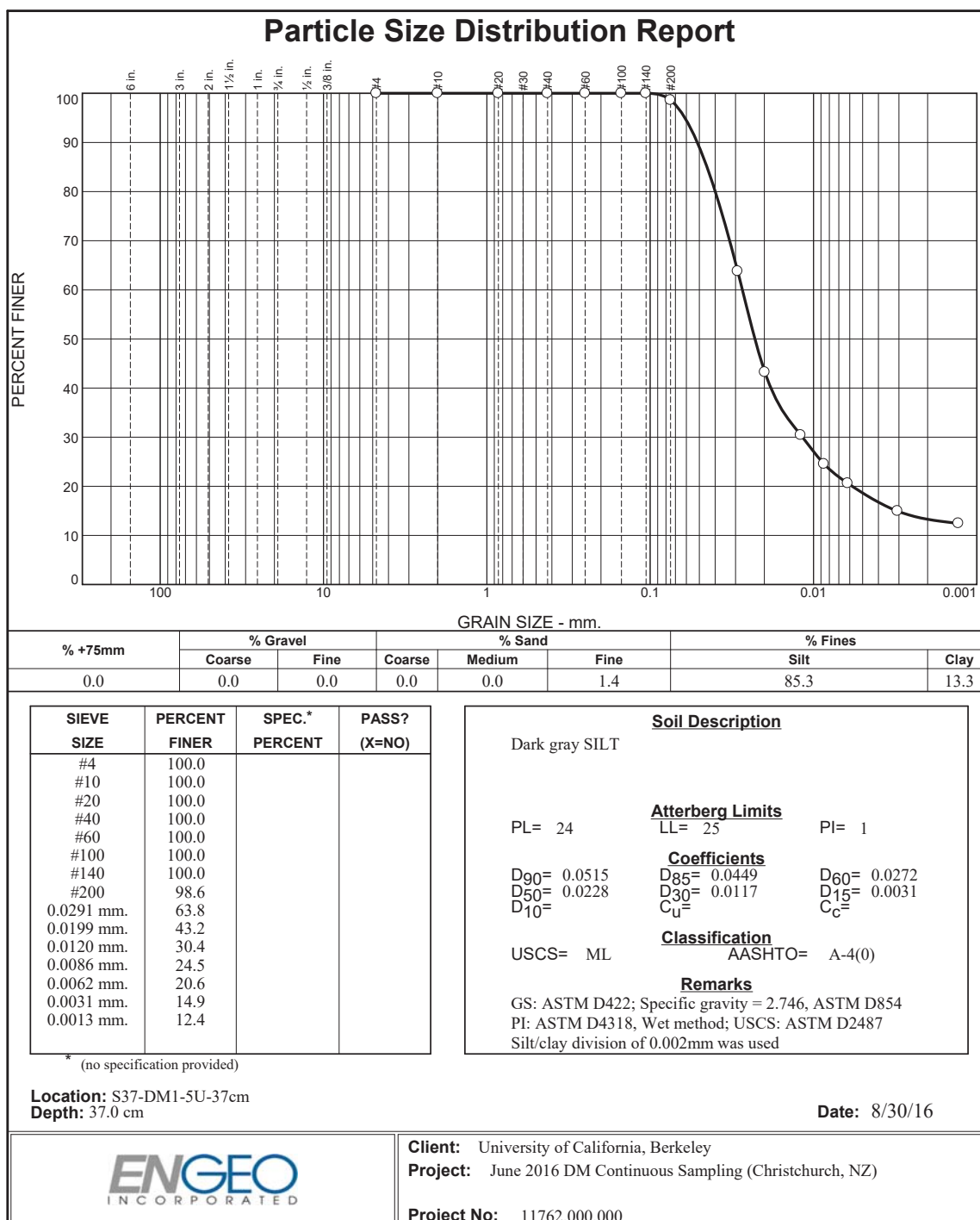
Remarks

GS: ASTM D422; Specific gravity = 2.709, ASTM D854
Silt/clay division of 0.002mm was used



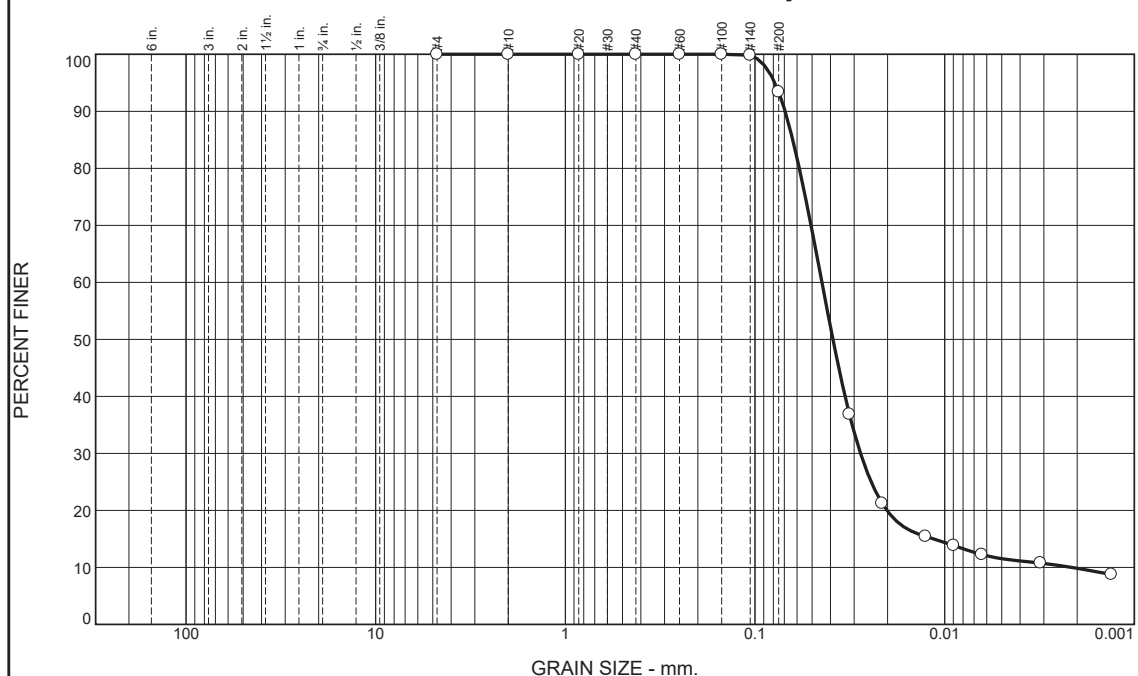
Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)
Project No: 11762.000.000

Tested By: M. Quasem **Checked By:** M. Tong



Tested By: M. Quasem Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	6.6	83.6	9.8

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	100.0		
#100	100.0		
#140	99.8		
#200	93.4		
0.0318 mm.	36.8		
0.0214 mm.	21.2		
0.0126 mm.	15.4		
0.0090 mm.	13.8		
0.0064 mm.	12.3		
0.0031 mm.	10.8		
0.0013 mm.	8.8		

* (no specification provided)

Location: S37-DM1-6U-23 to 27cm
Depth: 23.0-27.0 cm

Date: 8/30/16

Soil Description

Dark grayish brown SILT

Atterberg Limits

PL= LL= PI=

Coefficients

D₉₀= 0.0694 D₈₅= 0.0633 D₆₀= 0.0444
D₅₀= 0.0388 D₃₀= 0.0278 D₁₅= 0.0115
D₁₀= 0.0021 C_u= 20.66 C_c= 8.10

Classification

USCS= AASHTO=

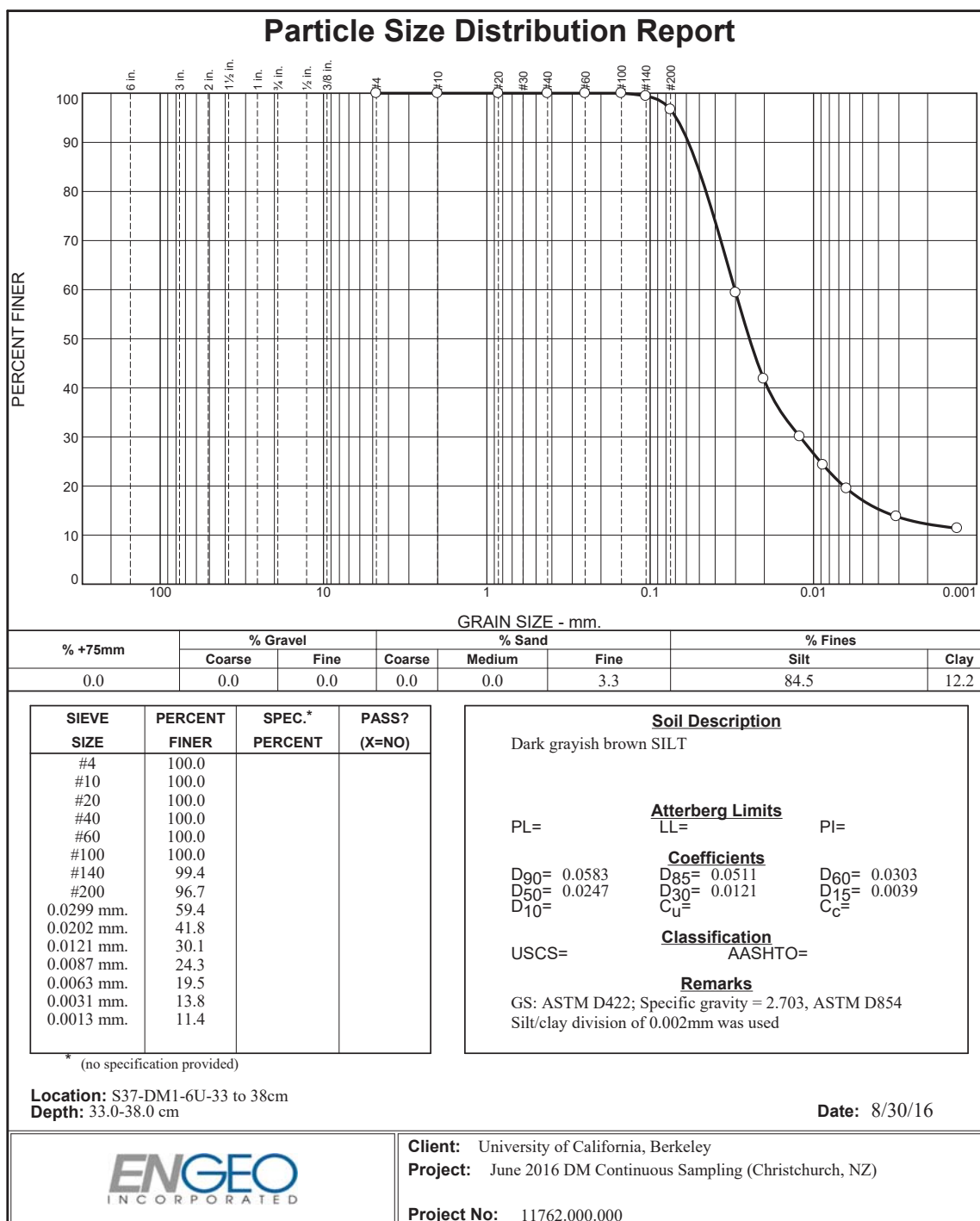
Remarks

GS: ASTM D422; Specific gravity = 2.701, ASTM D854
Silt/clay division of 0.002mm was used

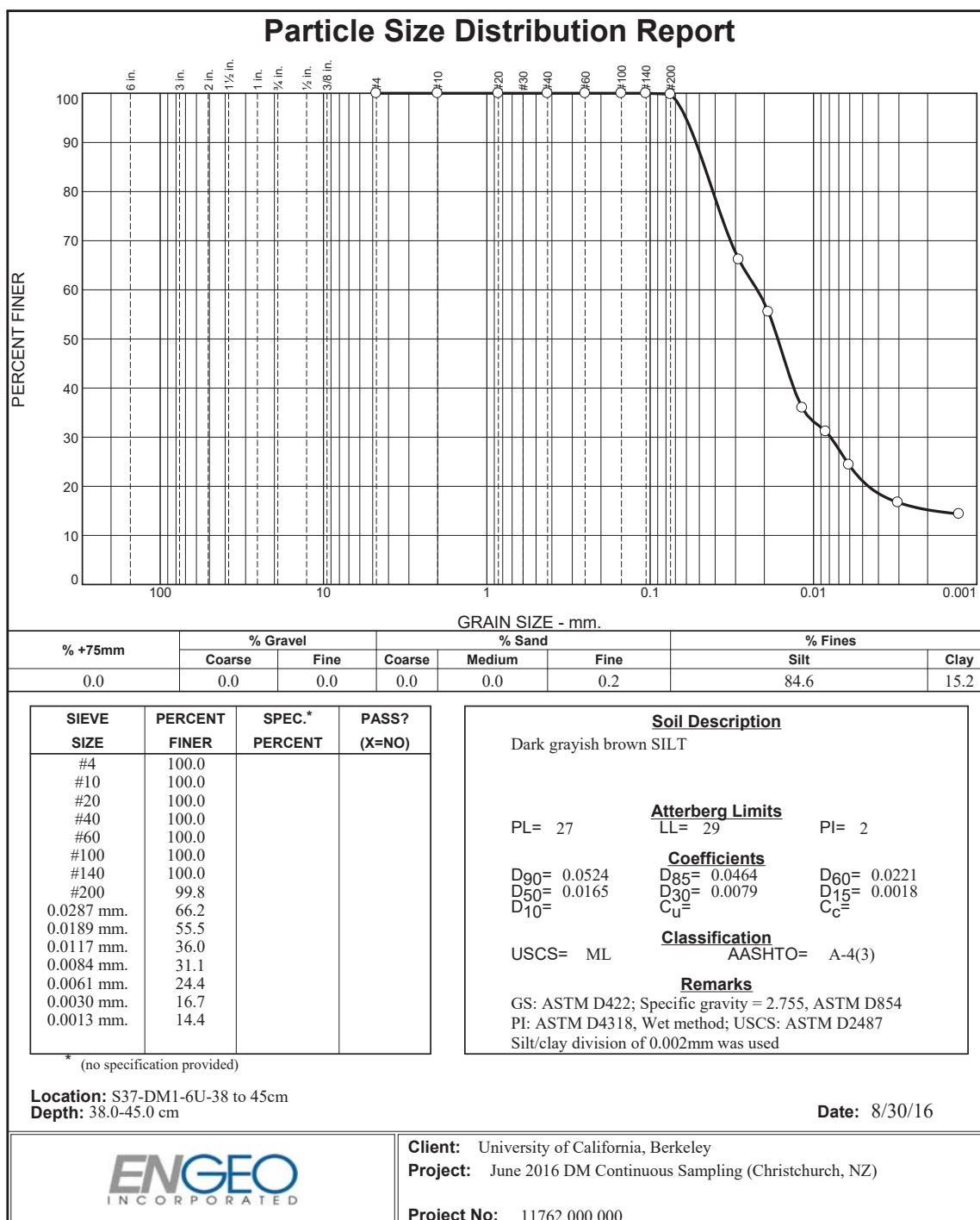


Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)
Project No: 11762.000.000

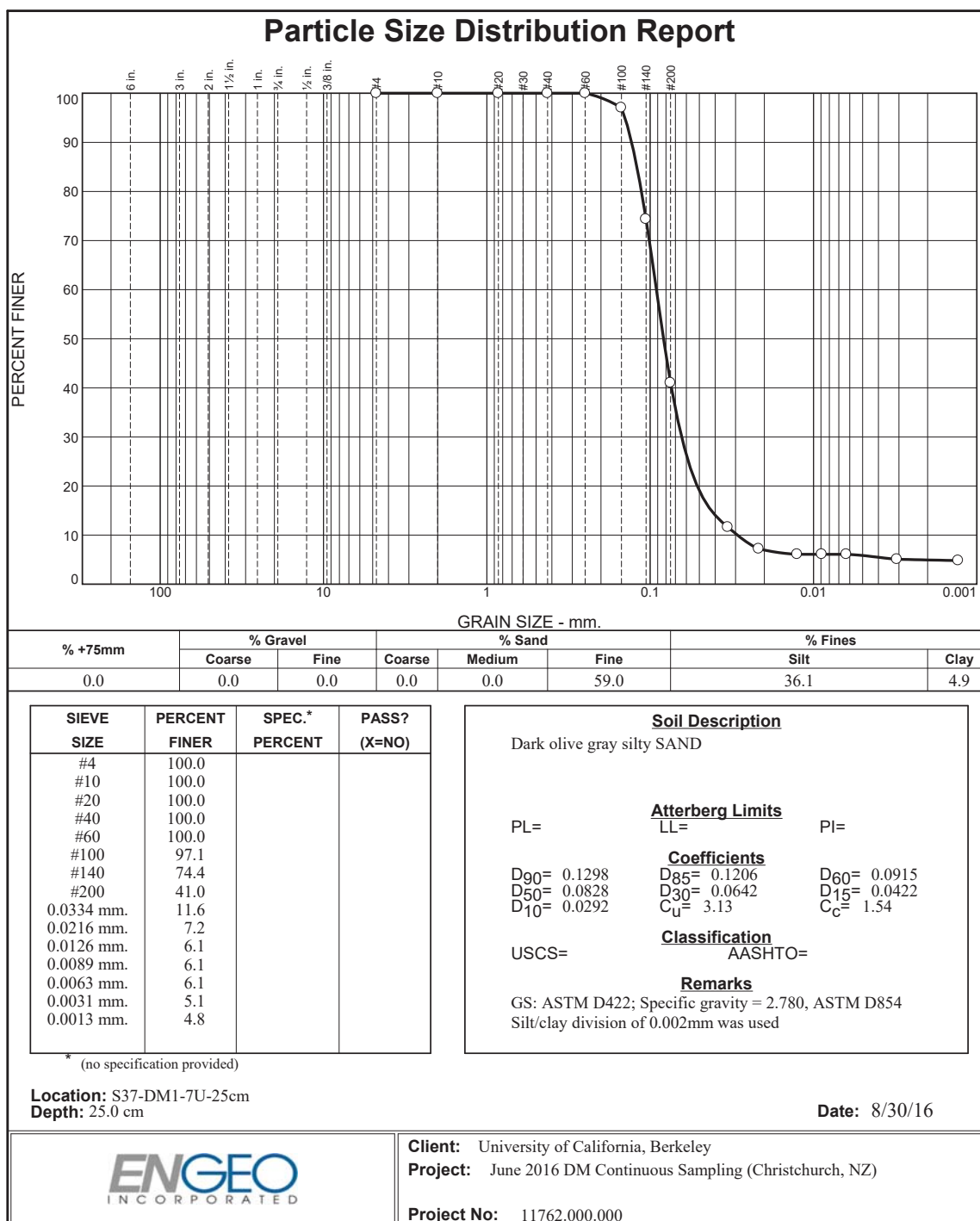
Tested By: M. Quasem Checked By: M. Tong



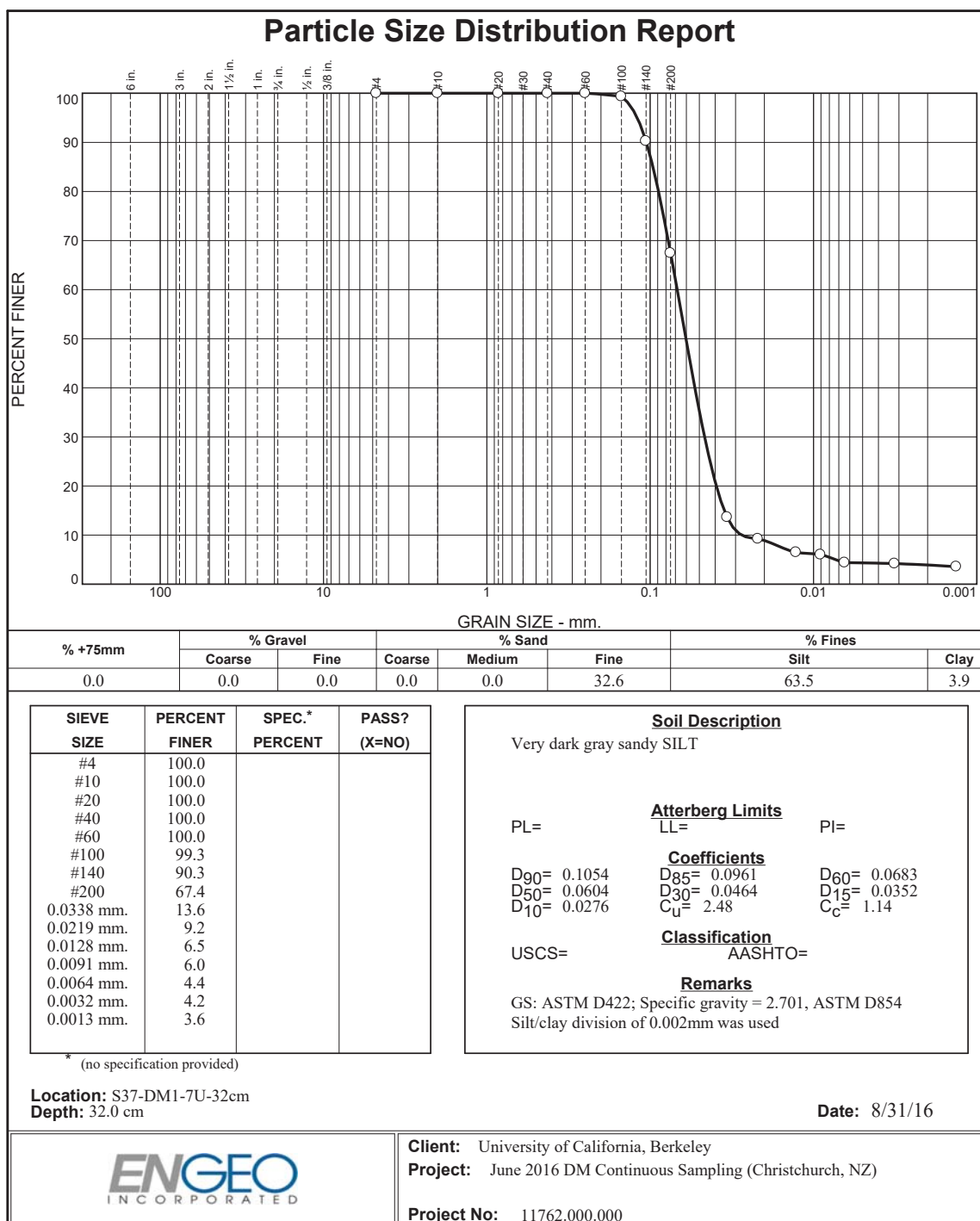
Tested By: M. Quasem Checked By: M. Tong



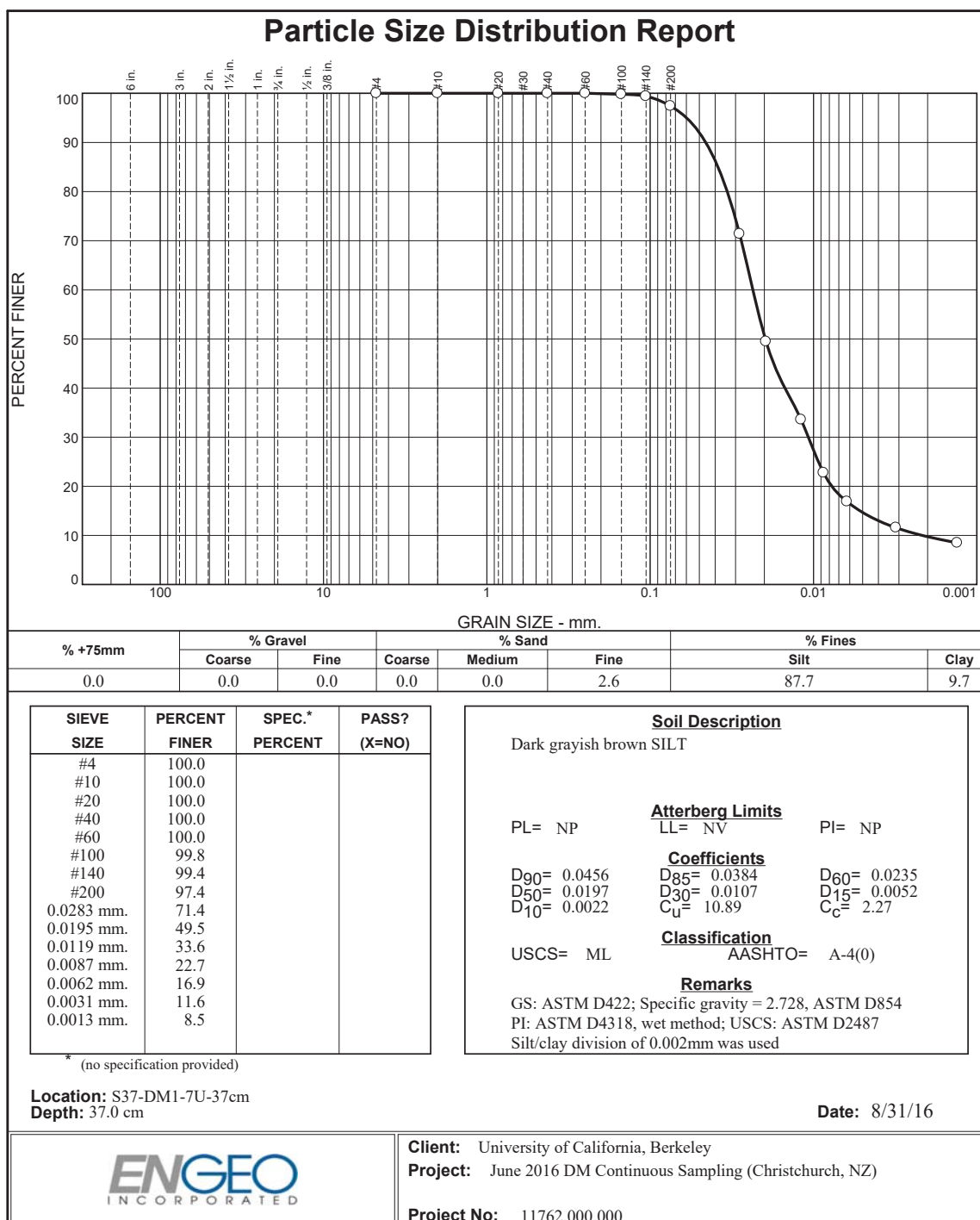
Tested By: M. Quasem Checked By: M. Tong



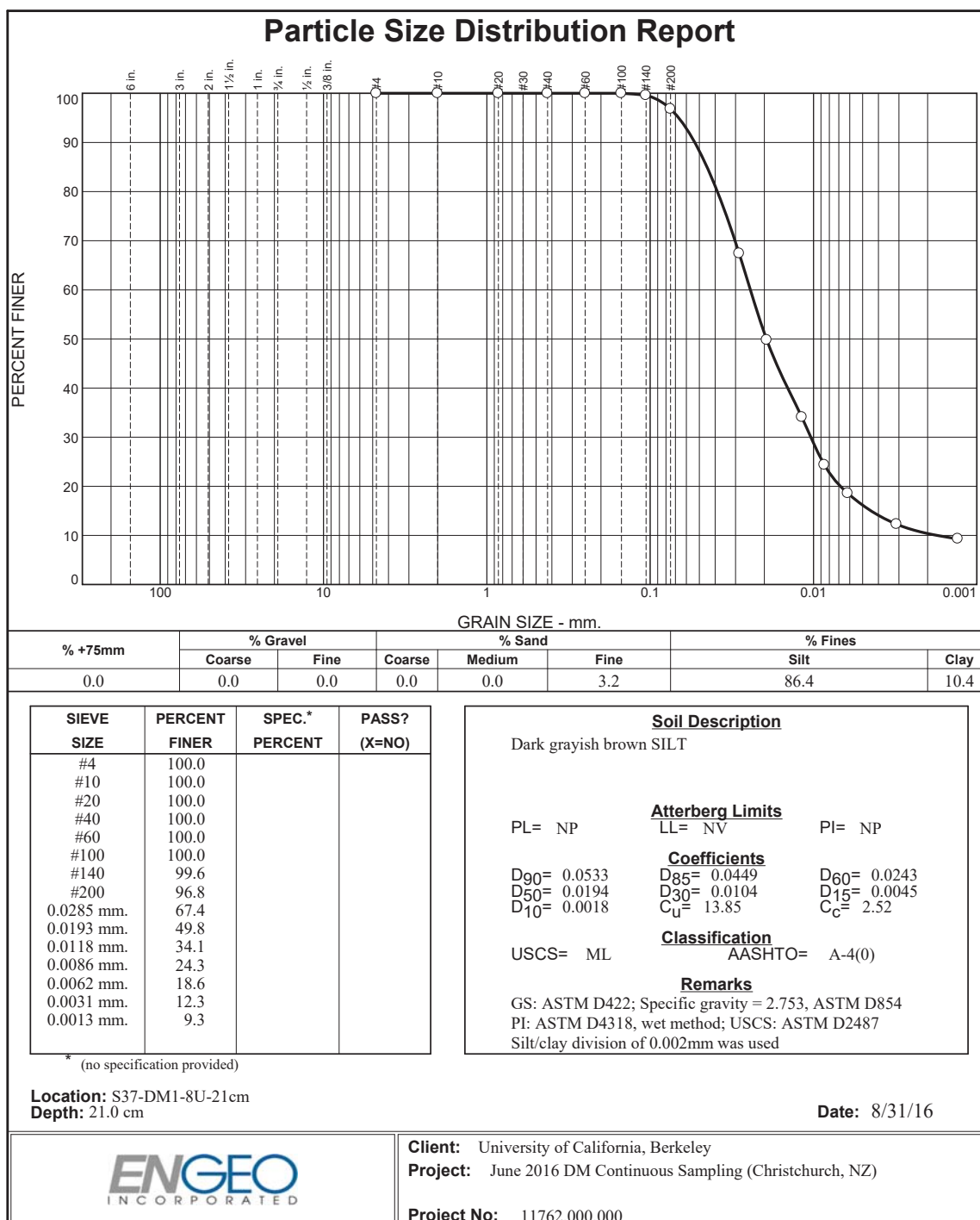
Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

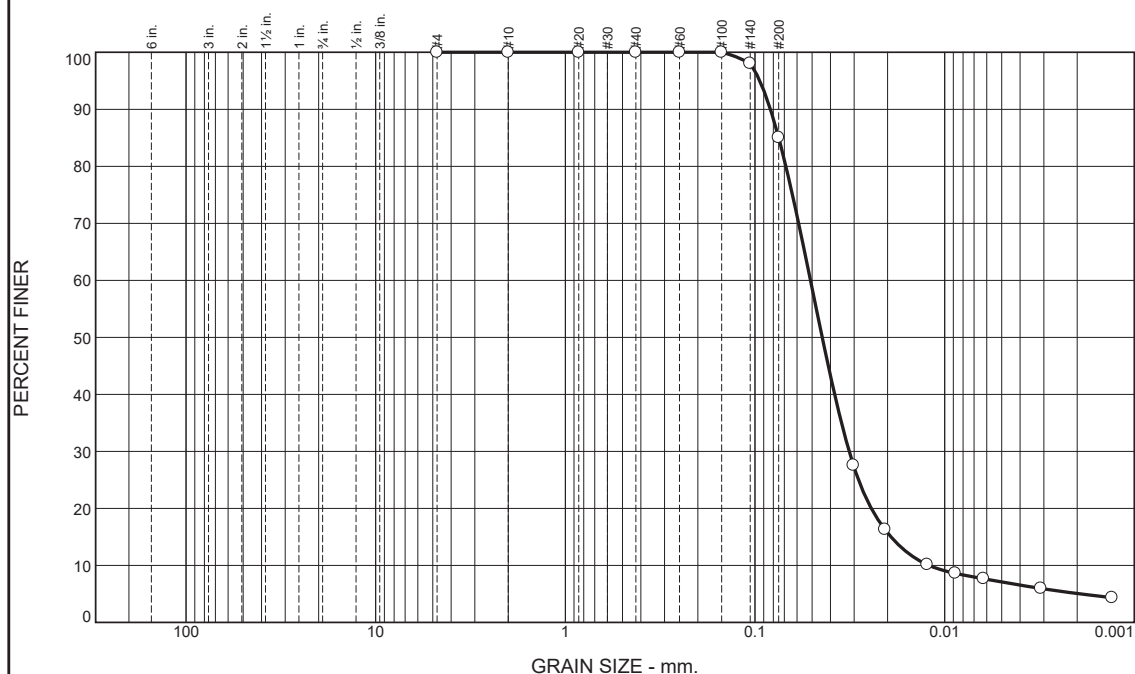


Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

Particle Size Distribution Report



% +75mm	% Gravel		% Sand			% Fines	
	Coarse	Fine	Coarse	Medium	Fine	Silt	Clay
0.0	0.0	0.0	0.0	0.0	15.0	79.9	5.1

SIEVE SIZE	PERCENT FINER	SPEC.* PERCENT	PASS? (X=NO)
#4	100.0		
#10	100.0		
#20	100.0		
#40	100.0		
#60	100.0		
#100	100.0		
#140	98.0		
#200	85.0		
0.0303 mm.	27.5		
0.0206 mm.	16.3		
0.0124 mm.	10.1		
0.0088 mm.	8.6		
0.0062 mm.	7.7		
0.0031 mm.	6.0		
0.0013 mm.	4.3		

* (no specification provided)

Location: S37-DM1-8U-25cm to end
Depth: 25.0 cm to end

Date: 8/31/16

Soil Description

Dark grayish brown SILT

Atterberg Limits

PL= LL= PI=

Coefficients

D₉₀= 0.0829 D₈₅= 0.0750 D₆₀= 0.0510
D₅₀= 0.0442 D₃₀= 0.0319 D₁₅= 0.0192
D₁₀= 0.0121 C_u= 4.21 C_c= 1.65

Classification

USCS= AASHTO=

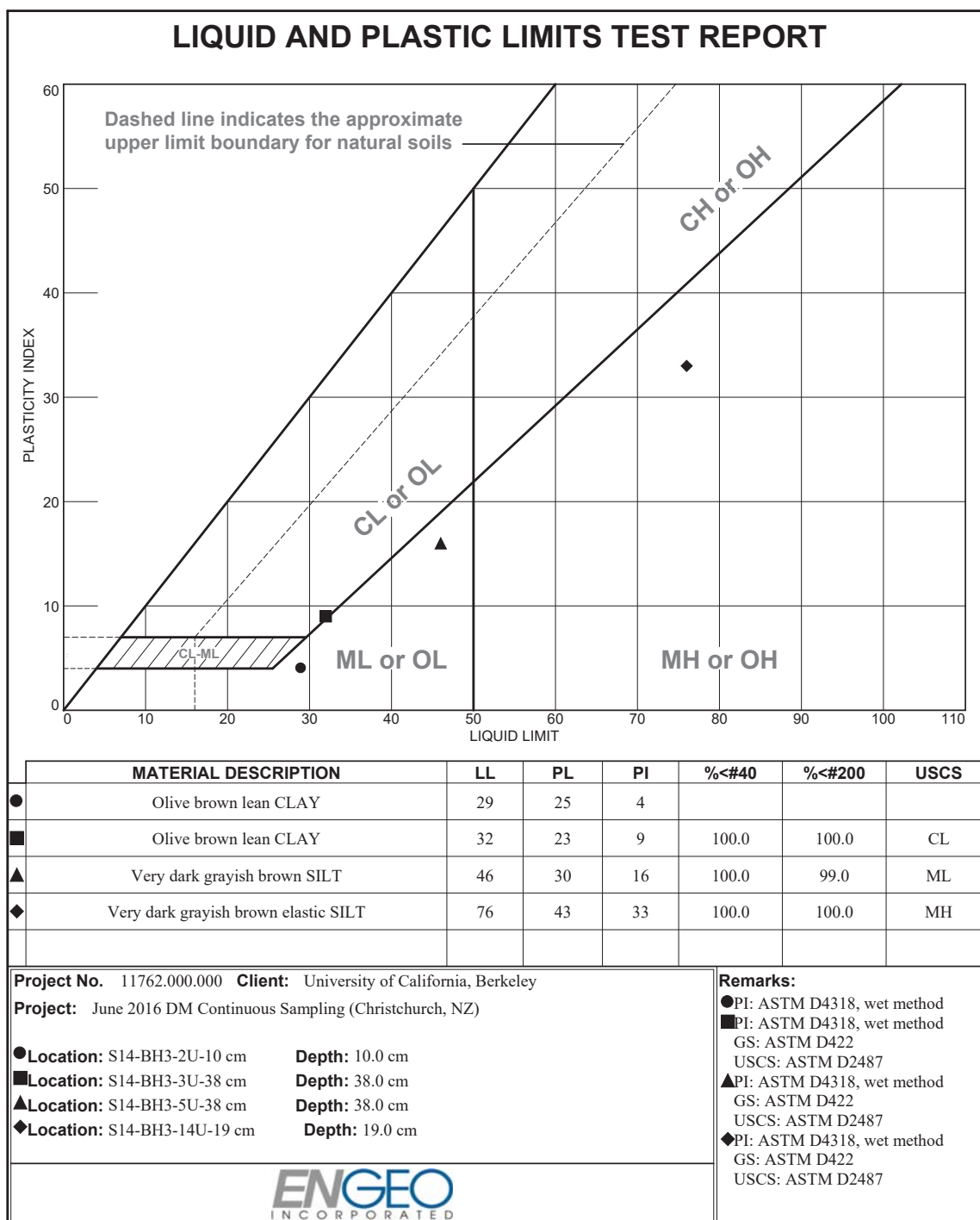
Remarks

GS: ASTM D422; Specific gravity = 2.747, ASTM D854
Silt/clay division of 0.002mm was used

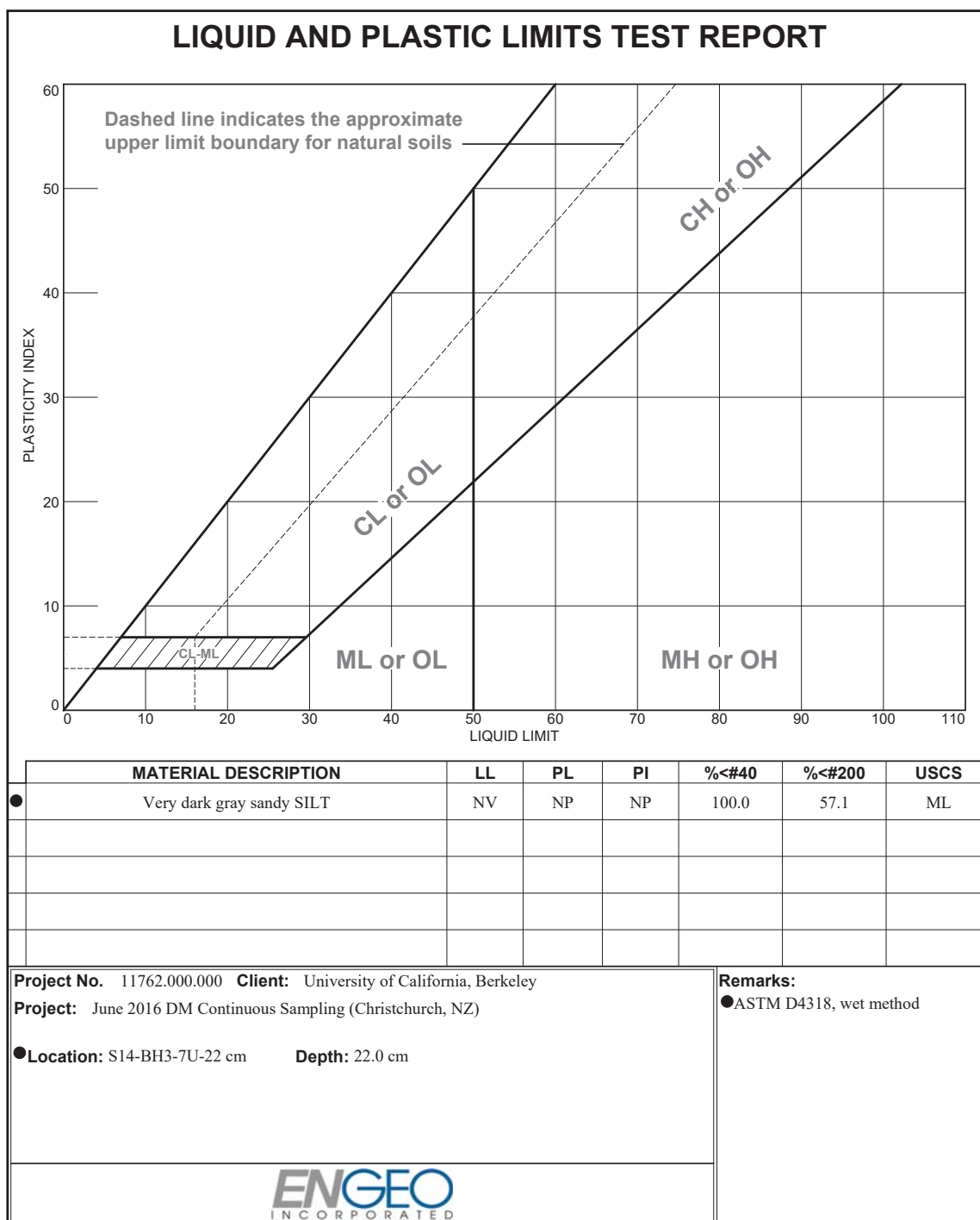


Client: University of California, Berkeley
Project: June 2016 DM Continuous Sampling (Christchurch, NZ)
Project No: 11762.000.000

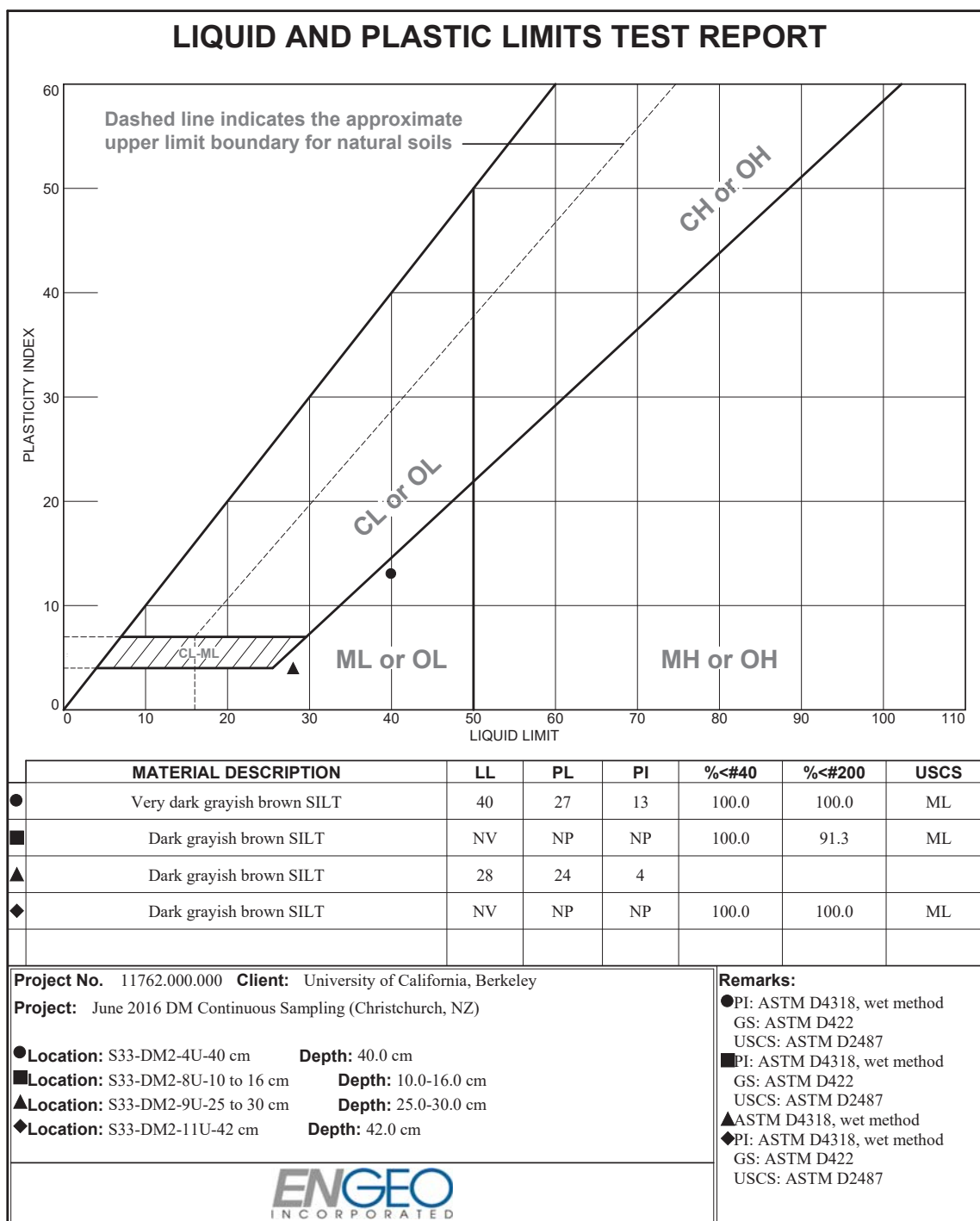
Tested By: M. Quasem **Checked By:** M. Tong



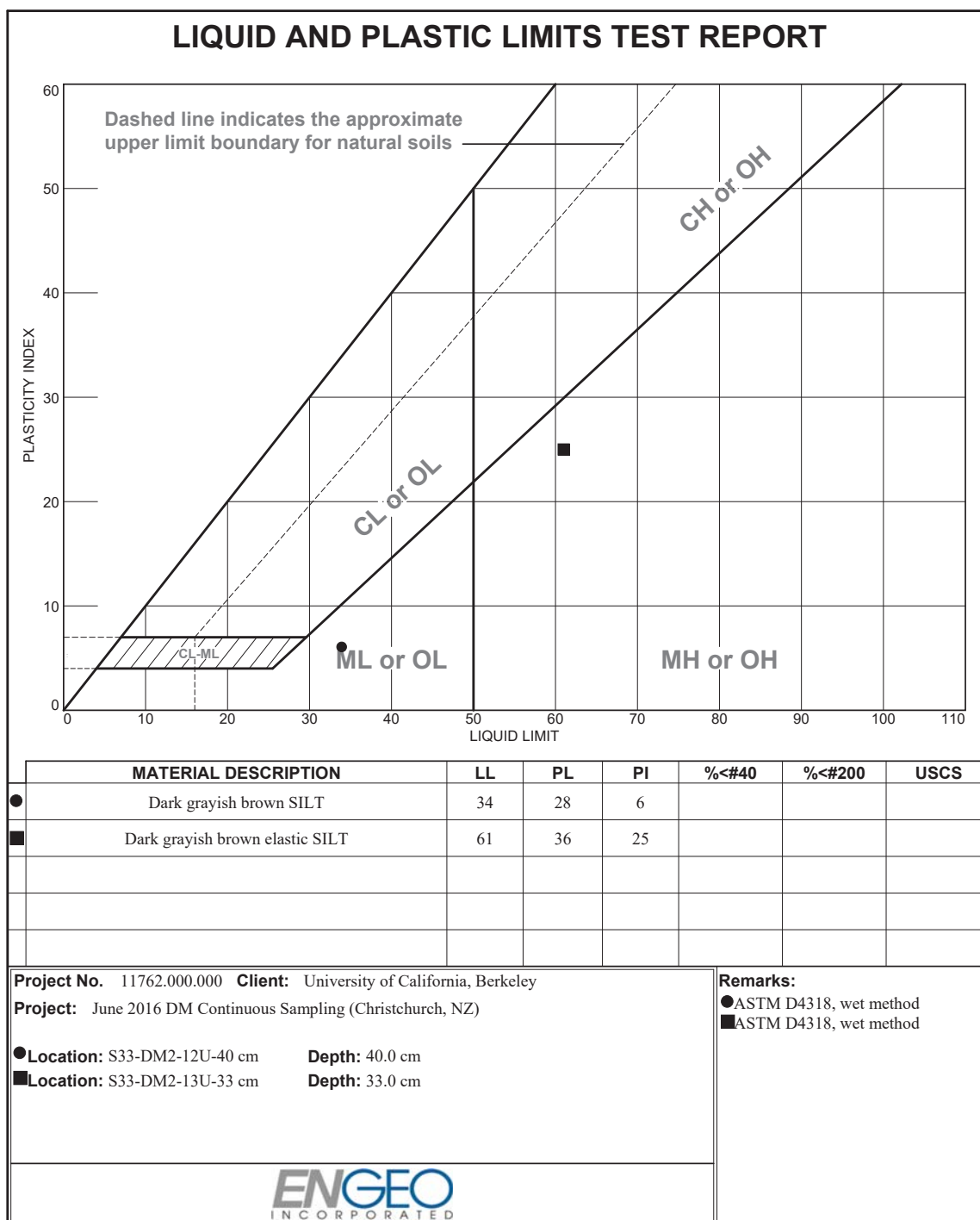
Tested By: M. Quasem Checked By: M. Tong



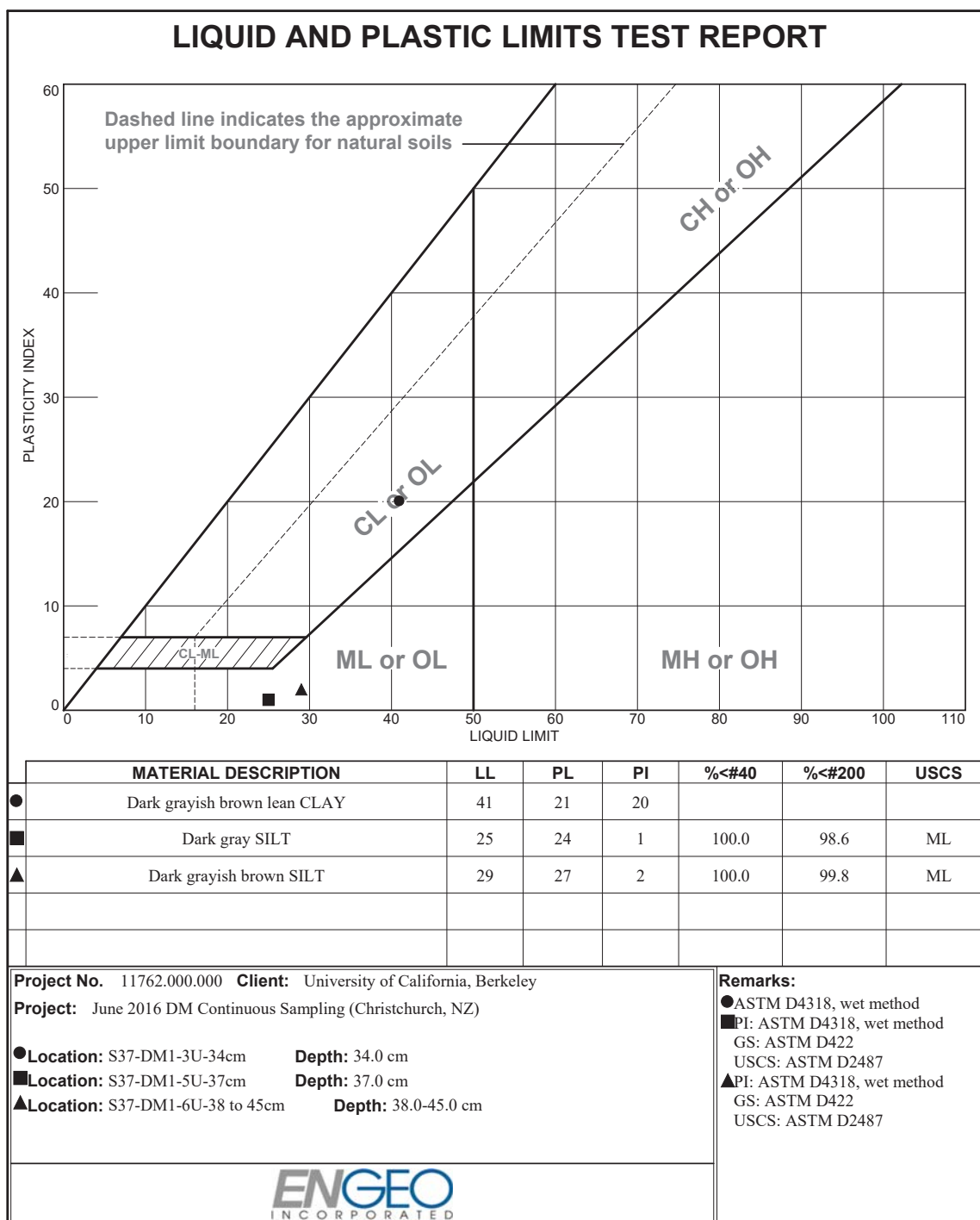
Tested By: M. Quasem Checked By: M. Tong



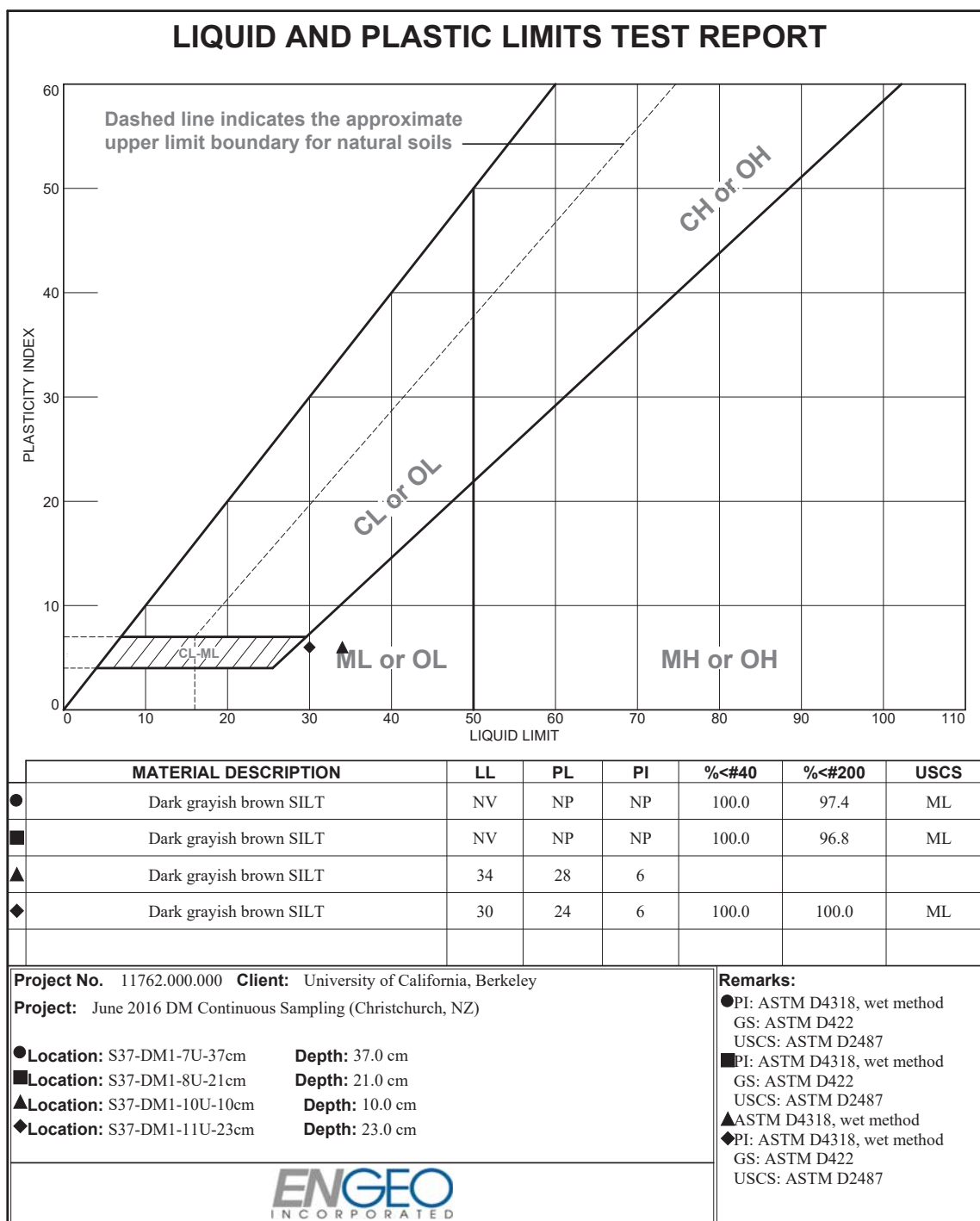
Tested By: M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong



Tested By: ☐ G. Criste ☐ M. Quasem M. Quasem Checked By: M. Tong



Tested By: M. Quasem Checked By: M. Tong

Appendix C

Supporting Data and Information for Cyclic Triaxial Testing Program

- C.1 Introduction
- C.2 Summary Tables and Figures
- C.3 Specimen Photographs
- C.4 Particle Size Distributions
- C.5 Processed Cyclic Triaxial Test Data
- C.6 Raw Cyclic Triaxial Test Data (Electronic)

Appendix C.1

Introduction

APPENDIX C.1: INTRODUCTION

The material provided in this appendix describes the cyclic triaxial (CTX) testing program conducted in 2014.

High-quality (“undisturbed”) samples were obtained using the Dames & Moore sampling device at select sites in Christchurch, New Zealand and were tested by the dissertation author using the CKC electropneumatic triaxial testing device at the University of Canterbury Geomechanics Laboratory.

Appendix C.2 provides summary tables and figures from the CTX testing program.

Appendix C.3 provides photographs of the CTX specimens.

Appendix C.4 provides particle size distributions for the CTX specimens.

Appendix C.5 provides processed CTX test data.

Appendix C.6 provides raw CTX test data (electronic copy).

The test data provided for each specimen includes isotropic consolidation, CTX testing, and post-CTX reconsolidation.

CTX test data were processed to correct axial stresses for membrane effects following the equations proposed by Duncan & Seed 1967. The Young’s modulus of the membrane was assumed to be 14 kg/cm^2 . This corrects axial stresses for loads carried by the membrane rather than the soil. During cyclic loading, where the specimen is subjected to both compression and extension, the membrane correction acts opposite to the applied load.

The CKC testing device uses the Automated Triaxial Testing System software developed by Li et al. 1988. A Windows version of the software was installed on the testing system computer in 2014 using the file “Triaxial_W.exe”. The software automatically corrects the area of the specimen throughout testing with the assumption that the specimen deforms as a right cylinder.

Appendix C.2

Summary Tables and Figures

Table C.2-1: Characteristics of CTX test specimens

Specimen	Mid-Depth (m)	$q_{t1n,cs}$	I_c	FC (%)	D10 (μm)	D50 (μm)	D60 (μm)	C_u	LL	PI	G_s	e_{min}	e_{max}
S2-DM1-3U-A	3.93	62	3.06	98	5	11	13	3.0	40	12	2.73	1.685	---
S2-DM1-3U-B	4.09	62	3.10	87	4	12	16	4.4	42	16	---	---	---
S2-DM1-5U-A	5.57	100	2.05	25	41	108	122	2.9	---	NP	2.70	0.648	1.290
S2-DM1-7U-A	8.07	100	2.00	30	27	104	118	4.3	---	NP	---	---	---
S2-DM1-7U-B	8.22	100	2.12	43	23	84	97	4.2	---	NP	2.69	0.667	1.371
S2-DM1-8U-A	8.87	111	1.84	8	82	186	207	2.5	---	NP	2.66	0.620	1.136
S14-DM2-2U-A	1.72	77	2.79	99	4	12	14	3.3	31, 30	7, 6	2.63	---	---
S14-DM2-5U-A	5.17	101	2.00	47	18	79	95	5.2	---	NP	---	0.634	1.395
S14-DM2-5U-B	5.32	105	2.00	36	27	96	111	4.1	---	NP	---	---	---
S14-DM2-6U-A	6.67	66	2.69	54	13	69	83	6.6	---	NP	2.69	0.648	1.521
S14-DM2-6U-B	6.825	86	2.41	69	10	50	62	5.9	---	NP	---	---	---
S21-DM1-2U-A	1.77	91	2.32	94	11	37	43	4.0	26; 28, 22	2; 8, 2	2.72	---	---
S21-DM1-3U-A	2.32	77	2.42	61	22	65	74	3.4	---	NP	---	---	---
S21-DM1-3U-B	2.475	83	2.13	72	19	57	64	3.4	---	NP	2.69	---	---
S23-DM1-3U-A	3.39	73	2.66	91	10	31	38	3.8	28	5	2.72	---	---
S23-DM1-3U-B	3.545	71	2.71	92	11	30	37	3.5	33	7	---	---	---
S23-DM1-4U-A	3.97	68	2.93	97	7	17	20	2.9	38, 36	7, 5	2.71	---	---
S23-DM1-4U-B	4.125	76	2.49	94	7	18	23	3.5	30	4	---	---	---
S23-DM1-5U-A	5.07	79	2.38	94	5	13	17	3.5	33, 30	9, 6	2.72	---	---
S23-DM1-7U-A	6.27	92	2.12	69	8	31	50	6.5	27	6	---	---	---
S23-DM1-7U-B	6.425	95	2.20	75	6	28	45	7.0	27, 25	7, 5	2.69	---	---
S23-DM1-8U-A	8.37	88	2.36	60	16	64	75	4.7	24	NP	2.67	---	---
S33-DM1-2U-B	2.125	65	3.06	92	5	17	22	4.3	41	15	2.67	1.350	3.065
S33-DM1-3U-A	2.57	67	3.08	100	3	7	8	2.4	38	12	2.70	1.263	2.914
S33-DM1-3U-B	2.725	73	2.91	98	8	21	25	3.3	26	5	---	---	---
S33-DM1-4U-A	3.22	120	1.82	11	72	127	140	1.9	---	NP	2.68	0.596	1.298
S33-DM1-5U-A	3.82	118	1.95	10	76	116	126	1.7	---	NP	2.69	0.684	1.321
S33-DM1-5U-B	3.975	126	1.81	49, 82, 12	31, 11, 69	75, 41, 135	84, 49, 150	2.7, 4.4, 2.2	23	NP	---	---	---
S33-DM1-6U-A	4.52	70	2.68	87	9	33	41	4.6	23	1	2.69	---	---

Specimen	Mid-Depth (m)	$q_{tN,CS}$	I_c	FC (%)	D10 (μm)	D50 (μm)	D60 (μm)	C_u	LL	PI	G_s	e_{min}	e_{max}
S33-DM1-6U-B	4.675	66	2.83	47, 78	35, 14	78, 49	88, 57	2.5, 3.9	---	NP	---	---	---
S33-DM1-7U-A	5.12	83	2.37	83	9	37	46	4.9	---	---	2.68	---	---
S33-DM1-8U-A	5.72	80	2.53	100	5	10	11	2.2	39	10	2.67	---	---
S33-DM1-8U-B	5.875	82	2.62	100	4	7	8	2.3	38	10	---	---	---
EQC3-DM1-3U-B	3.575	149	1.64	7	84	181	208	2.5	---	NP	2.69	0.588	1.114
EQC3-DM1-4U-A	4.17	168	1.64	2	141	240	261	1.9	---	NP	2.68	0.625	1.052
EQC3-DM1-5U-A	5.67	143	1.67	2	154	284	313	2.0	---	NP	---	---	---
EQC3-DM1-5U-B	5.825	147	1.68	2	150	268	295	2.0	---	NP	2.68	0.623	1.026
EQC3-DM1-6U-A	6.45	135	1.69	1	168	271	296	1.8	---	NP	2.68	0.650	1.069
EQC4-DM1B-6U-A	6.17	109	1.64	1	134	201	218	1.6	---	NP	---	---	---
EQC4-DM1B-6U-B	6.325	115	1.64	1	139	213	229	1.6	---	NP	2.68	0.646	1.063
EQC4-DM1B-7U-A	6.87	125	1.65	9	82	168	185	2.3	---	NP	---	---	---
EQC4-DM2-3U-A	2.27	75	2.30	34	44	88	98	2.2	---	NP	2.68	0.666	1.390
EQC4-DM2-3U-B	2.425	85	2.36	36	29	94	108	3.8	---	NP	---	---	---
EQC4-DM4-4U-A	2.72	81	2.07	22	27	122	139	5.2	---	NP	2.64	---	---

- Specimen naming notation is "Site-Boring-Sample-Specimen." Nominal specimen height = 135-140 mm. Full recovery allows for 2 specimens from each DM tube.

- Geometric mean of $q_{tN,CS}$ and I_c estimated over specimen interval of 14 cm. In-situ water contents not available (samples allowed to drain prior to extrusion).

- Index testing (LL, PI, G_s , e_{max} , e_{min}) and particle size distributions (FC) conducted by laboratory personnel at Univ. of Canterbury Geomechanics Laboratory. Fines content (FC) defined at 75 μm as determined using laser analysis; average values provided. Values shown in italics are from an adjacent sample not included in the 2014 CTX testing program. Multiple LL values indicate multiple Casagrande cup tests (second value from wedge-shaped grooving tool when flat grooving tool would not work with soil). G_s typically determined for one specimen from each sample tube. e_{min} and e_{max} tests conducted following the Japanese standard.

- Specimens S33-DM1-5U-B and S33-DM1-6U-B showed clear layering and were separated into portions for particle size analysis. Values shown for S33-DM1-5U-B are for the top, middle, and bottom portions of the specimen, while the values shown for S33-DM1-6U-B are for the ends and middle portions of the specimen. Atterberg Limits for S21-DM1-2U-A are shown for two portions of the specimen, one of which was siltier and one of which was clayier.

Table C.2-2: CTX specimen parameters and test results

Specimen	B_c^a	σ'_c (kPa)	ρ_c (kg/m ³)	e_c	f (Hz)	CSR	$N_{3\%,SA}$	$N_{5\%,SA}$	$\varepsilon_{a,max}$ (%)	$\varepsilon_{v,recon}$ (%)
S2-DM1-3U-A	0.976	62	1375	0.98	0.1	0.36	4	4	-7.9	---
S2-DM1-3U-B	1	62	1381	0.98	0.1	0.26	36	39	-6.6	---
S2-DM1-5U-A ^b	0.963	75	1473	0.83	0.1	0.25	100	100	-0.1	0.05
S2-DM1-7U-A	0.961	104	1551	0.73	0.1	0.3	10	12	-6.7	1.7
S2-DM1-7U-B	0.958	108	1546	0.74	0.1	0.25	43	45	-4.8	1.3
S2-DM1-8U-A ^c	0.969	113	1443	0.84	0.1	0.36	3	5	-8.0	2.35
S14-DM2-2U-A ^d	0.975	50	1437	0.83	0.1	0.32	6	8	-7.4	---
S14-DM2-5U-A	0.973	72	1509	0.78	0.1	0.3	11	15	-8.0	1.2
S14-DM2-5U-B ^{**}	---	---	---	---	---	---	---	---	---	---
S14-DM2-6U-A	0.968	75	1614	0.67	0.1	0.36	11	14	-5.5	0.95
S14-DM2-6U-B	0.98	88	1611	0.67	0.1	0.42	3	4	-5.5	2.5
S21-DM1-2U-A	0.978	35	1467	0.85	1	0.25	67	75	-6.4	3.1
S21-DM1-3U-A	0.972	46	1481	0.82	1	0.43	4	7.5	-6.2	2.25
S21-DM1-3U-B	0.977	47	1463	0.84	1	0.3	19	23	-7.1	2.9
S23-DM1-3U-A	0.965	52	1362	1.00	1	0.4	5	8	-7.1	2.2
S23-DM1-3U-B	0.973	53	1310	1.08	1	0.3	12	16	-6.1	2.35
S23-DM1-4U-A ^{**}	---	---	---	---	---	---	---	---	---	---
S23-DM1-4U-B	0.986	59	1366	0.98	1	0.35	6	10	-8.1	2.7
S23-DM1-5U-A	0.985	68	1289	1.11	1	0.25	36	43	-7.7	3.1
S23-DM1-7U-A	0.917	79	1574	0.71	1	0.32	5	7	-8.0	3.1
S23-DM1-7U-B	0.972	81	1597	0.68	1	0.4	4	6	-8.0	3.15
S23-DM1-8U-B-A	0.967	99	1518	0.76	1	0.25	18	25	-6.9	2.5
S33-DM1-2U-B	0.997	42	1382	0.93	1	0.42	16	24	-5.6	1.1
S33-DM1-3U-A	0.99	47	1454	0.86	1	0.35	5	8	-8.1	2.95
S33-DM1-3U-B	0.97	48	1435	0.88	1	0.25	27	29	-6.2	2.5
S33-DM1-4U-A	0.963	52	1546	0.73	1	0.35	52	48	-3.7	1.75
S33-DM1-5U-A	0.976	58	1439	0.87	1	0.43	2	3	-8.1	2.3
S33-DM1-5U-B	0.976	60	1436	0.87	1	0.39	3	5	-8.0	2.45
S33-DM1-6U-A	0.983	64	1363	0.97	1	0.47	1	1	-6.0	2
S33-DM1-6U-B	0.975	66	1369	0.96	1	0.25	11	13	-8.5	3.4
S33-DM1-7U-A	0.979	70	1361	0.97	1	0.42	1	2	-8.1	2.4

Specimen	B_c^a	σ'_c (kPa)	ρ_c (kg/m ³)	e_c	f (Hz)	CSR	$N_{3\%,SA}$	$N_{5\%,SA}$	$\epsilon_{a,max}$ (%)	$\epsilon_{v,recon}$ (%)
S33-DM1-8U-A	0.988	75	1390	0.92	1	0.35	5	7.5	-6.1	2.4
S33-DM1-8U-B	0.994	77	1333	1.00	1	0.3	9	12	-6.1	1.8
EQC3-DM1-3U-B	0.974	46	1515	0.78	0.1	0.44	7	12	-5.8	1.75
EQC3-DM1-4U-A	0.976	52	1562	0.72	0.1	0.49	16	18	-3.6	1.4
EQC3-DM1-5U-A	0.955	65	1574	0.70	0.1	0.3	54	66	-4.5	2.15
EQC3-DM1-5U-B	0.962	67	1588	0.69	0.1	0.41	28	36	-5.1	1.95
EQC3-DM1-6U-A	0.973	73	1562	0.72	1	0.4	8	12	-4.5	---
EQC4-DM1B-6U-A	0.982	80	1535	0.75	0.1	0.5	4	6.5	-5.7	2.05
EQC4-DM1B-6U-B	0.982	82	1549	0.73	0.1	0.38	13	18	-4.7	1.5
EQC4-DM1B-7U-A	0.978	88	1496	0.79	0.1	0.34	5	7.5	-6.0	1.9
EQC4-DM2-3U-A	0.984	43	1377	0.95	1	0.35	12	14	-6.1	2.2
EQC4-DM2-3U-B	0.964	45	1426	0.88	1	0.48	5	7	-6.0	1.75
EQC4-DM4-4U-A	0.99	48	1169	1.26	1	0.28	87	95	-6.0	3.5

B = B-value

σ'_c = testing stress (1.1*in-situ vertical effective stress)

ρ_c = dry density

e_c = void ratio

f = frequency of cyclic loading

CSR = cyclic stress ratio

$N_{3\%,SA}$ = number of cycles to 3% single-amplitude axial strain

$N_{5\%,DA}$ = number of cycles to 3% single-amplitude axial strain

$\epsilon_{a,max}$ = maximum axial strain during cyclic testing

$\epsilon_{vol,recon}$ = estimated final volumetric strain during post-liquefaction reconsolidation

^a Specimens were saturated through vacuum extraction and back-pressure saturation. Subscript “c” denotes value after consolidation to testing stress, prior to cyclic triaxial testing.

^b Specimen likely disturbed during laboratory extrusion process.

^c Apparent void in sample tube below top portion removed for this specimen. Bottom portion of sample not tested (e.g., Specimen “S2-DM1-8U-B”).

^d Power surge immediately prior to testing may have affected effective stress measurements through signal conditioner.

** CTX tests were not completed successfully due to equipment issues.

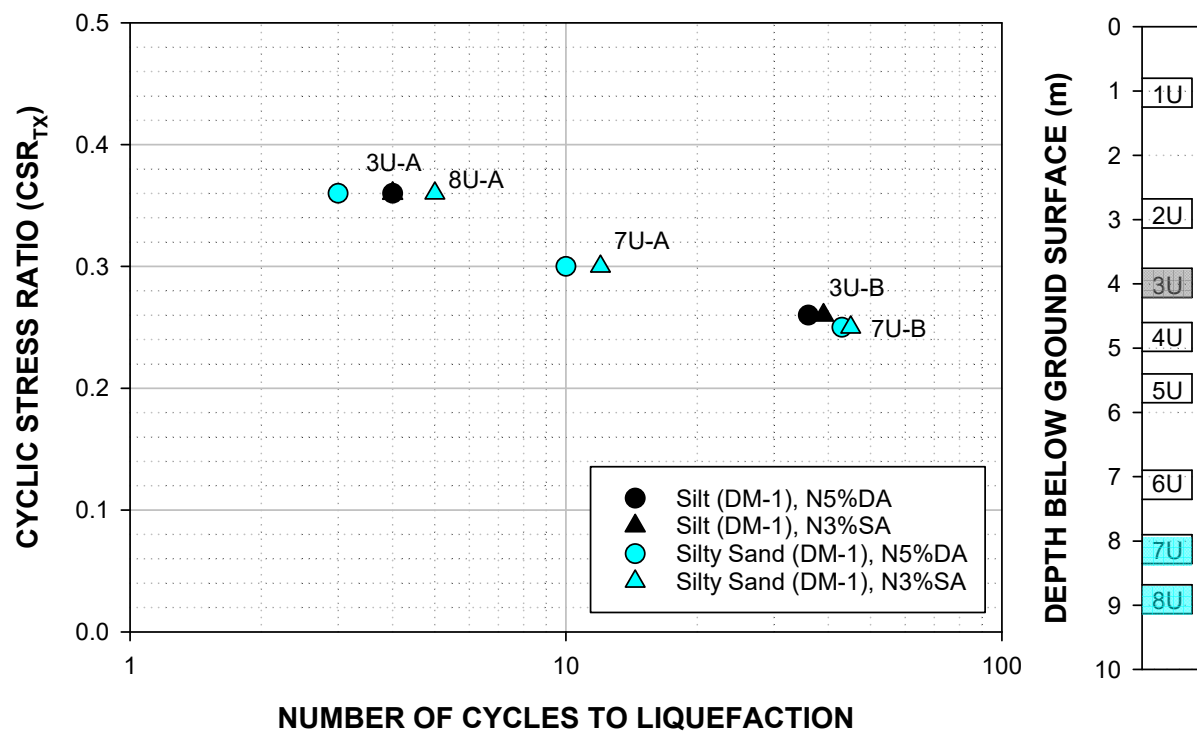


Figure C.2-1: Site 2 (Gainsborough) CSR vs. Number of Cycles

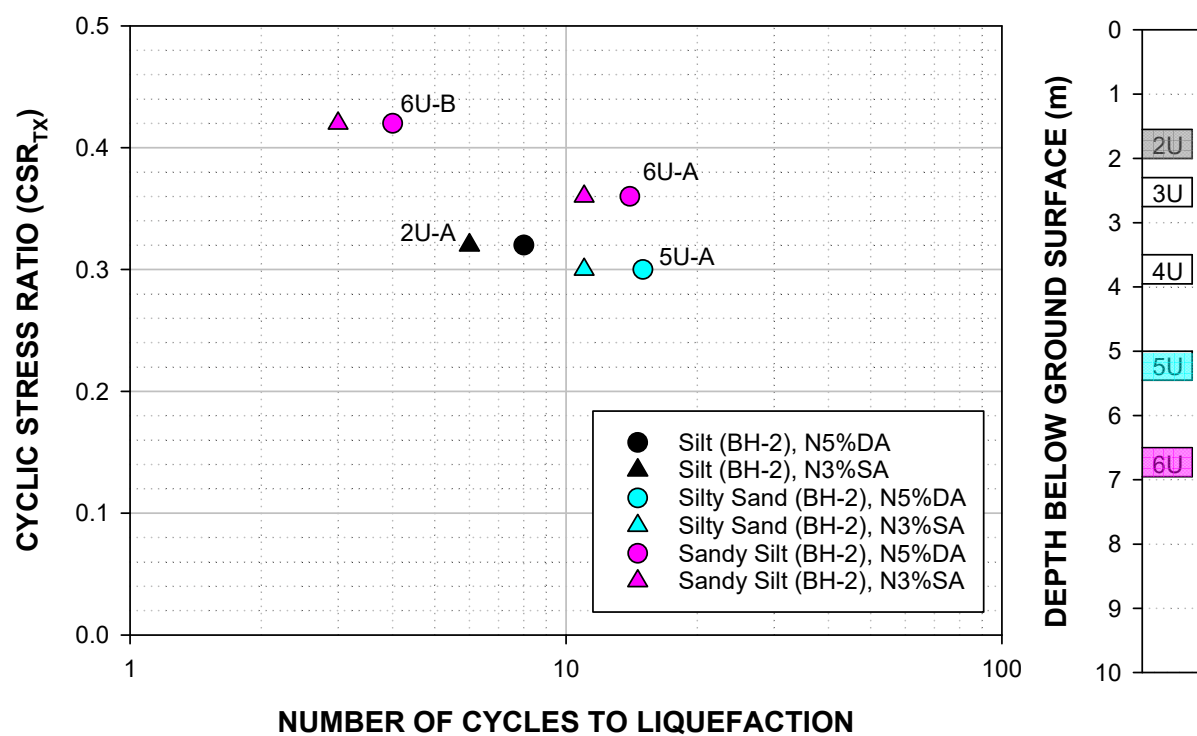


Figure C.2-2: Site 14 (Barrington) CSR vs. Number of Cycles

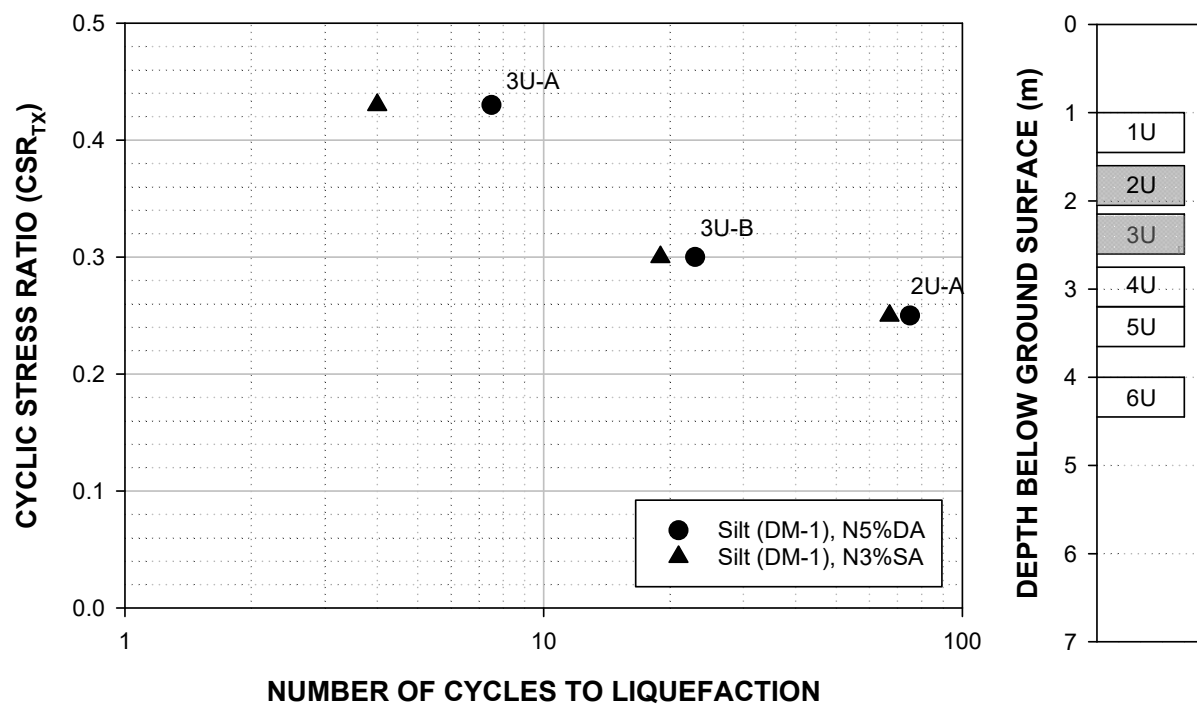


Figure C.2-3: Site 21 (Caulfield) CSR vs. Number of Cycles

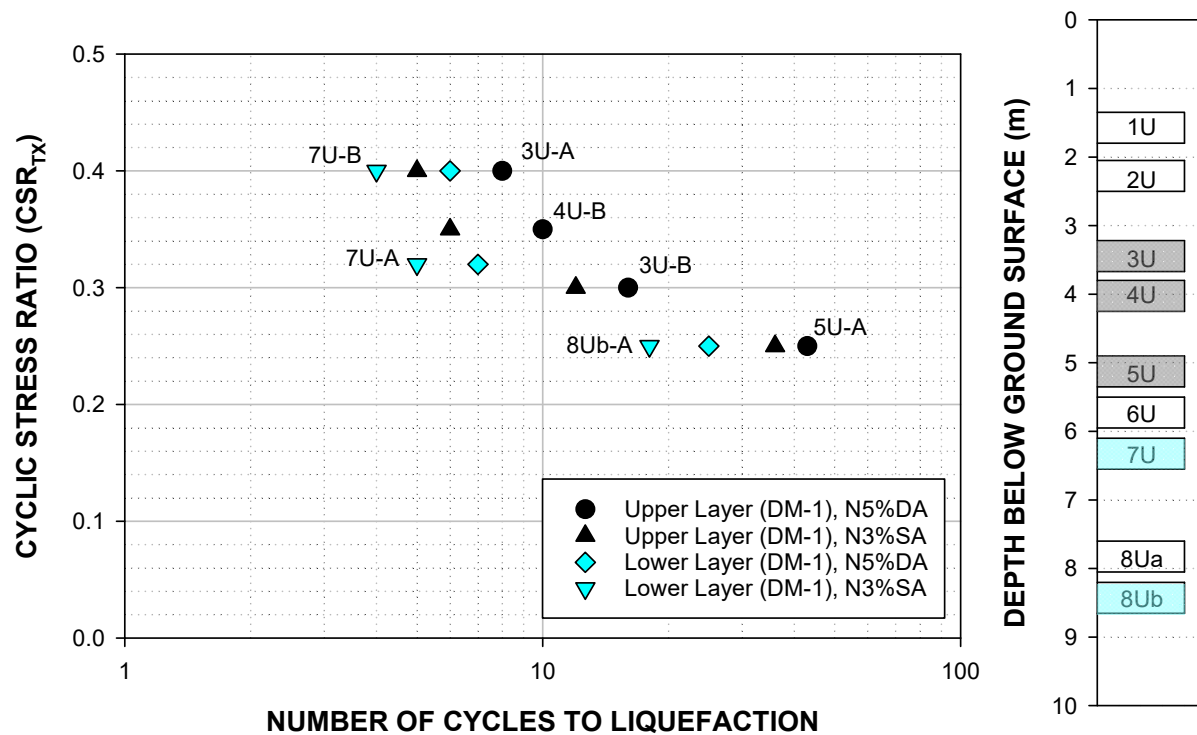


Figure C.2-4: Site 23 (Riccanton) CSR vs. Number of Cycles

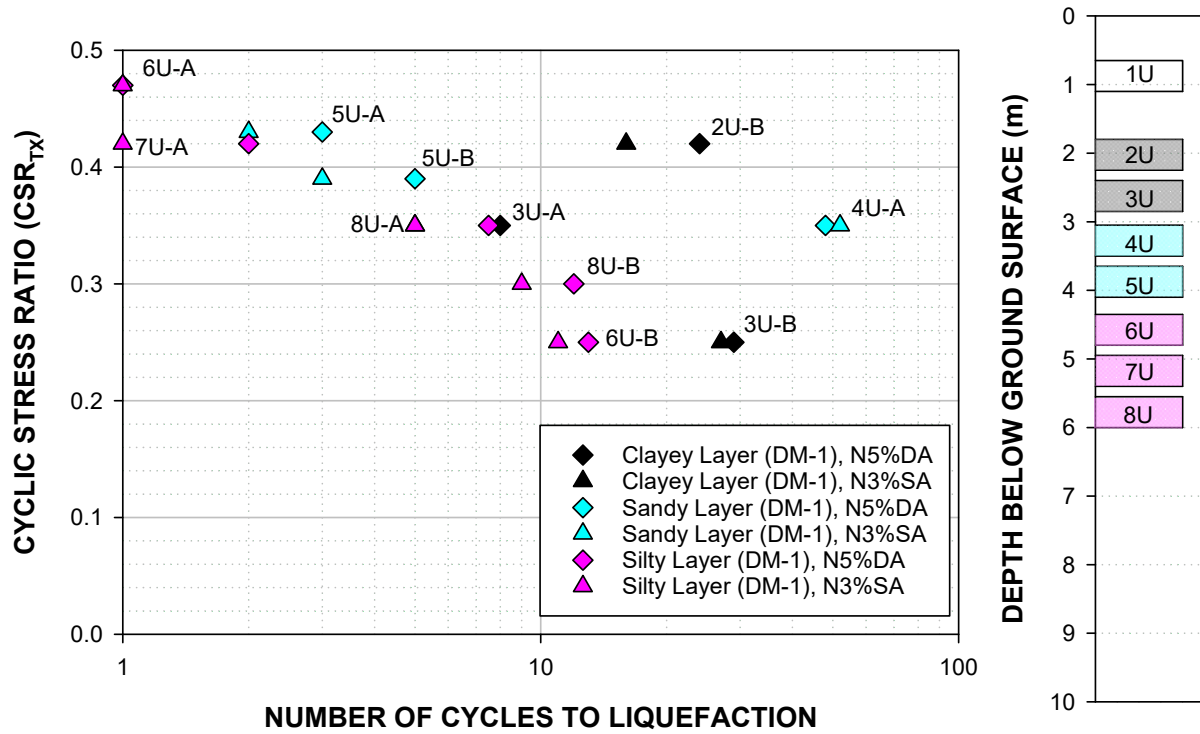


Figure C.2-5: Site 33 (Cashmere) CSR vs. Number of Cycles

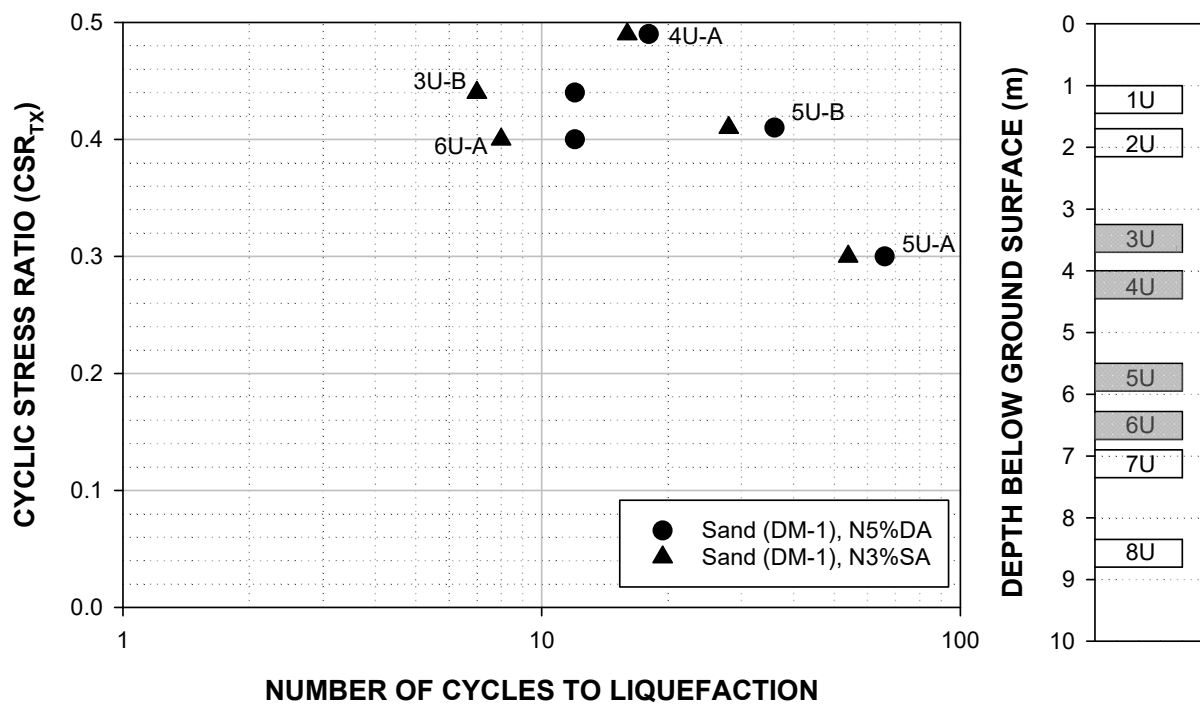


Figure C.2-6: EQC-3 (Avondale) CSR vs. Number of Cycles

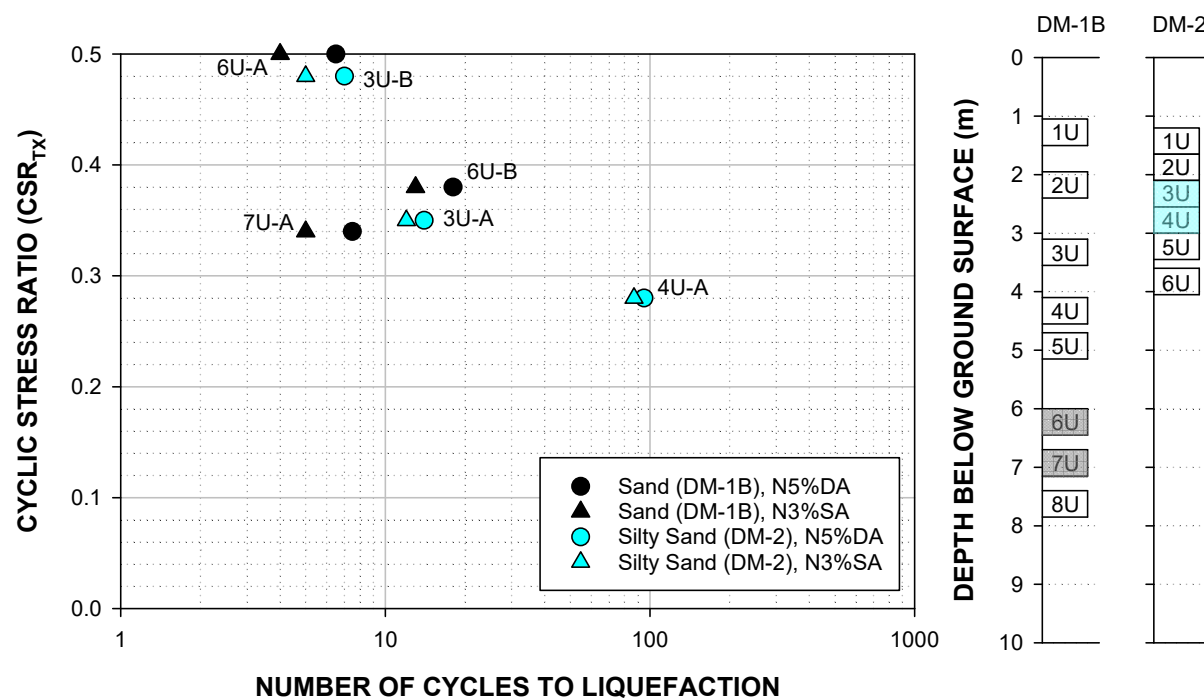


Figure C.2-7: EQC-4 (Avondale) CSR vs. Number of Cycles

Appendix C.3

Specimen Photographs

C.3.1	Site 2
C.3.2	Site 14
C.3.3	Site 21
C.3.4	Site 23
C.3.5	Site 33
C.3.6	EQC-3
C.3.7	EQC-4



Figure C.3.1-1: S2-DM1-3U-A, As-Extruded

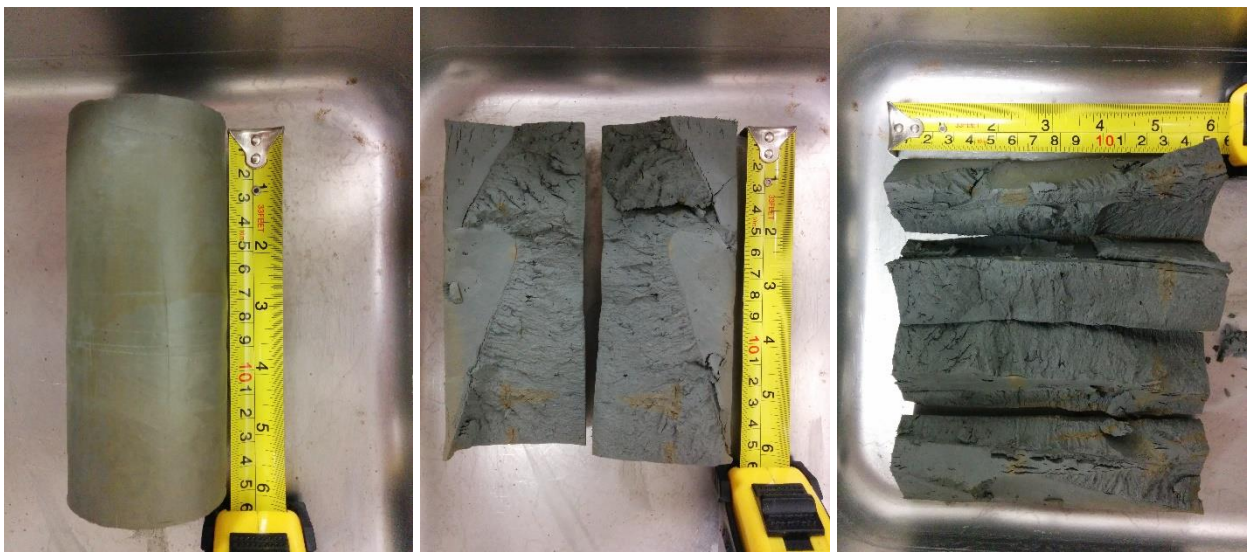


Figure C.3.1-2: S2-DM1-3U-A, Tested



Figure C.3.1-3: S2-DM1-3U-B, As-Extruded



Figure C.3.1-4: S2-DM1-3U-B, Tested



Figure C.3.1-5: S2-DM1-4U (not tested), As-Extruded

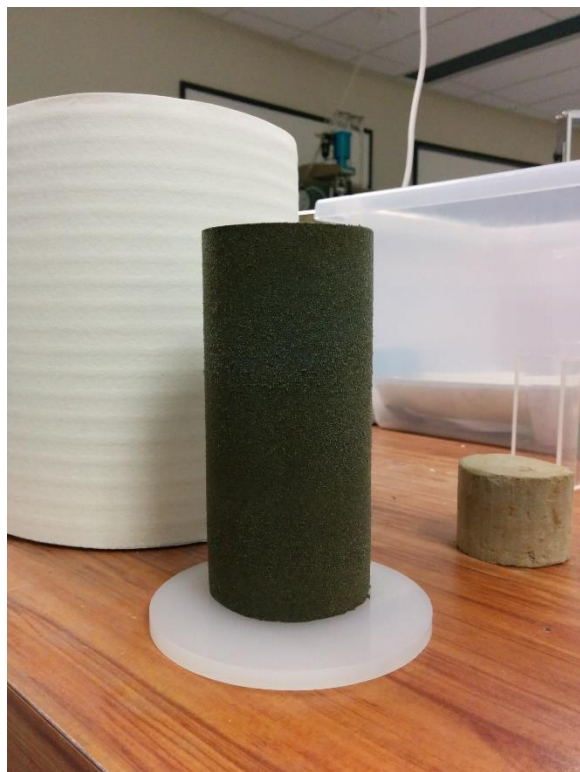


Figure C.3.1-6: S2-DM1-5U-A, As-Extruded

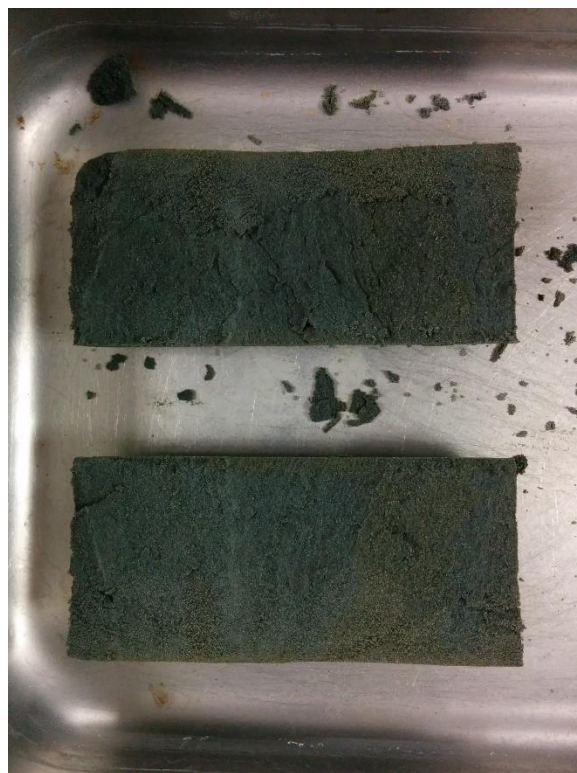


Figure C.3.1-7: S2-DM1-5U-A, Tested



Figure C.3.1-8: S2-DM1-7U-A, As-Extruded

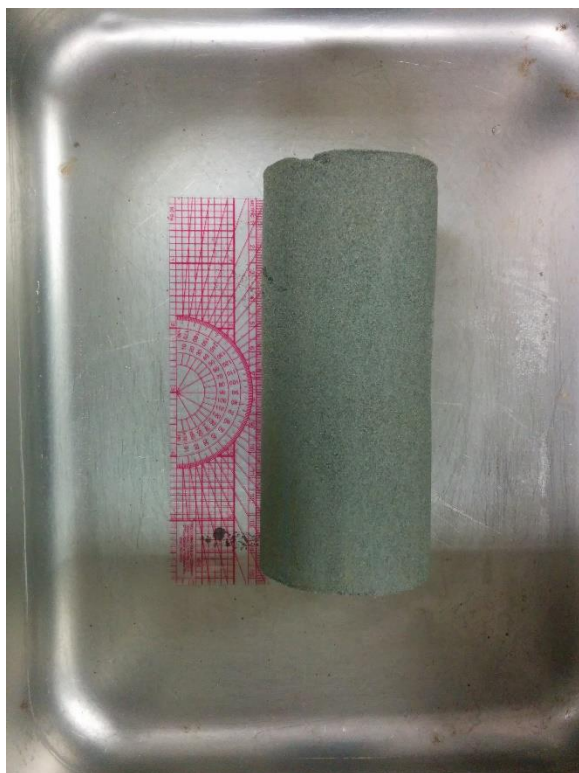


Figure C.3.1-9: S2-DM1-7U-A, Tested

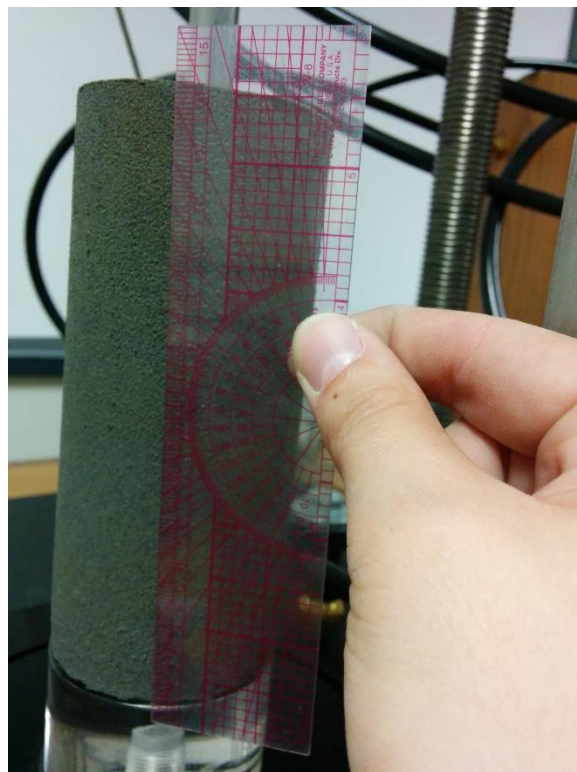
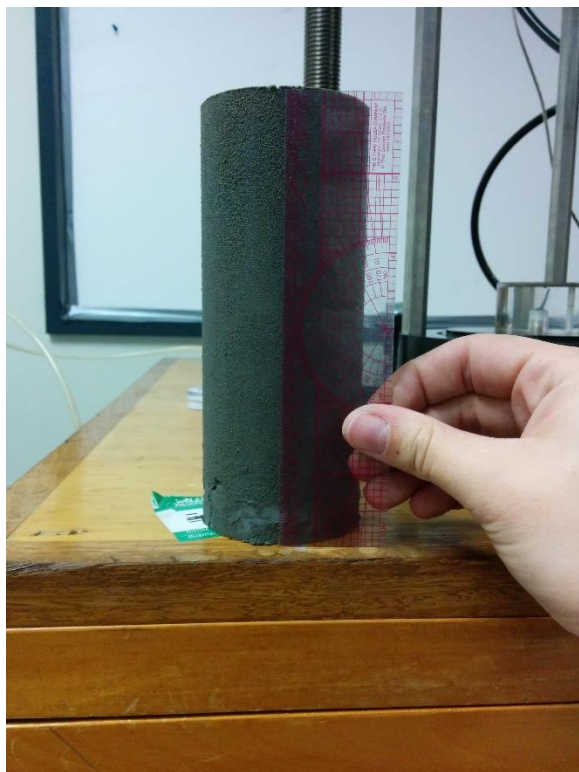


Figure C.3.1-10: S2-DM1-7U-B, As-Extruded

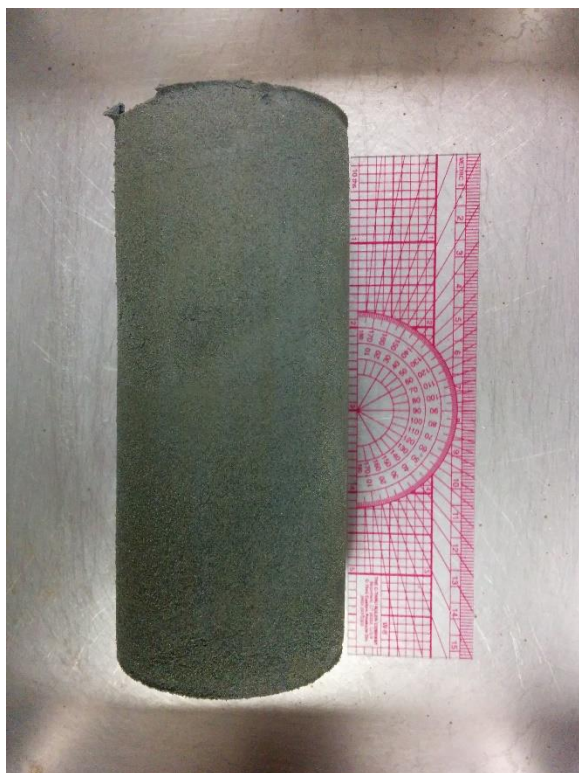


Figure C.3.1-11: S2-DM1-7U-B, Tested



Figure C.3.1-12: S2-DM1-8U-A, As-Extruded



Figure C.3.1-13: S2-DM1-8U-A, Tested

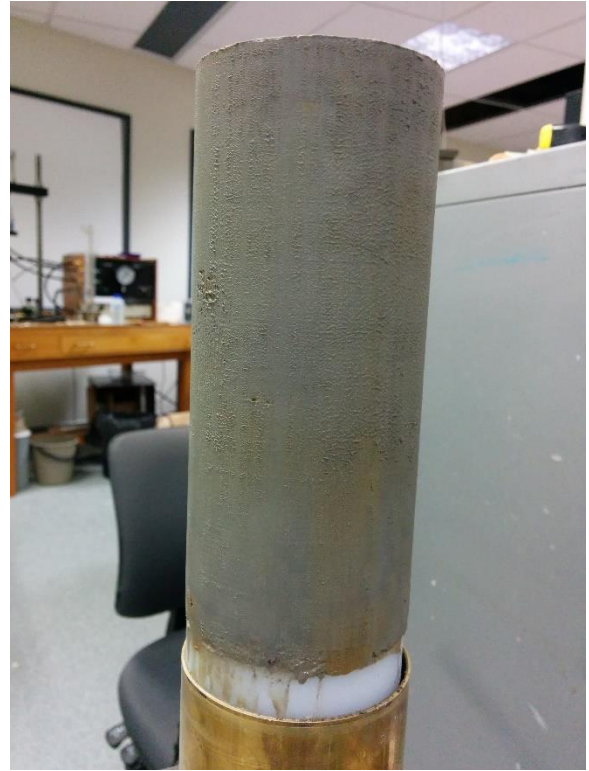


Figure C.3.2-1: S14-DM2-2U-A, As-Extruded



Figure C.3.2-2: S14-DM2-2U-A, Tested

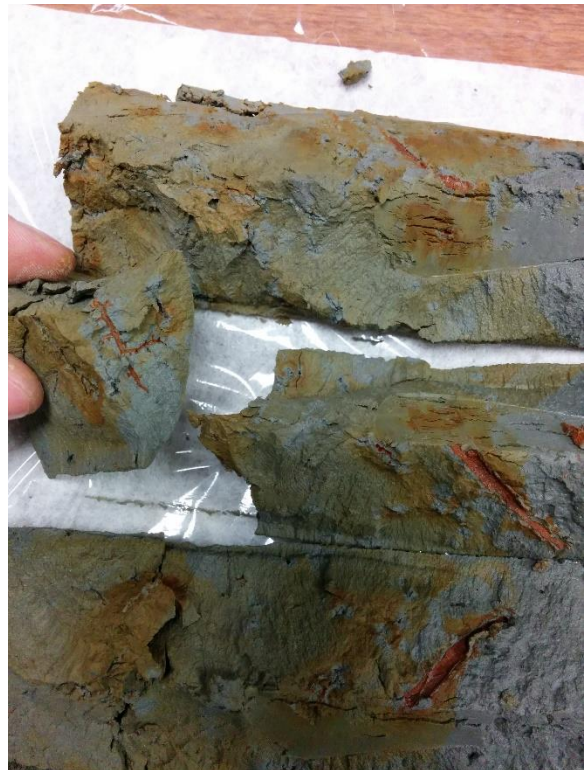


Figure C.3.2-3: S14-DM2-2U-B (not tested), As-Extruded



Figure C.3.2-4: S14-DM2-3U (not tested), As-Extruded



Figure C.3.2-5: S14-DM2-5U-A, As-Extruded

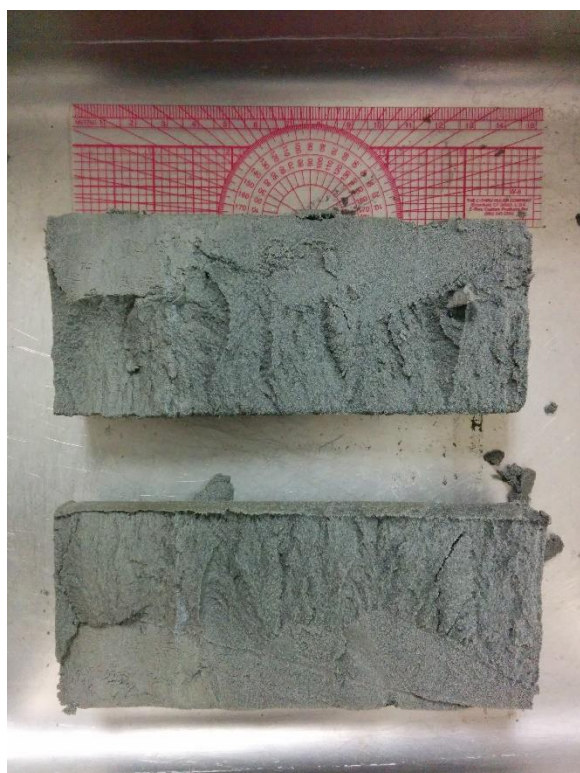


Figure C.3.2-6: S14-DM2-5U-A, Tested



Figure C.3.2-7: S14-DM2-5U-B, As-Extruded



Figure C.3.2-8: S14-DM2-5U-B, Tested (mechanical issue during testing – CTX data not used)



Figure C.3.2-9: S14-DM2-6U-A, As-Extruded

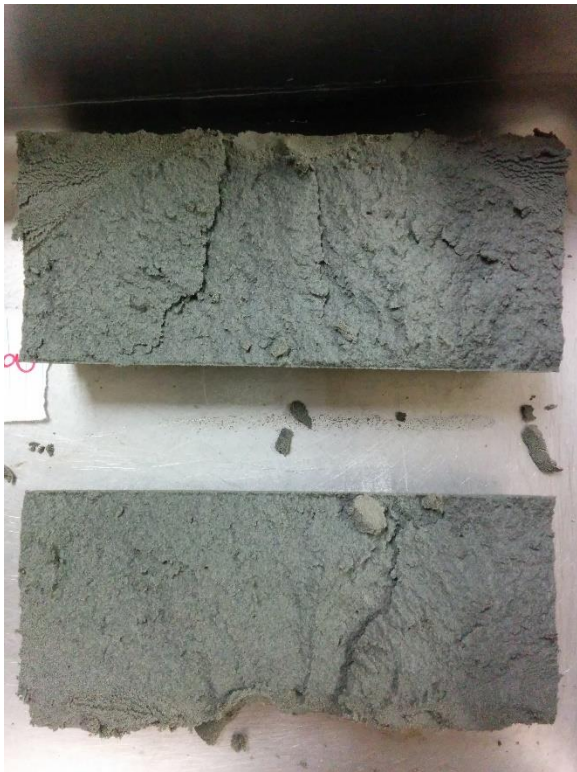


Figure C.3.2-10: S14-DM2-6U-A, Tested

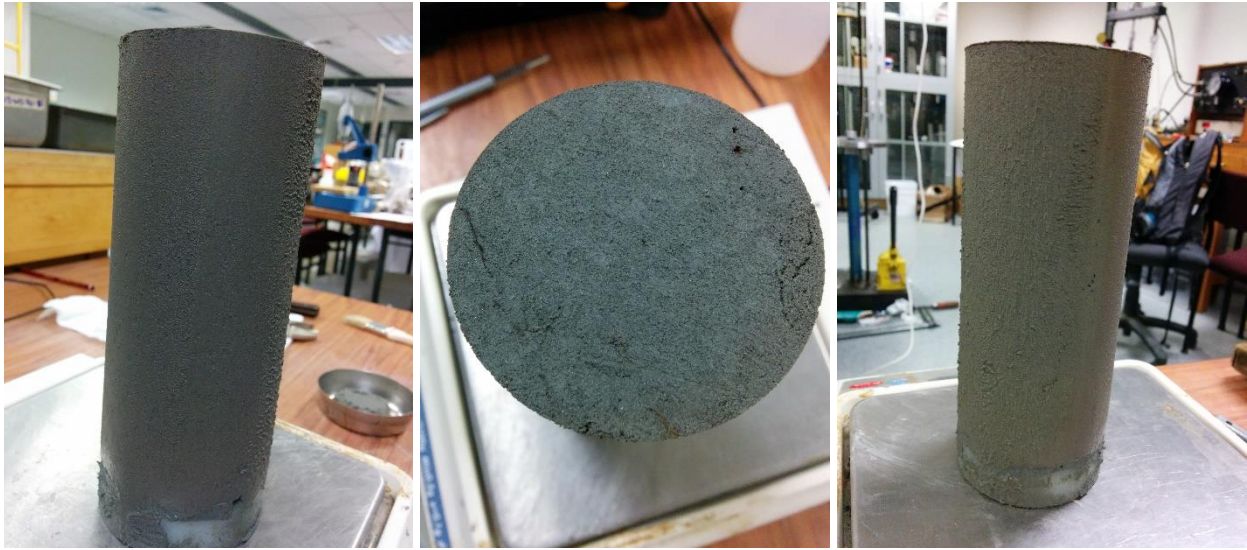


Figure C.3.2-11: S14-DM2-6U-B, As-Extruded



Figure C.3.2-12: S14-DM2-6U-B, Tested



Figure C.3.3-1: S21-DM1-2U-A, As-Extruded

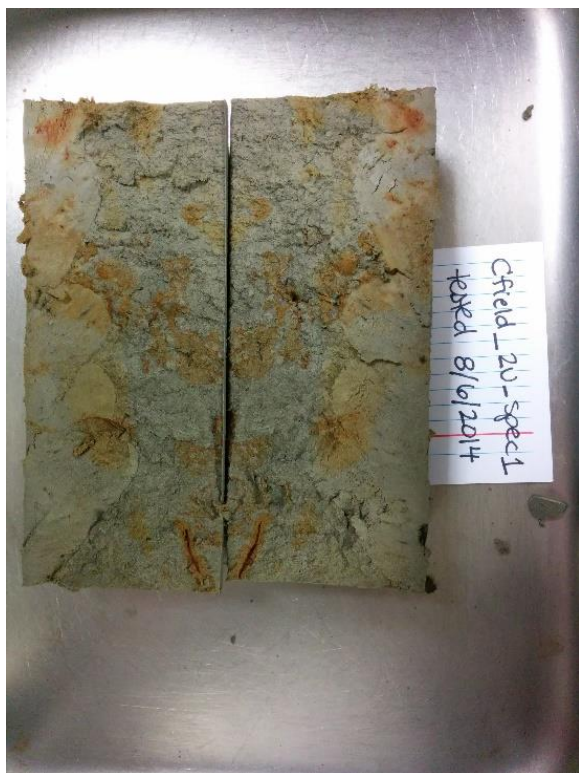


Figure C.3.3-2: S21-DM1-2U-A, Tested

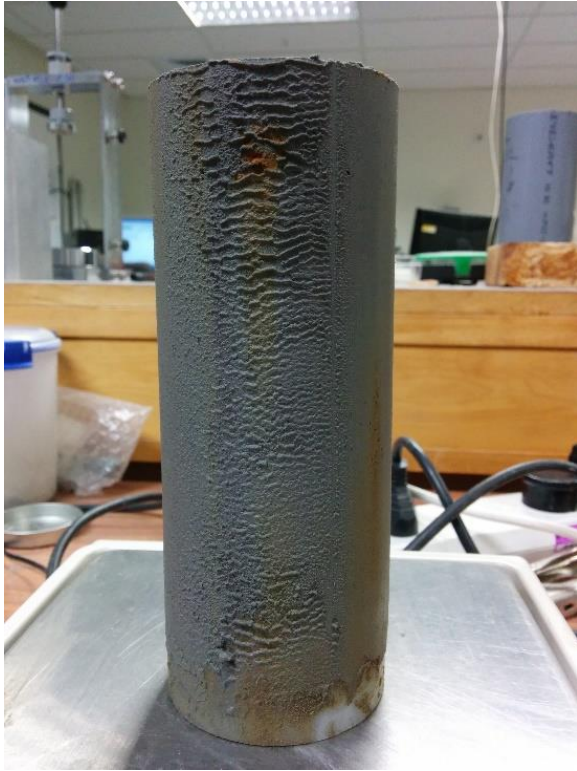


Figure C.3.3-3: S21-DM1-3U-A, As-Extruded



Figure C.3.3-4: S21-DM1-3U-A, Tested

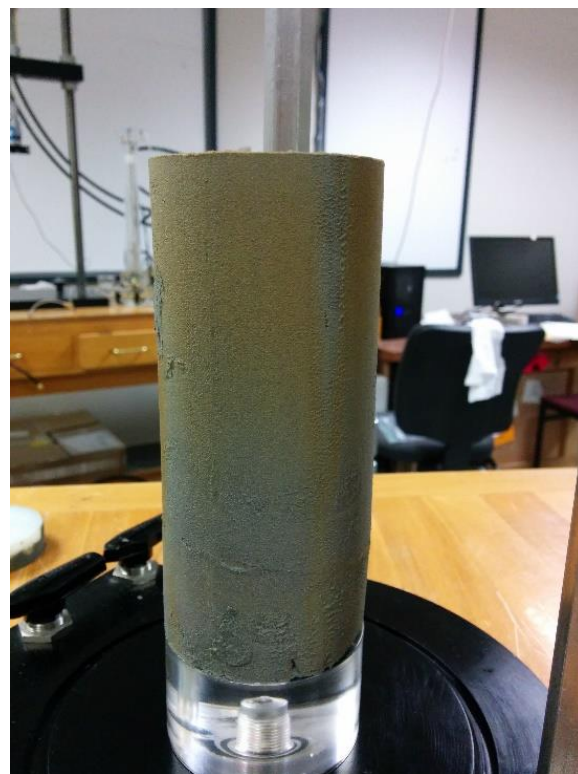
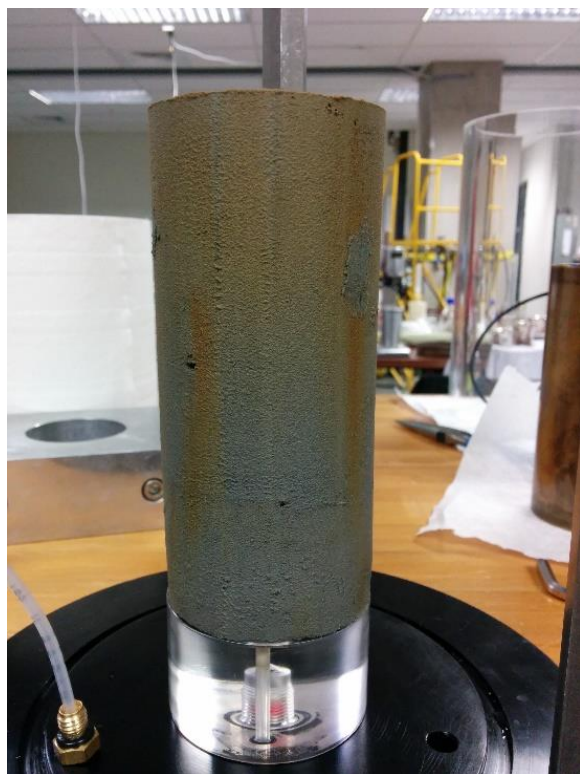


Figure C.3.3-5: S21-DM1-3U-B, As-Extruded



Figure C.3.3-6: S21-DM1-3U-B, Tested

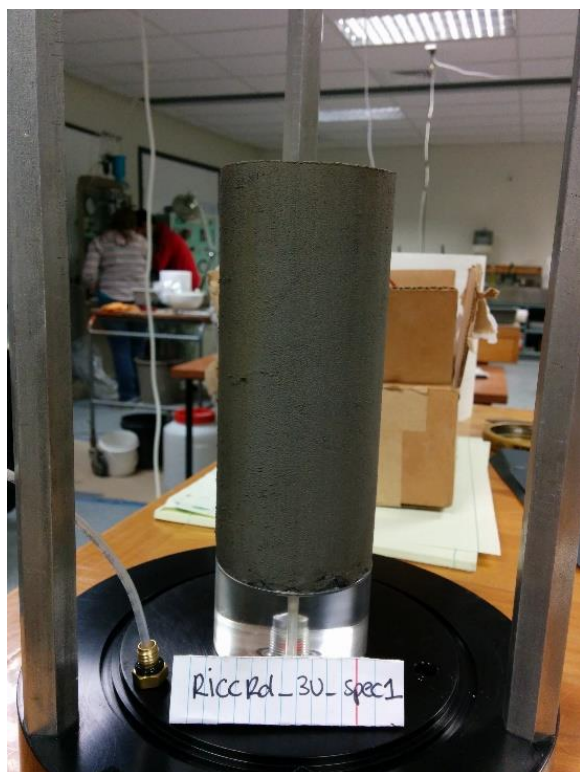


Figure C.3.4-1: S23-DM1-3U-A, As-Extruded

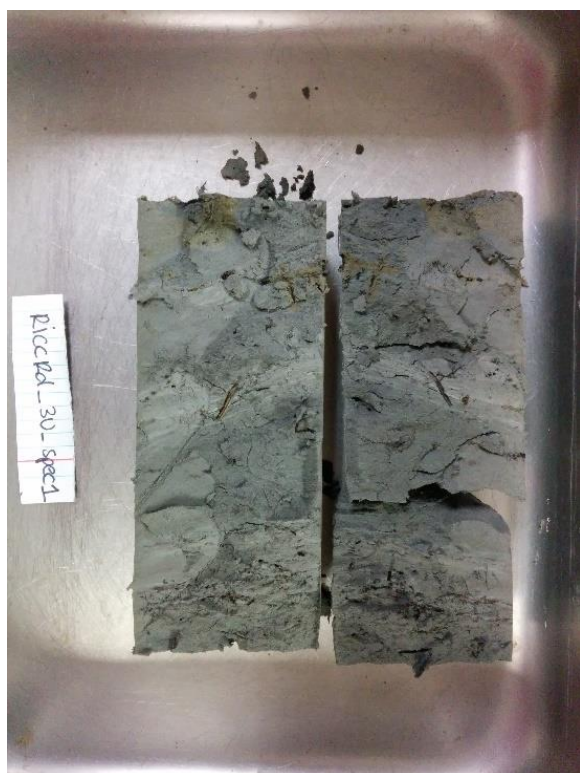


Figure C.3.4-2: S23-DM1-3U-A, Tested



Figure C.3.4-3: S23-DM1-3U-B, As-Extruded



Figure C.3.4-4: S23-DM1-3U-B, Tested

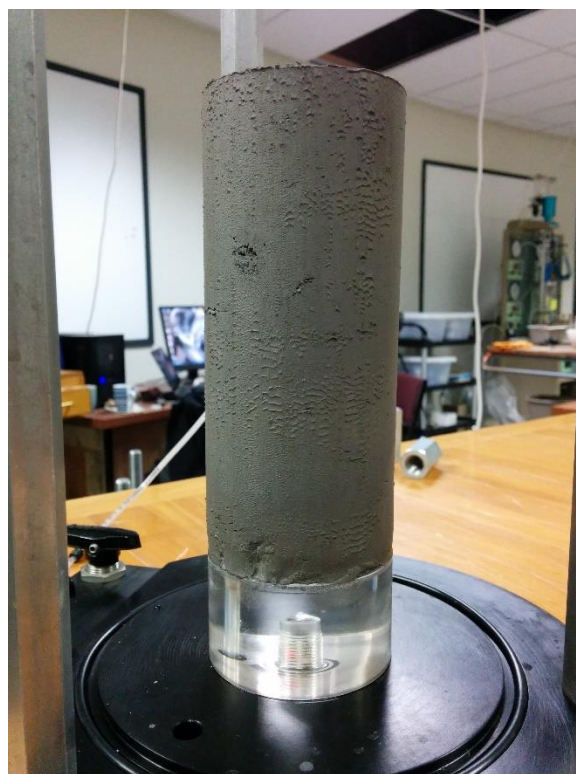
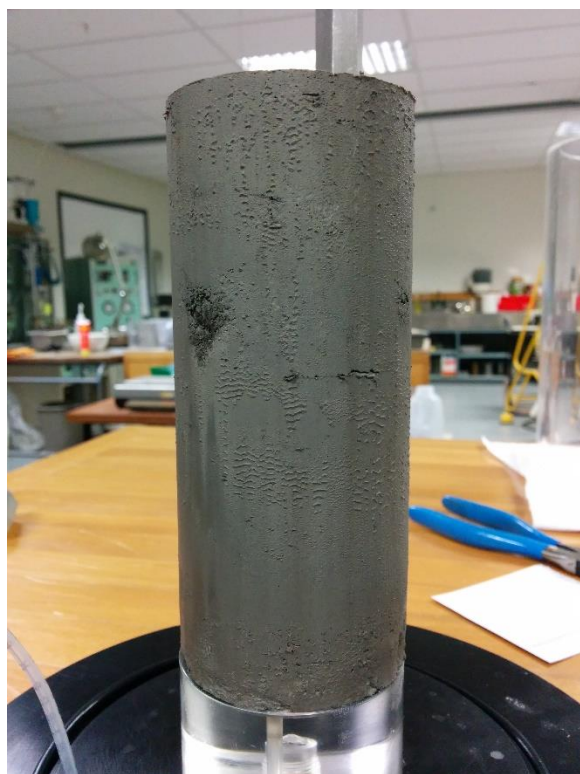


Figure C.3.4-5: S23-DM1-4U-A, As-Extruded



Figure C.3.4-6: S23-DM1-4U-A, After Testing Attempted (CKC equipment malfunction)

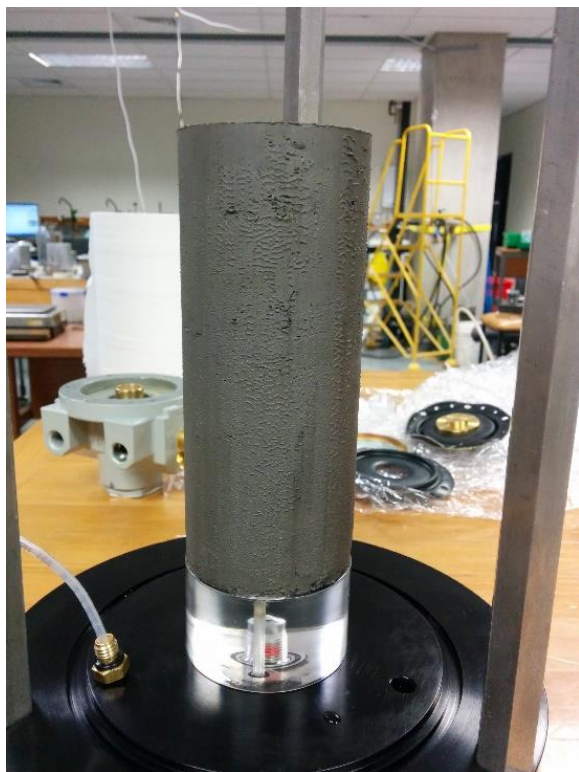


Figure C.3.4-7: S23-DM1-4U-B, As-Extruded



Figure C.3.4-8: S23-DM1-4U-B, Tested



Figure C.3.4-9: S23-DM1-5U-A, As-Extruded



Figure C.3.4-10: S23-DM1-5U-A, Tested

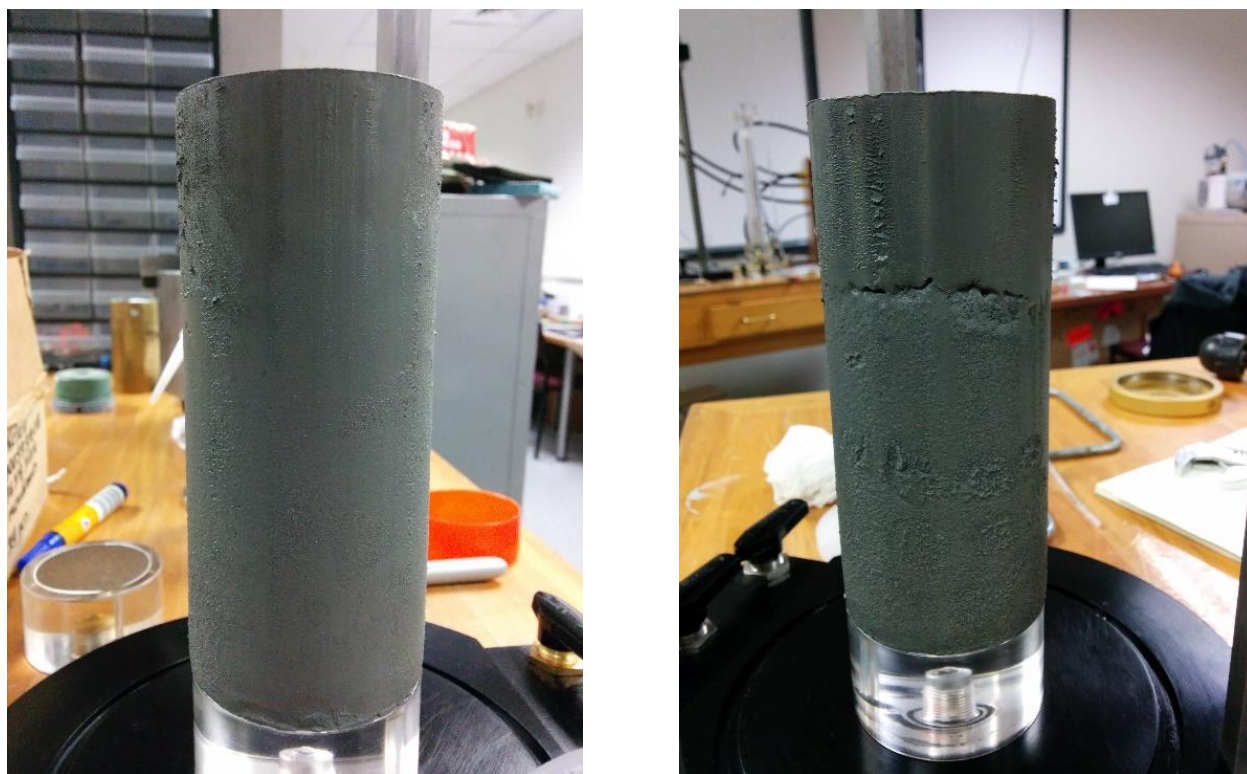


Figure C.3.4-11: S23-DM1-7U-A, As-Extruded



Figure C.3.4-12: S23-DM1-7U-A, Tested

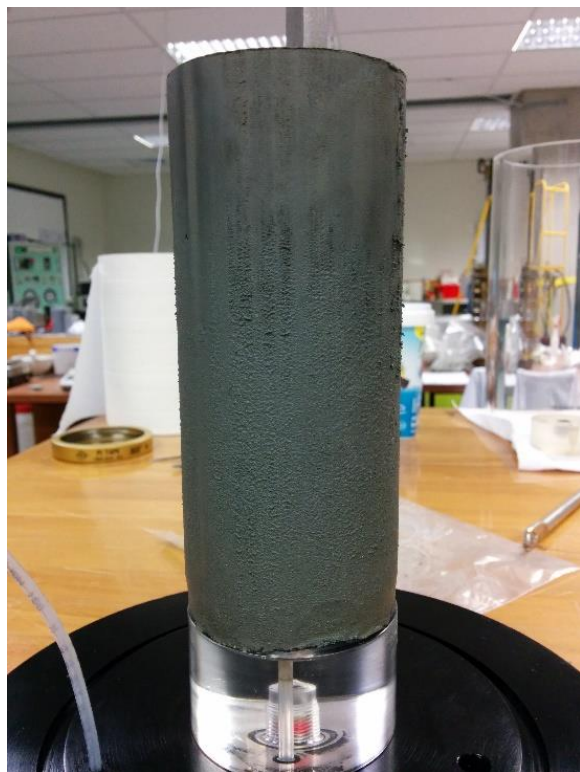


Figure C.3.4-13: S23-DM1-7U-B, As-Extruded



Figure C.3.4-14: S23-DM1-7U-B, Tested

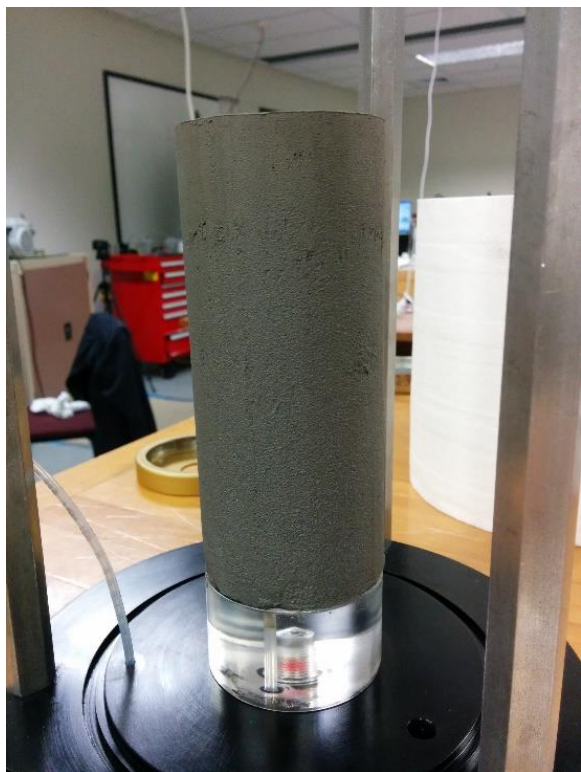


Figure C.3.4-15: S23-DM1-8Ub-A, As-Extruded



Figure C.3.4-16: S23-DM1-8Ub-A, Tested



Figure C.3.5-1: S33-DM1-2U-B, As-Extruded



Figure C.3.5-2: S33-DM1-2U-B, Tested



Figure C.3.5-3: S33-DM1-3U-A, As-Extruded

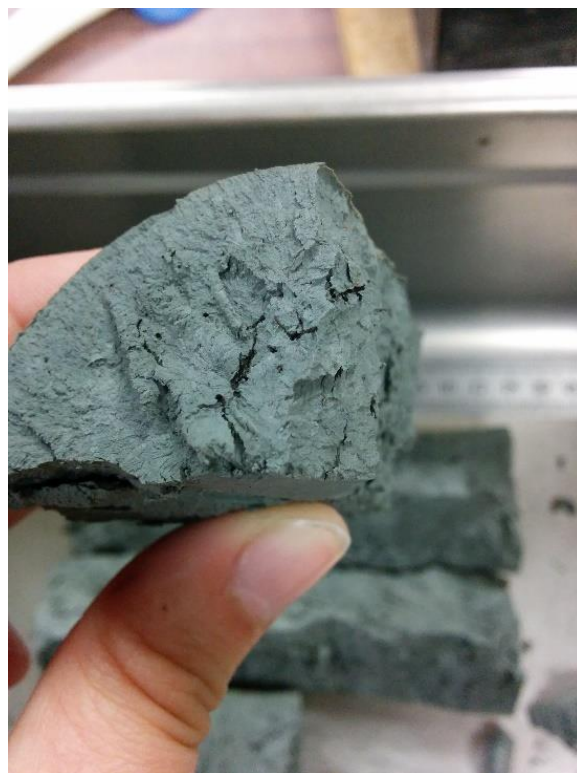


Figure C.3.5-4: S33-DM1-3U-A, Tested

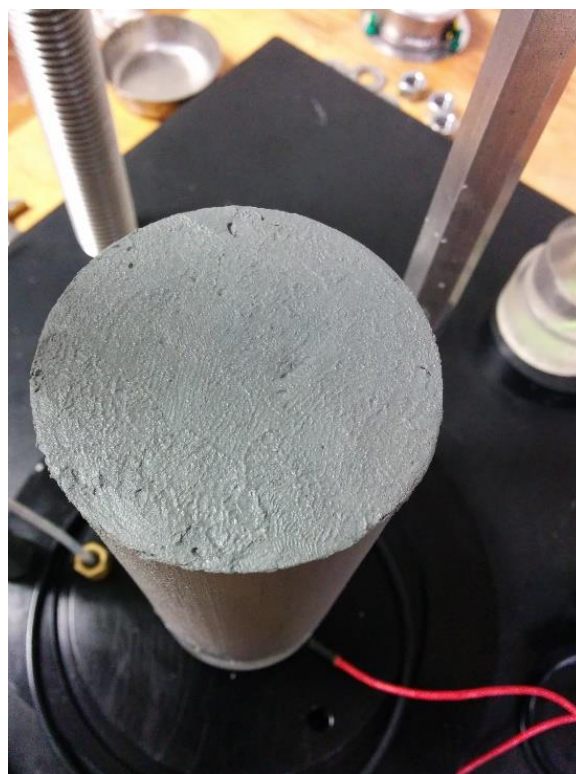
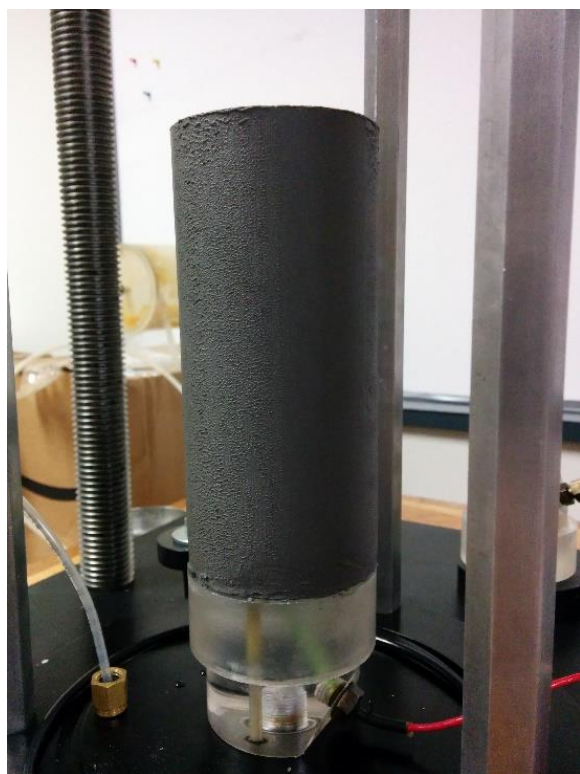


Figure C.3.5-5: S33-DM1-3U-B, As-Extruded

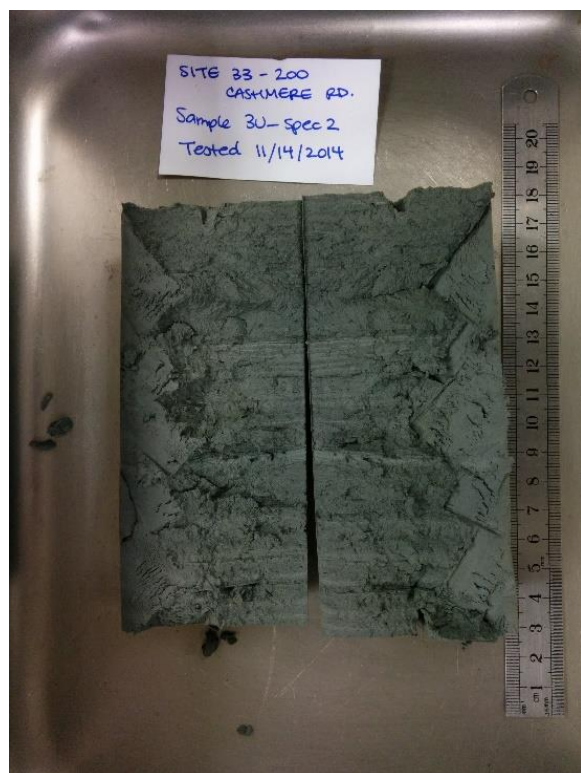


Figure C.3.5-6: S33-DM1-3U-B, Tested



Figure C.3.5-7: S33-DM1-4U-A, As-Extruded



Figure C.3.5-8: S33-DM1-4U-A, Tested



Figure C.3.5-9: S33-DM1-5U-A, As-Extruded



Figure C.3.5-10: S33-DM1-5U-A, Tested

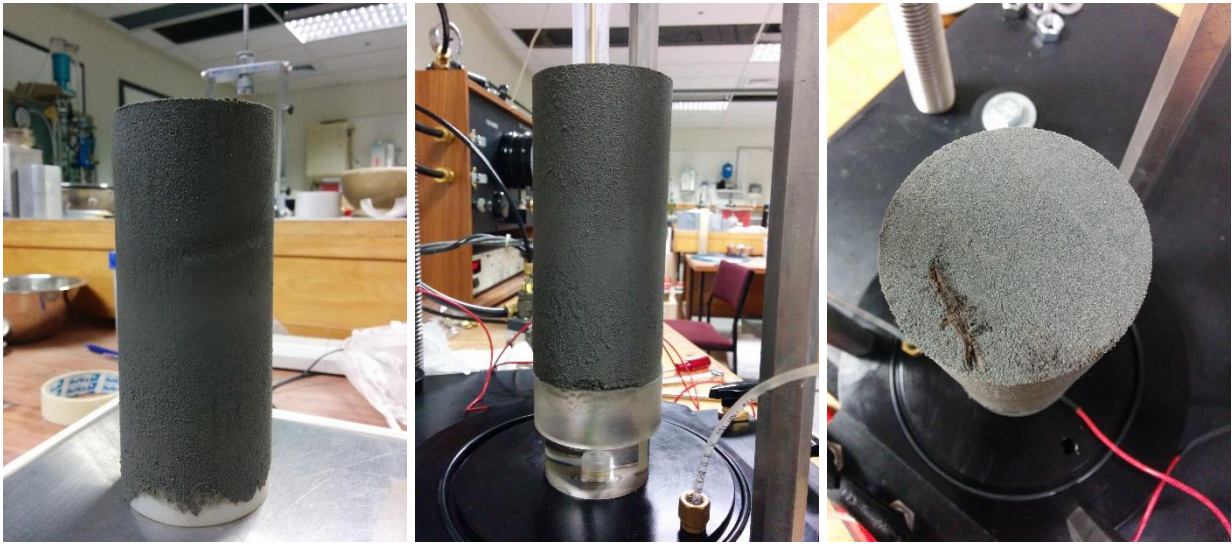


Figure C.3.5-11: S33-DM1-5U-B, As-Extruded

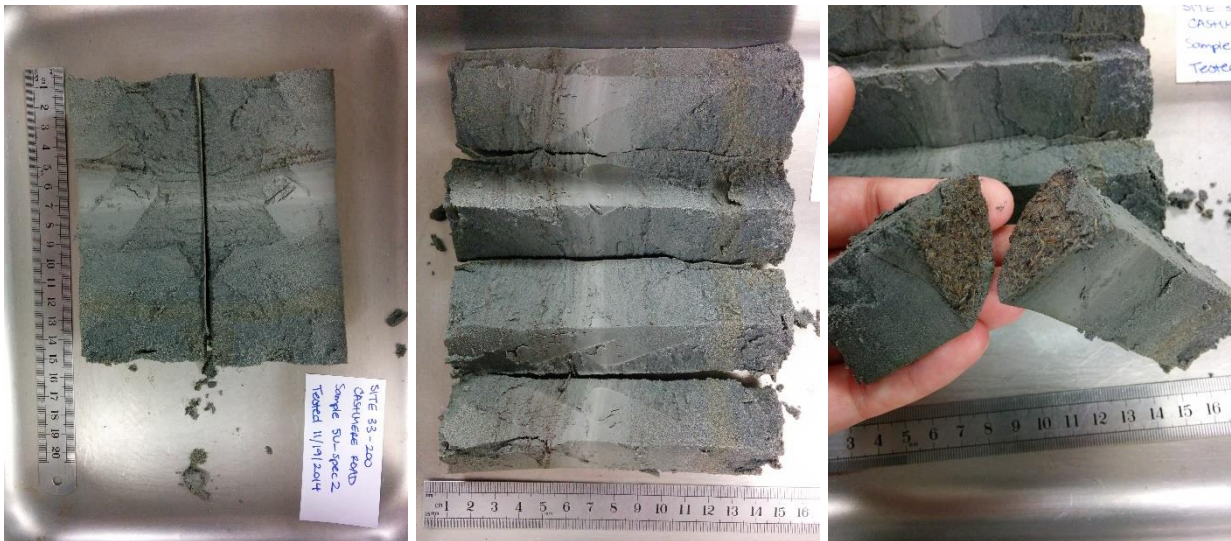


Figure C.3.5-12: S33-DM1-5U-B, Tested

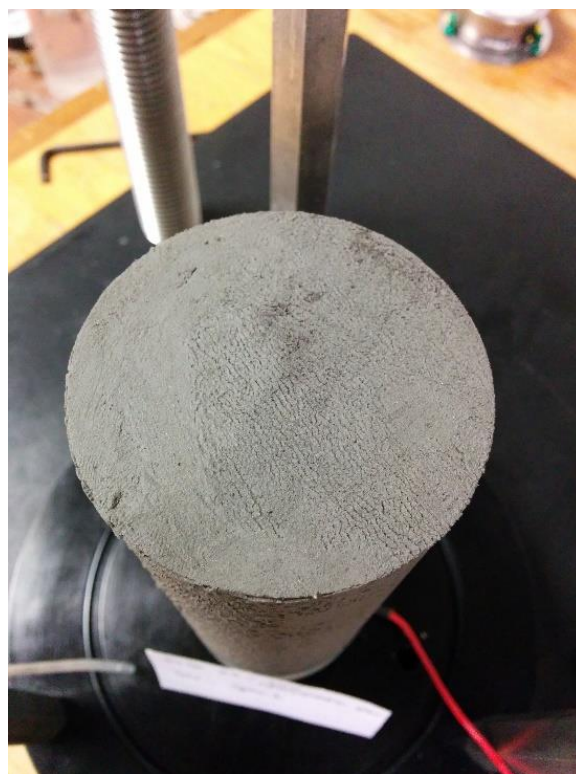
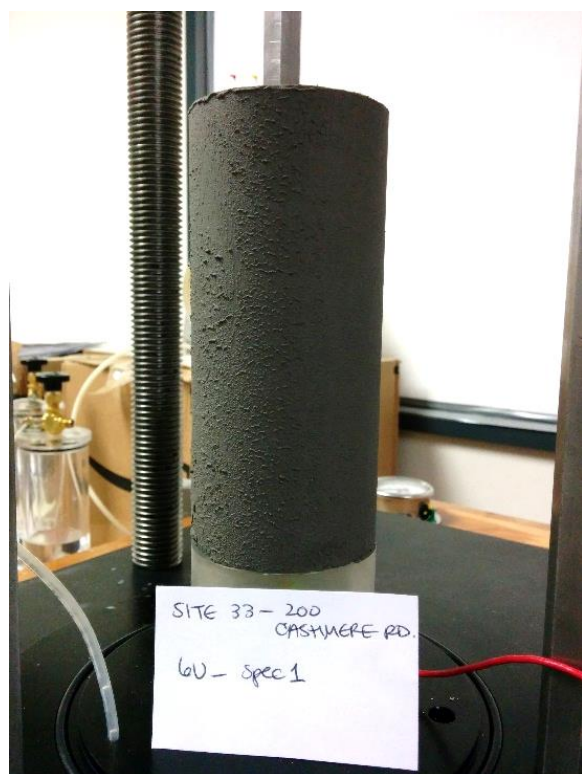


Figure C.3.5-13: S33-DM1-6U-A, As-Extruded



Figure C.3.5-14: S33-DM1-6U-A, Tested

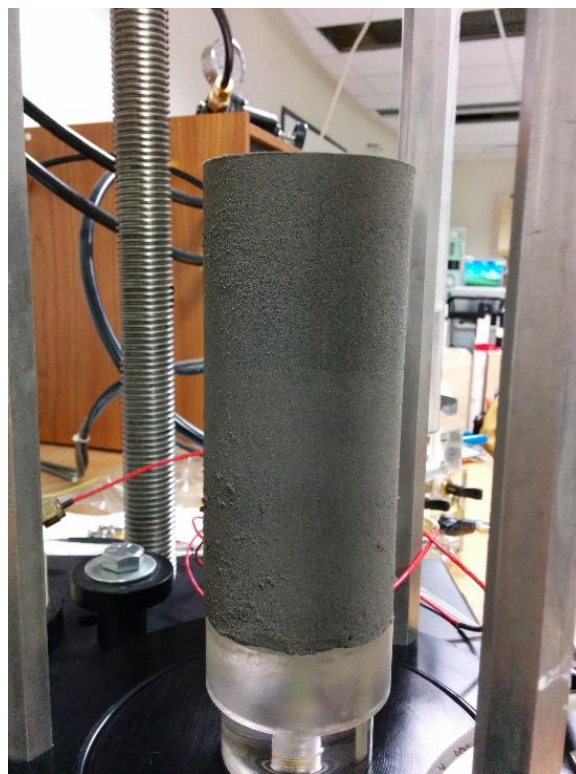


Figure C.3.5-15: S33-DM1-6U-B, As-Extruded

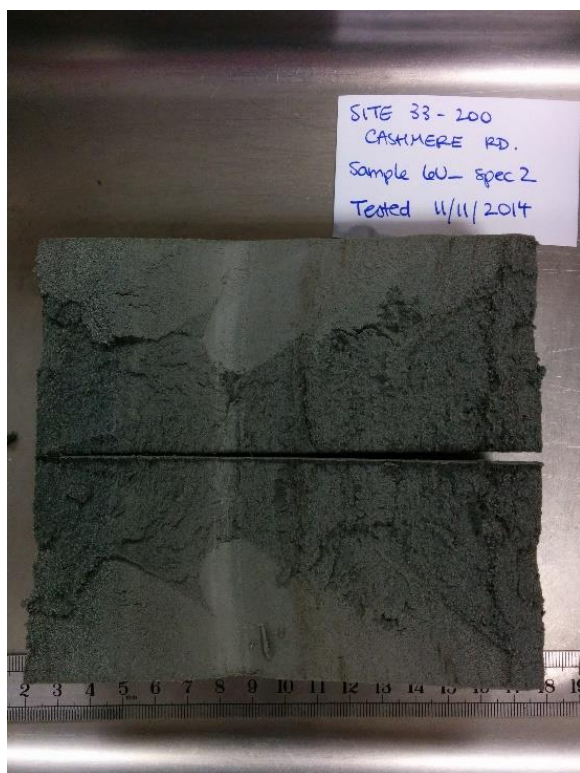


Figure C.3.5-16: S33-DM1-6U-B, Tested

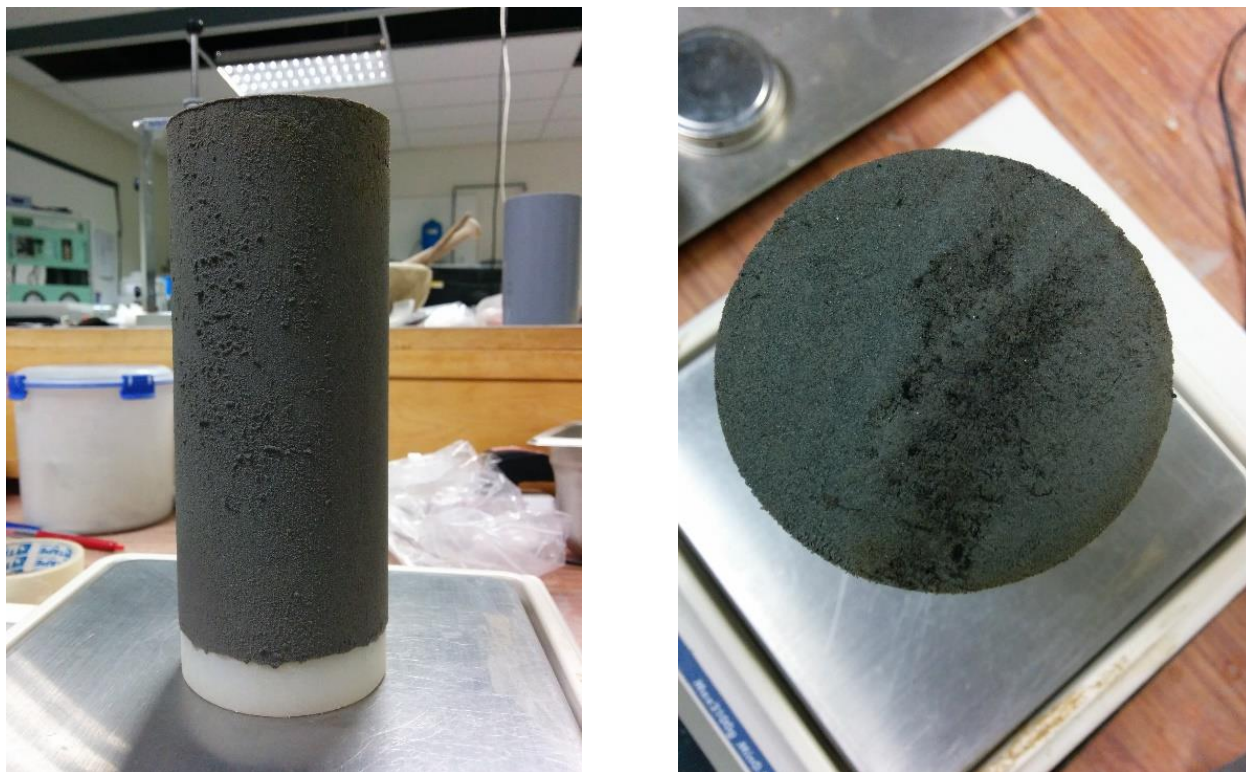


Figure C.3.5-17: S33-DM1-7U-A, As-Extruded



Figure C.3.5-18: S33-DM1-7U-A, Tested



Figure C.3.5-19: S33-DM1-8U-A, As-Extruded



Figure C.3.5-20: S33-DM1-8U-A, Tested

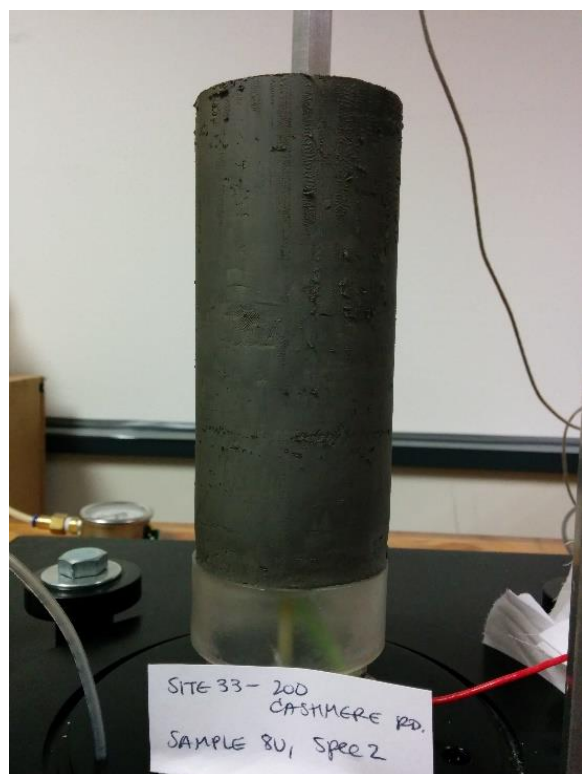


Figure C.3.5-21: S33-DM1-8U-B, As-Extruded



Figure C.3.5-22: S33-DM1-8U-B, Tested

Appendix C.4

Particle Size Distributions

APPENDIX C.4: PARTICLE SIZE DISTRIBUTIONS

Conventional laboratory testing of CTX specimens was conducted by personnel at the Univ. of Canterbury Geomechanics Laboratory. Particle size analysis was primarily conducted by the laser analysis diffraction method using a Horiba LA-950 machine. Sieve/hydrometer tests were conducted on some specimens for comparison with the particle size distributions obtained through laser analysis. The soil sample size used in laser analysis is very small (pea-sized), therefore multiple samples were run for each specimen using laser analysis to obtain an average particle size distribution for each specimen. Particle size distributions are shown in the following figures. Summary figures are shown for each site, followed by figures for individual specimens.

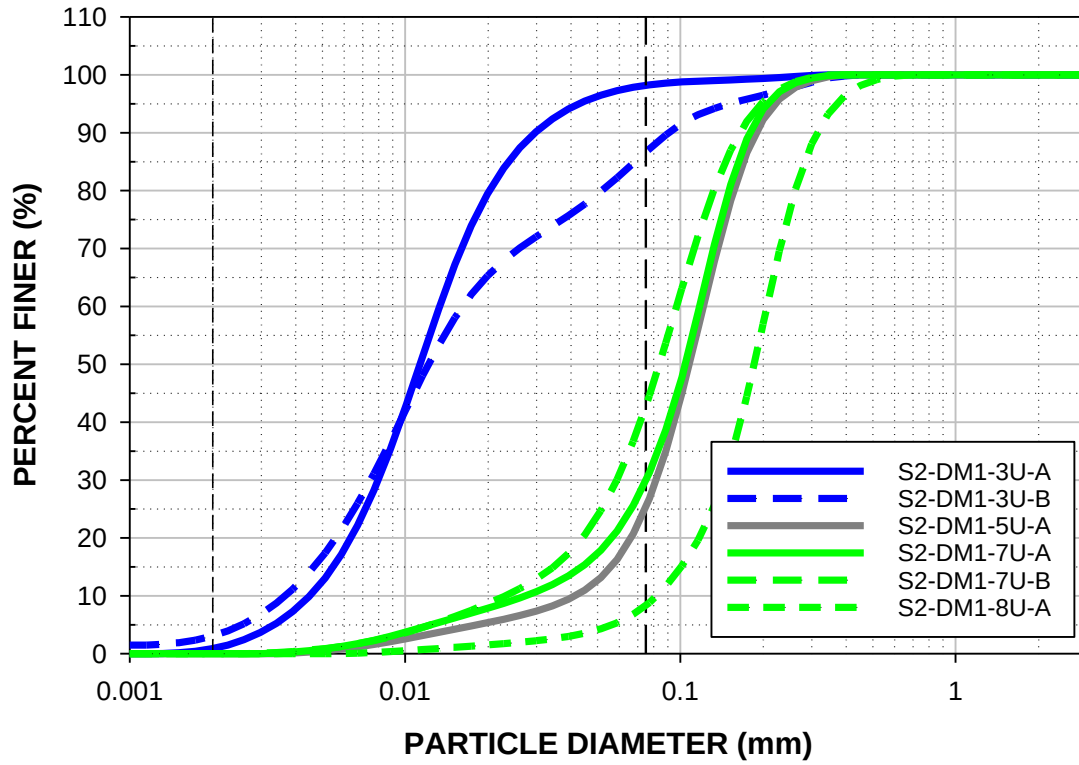


Figure C.4-1: Site 2 Particle Size Distributions (Laser Analysis – average for each specimen)

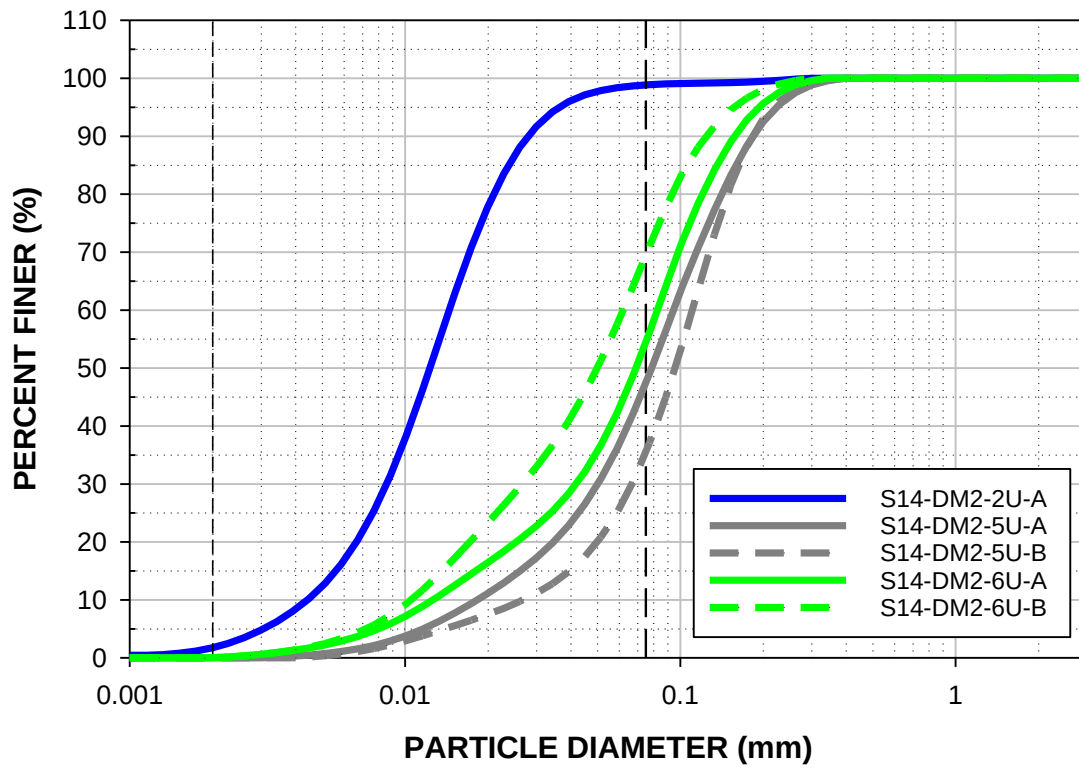


Figure C.4-2: Site 14 Particle Size Distributions (Laser Analysis – average for each specimen)

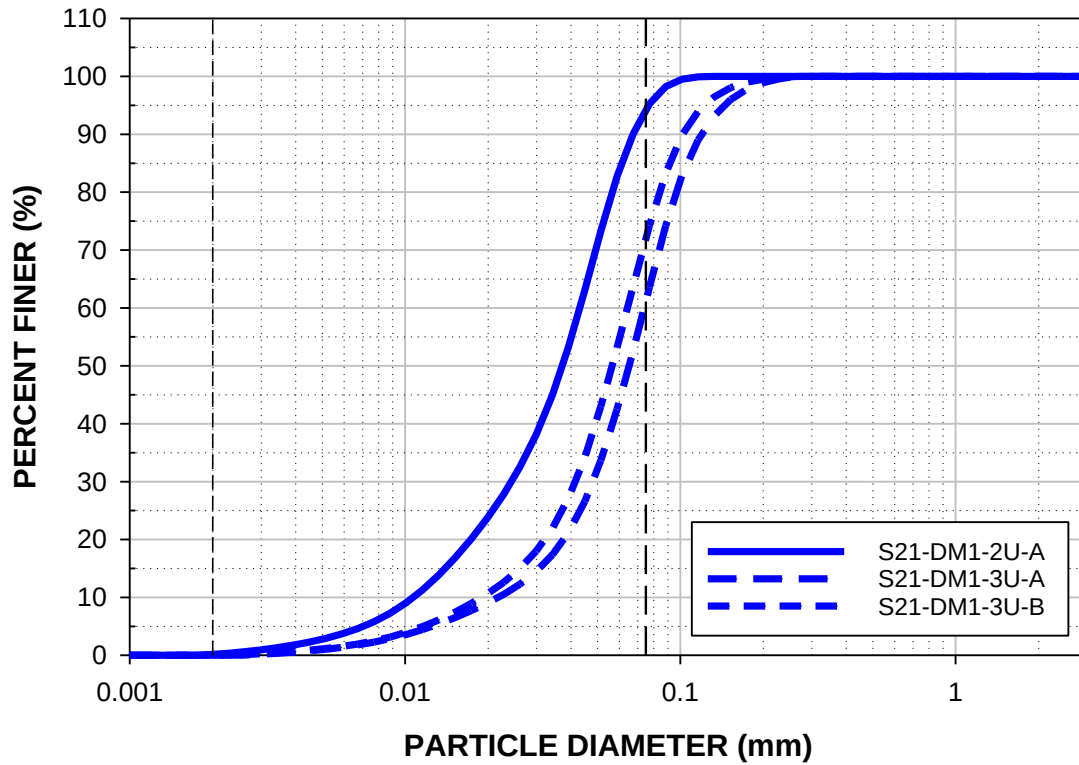


Figure C.4-3: Site 21 Particle Size Distributions (Laser Analysis – average for each specimen)

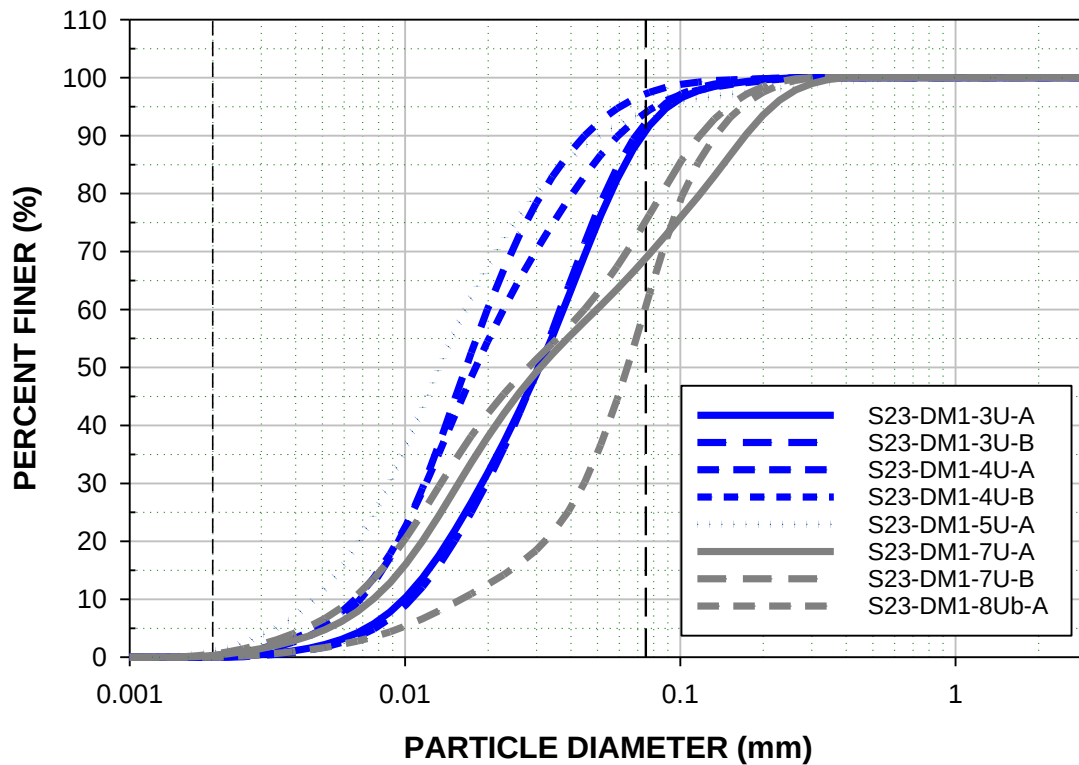


Figure C.4-4: Site 23 Particle Size Distributions (Laser Analysis – average for each specimen)

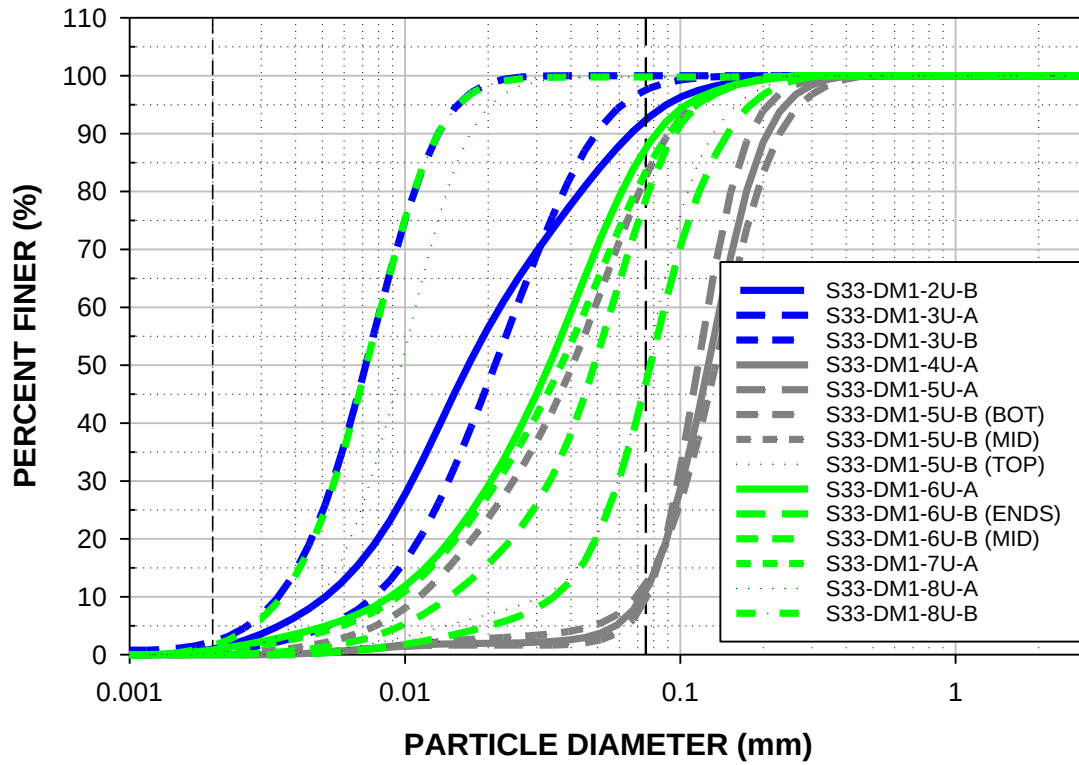


Figure C.4-5: Site 33 Particle Size Distributions (Laser Analysis – average for each specimen)

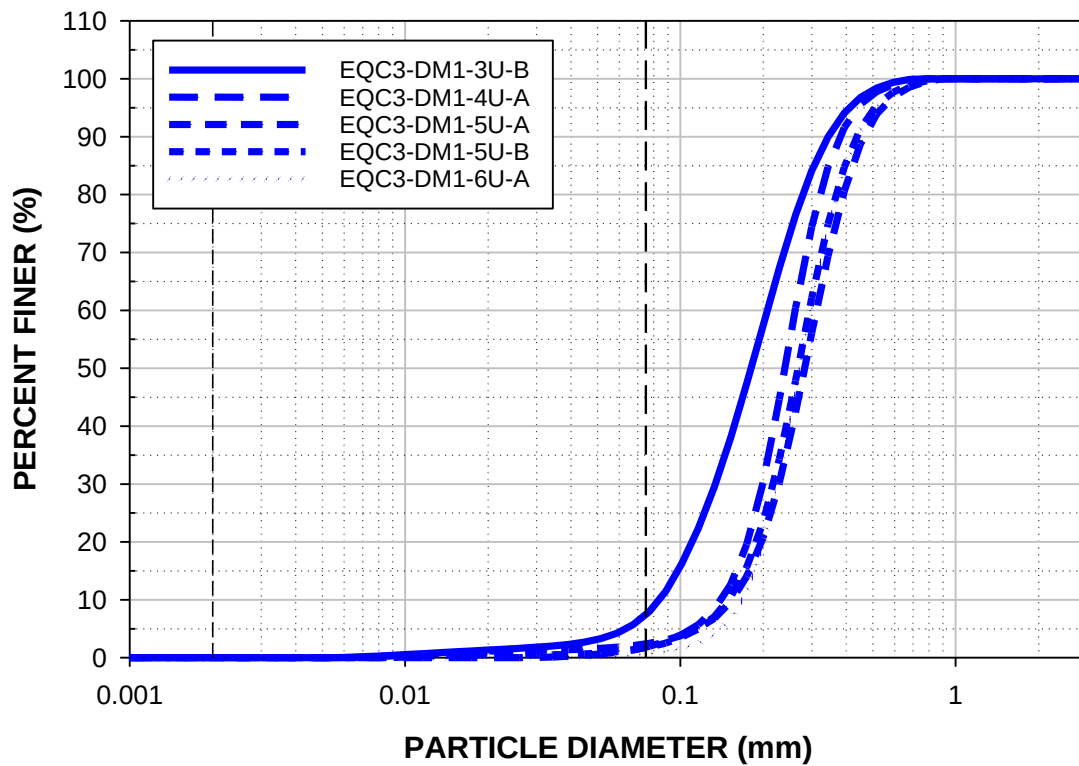


Figure C.4-6: EQC-3 Particle Size Distributions (Laser Analysis – average for each specimen)

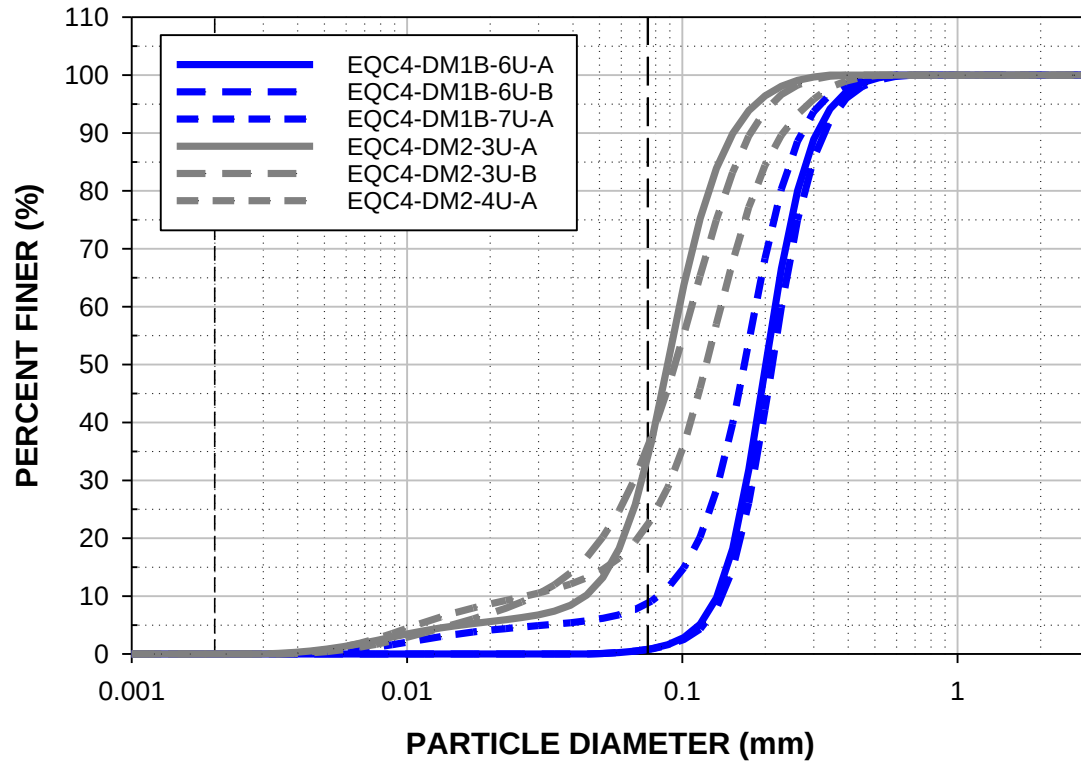


Figure C.4-7: EQC-4 Particle Size Distributions (Laser Analysis – average for each specimen)

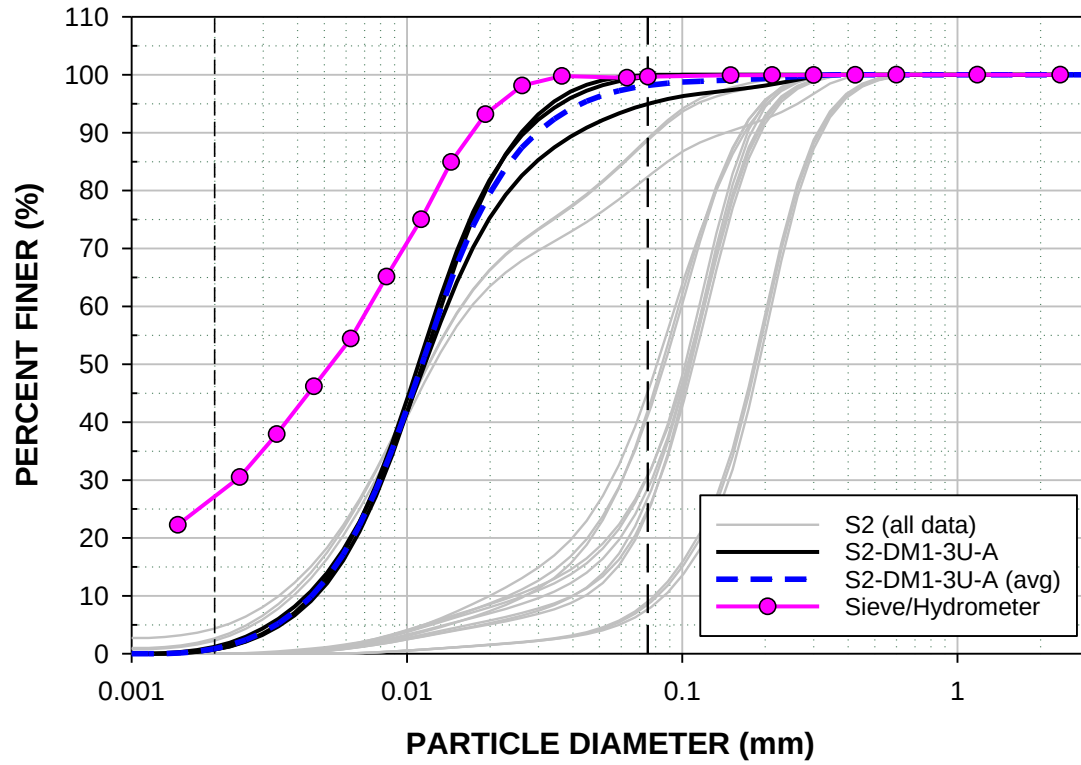


Figure C.4-8: S2-DM1-3U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

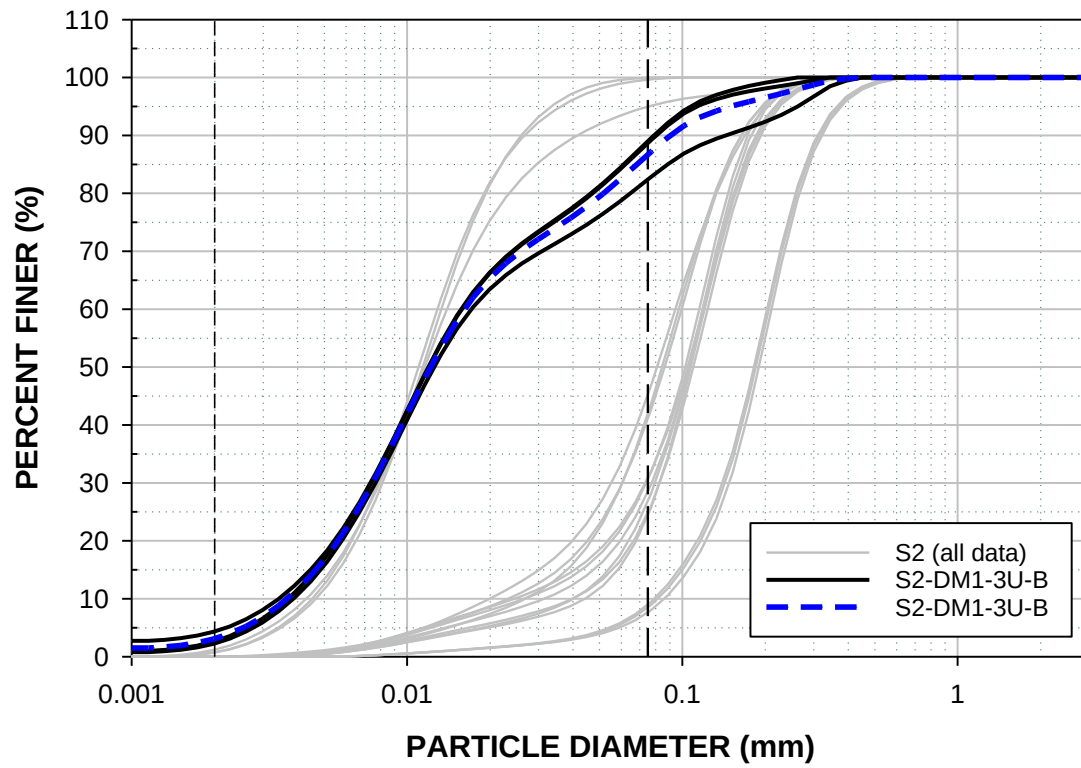


Figure C.4-9: S2-DM1-3U-B, Particle Size Distribution (Laser Analysis)

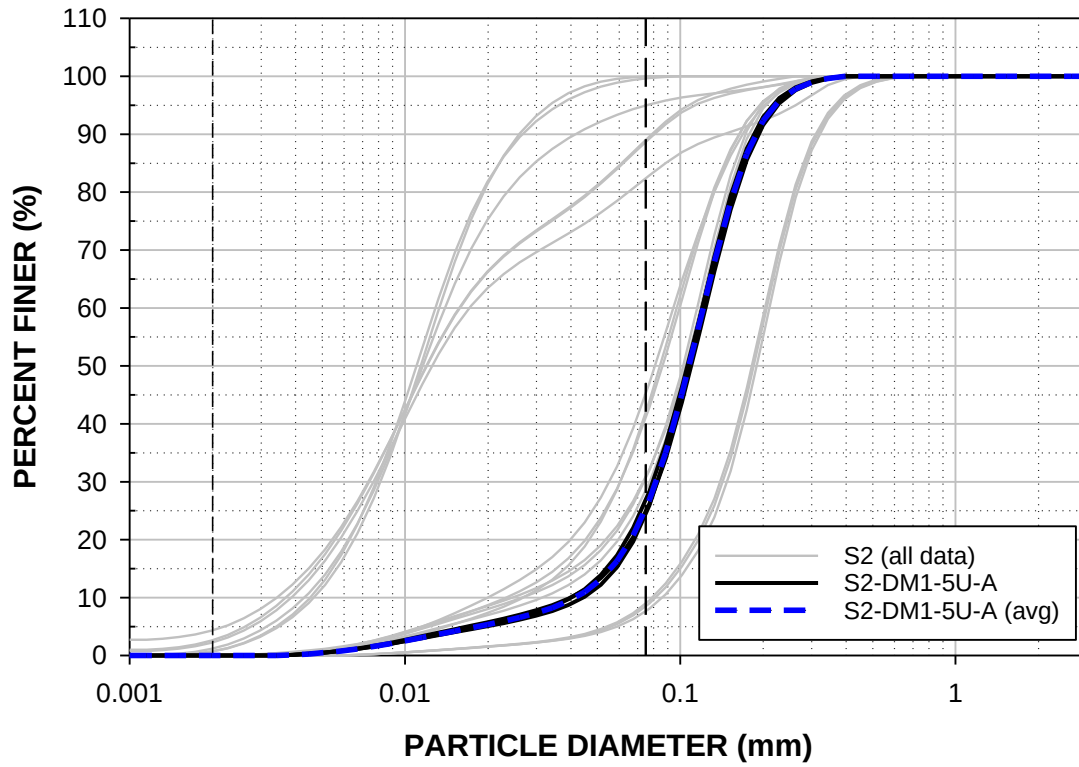


Figure C.4-10: S2-DM1-5U-A, Particle Size Distribution (Laser Analysis)

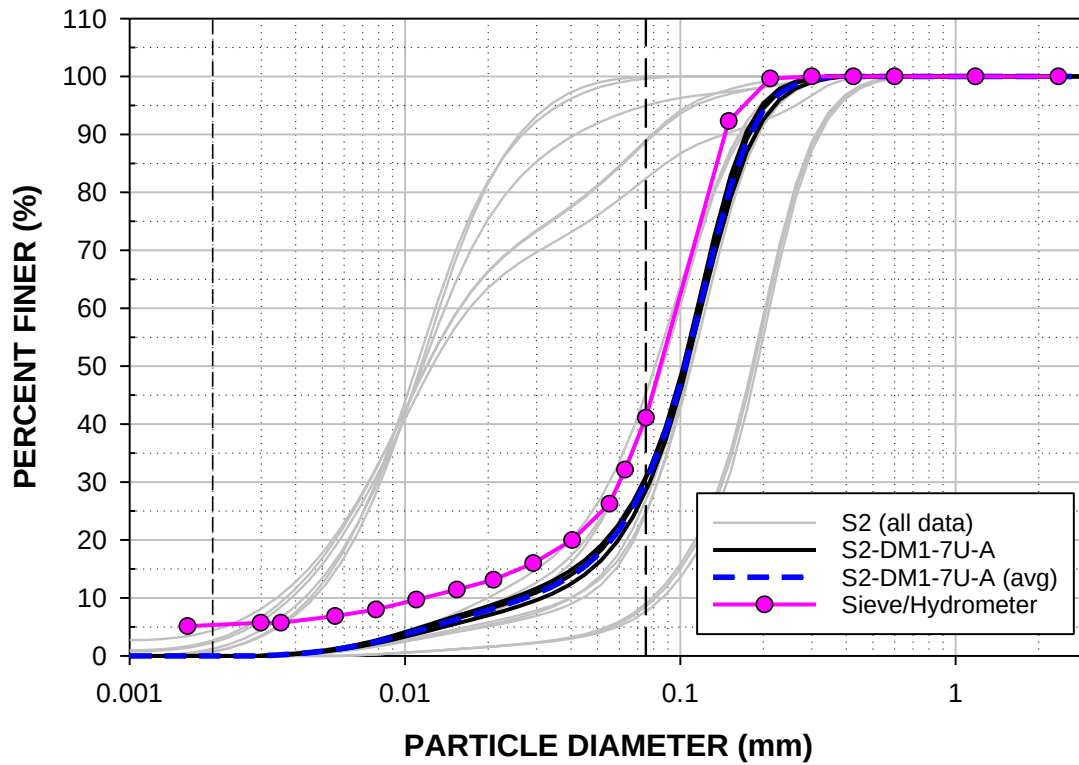


Figure C.4-11: S2-DM1-7U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

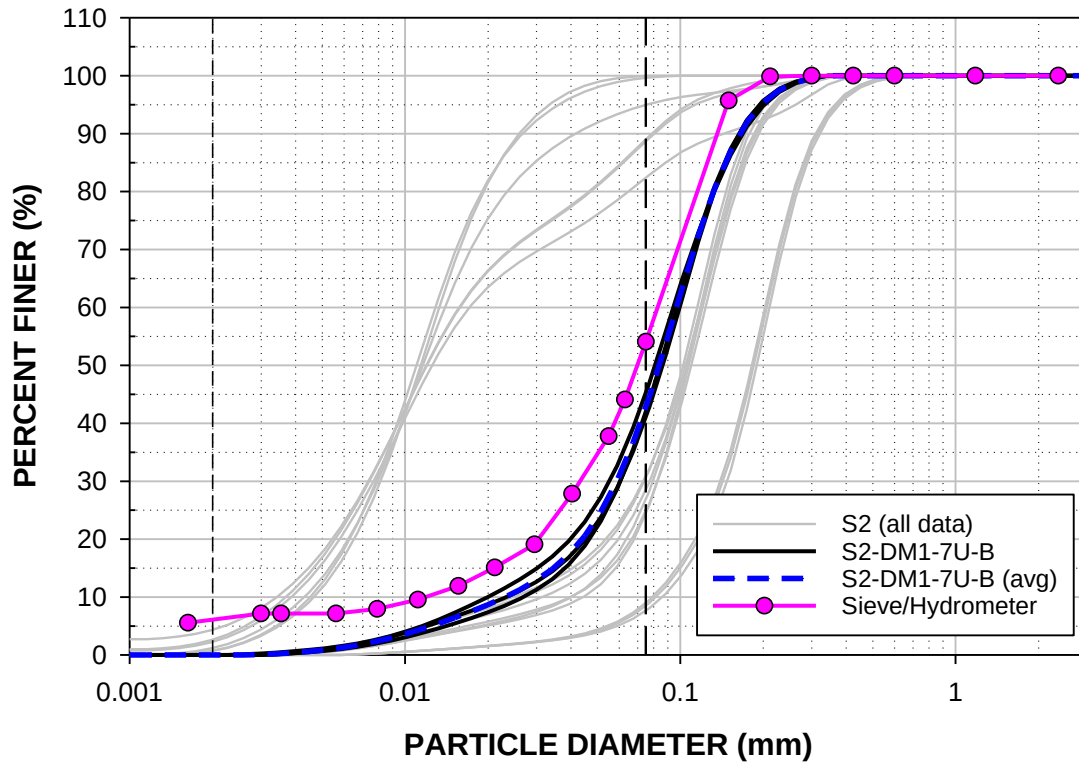


Figure C.4-12: S2-DM1-7U-B, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

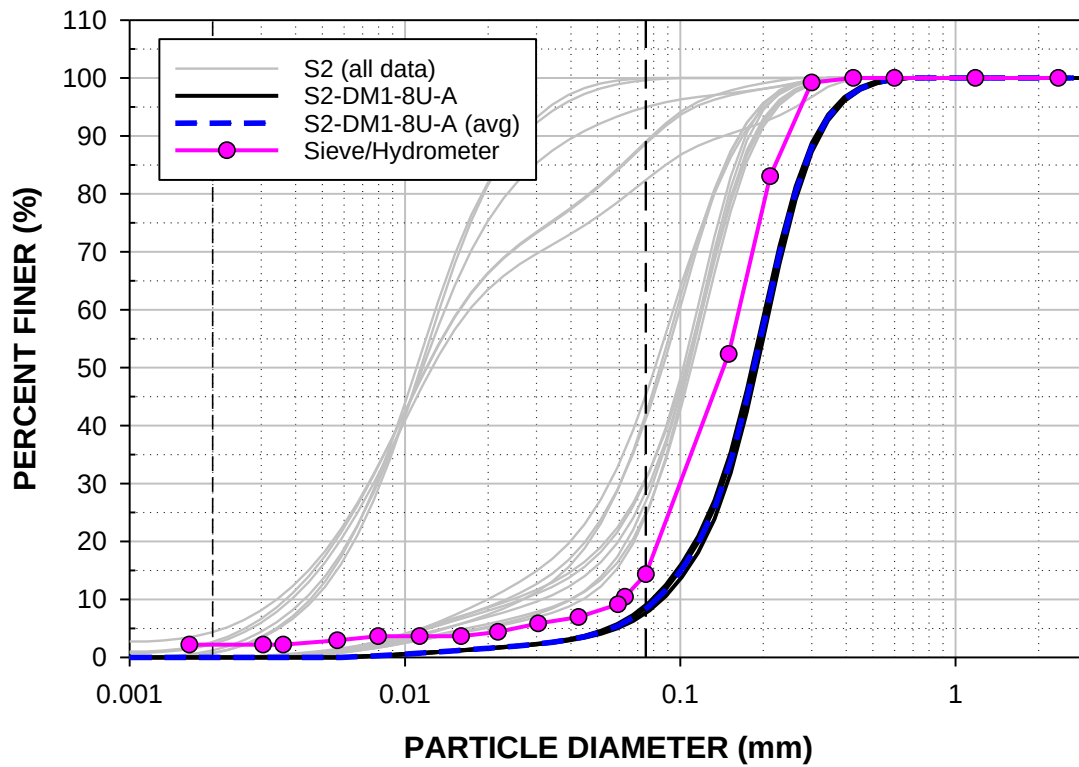


Figure C.4-13: S2-DM1-8U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

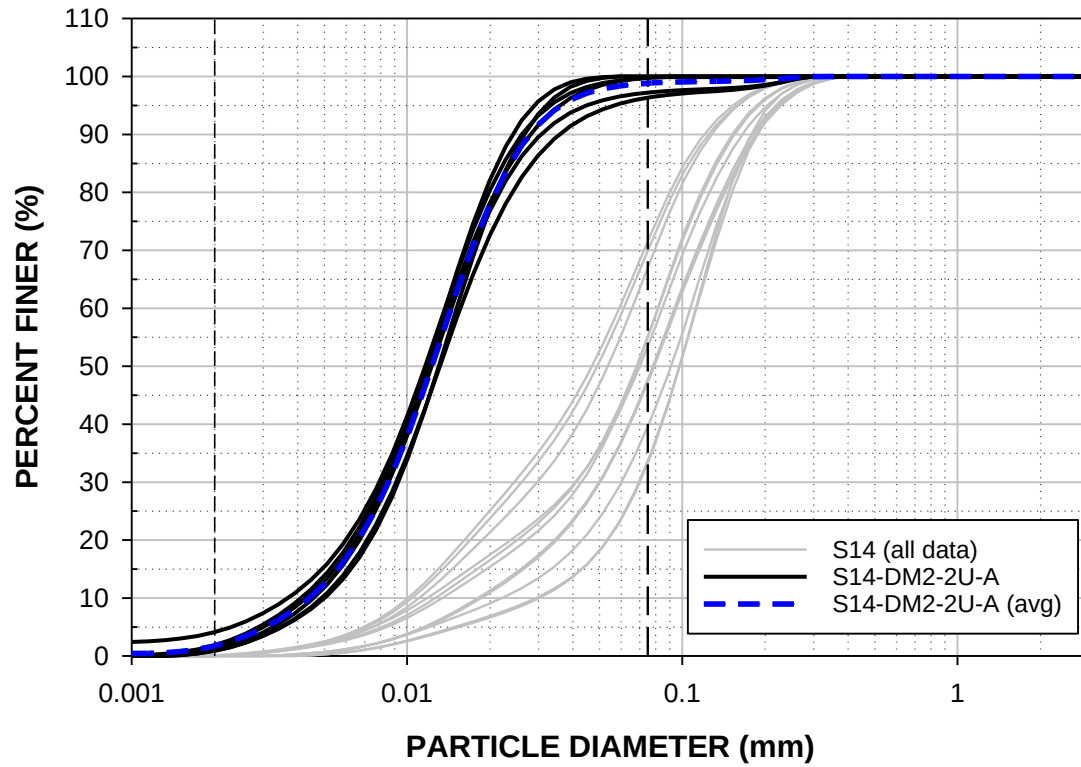


Figure C.4-14: S14-DM2-2U-A, Particle Size Distribution (Laser Analysis)

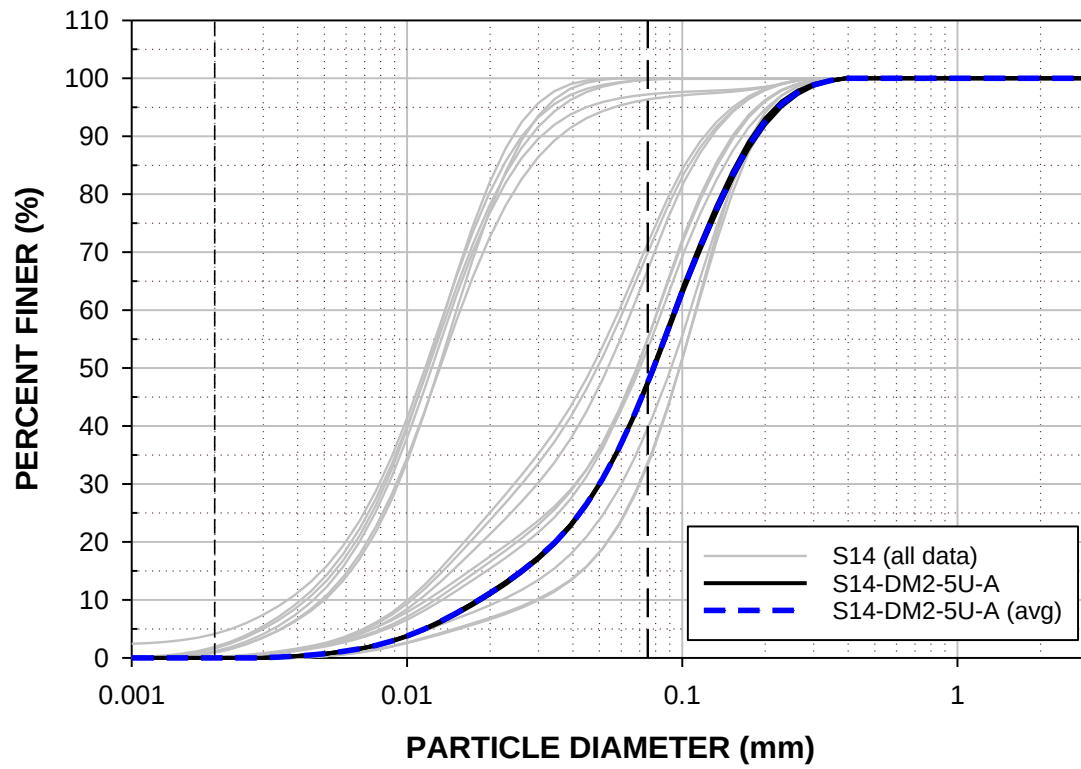


Figure C.4-15: S14-DM2-5U-A, Particle Size Distribution (Laser Analysis)

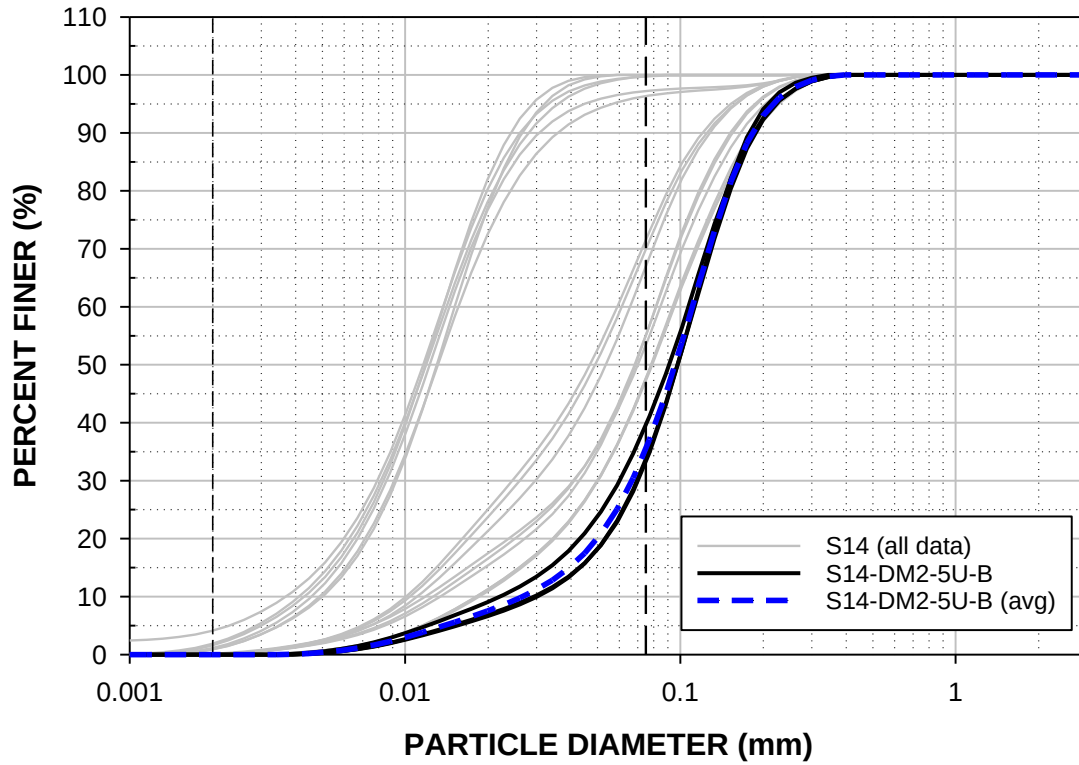


Figure C.4-16: S14-DM2-5U-B, Particle Size Distribution (Laser Analysis)

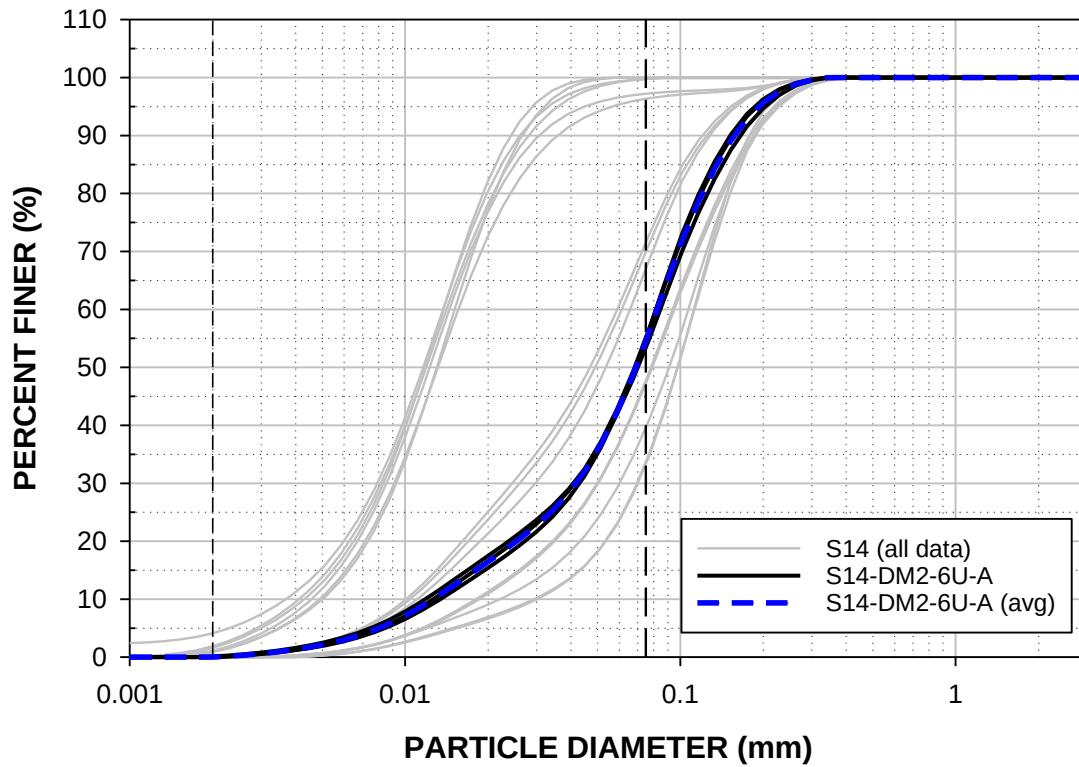


Figure C.4-17: S14-DM2-6U-A, Particle Size Distribution (Laser Analysis)

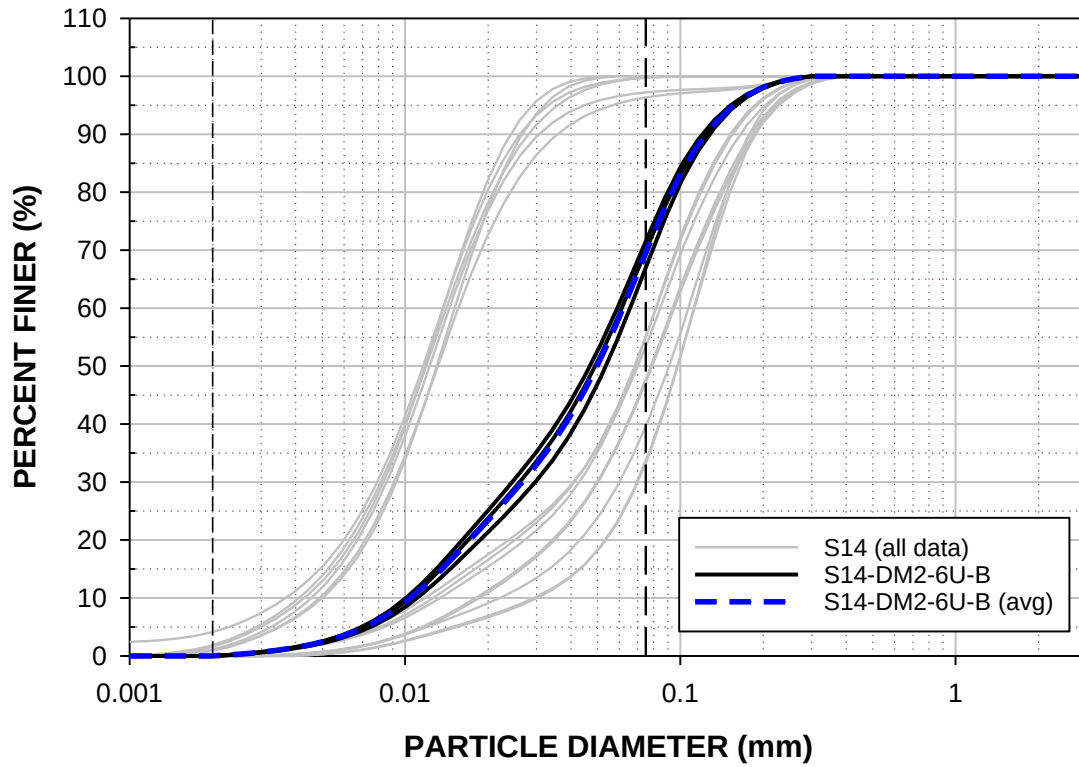


Figure C.4-18: S14-DM2-6U-B, Particle Size Distribution (Laser Analysis)

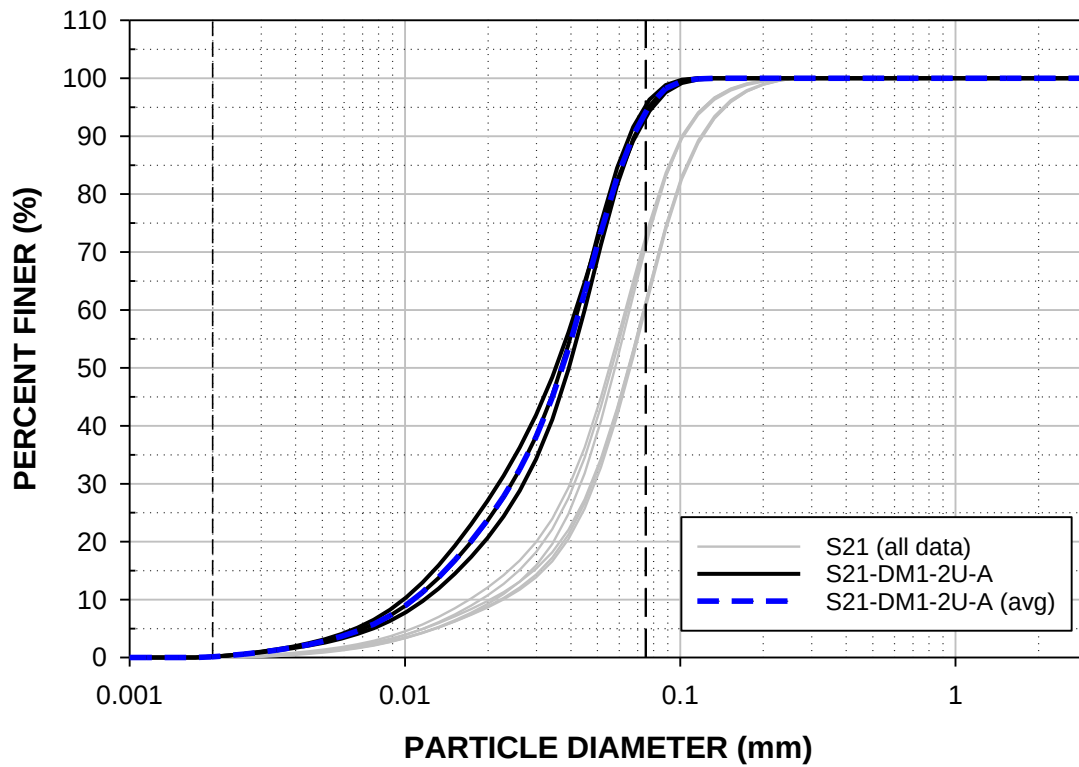


Figure C.4-19: S21-DM1-2U-A, Particle Size Distribution (Laser Analysis)

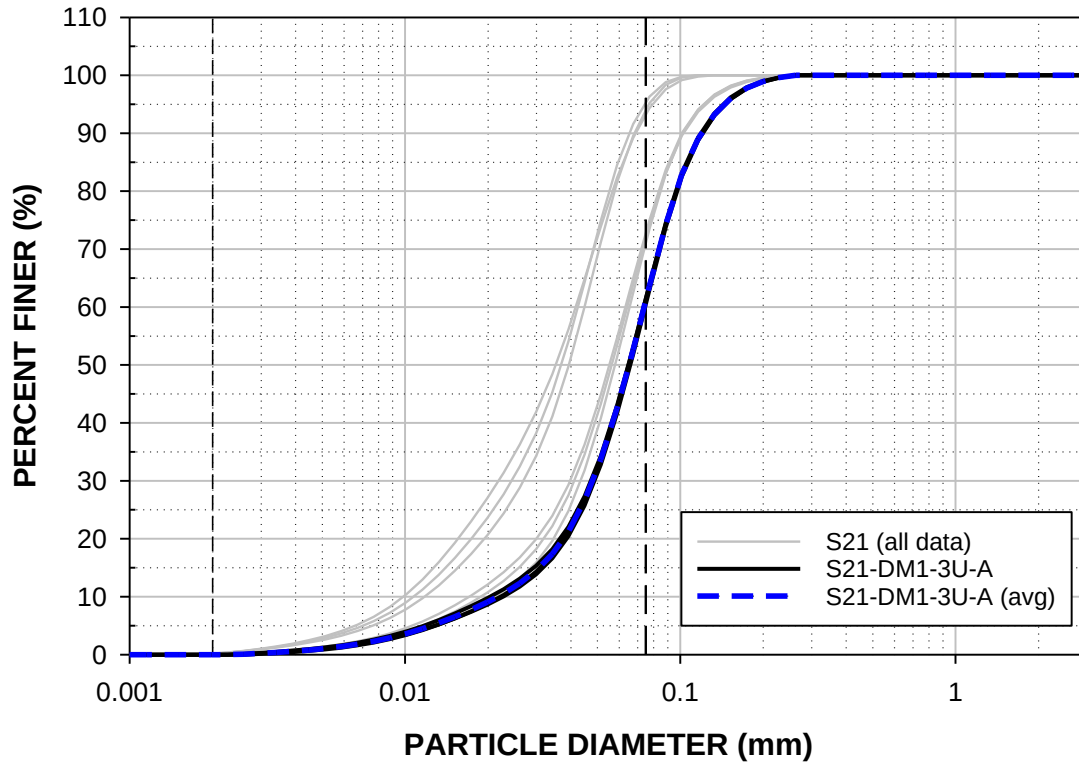


Figure C.4-20: S21-DM1-3U-A, Particle Size Distribution (Laser Analysis)

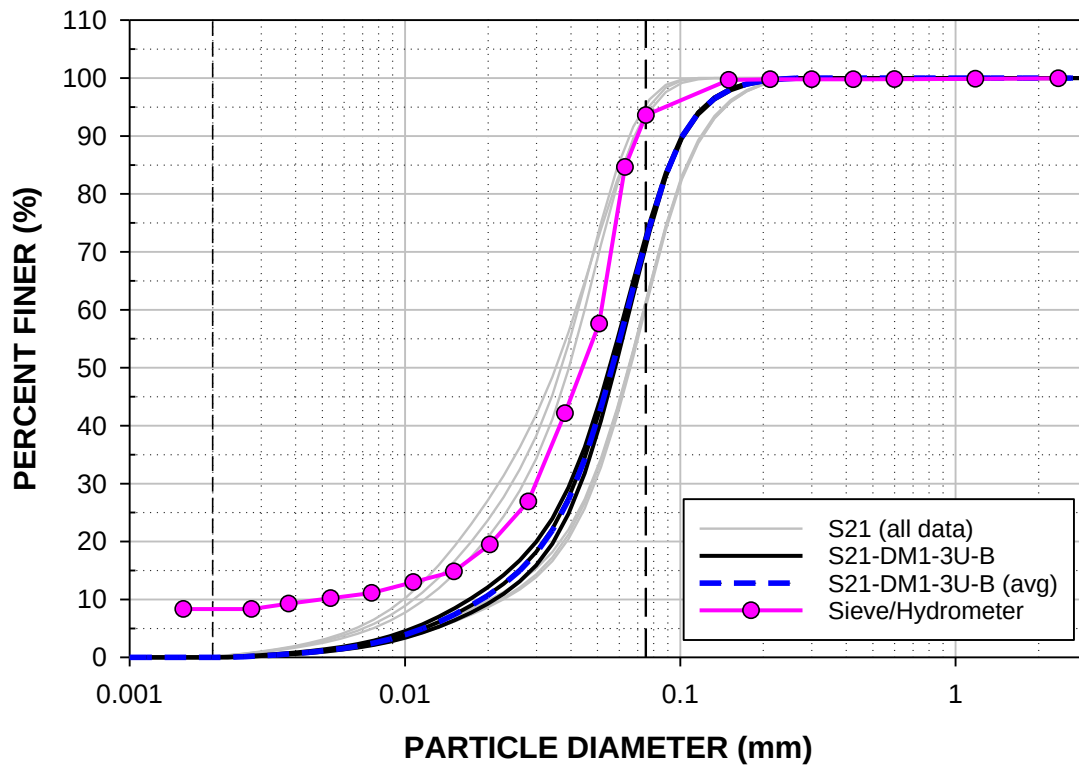


Figure C.4-21: S21-DM1-3U-B, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

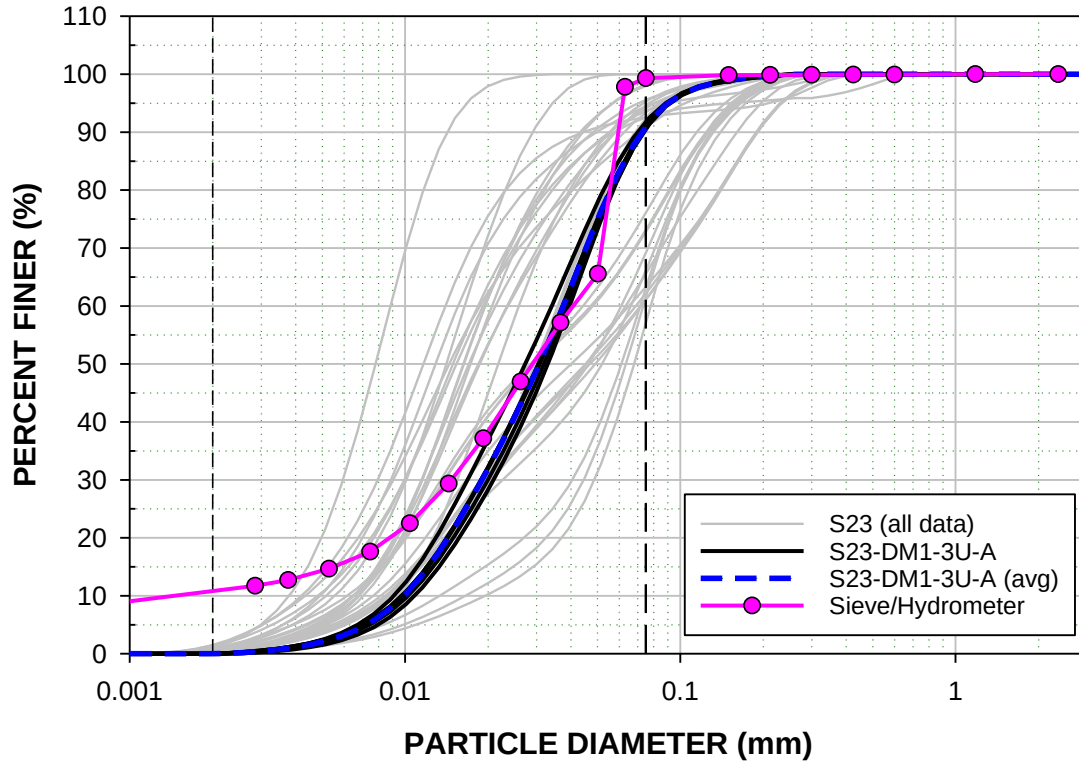


Figure C.4-22: S23-DM1-3U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

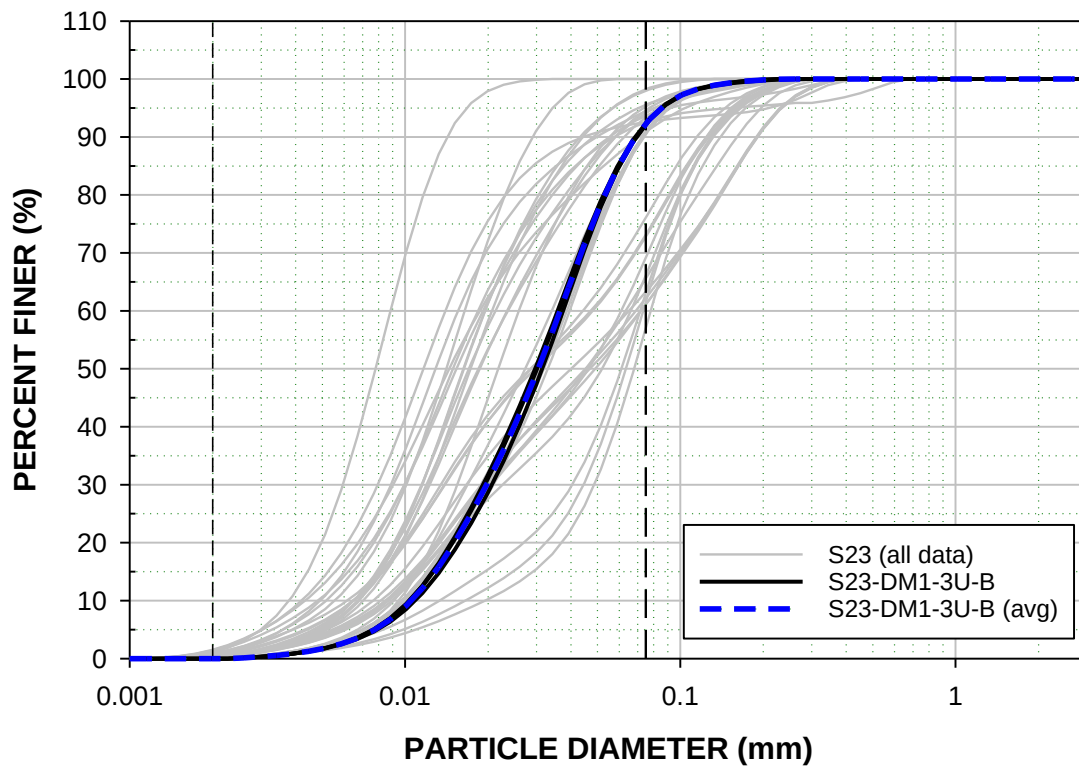


Figure C.4-23: S23-DM1-3U-B, Particle Size Distribution (Laser Analysis)

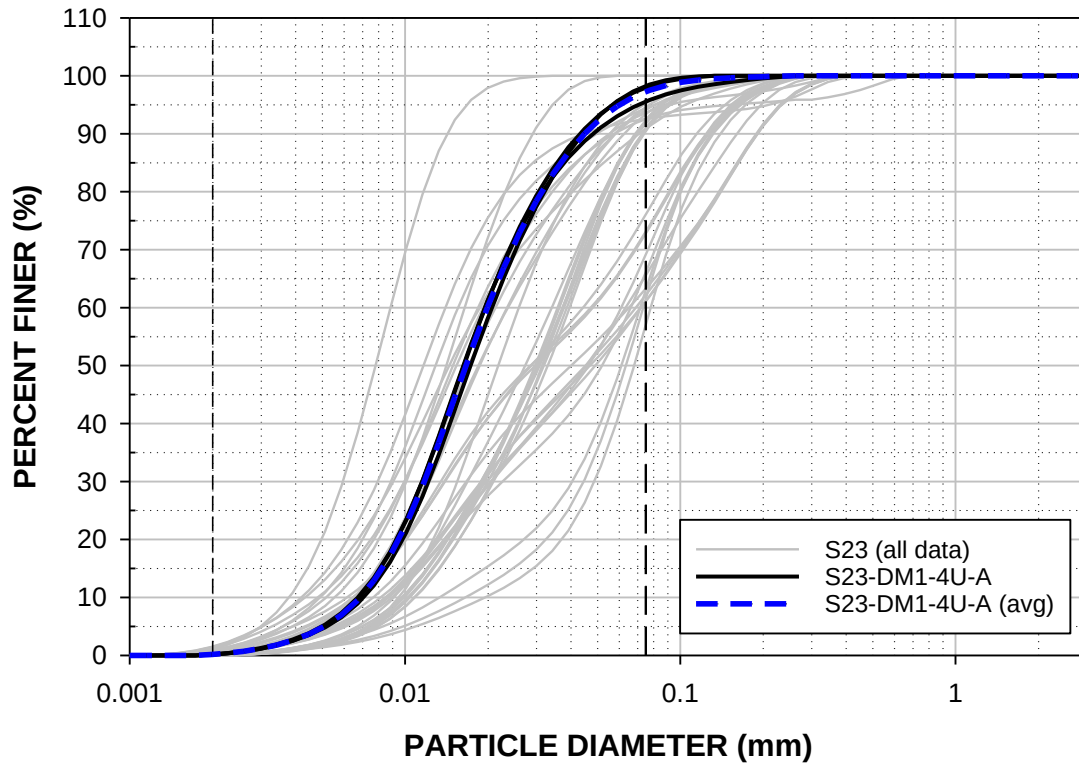


Figure C.4-24: S23-DM1-4U-A, Particle Size Distribution (Laser Analysis)

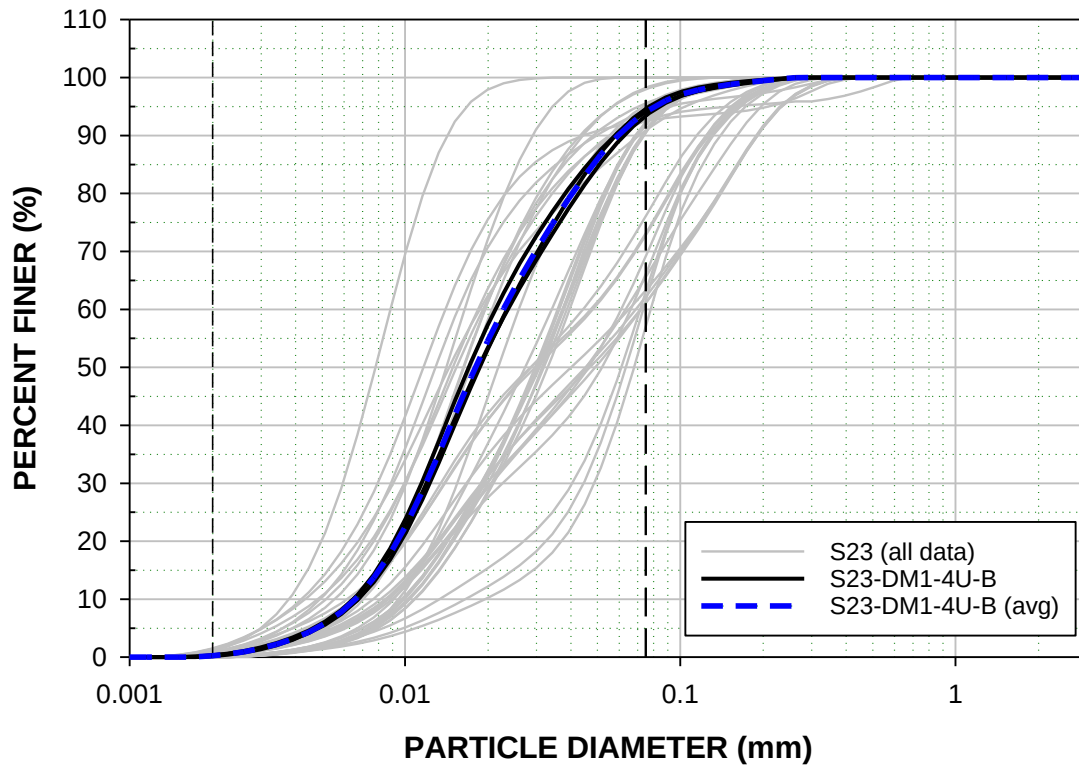


Figure C.4-25: S23-DM1-4U-B, Particle Size Distribution (Laser Analysis)

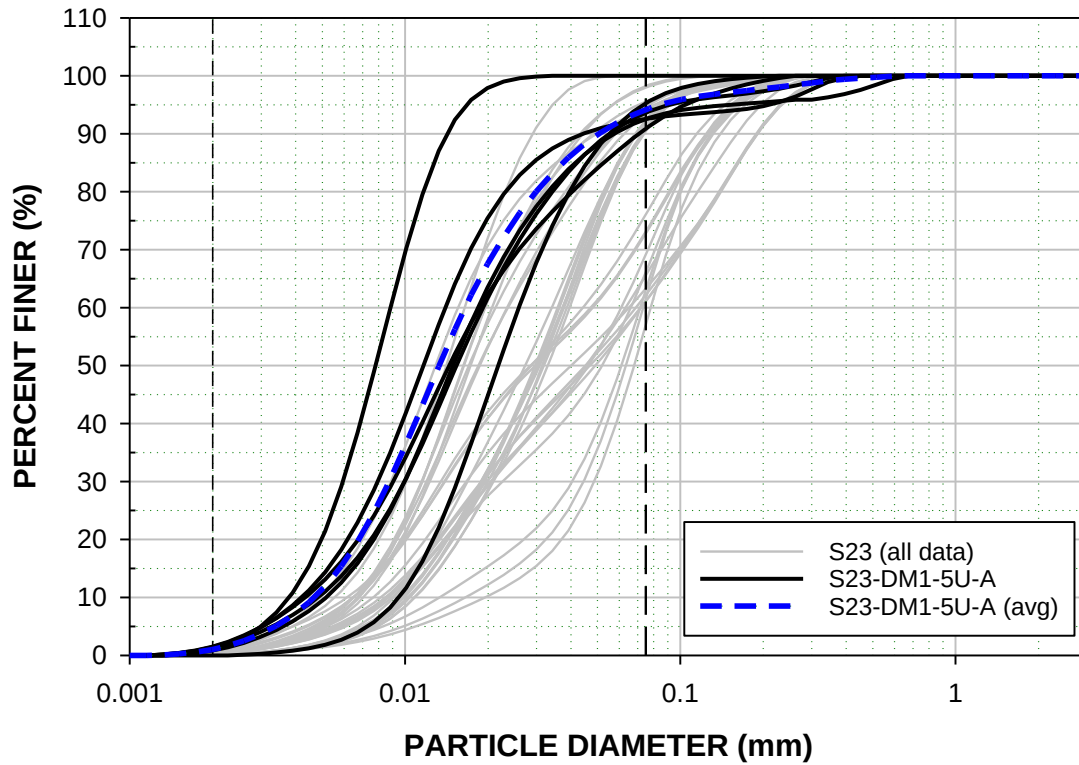


Figure C.4-26: S23-DM1-5U-A, Particle Size Distribution (Laser Analysis)

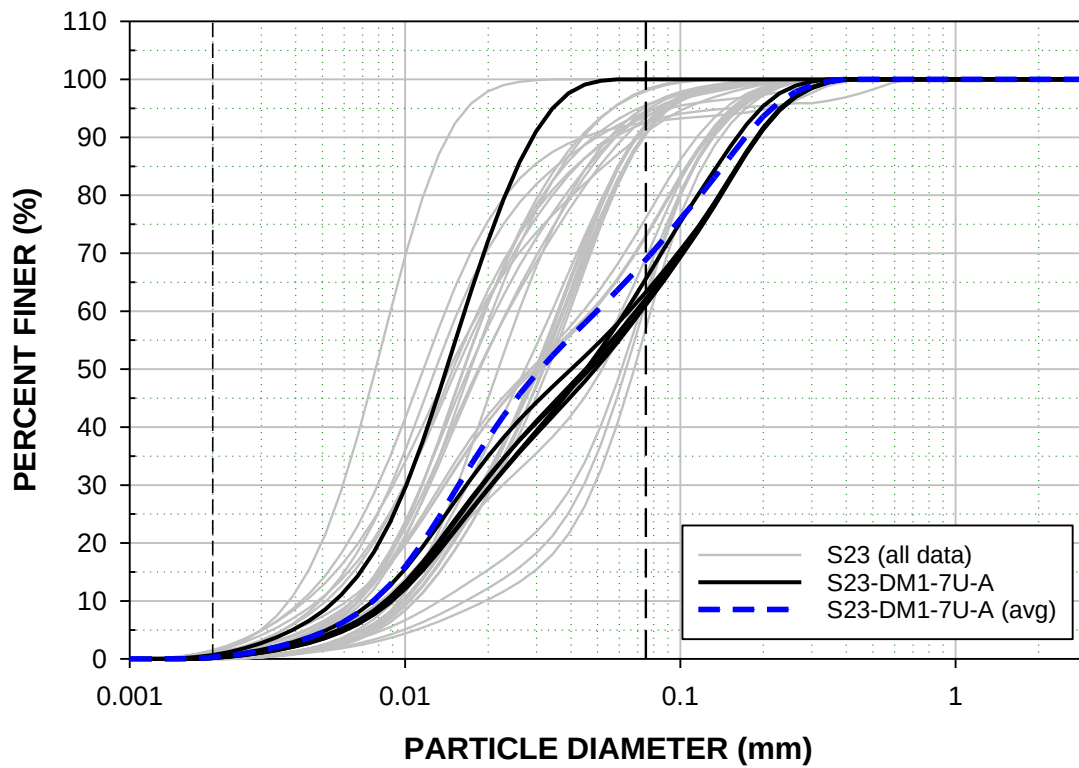


Figure C.4-27: S23-DM1-7U-A, Particle Size Distribution (Laser Analysis)

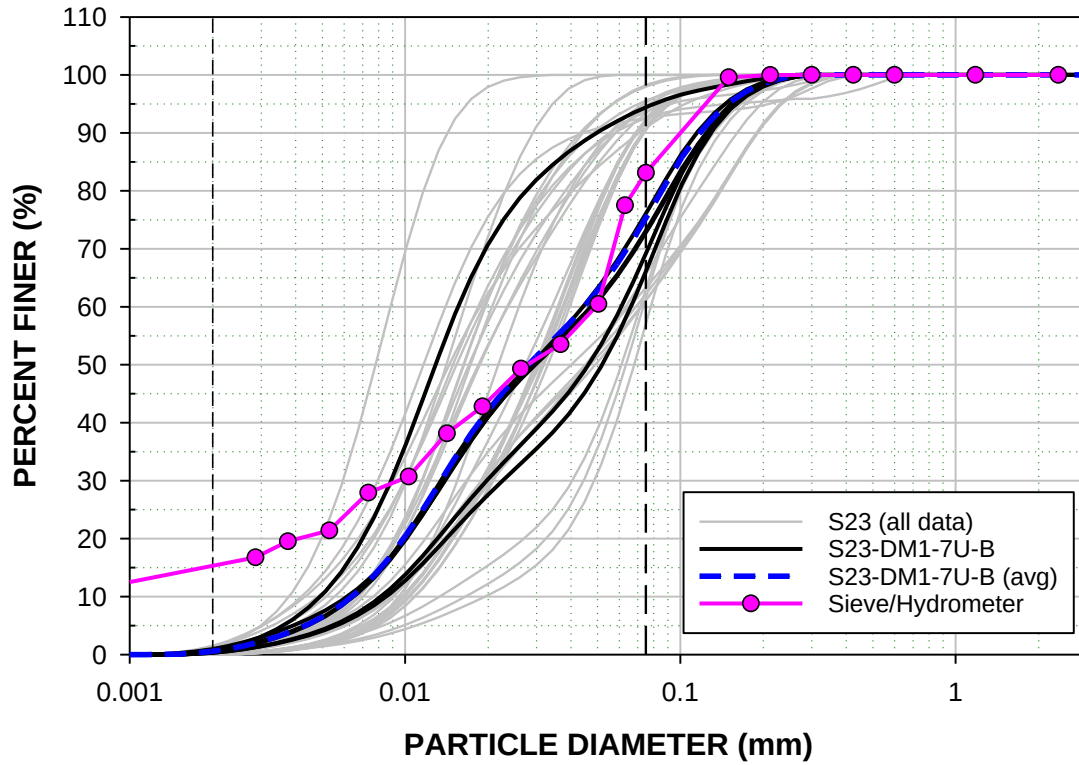


Figure C.4-28: S23-DM1-7U-B, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

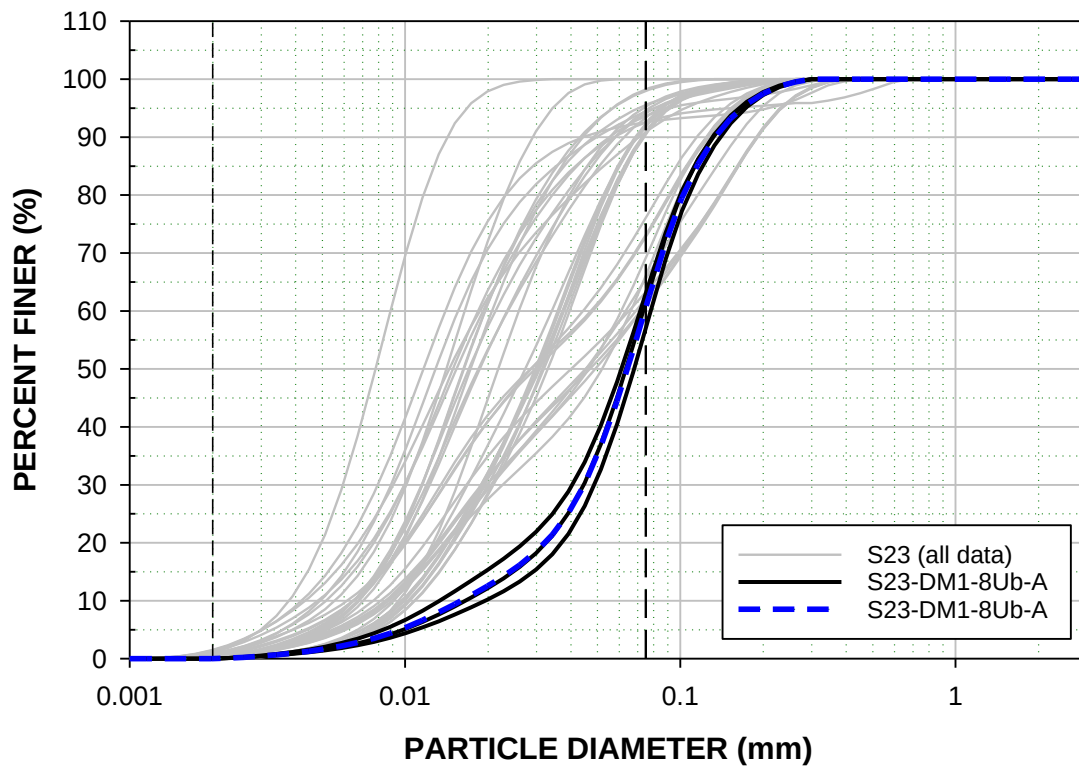


Figure C.4-29: S23-DM1-8Ub-A, Particle Size Distribution (Laser Analysis)

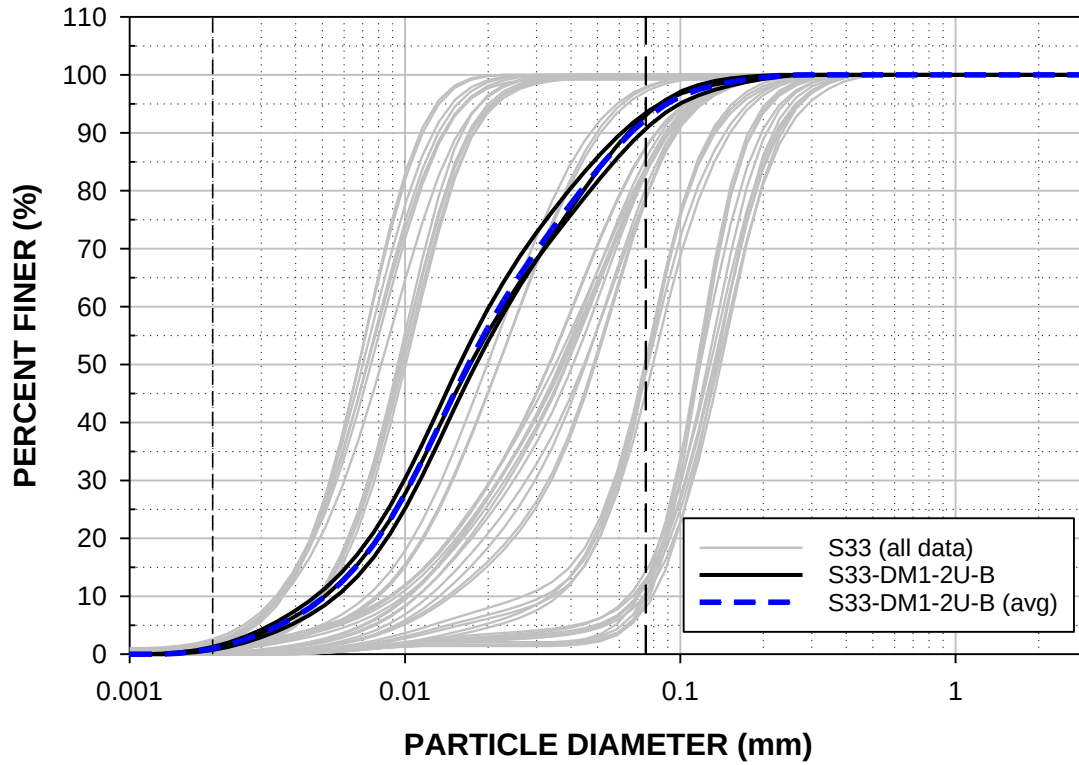


Figure C.4-30: S33-DM1-2U-B, Particle Size Distribution (Laser Analysis)

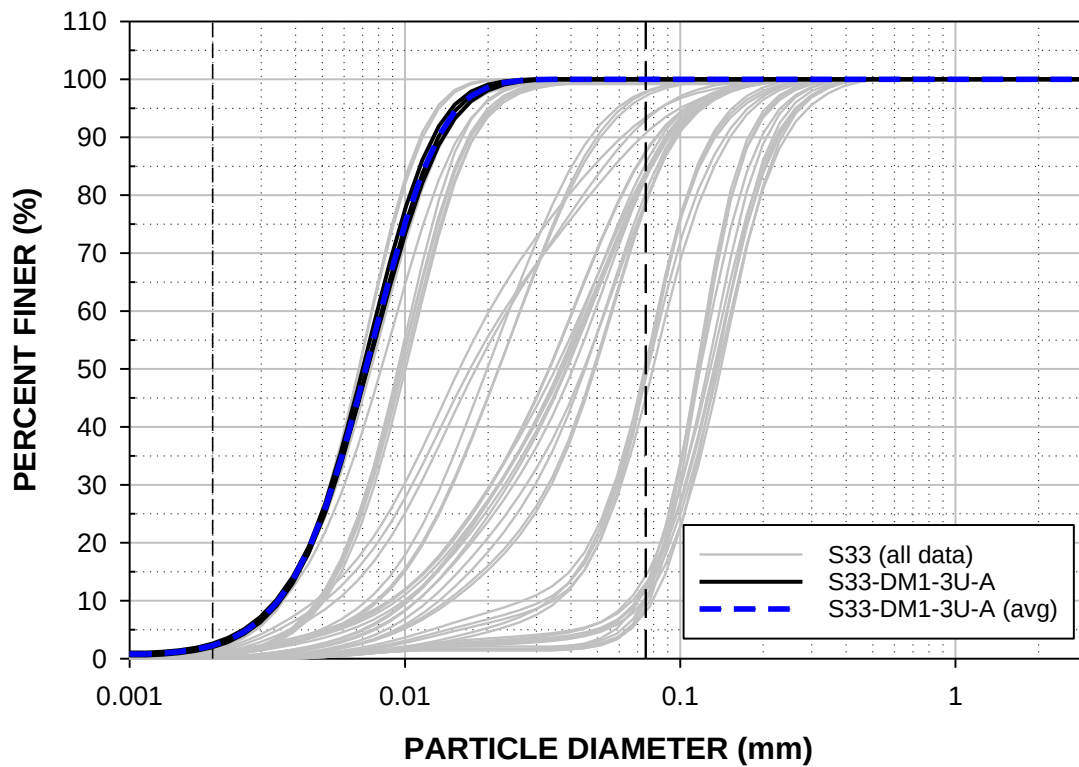


Figure C.4-31: S33-DM1-3U-A, Particle Size Distribution (Laser Analysis)

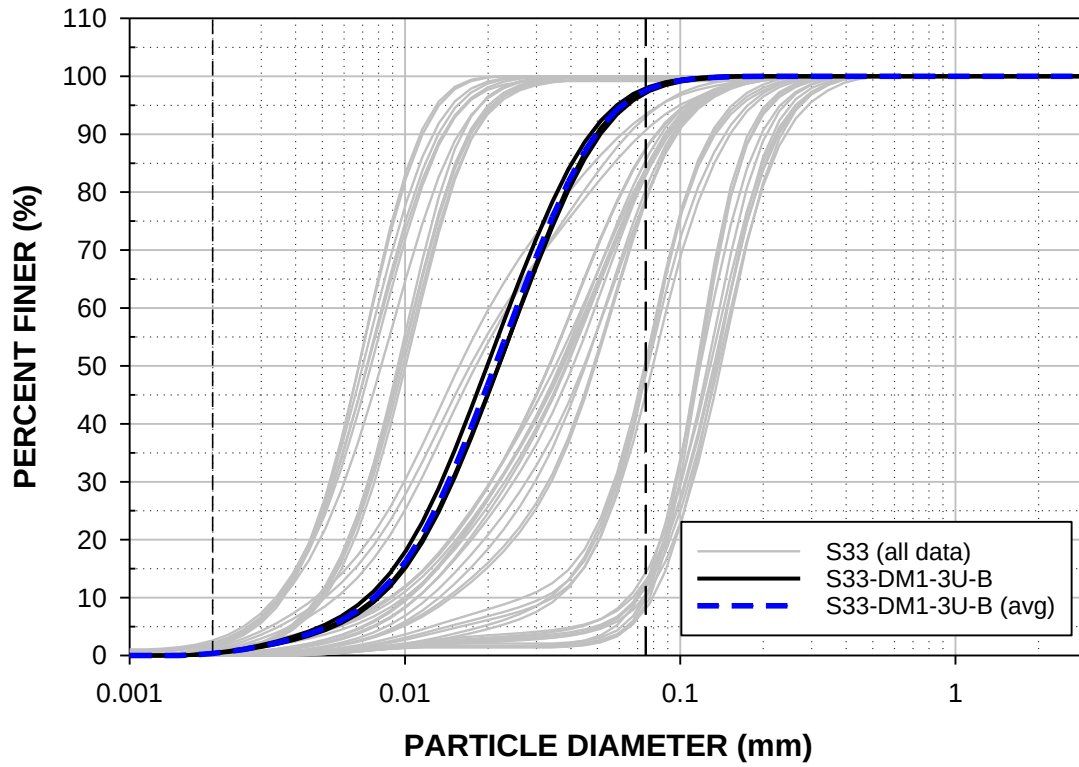


Figure C.4-32: S33-DM1-3U-B, Particle Size Distribution (Laser Analysis)

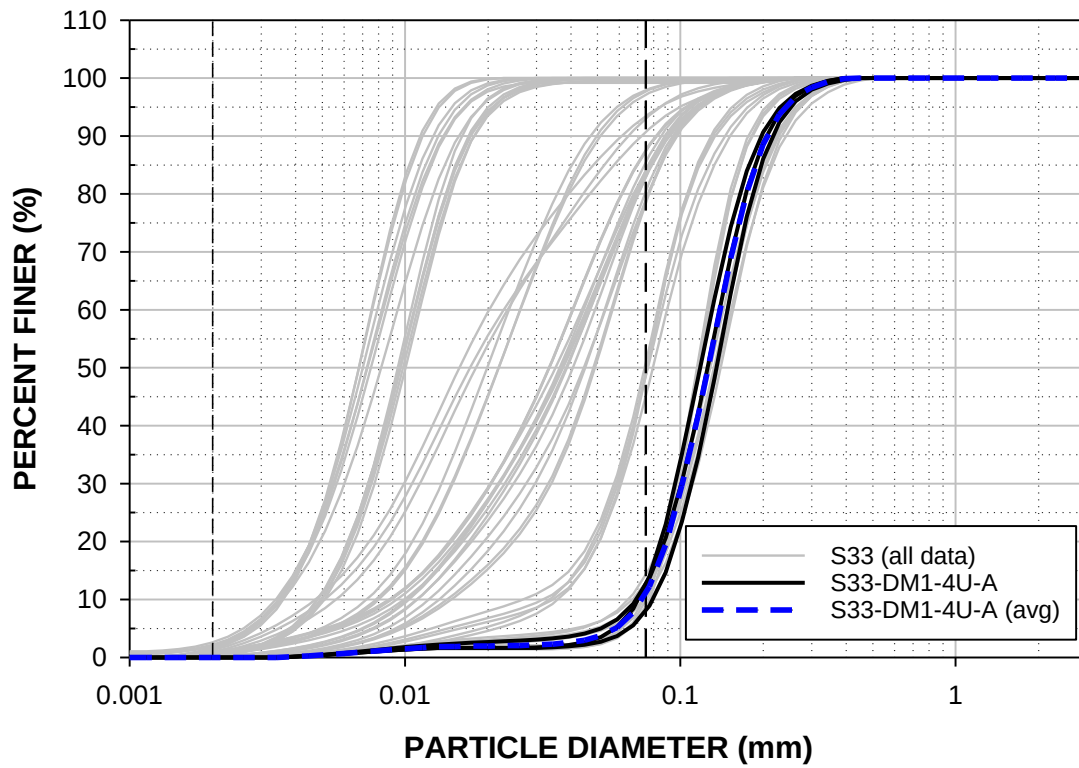


Figure C.4-33: S33-DM1-4U-A, Particle Size Distribution (Laser Analysis)

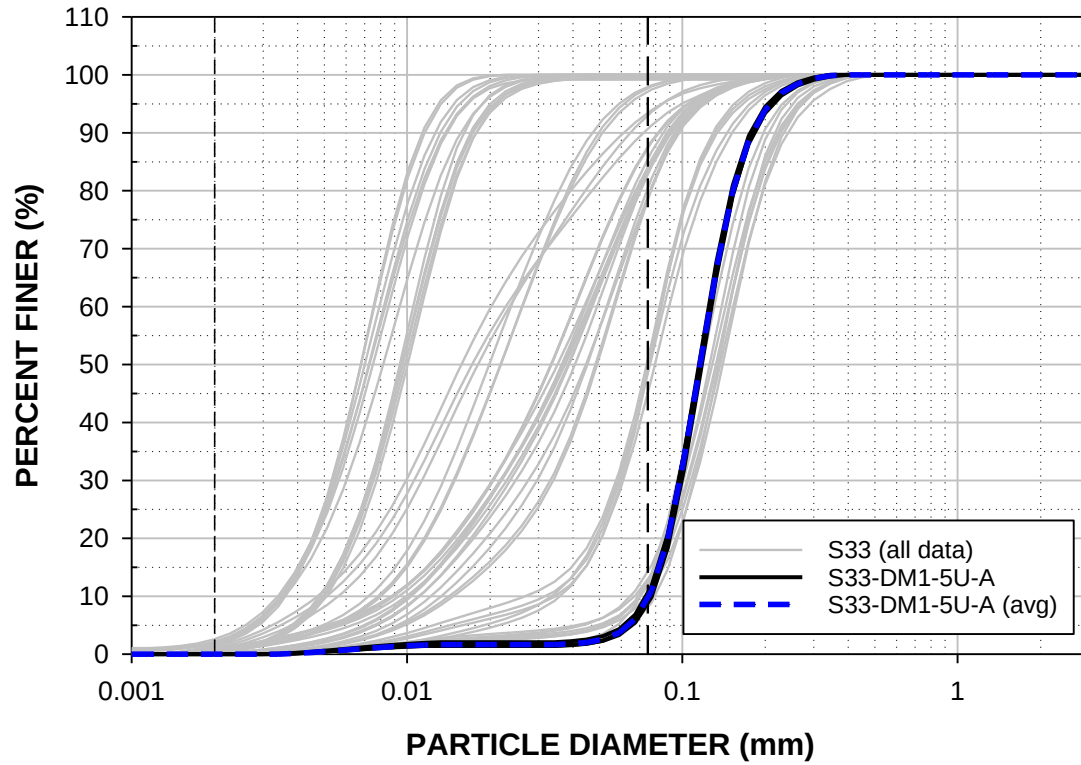


Figure C.4-34: S33-DM1-5U-A, Particle Size Distribution (Laser Analysis)

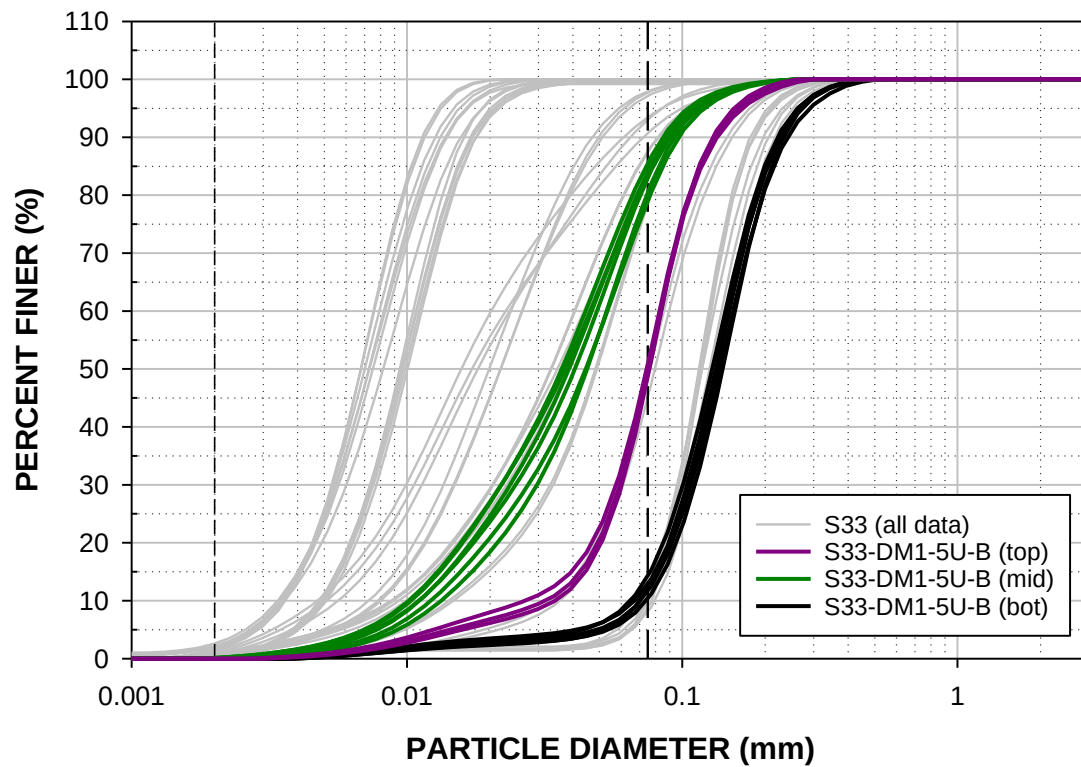


Figure C.4-35: S33-DM1-5U-B, Particle Size Distribution (Laser Analysis)

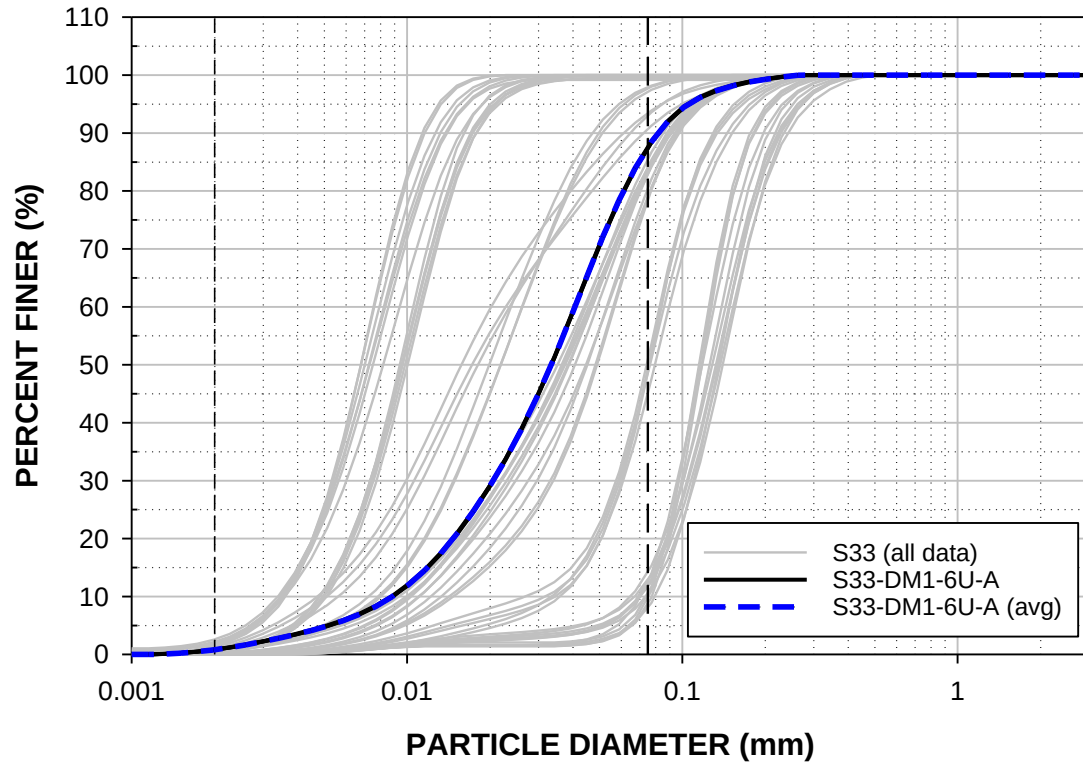


Figure C.4-36: S33-DM1-6U-A, Particle Size Distribution (Laser Analysis)

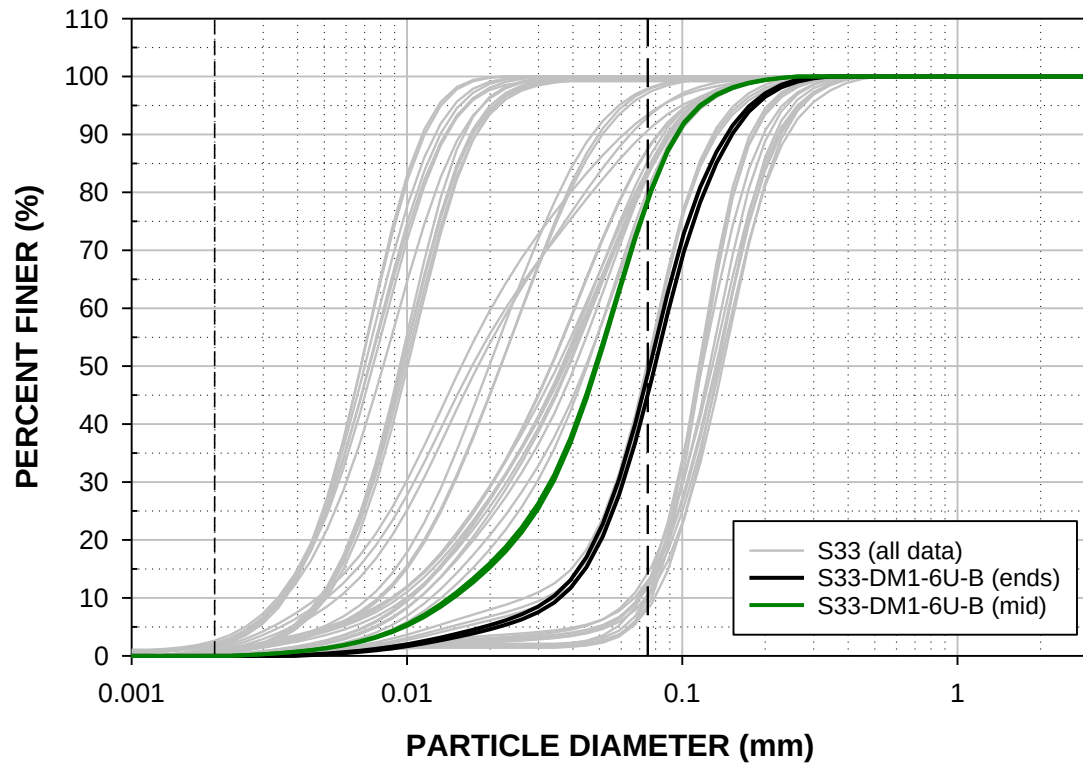


Figure C.4-37: S33-DM1-6U-B, Particle Size Distribution (Laser Analysis)

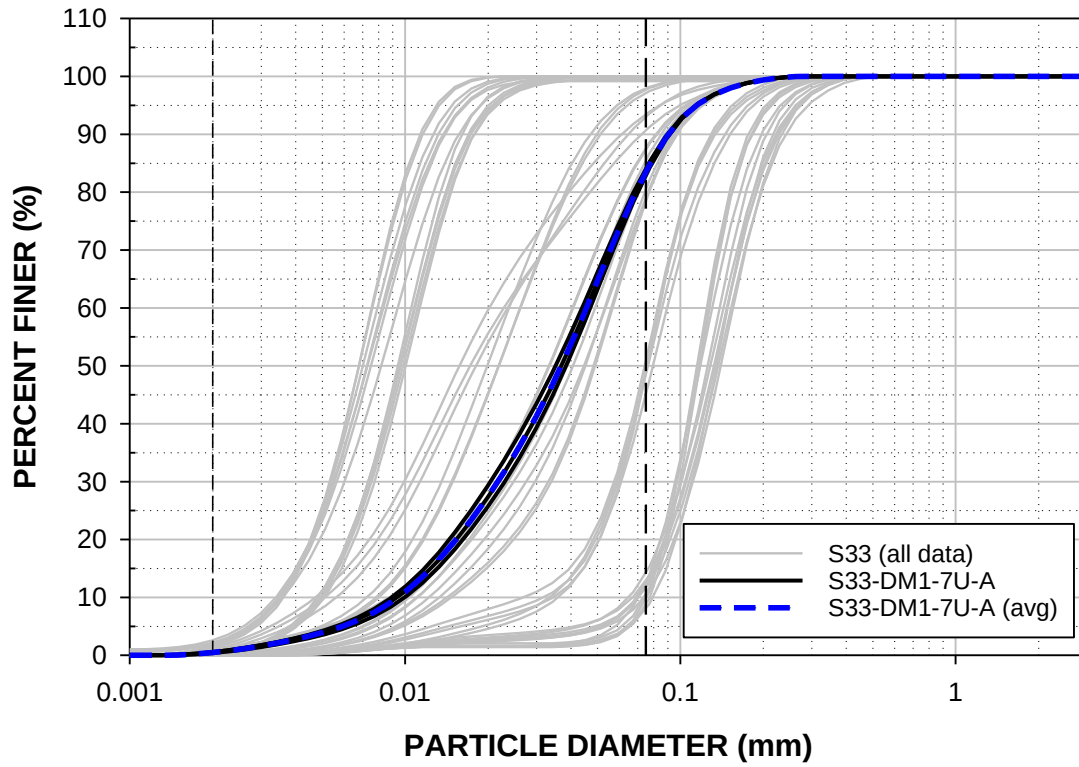


Figure C.4-38: S33-DM1-7U-A, Particle Size Distribution (Laser Analysis)

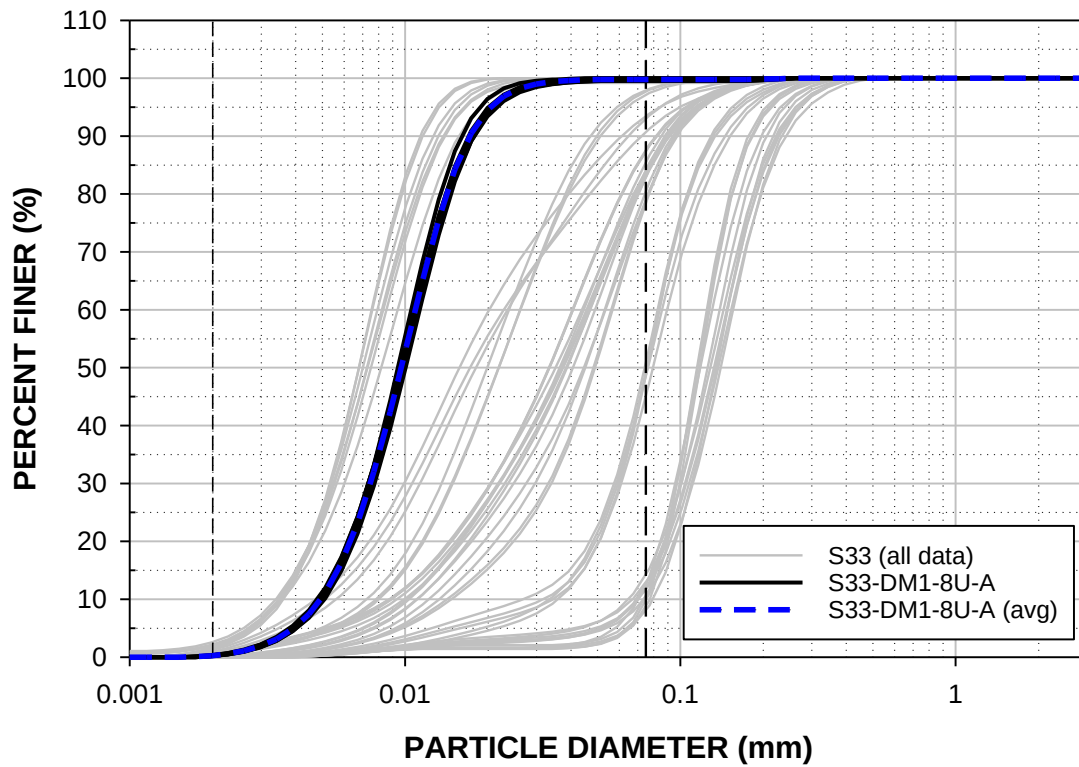


Figure C.4-39: S33-DM1-8U-A, Particle Size Distribution (Laser Analysis)

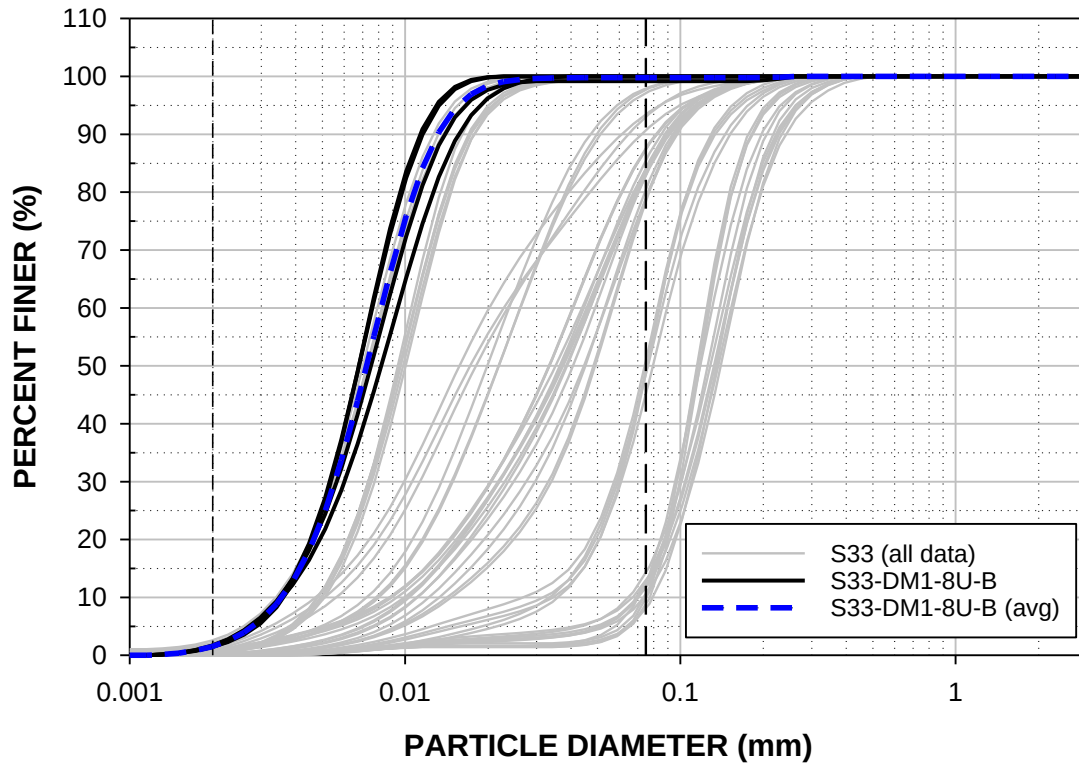


Figure C.4-40: S33-DM1-8U-B, Particle Size Distribution (Laser Analysis)

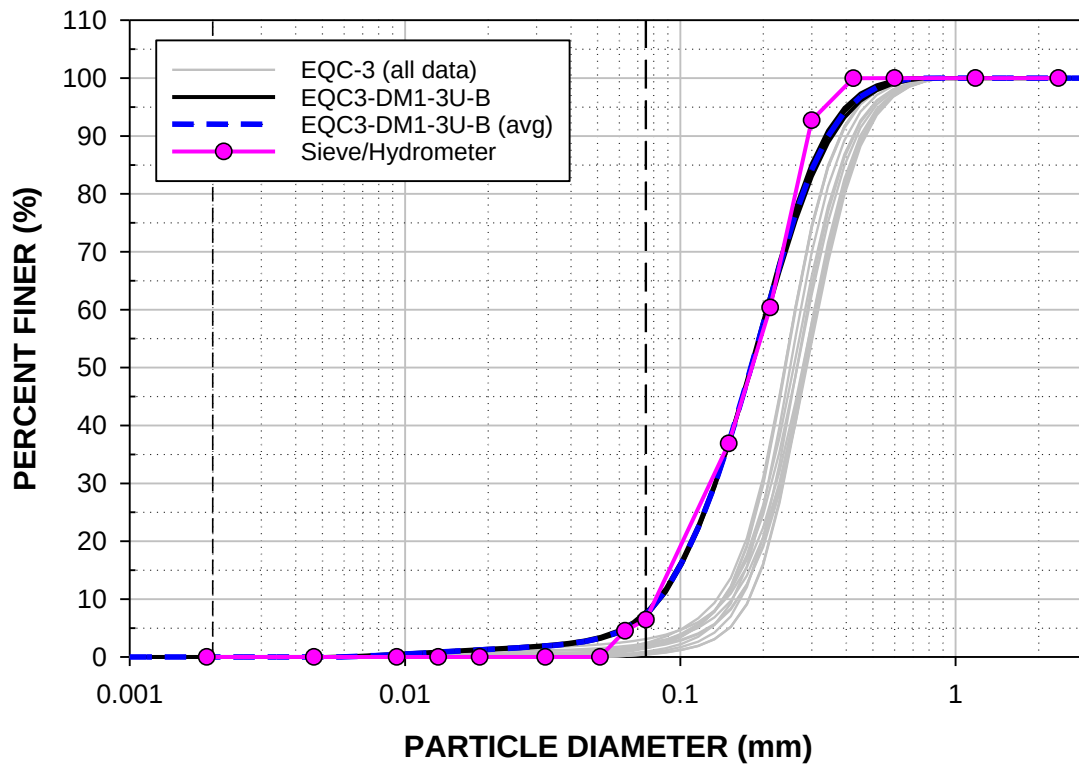


Figure C.4-41: EQC3-DM1-3U-B, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

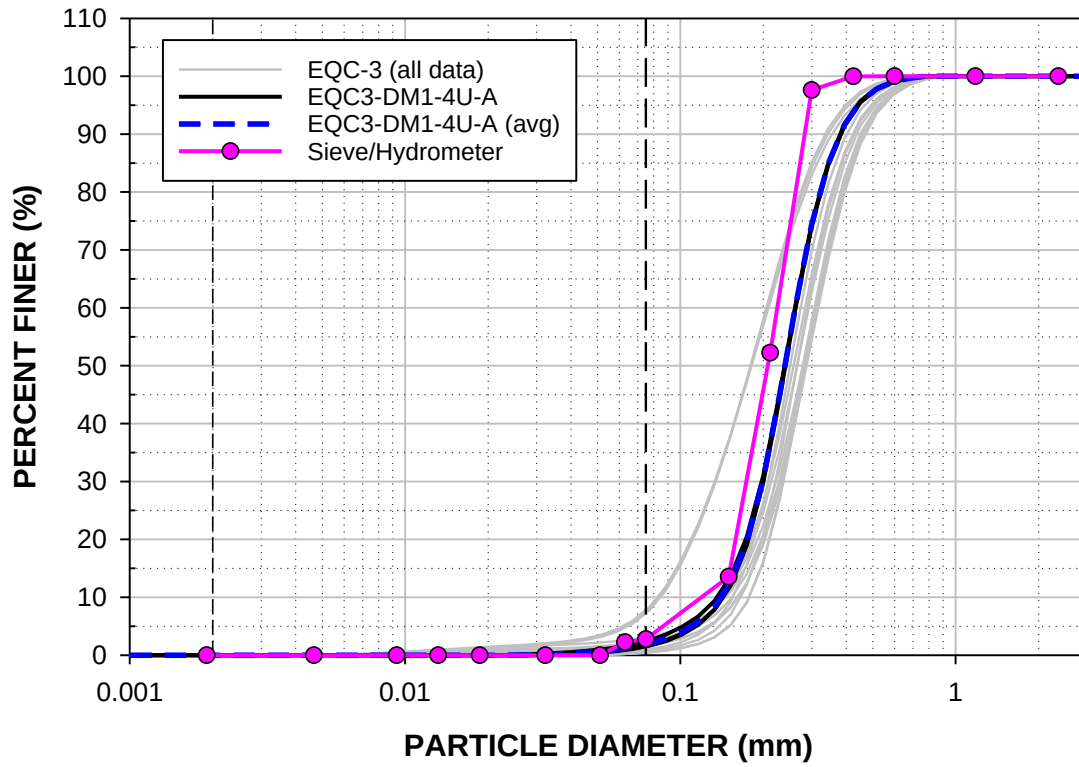


Figure C.4-42: EQC3-DM1-4U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

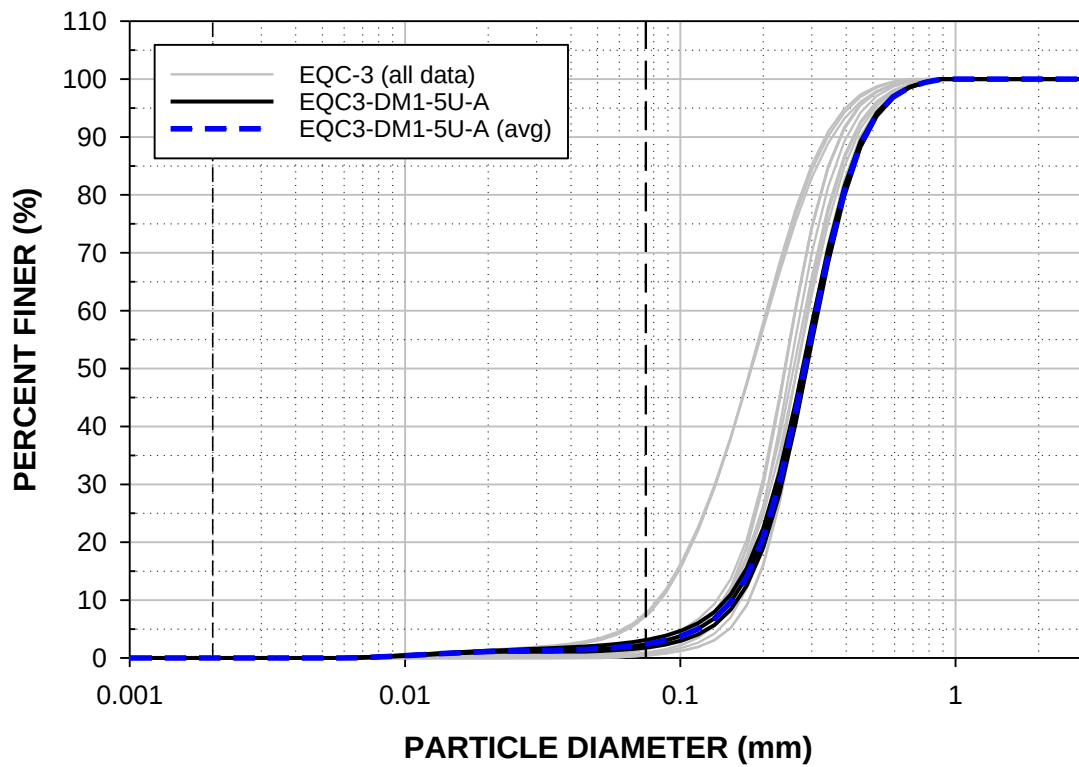


Figure C.4-43: EQC3-DM1-5U-A, Particle Size Distribution (Laser Analysis)

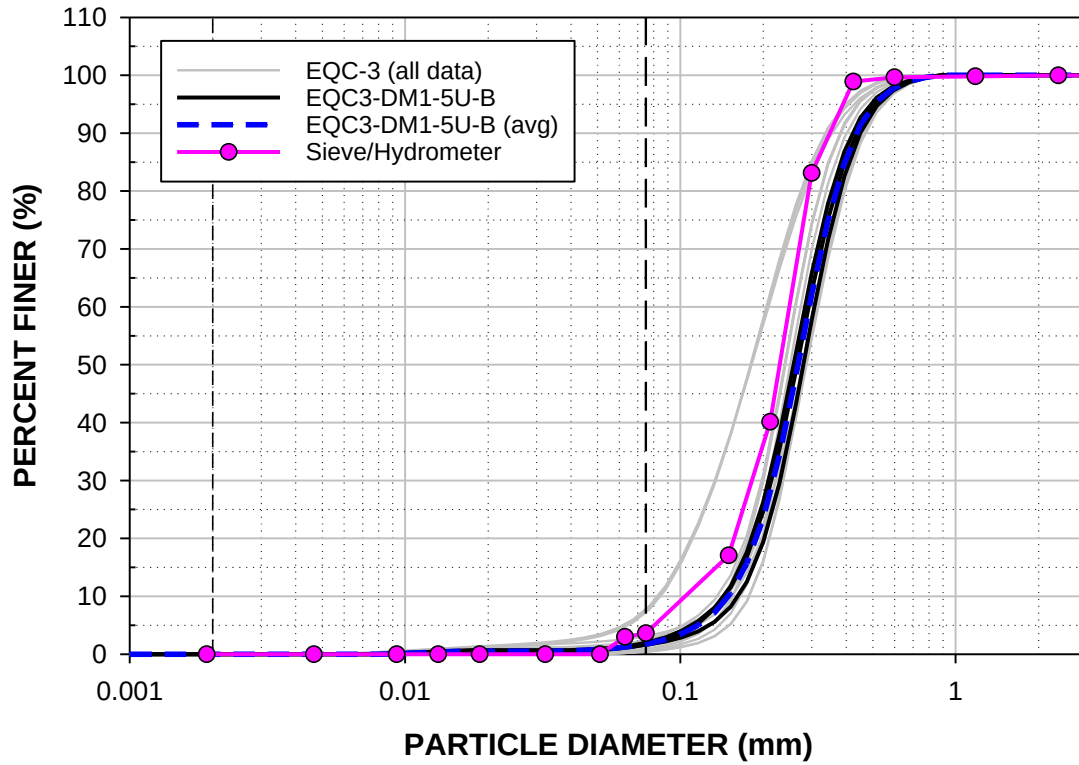


Figure C.4-44: EQC3-DM1-5U-B, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

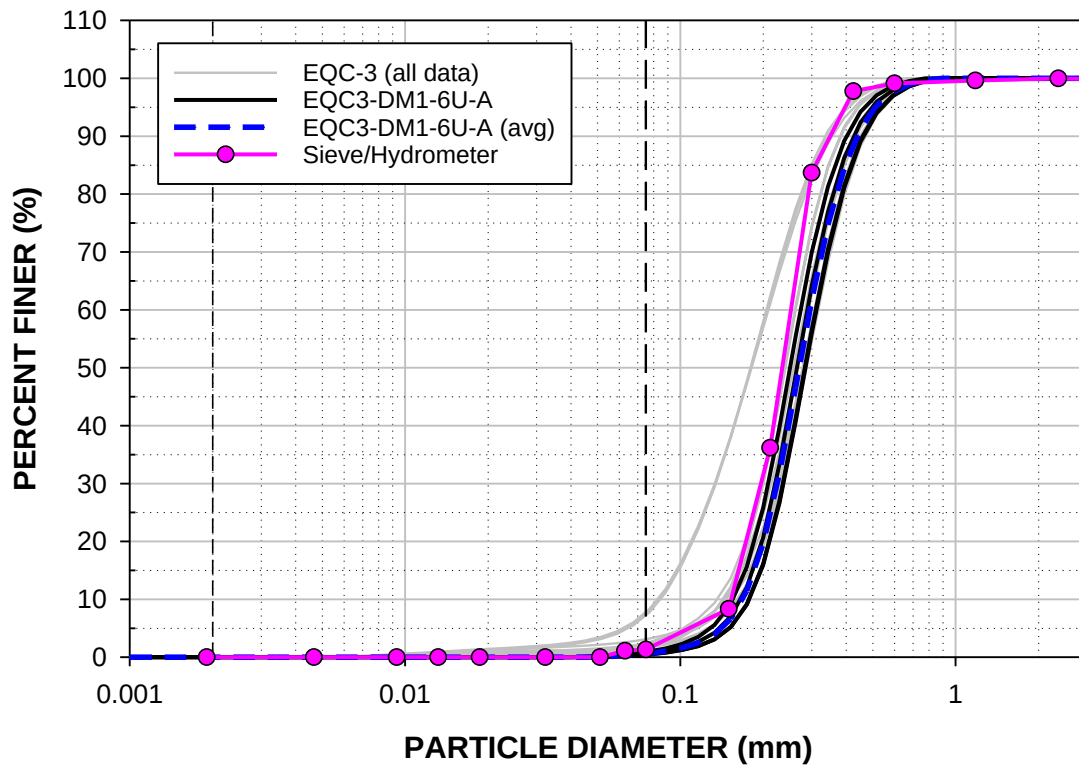


Figure C.4-45: EQC3-DM1-6U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

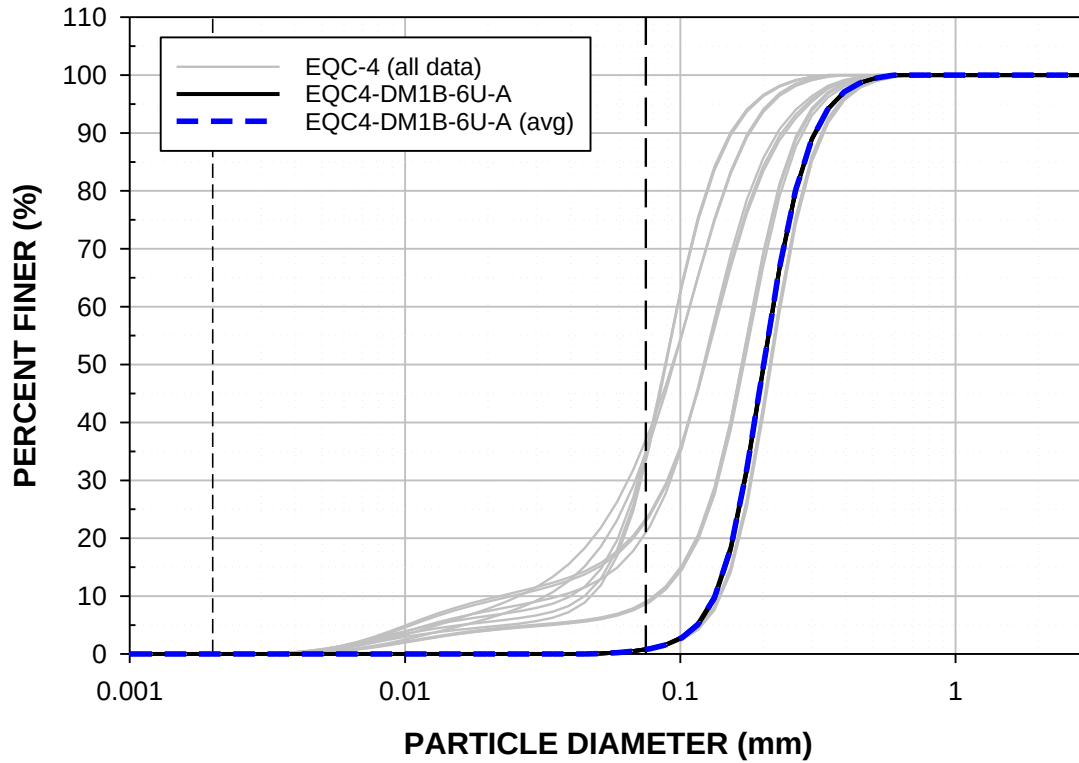


Figure C.4-46: EQC4-DM1B-6U-A, Particle Size Distribution (Laser Analysis)

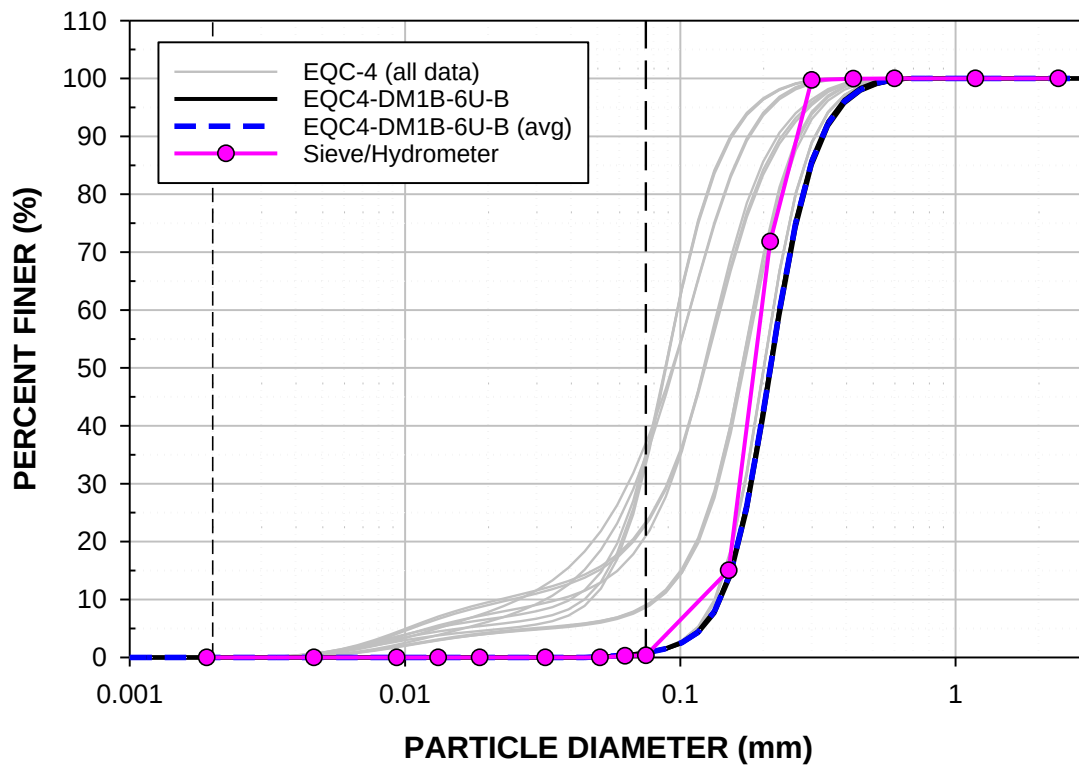


Figure C.4-47: EQC4-DM1B-6U-B, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

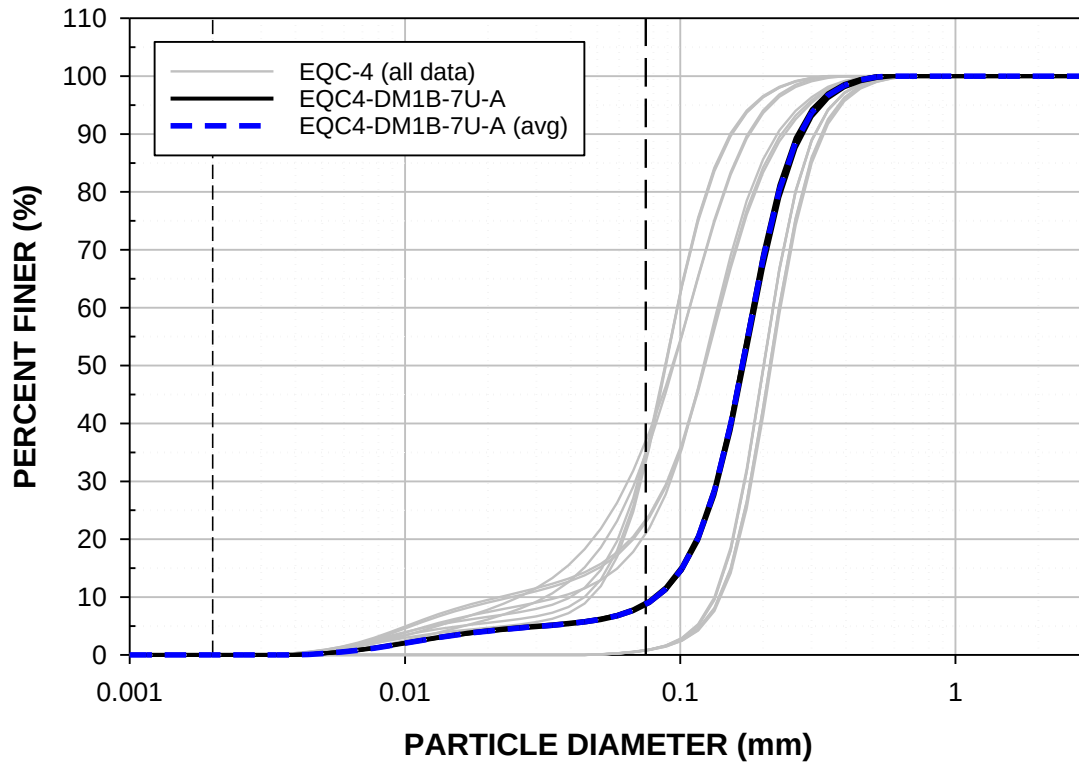


Figure C.4-48: EQC4-DM1B-7U-A, Particle Size Distribution (Laser Analysis)

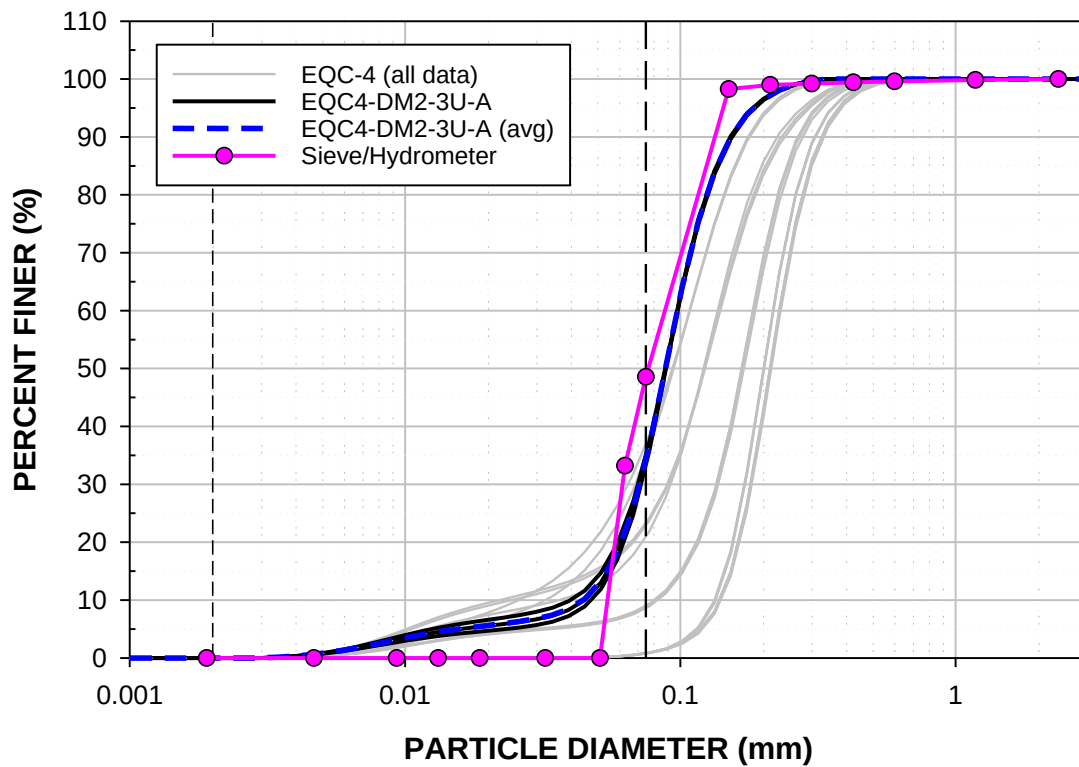


Figure C.4-49: EQC4-DM2-3U-A, Particle Size Distribution (Laser Analysis and Sieve/Hydrometer)

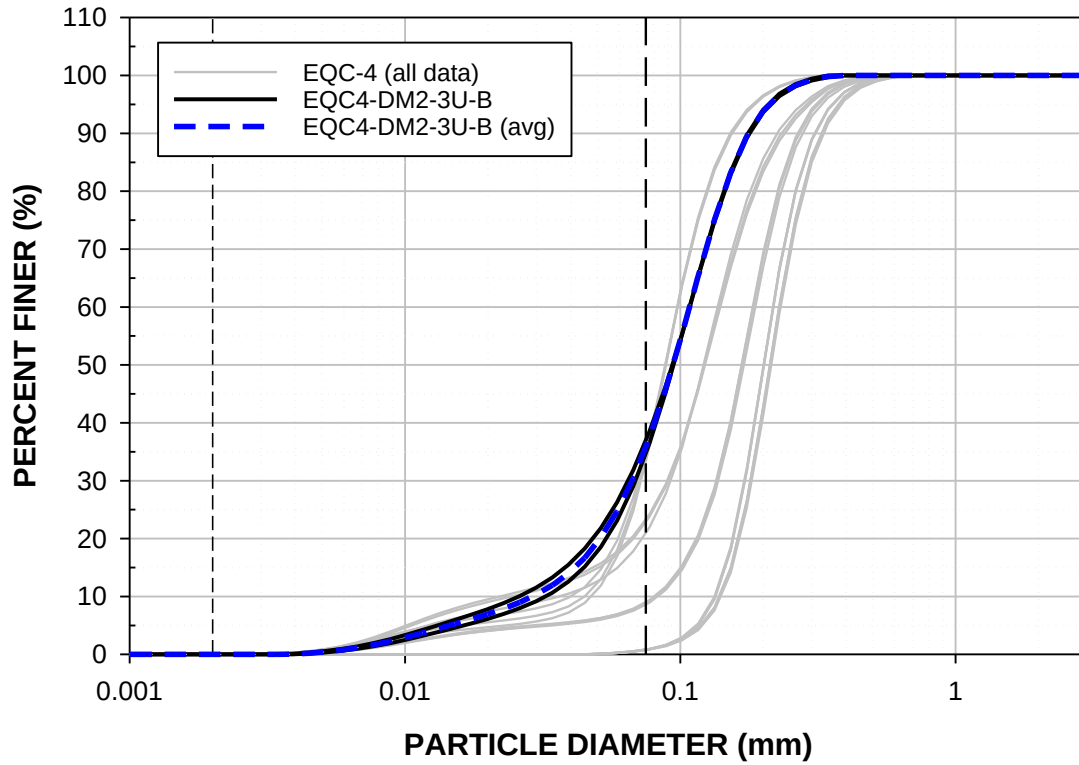


Figure C.4-50: EQC4-DM2-3U-B, Particle Size Distribution (Laser Analysis)

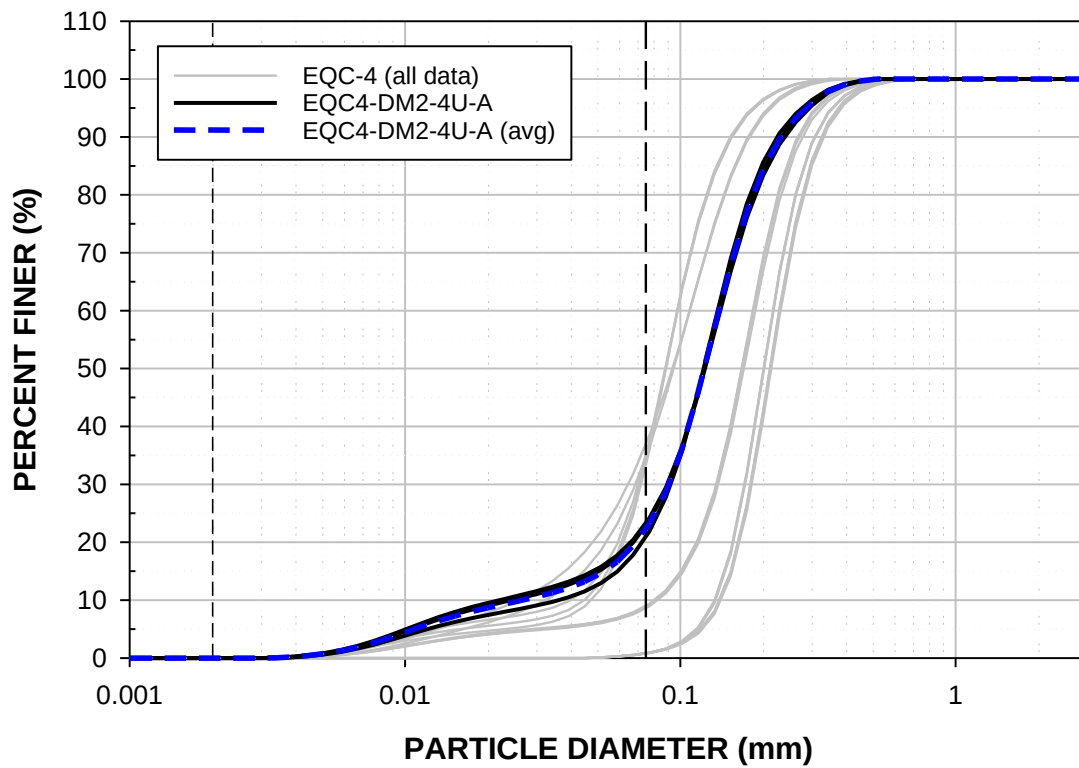
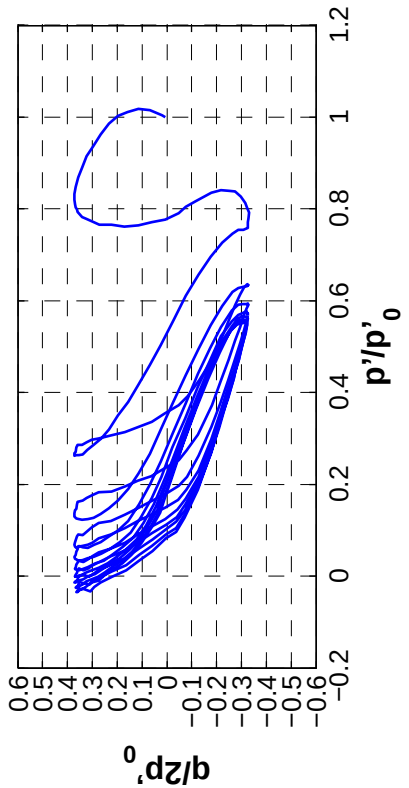
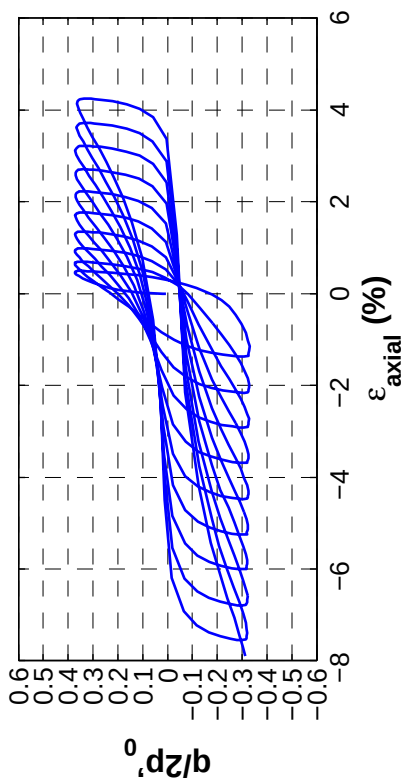
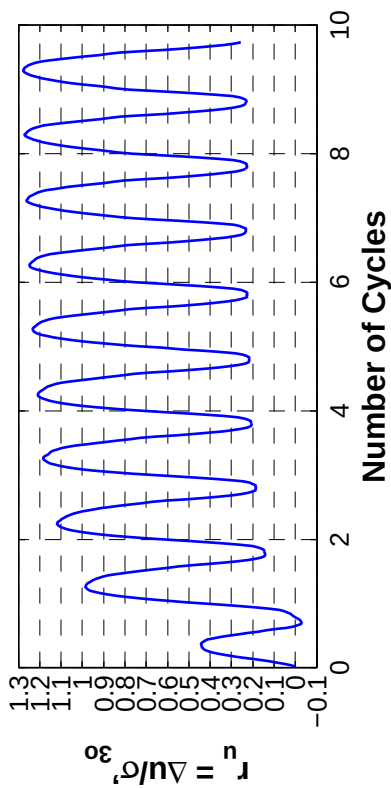
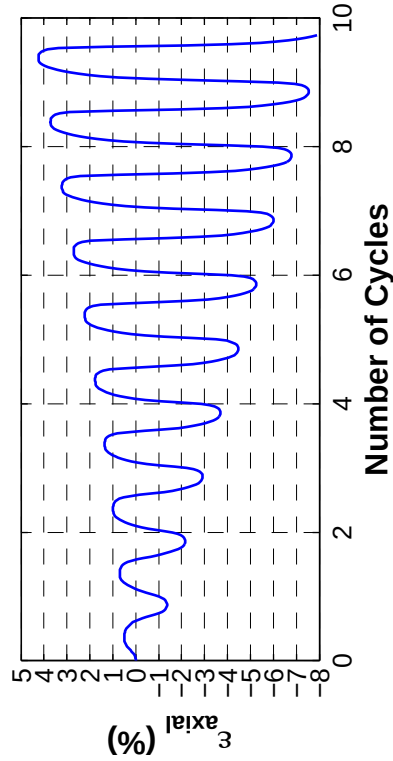
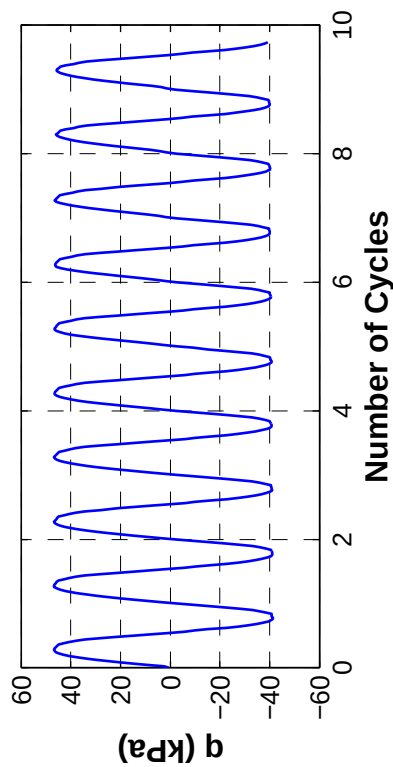


Figure C.4-51: EQC4-DM2-4U-A, Particle Size Distribution (Laser Analysis)

Appendix C.5

Processed Cyclic Triaxial Test Data

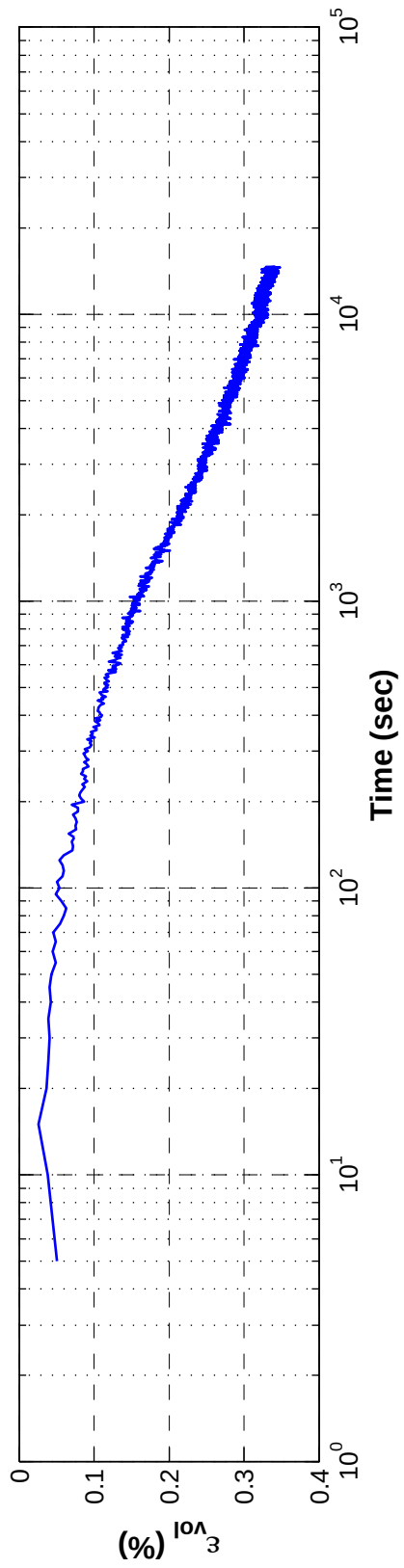
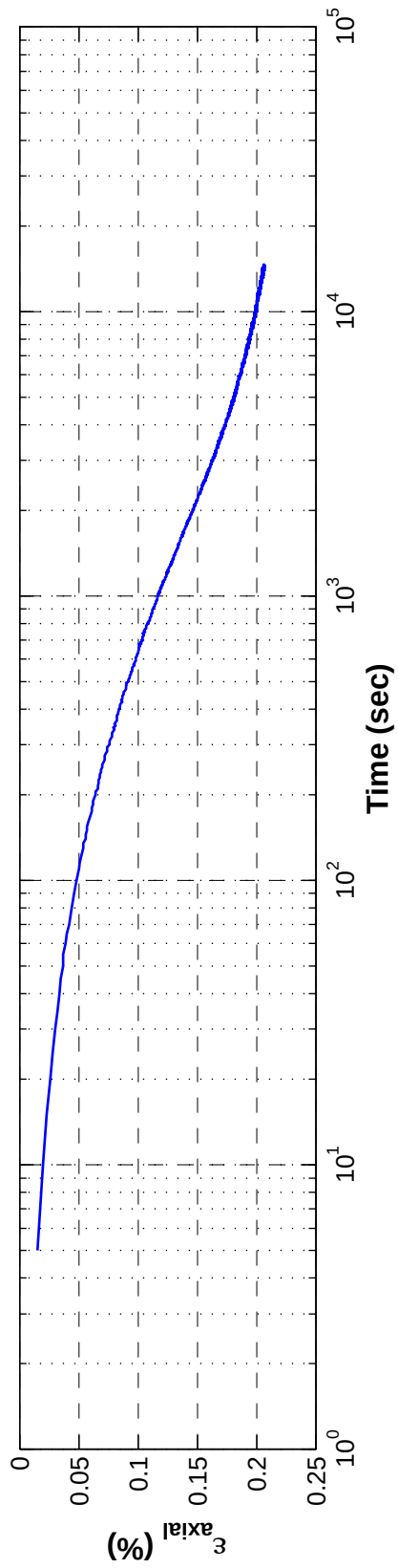
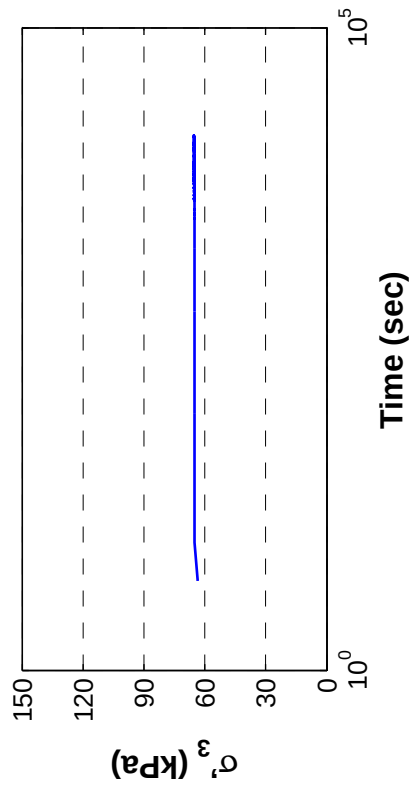


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 2	σ'_c (kPa):	62
Borehole:	DM-1	Loading Freq (Hz):	0.1
Sample No.:	3U	B-Value:	0.976
Sampler Type:	D&M	CSR:	0.36
Spec. Depth (m):	3.93	N to $\epsilon_{Ax-S.A.}$ =3%:	4
Date Tested:	04/23/14	N to $\epsilon_{Ax-D.A.}$ =5%:	4
Date Sampled:	03/18/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	140.316	Gs:	2.73
Spec. Diam. (mm):	61.23	e_c :	0.98
Dry Mass (g):	566.45	PI (%):	12
		FC (%):	98

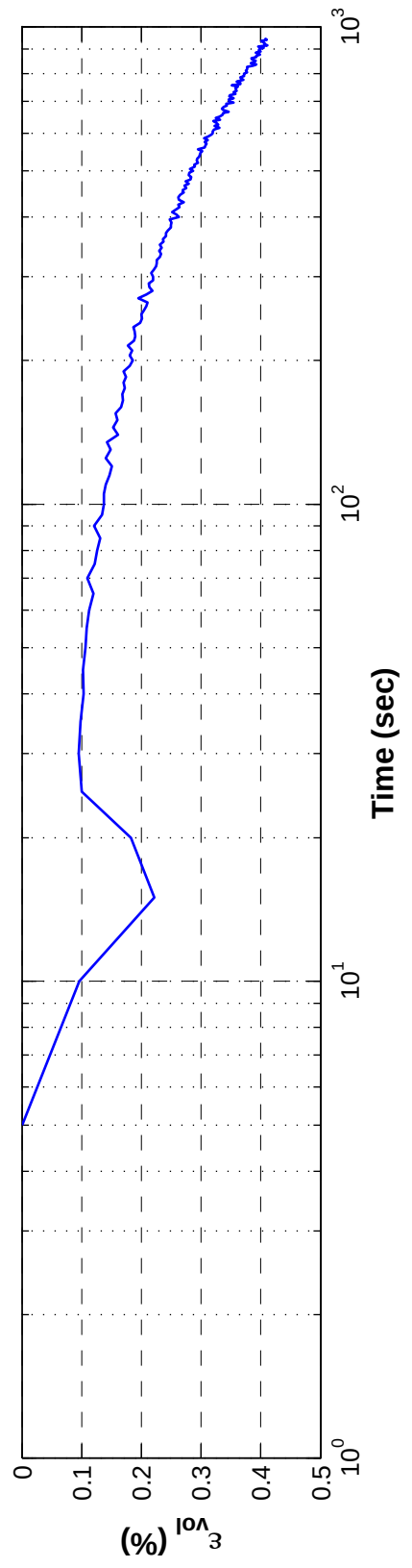
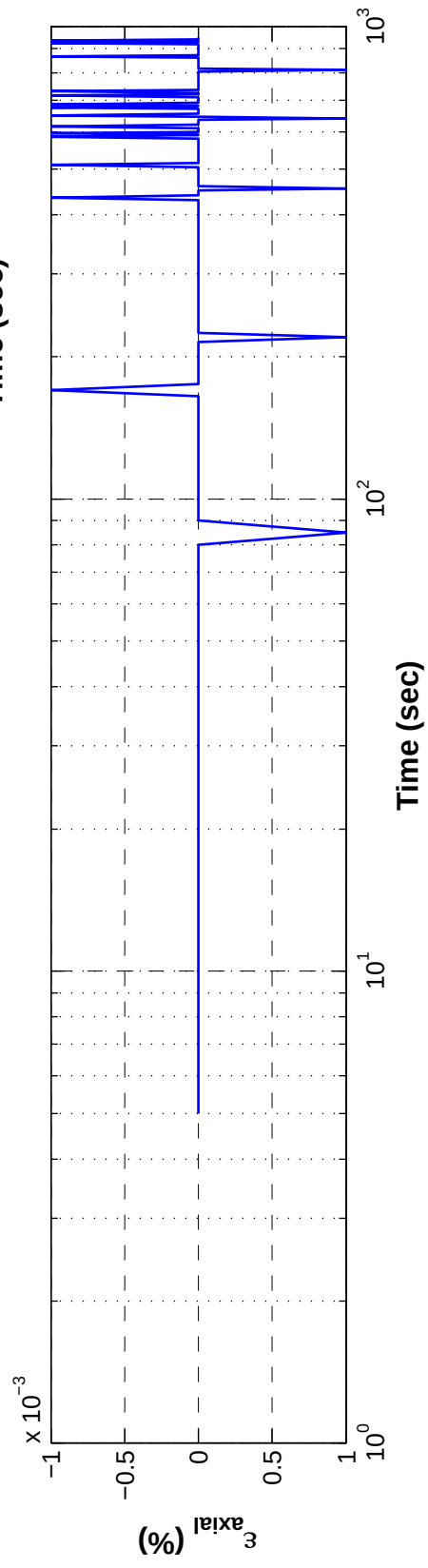
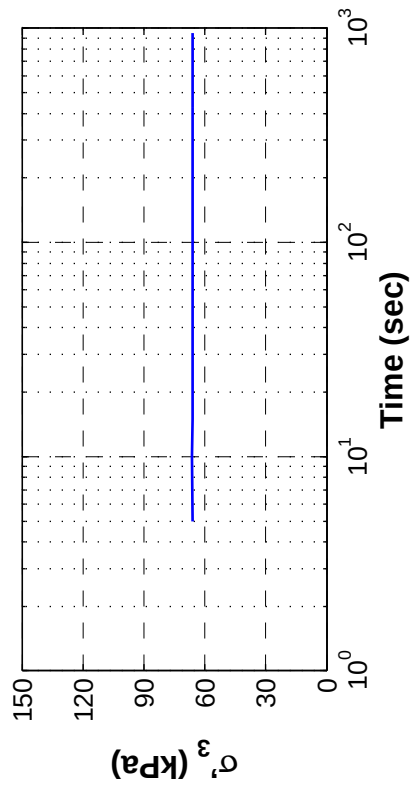
Specimen and Isotropic Consolidation Data

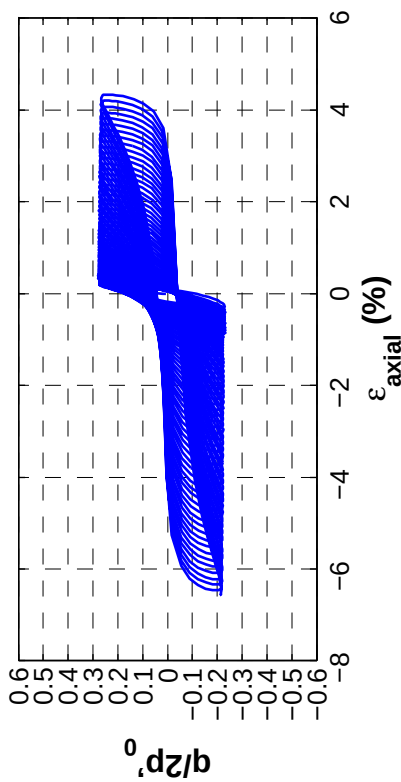
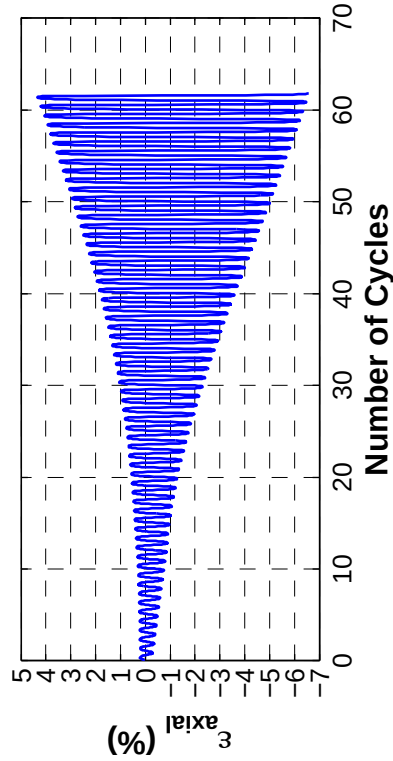
Site: Site 2
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.93
Date Tested: 04/23/14
Date Sampled: 03/18/14



Specimen and Post-CTX Reconsolidation Data

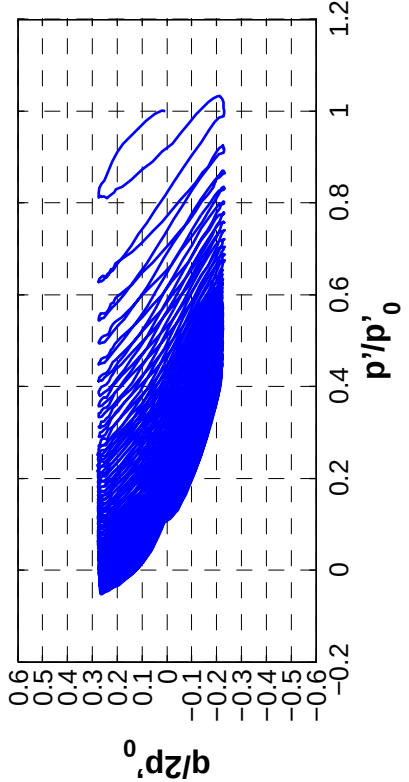
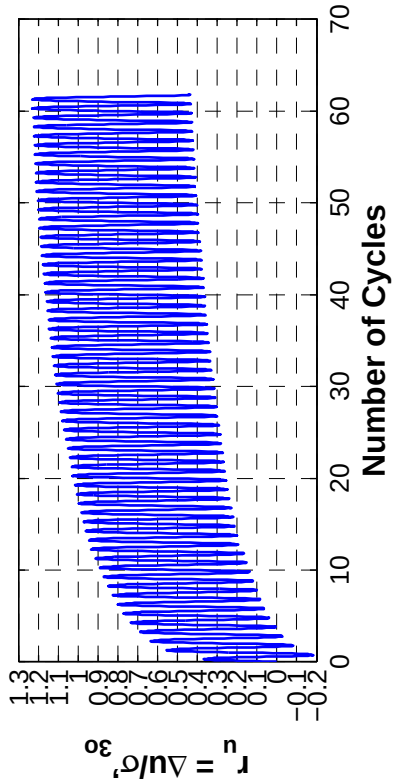
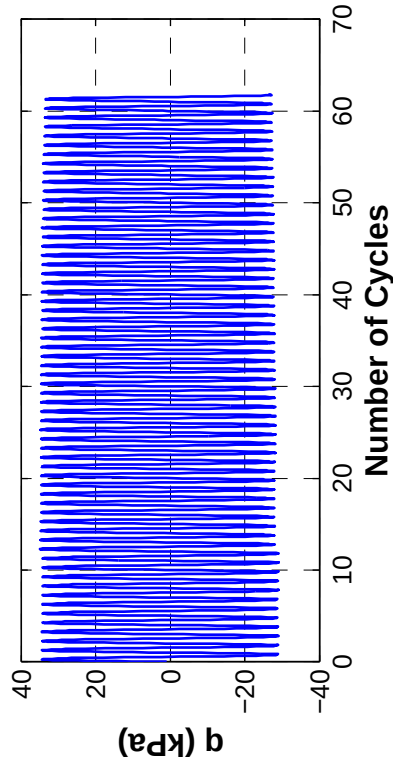
Site: Site 2
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.93
Date Tested: 04/23/14
Date Sampled: 03/18/14





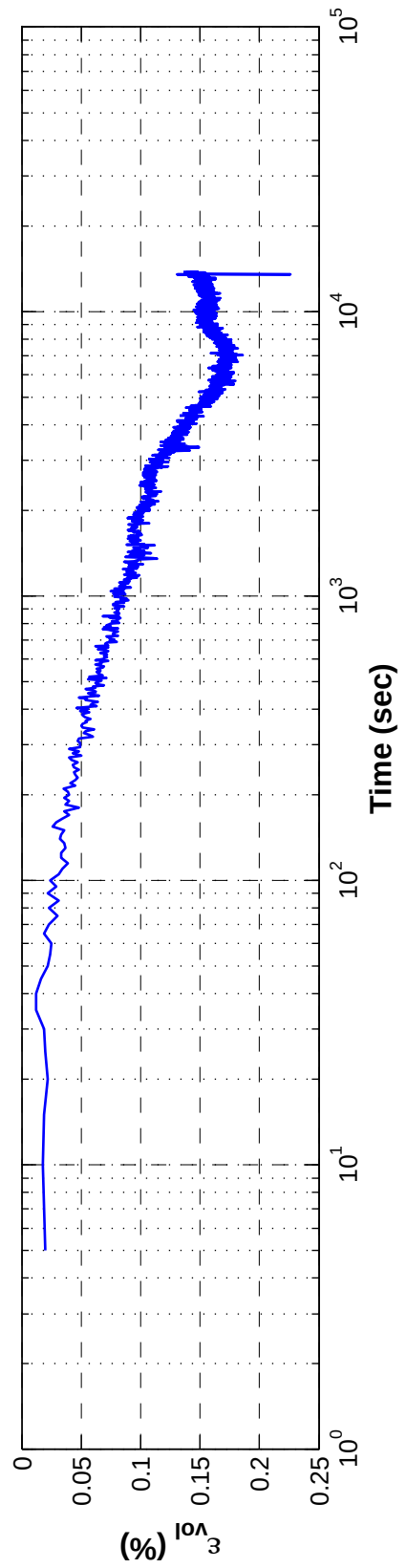
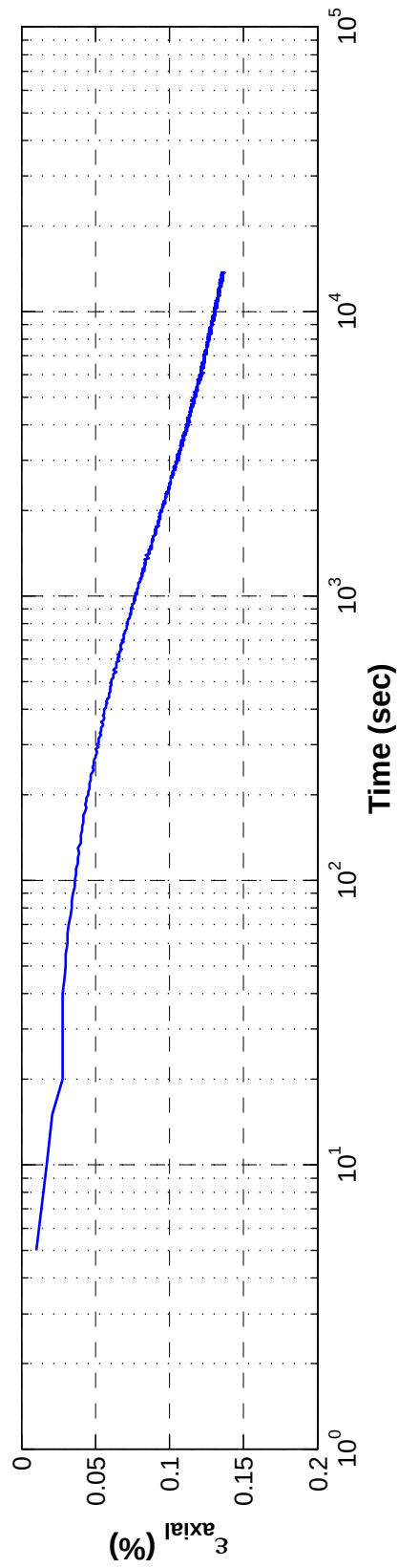
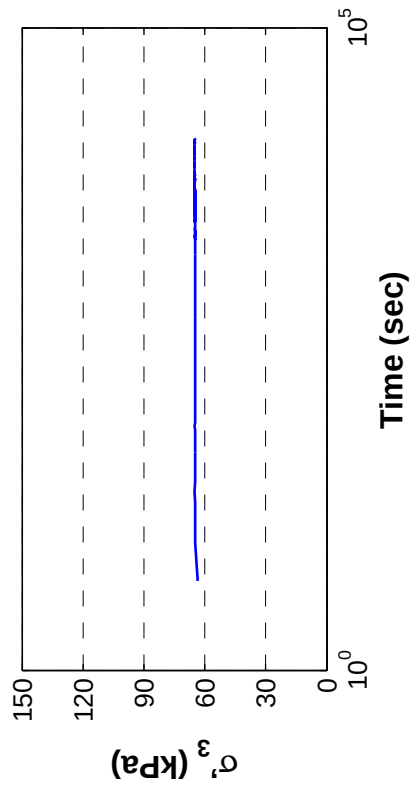
Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 2	σ'_c (kPa):	62
Borehole:	DM-1	Loading Freq (Hz):	0.1
Sample No.:	3U	B-Value:	1
Sampler Type:	D&M	CSR:	0.26
Spec. Depth (m):	4.09	N to $\epsilon_{Ax-S.A.}$ =3%:	36
Date Tested:	04/24/14	N to $\epsilon_{Ax-D.A.}$ =5%:	39
Date Sampled:	03/18/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	144.226	Gs:	---
Spec. Diam. (mm):	60.97	e_c :	0.98
Dry Mass (g):	581.59	PI (%):	16
		FC (%):	97



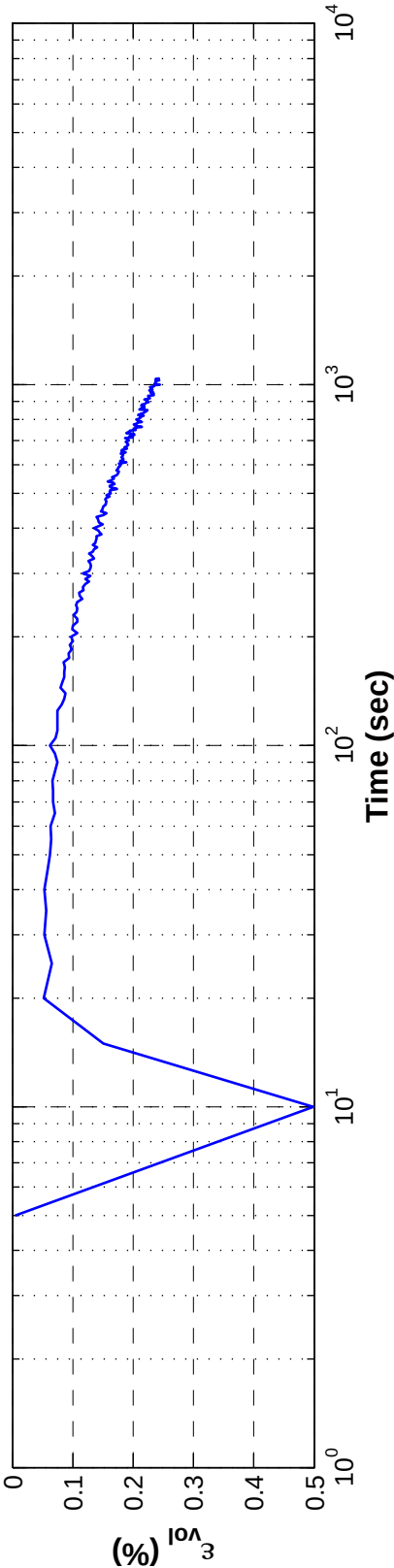
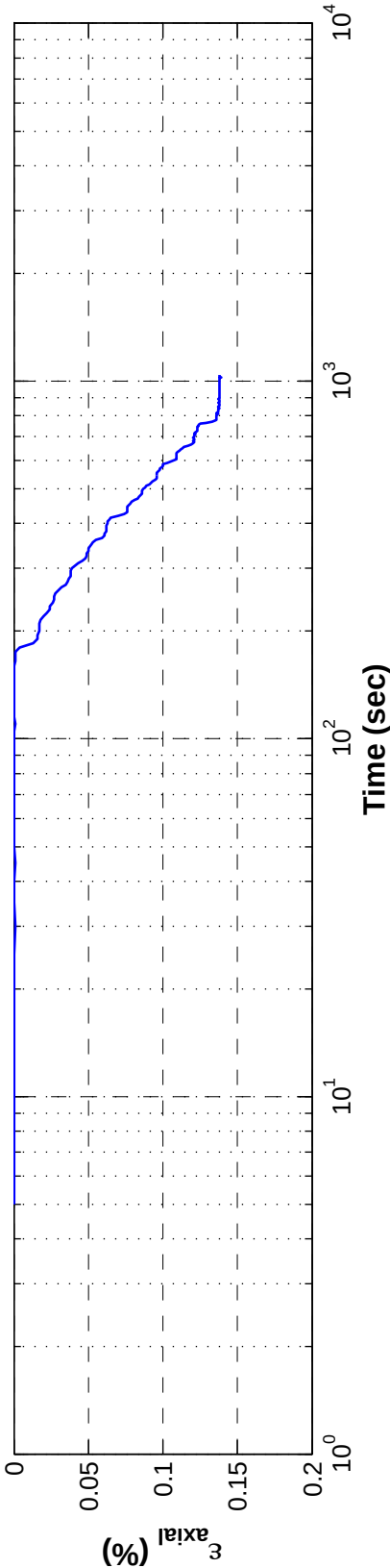
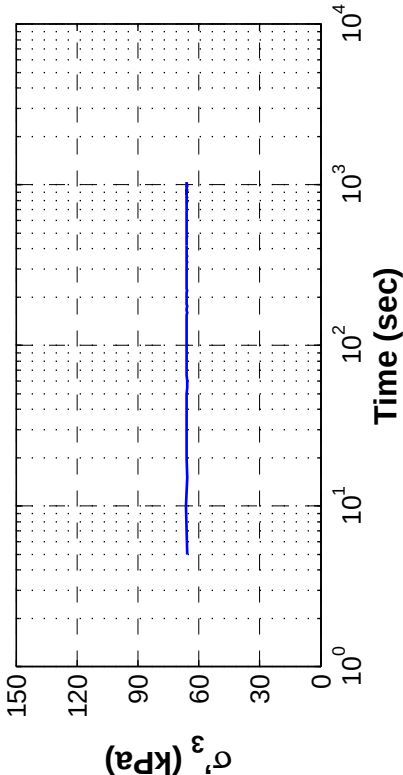
Specimen and Isotropic Consolidation Data

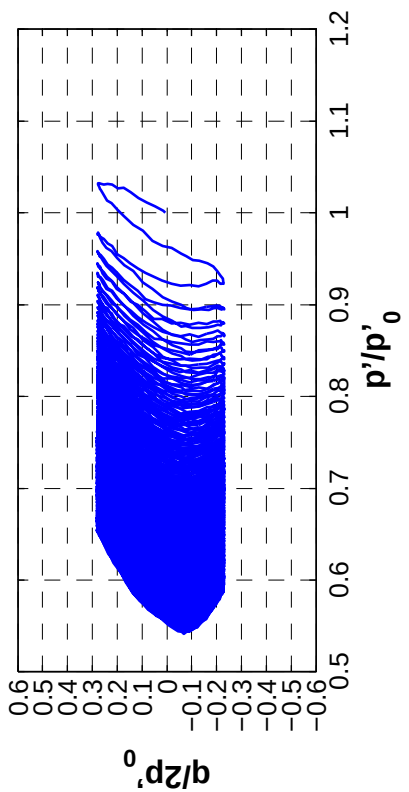
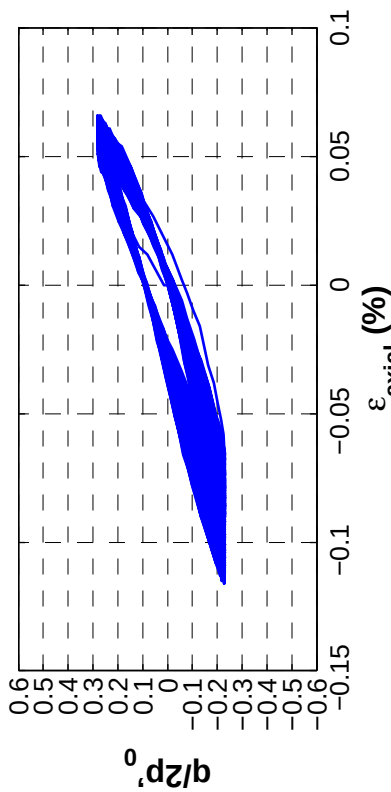
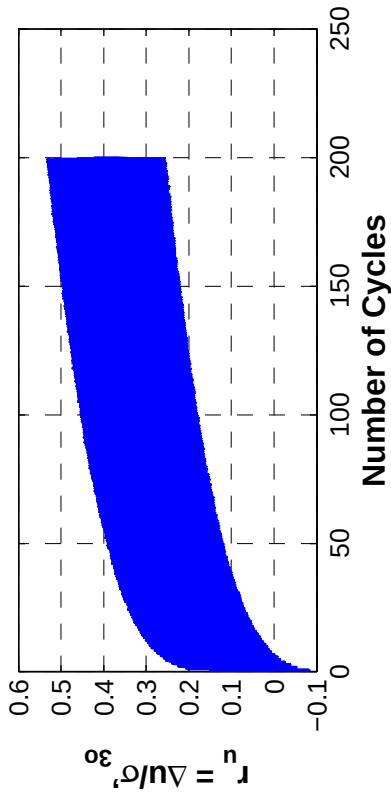
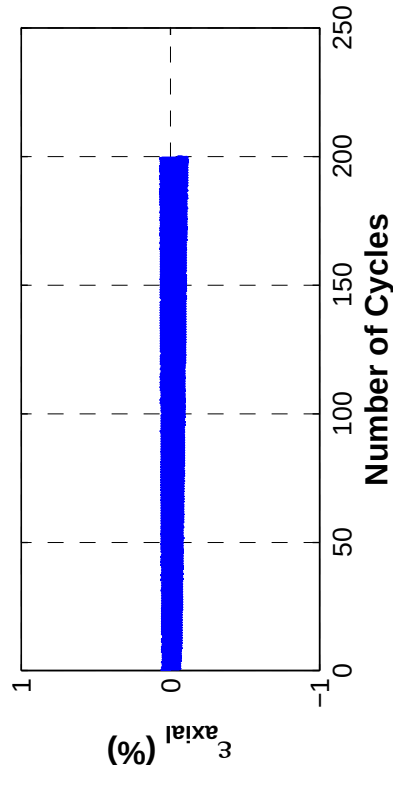
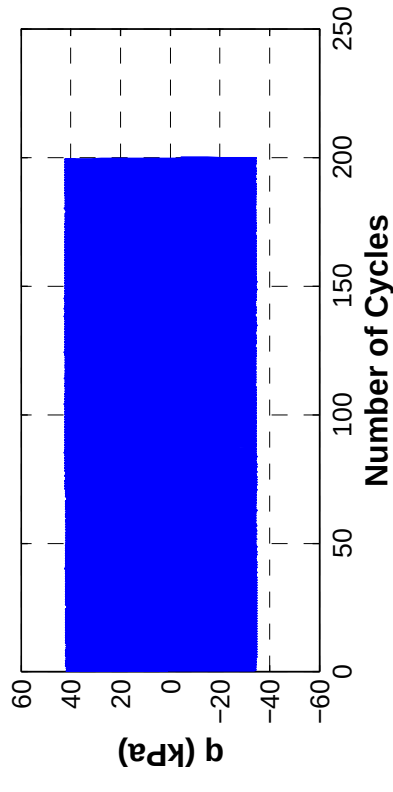
Site: Site 2
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 4.09
Date Tested: 04/24/14
Date Sampled: 03/18/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 2
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 4.09
Date Tested: 04/24/14
Date Sampled: 03/18/14



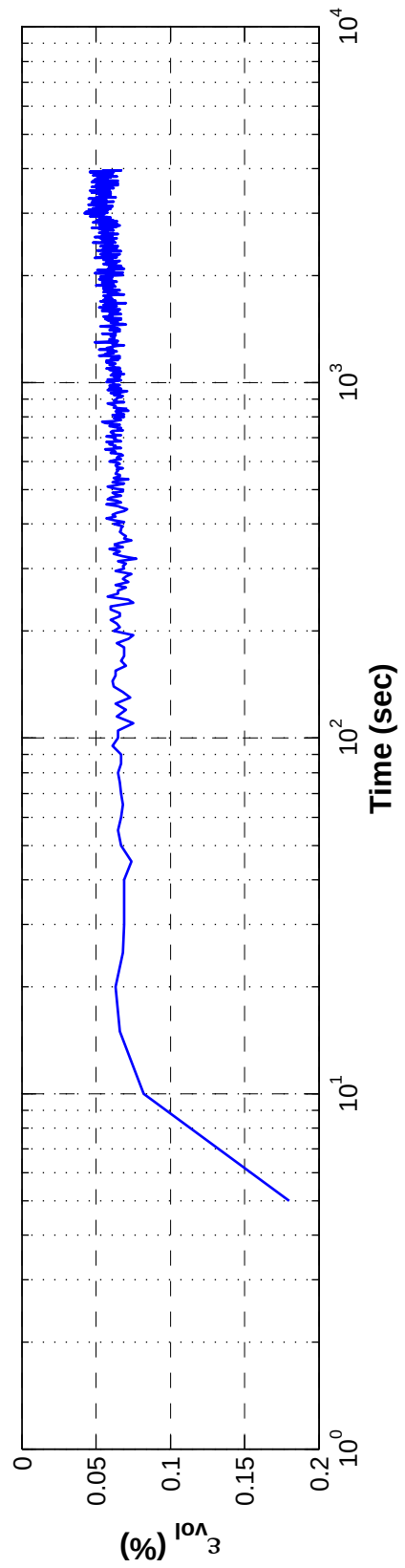
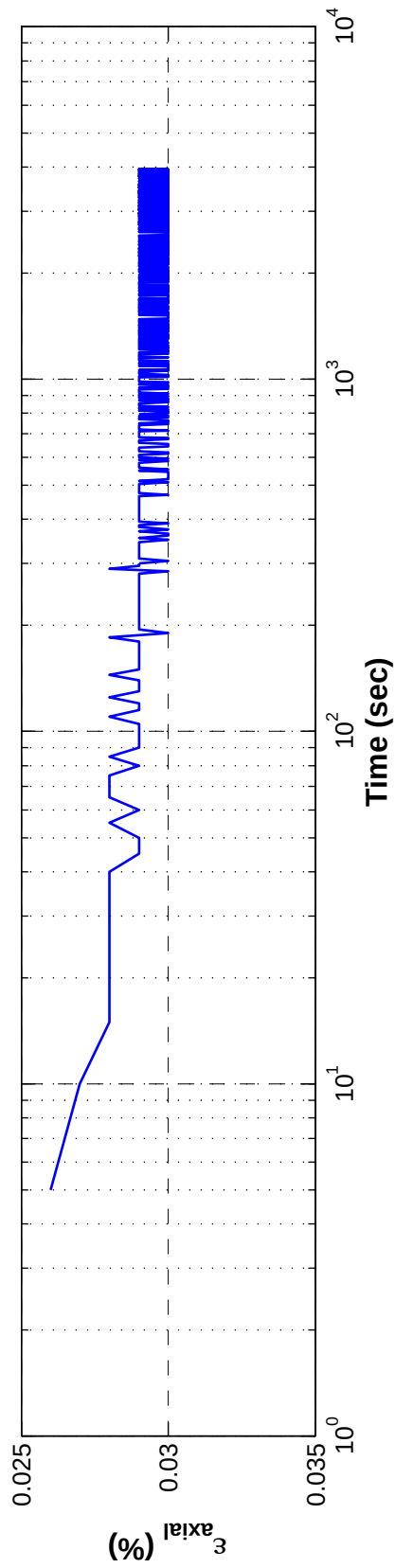
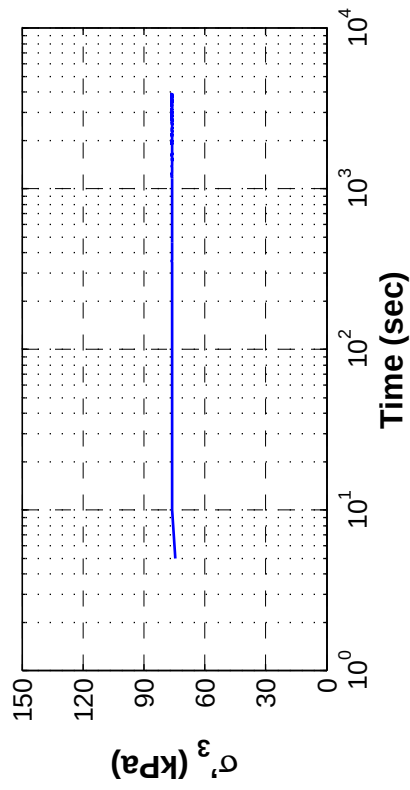


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 2	σ'_c (kPa):	75
Borehole:	DM-1	Loading Freq (Hz):	0.1
Sample No.:	5U	B-Value:	0.963
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	5.57	N to $\epsilon_{Ax-S.A.}$ =3%:	100
Date Tested:	04/14/14	N to $\epsilon_{Ax-D.A.}$ =5%:	100
Date Sampled:	03/19/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	136.786	Gs:	2.70
Spec. Diam. (mm):	61.168	e_c :	0.86
Dry Mass (g):	584.44	PI (%):	NP
		FC (%):	25

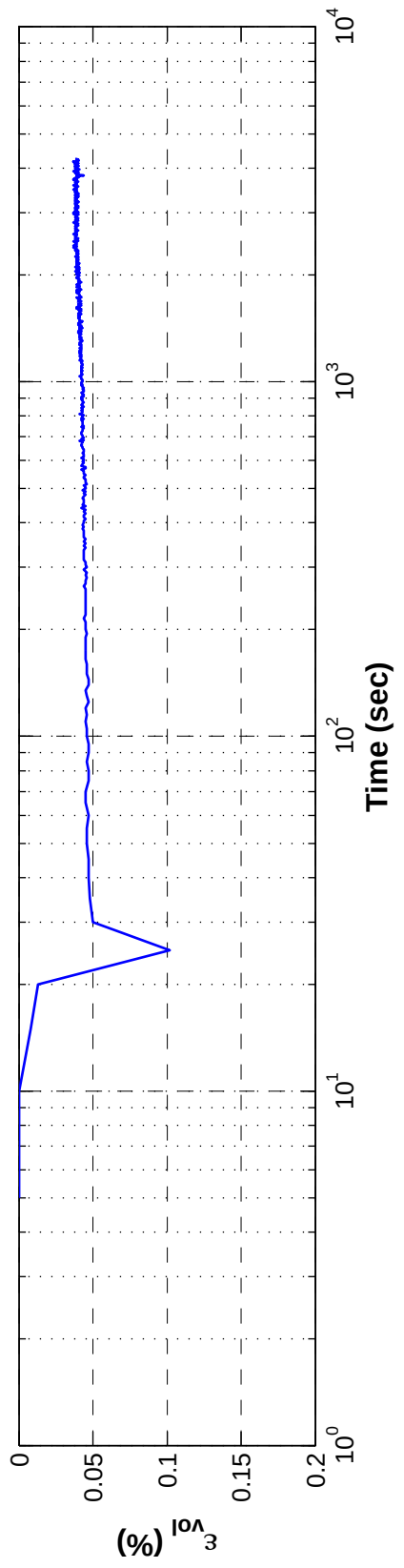
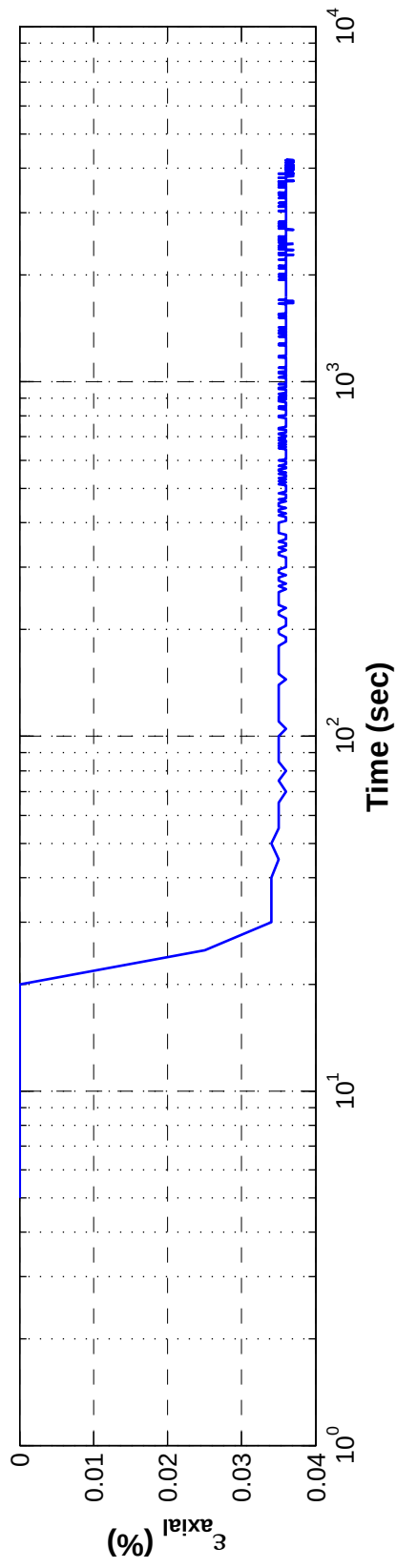
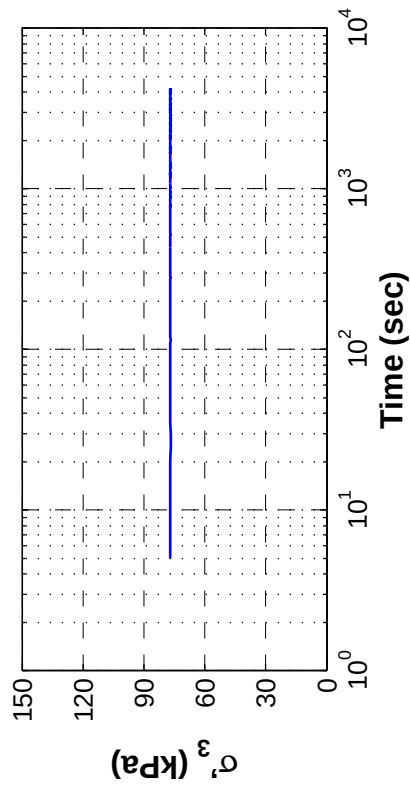
Specimen and Isotropic Consolidation Data

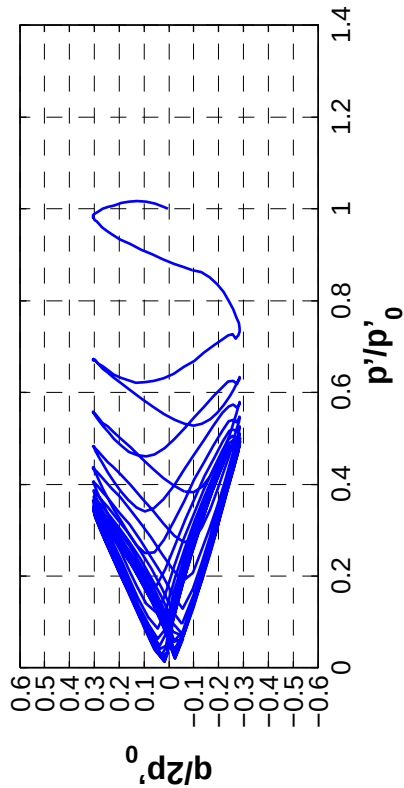
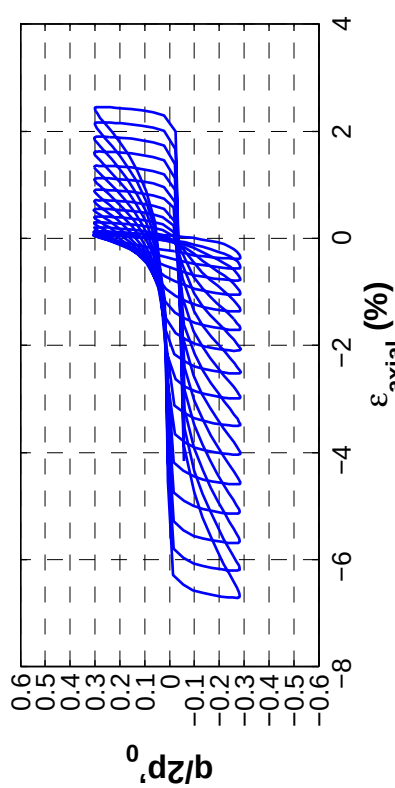
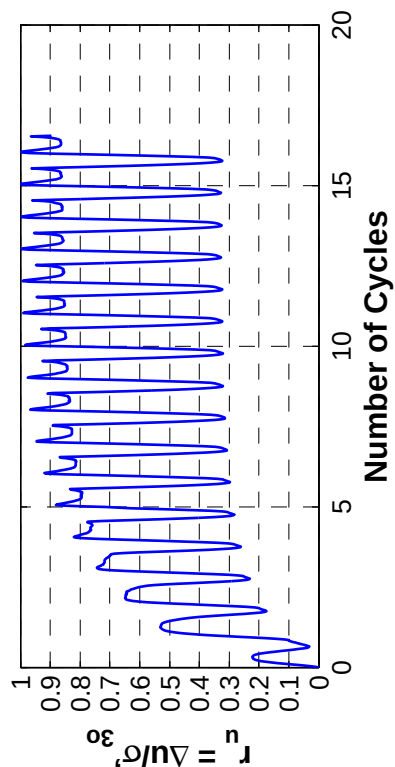
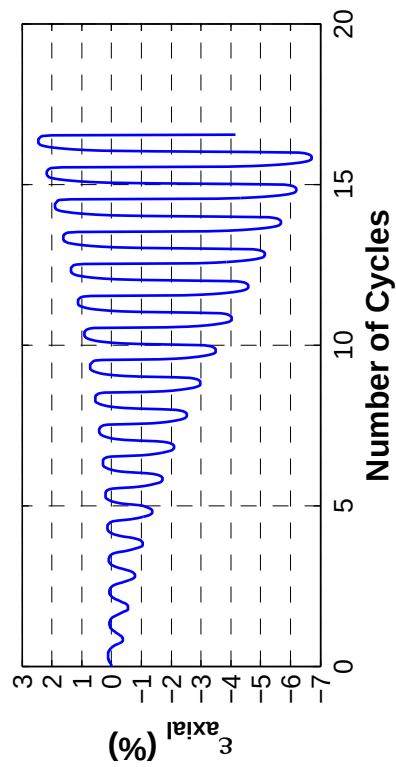
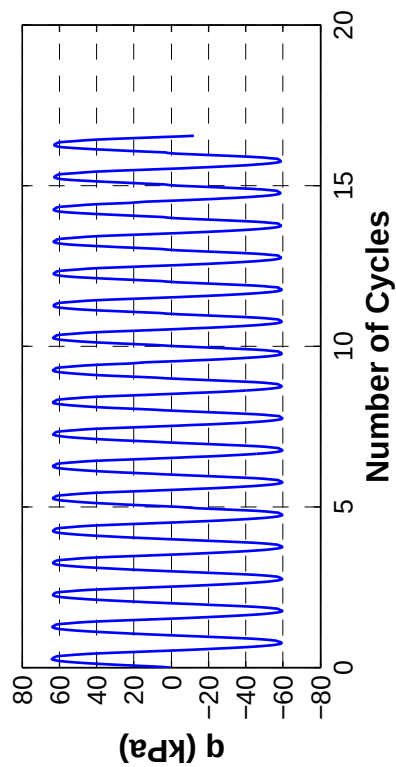
Site: Site 2
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.57
Date Tested: 04/14/14
Date Sampled: 03/19/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 2
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.57
Date Tested: 04/14/14
Date Sampled: 03/19/14



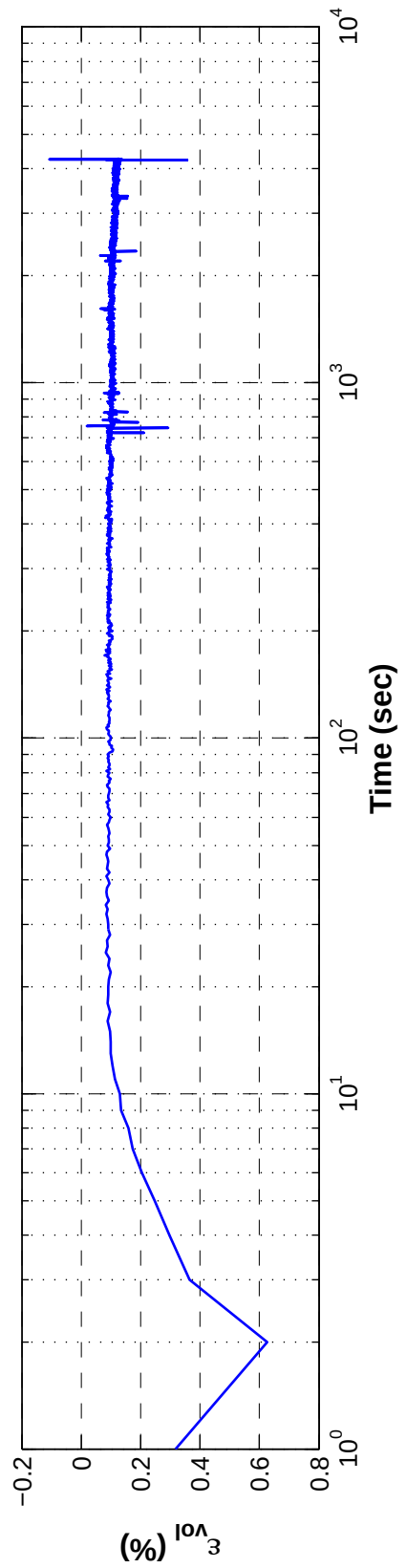
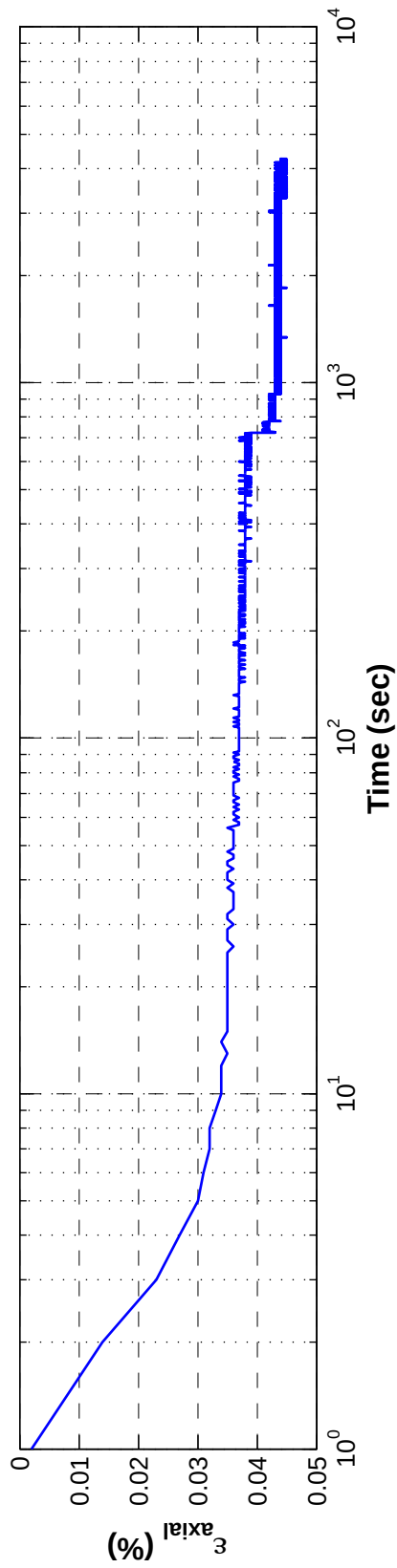
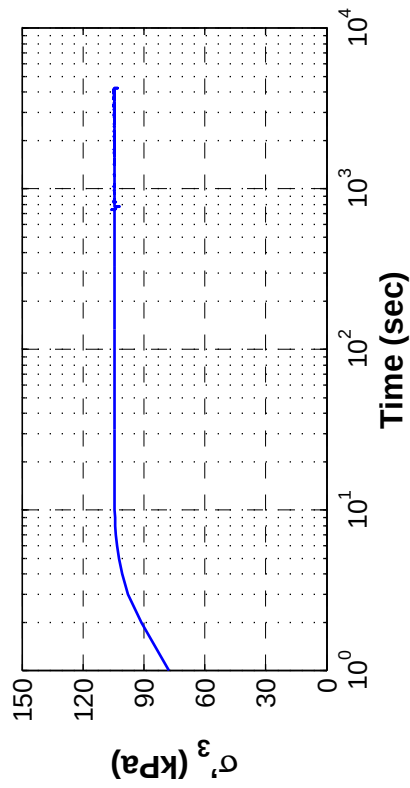


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 2	σ'_c (kPa):	104
Borehole:	DM-1	Loading Freq (Hz):	0.1
Sample No.:	7U	B-Value:	0.961
Sampler Type:	D&M	CSR:	0.3
Spec. Depth (m):	8.07	N to $\epsilon_{Ax-S.A.}$	=3%: 10
Date Tested:	05/05/14	N to $\epsilon_{Ax-D.A.}$	=5%: 12
Date Sampled:	03/19/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	136.826	Gs:	---
Spec. Diam. (mm):	61.09	e_c :	0.77
Dry Mass (g):	609.33	PI (%):	NP
		FC (%):	30

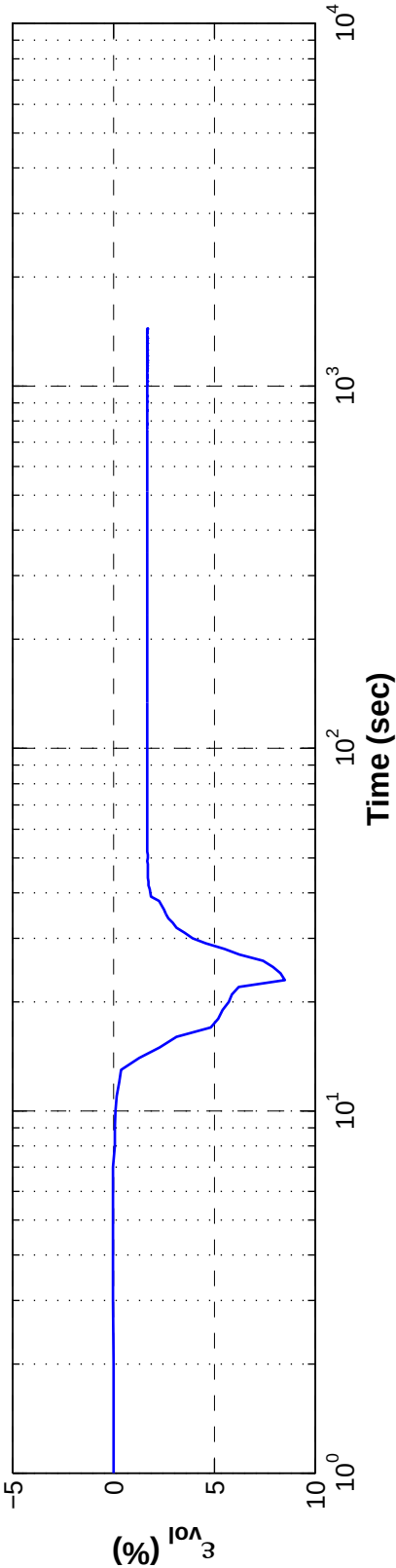
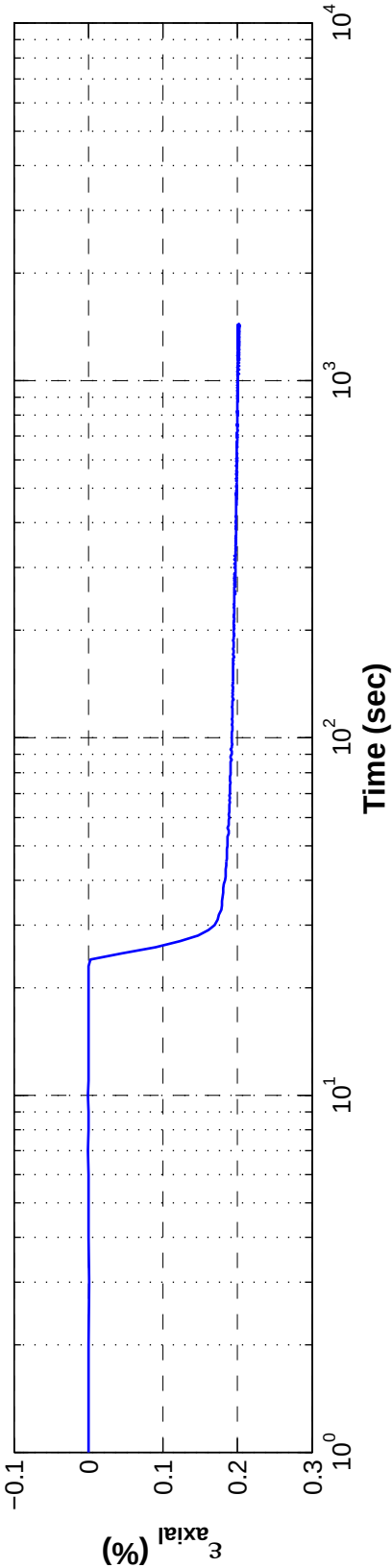
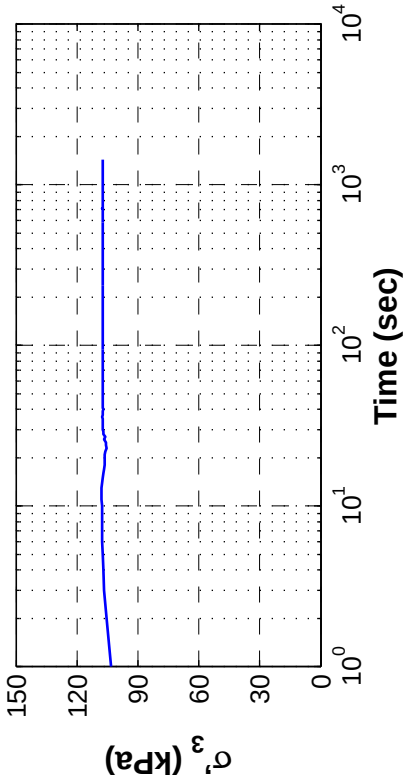
Specimen and Isotropic Consolidation Data

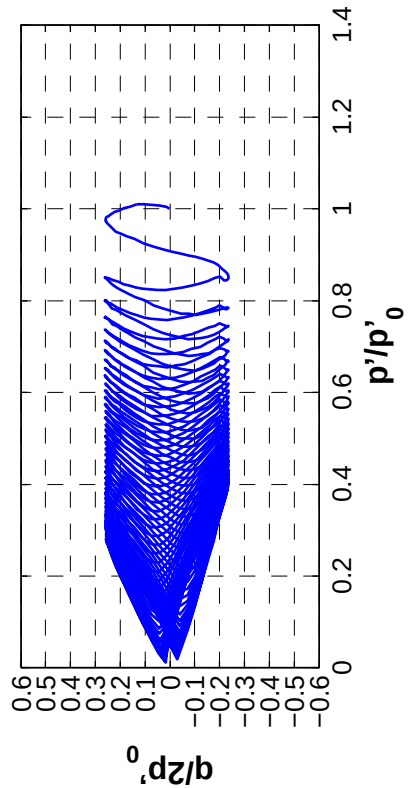
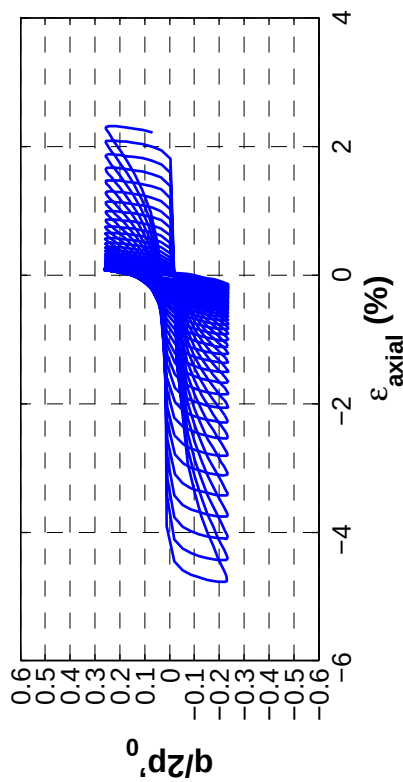
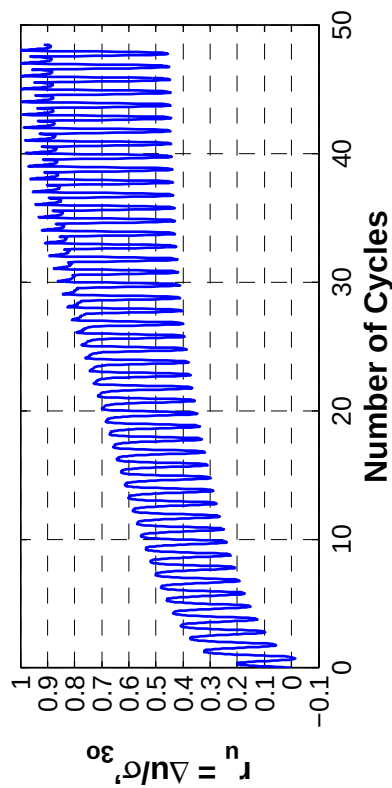
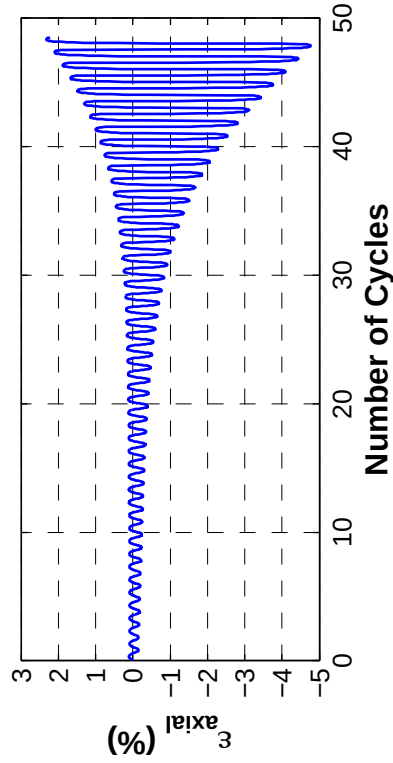
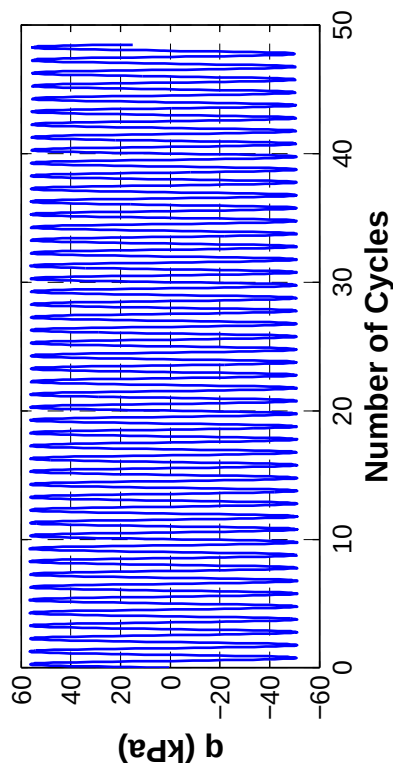
Site: Site 2
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 8.07
Date Tested: 05/05/14
Date Sampled: 03/19/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 2
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 8.07
Date Tested: 05/05/14
Date Sampled: 03/19/14



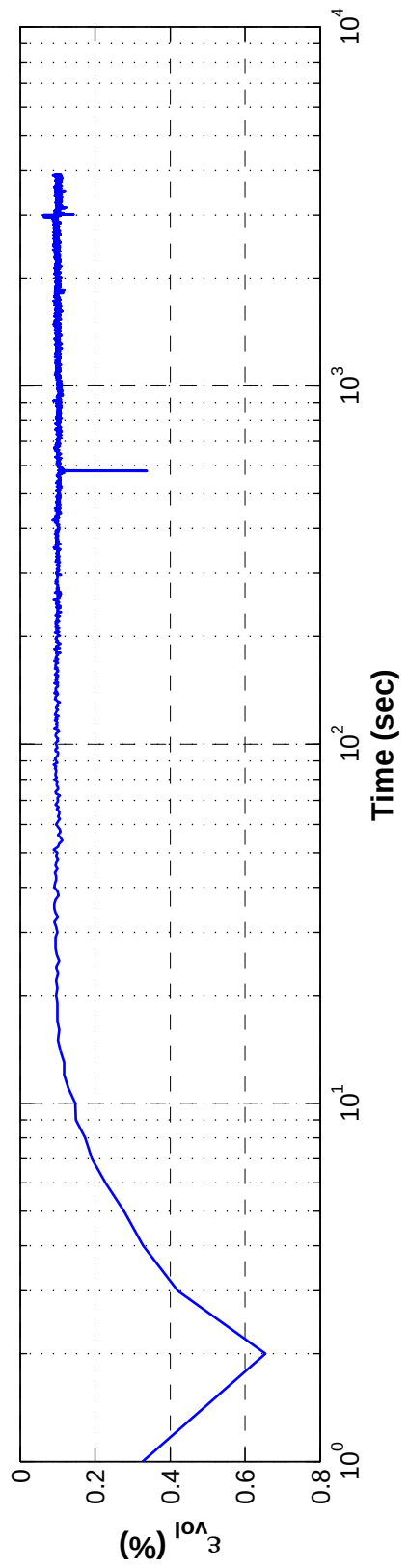
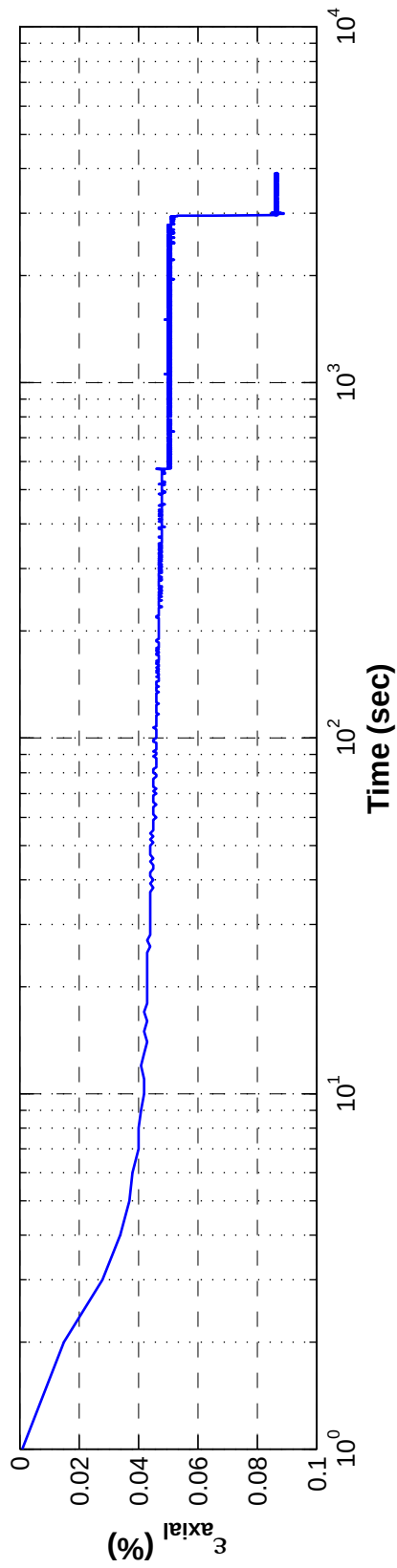
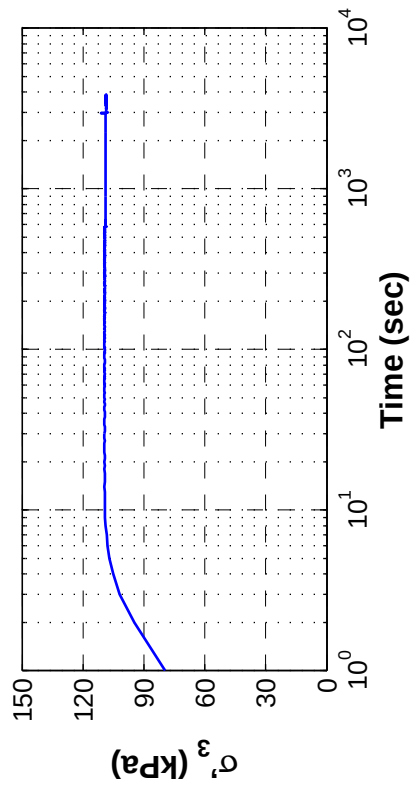


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 2	σ'_c (kPa):	108
Borehole:	DM-1	Loading Freq (Hz):	0.1
Sample No.:	7U	B-Value:	0.958
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	8.22	N to $\varepsilon_{AX-S.A.}$ =3%:	43
Date Tested:	05/06/14	N to $\varepsilon_{AX-D.A.}$ =5%:	45
Date Sampled:	03/19/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	138.116	Gs:	2.69
Spec. Diam. (mm):	61.14	e_c :	0.75
Dry Mass (g):	623.36	PI (%):	NP
		FC (%):	43

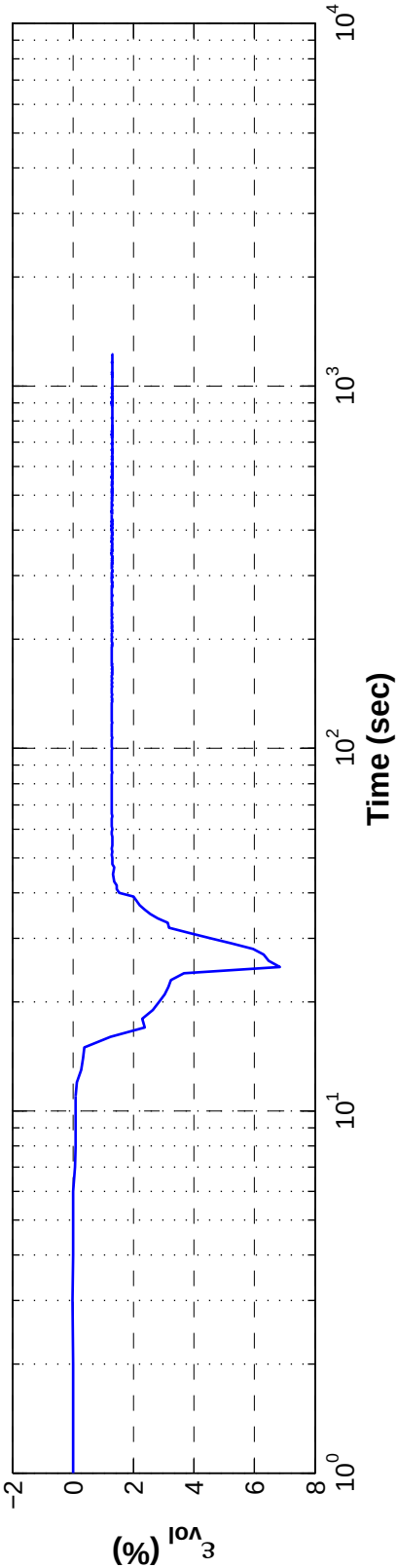
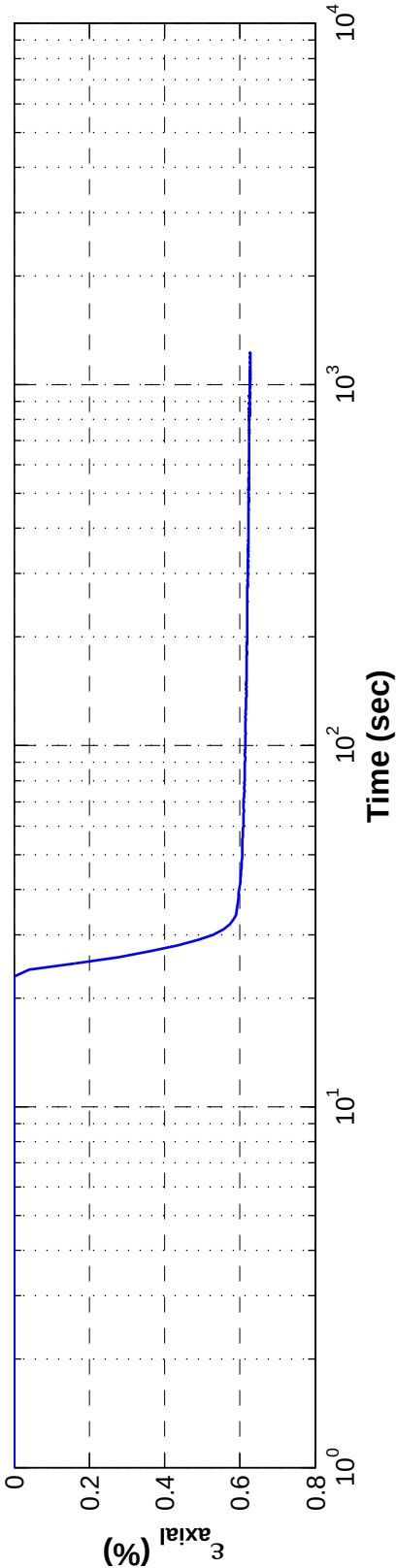
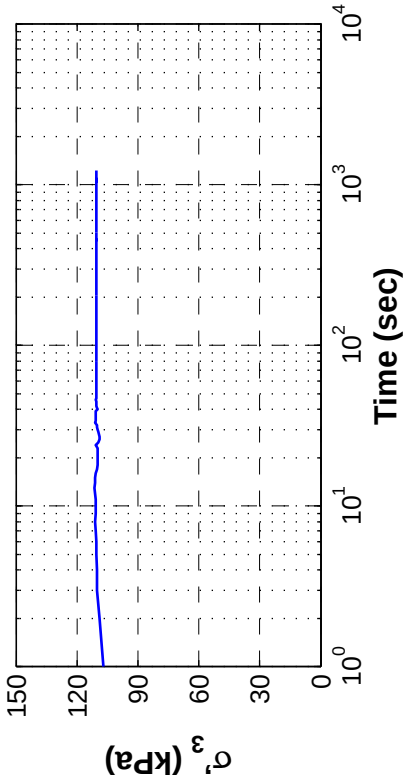
Specimen and Isotropic Consolidation Data

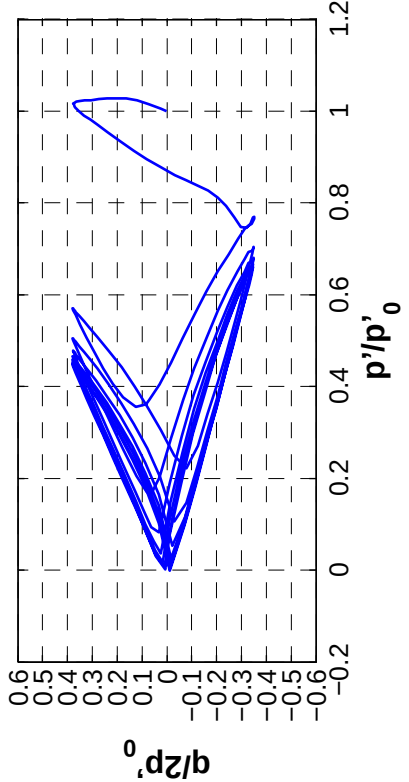
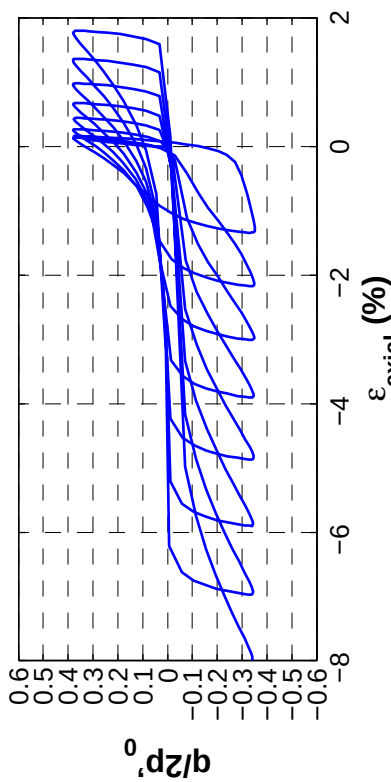
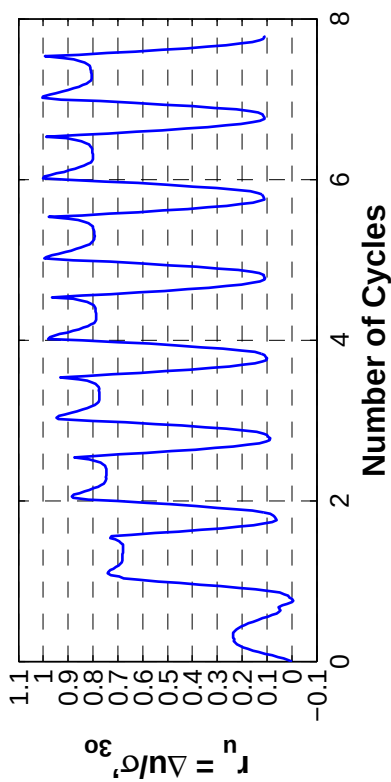
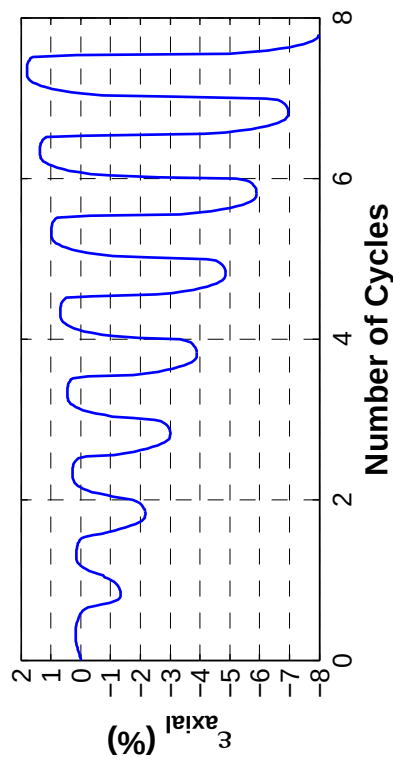
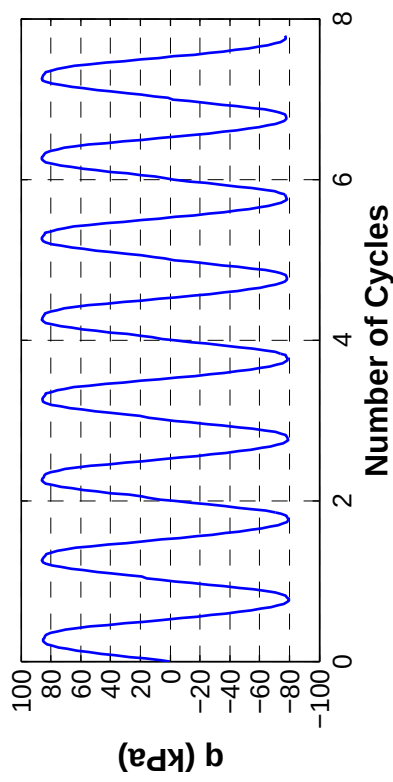
Site: Site 2
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 8.22
Date Tested: 05/06/14
Date Sampled: 03/19/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 2
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 8.22
Date Tested: 05/06/14
Date Sampled: 03/19/14



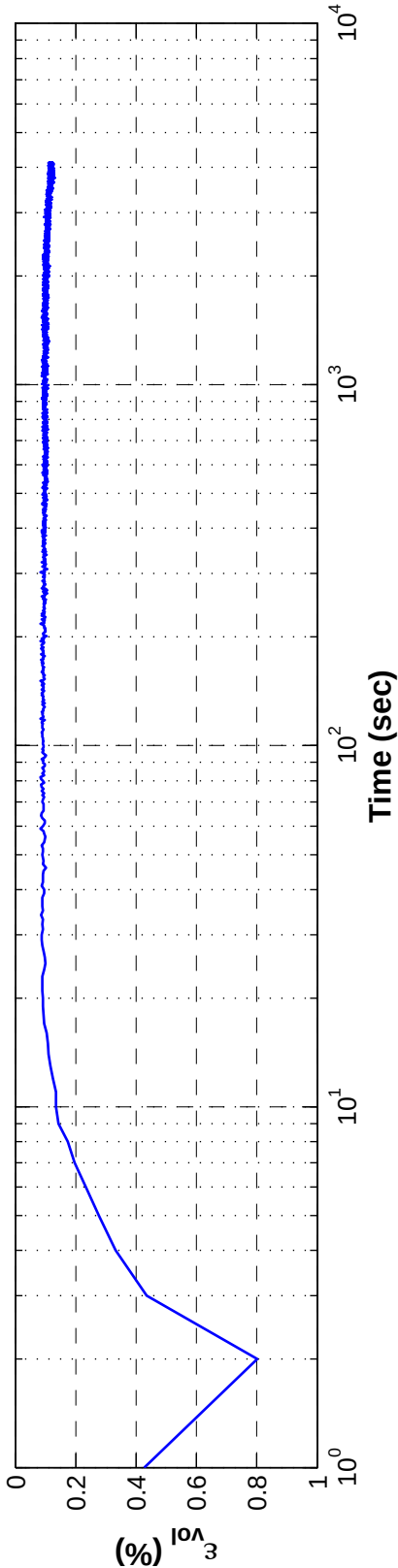
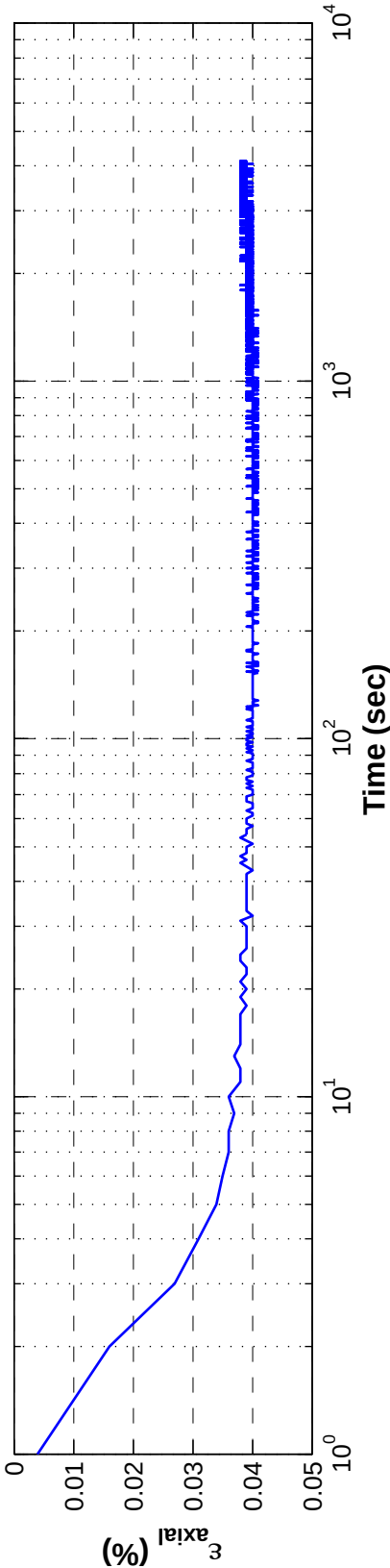
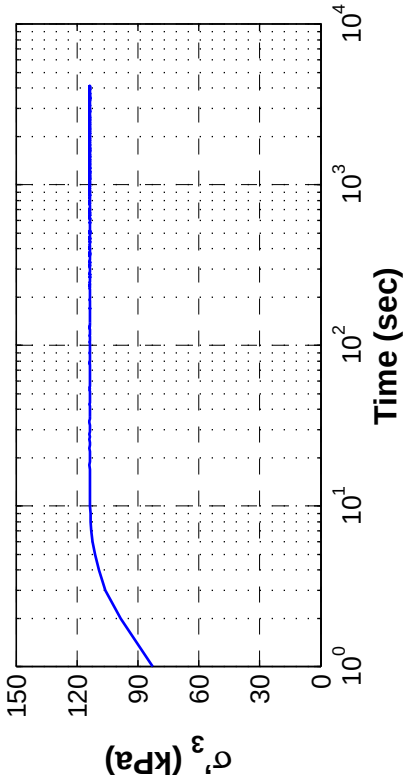


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 2	σ'_c (kPa):	113
Borehole:	DM-1	Loading Freq (Hz):	0.1
Sample No.:	8U	B-Value:	0.969
Sampler Type:	D&M	CSR:	0.36
Spec. Depth (m):	8.87	N to $\epsilon_{Ax-S.A.}$ =3%:	3
Date Tested:	04/30/14	N to $\epsilon_{Ax-D.A.}$ =5%:	5
Date Sampled:	03/19/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	137.136	Gs:	2.66
Spec. Diam. (mm):	61.04	e_c :	0.81
Dry Mass (g):	589.60	PI (%):	NP
		FC (%):	8

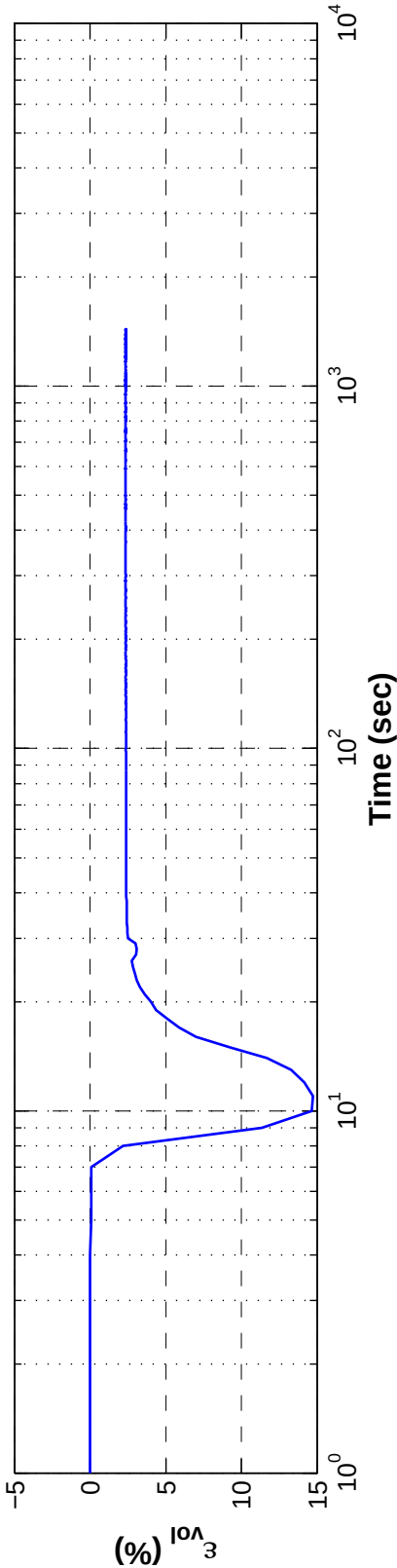
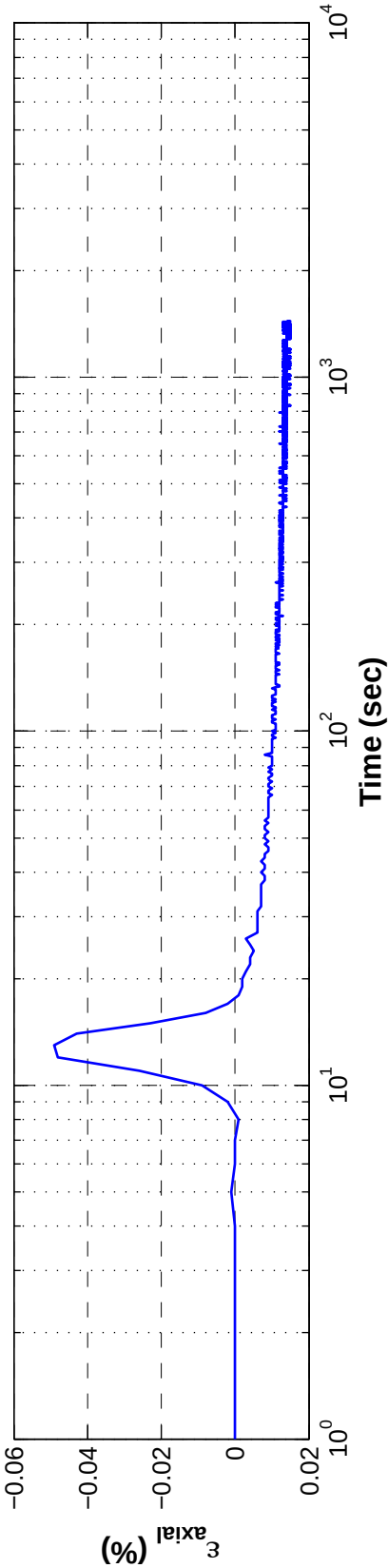
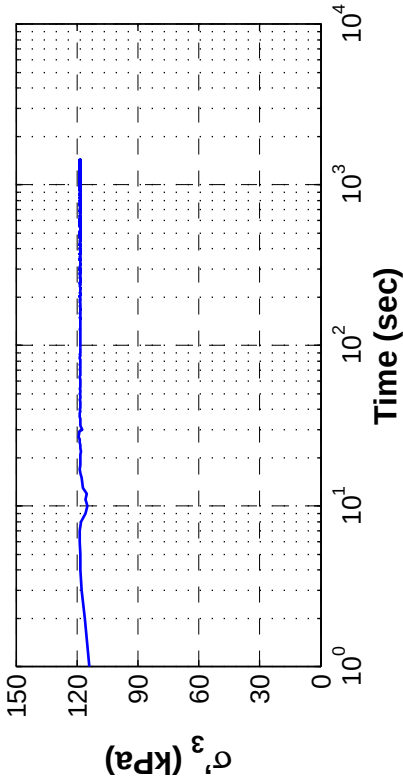
Specimen and Isotropic Consolidation Data

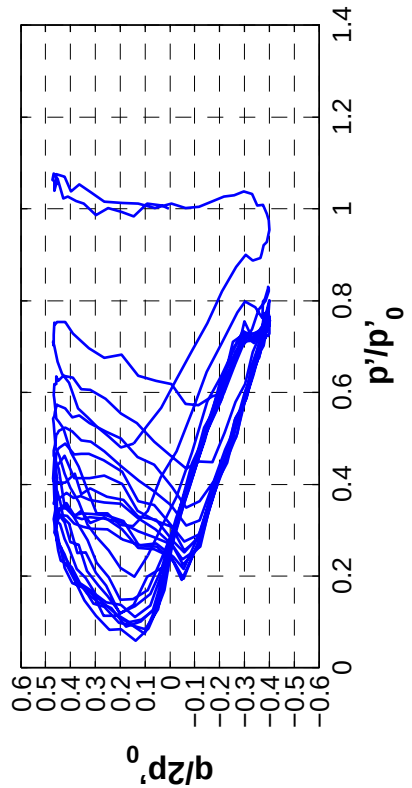
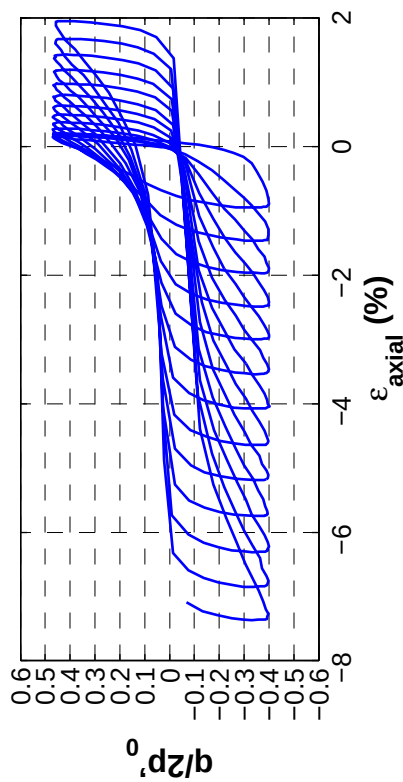
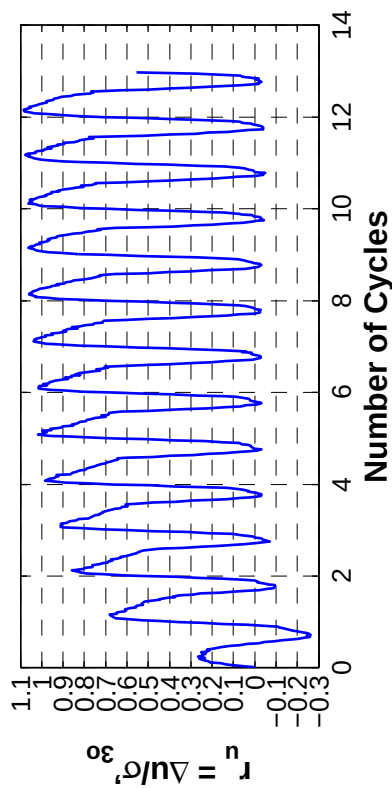
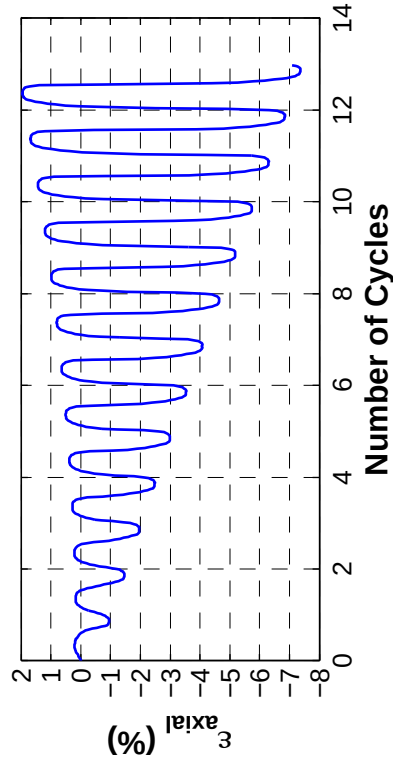
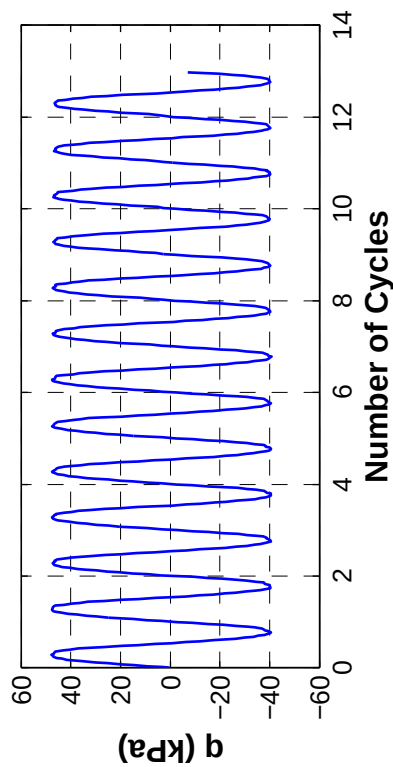
Site: Site 2
Borehole: DM-1
Sample No.: 8U
Sampler Type: D&M
Spec. Depth (m): 8.87
Date Tested: 04/30/14
Date Sampled: 03/19/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 2
Borehole: DM-1
Sample No.: 8U
Sampler Type: D&M
Spec. Depth (m): 8.87
Date Tested: 04/30/14
Date Sampled: 03/19/14



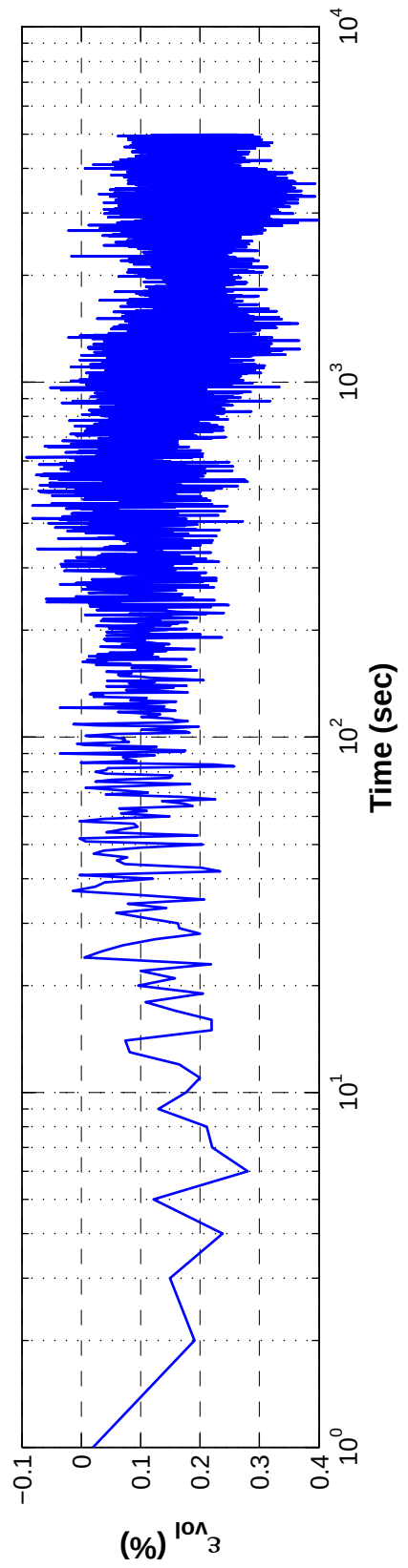
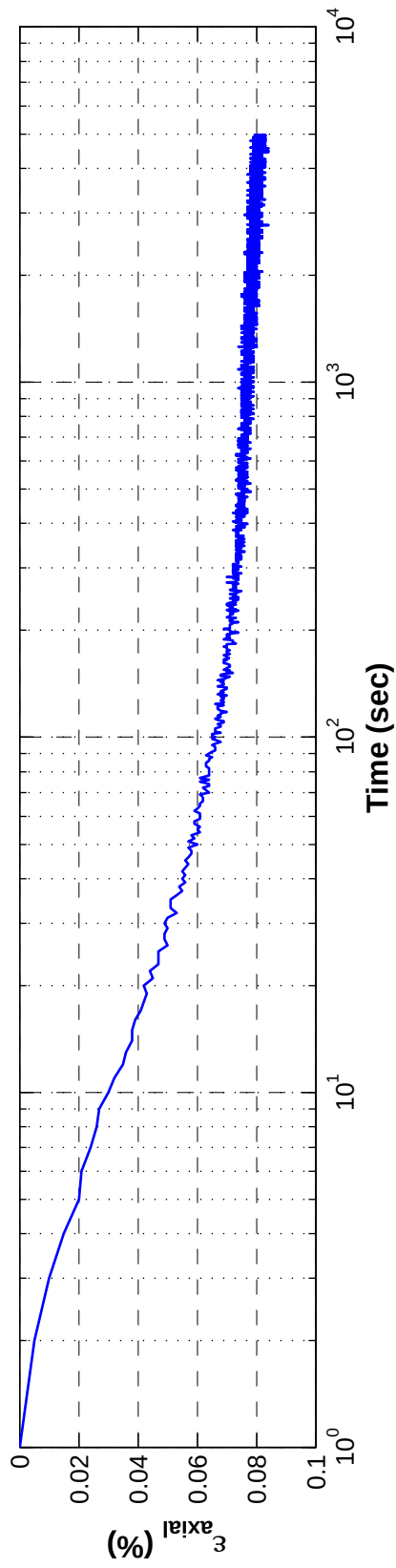
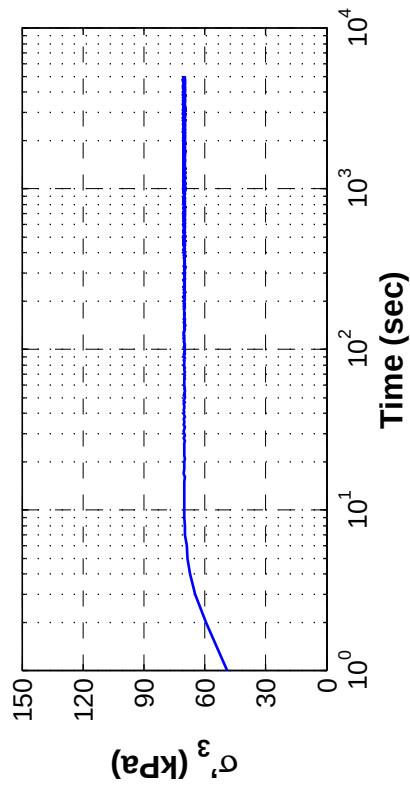


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 14	σ'_c (kPa):	50
Borehole:	BH-2	Loading Freq (Hz):	0.1
Sample No.:	2U	B-Value:	0.975
Sampler Type:	D&M	CSR:	0.32
Spec. Depth (m):	1.72	N to $\epsilon_{Ax-S.A.}$ =3%:	6
Date Tested:	05/15/14	N to $\epsilon_{Ax-D.A.}$ =5%:	8
Date Sampled:	03/24/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	140.806	Gs:	---
Spec. Diam. (mm):	61.38	e_c :	0.83
Dry Mass (g):	596.26	PI (%):	7
		FC (%):	99

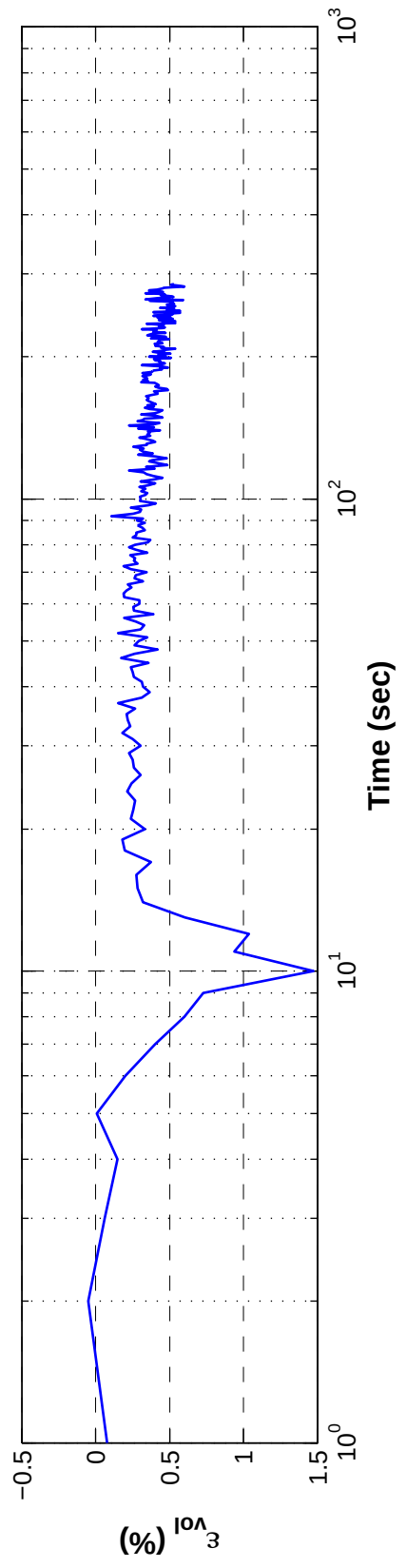
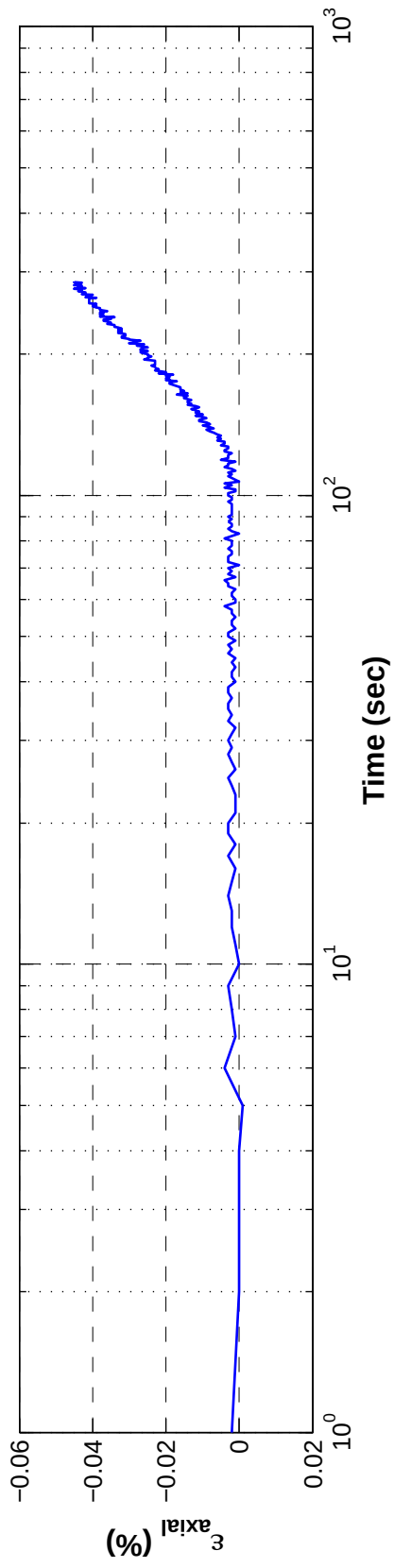
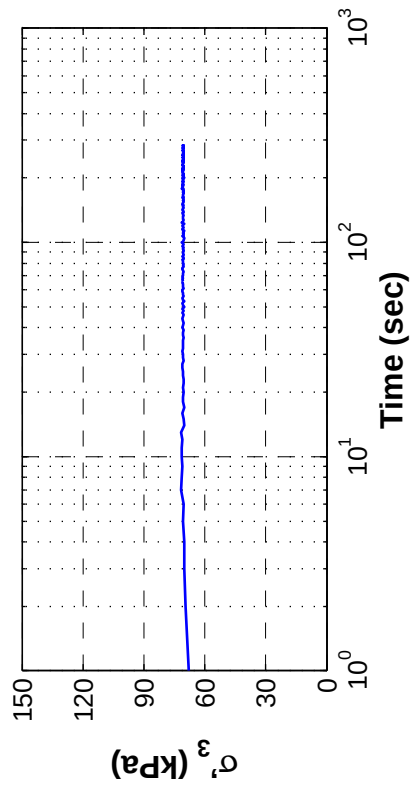
Specimen and Isotropic Consolidation Data

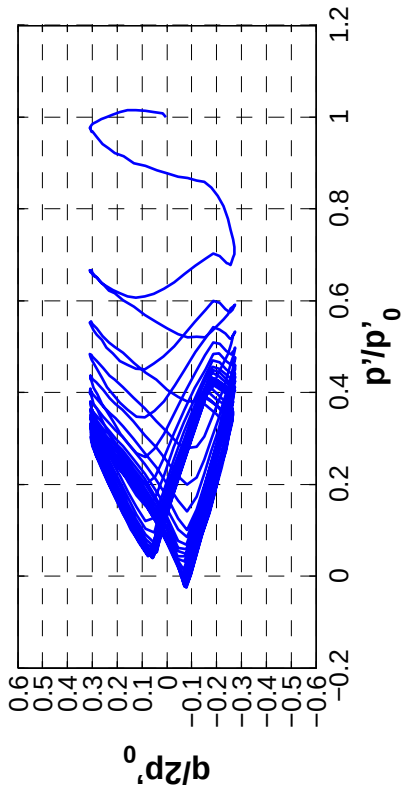
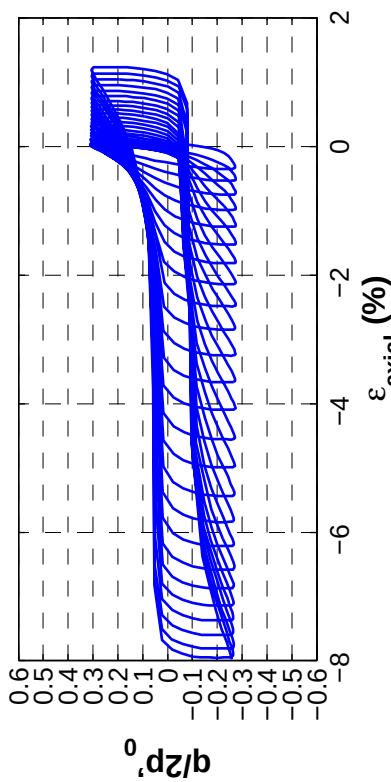
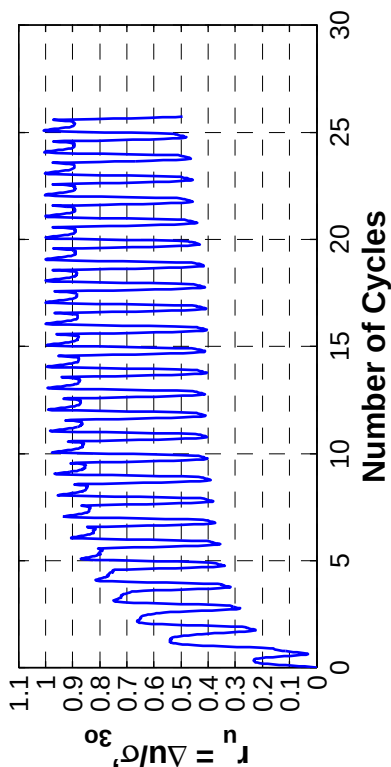
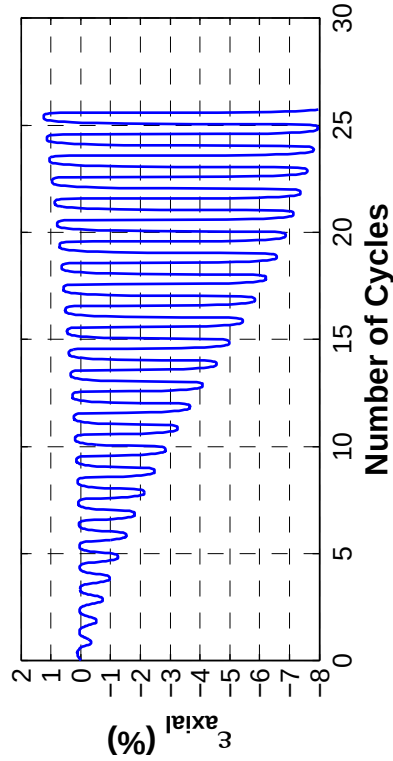
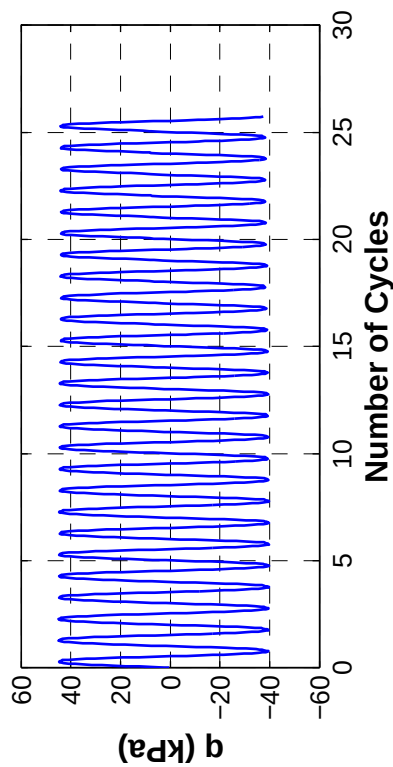
Site: Site 14
Borehole: BH-2
Sample No.: 2U
Sampler Type: D&M
Spec. Depth (m): 1.72
Date Tested: 05/15/14
Date Sampled: 03/24/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 14
Borehole: BH-2
Sample No.: 2U
Sampler Type: D&M
Spec. Depth (m): 1.72
Date Tested: 05/15/14
Date Sampled: 03/24/14



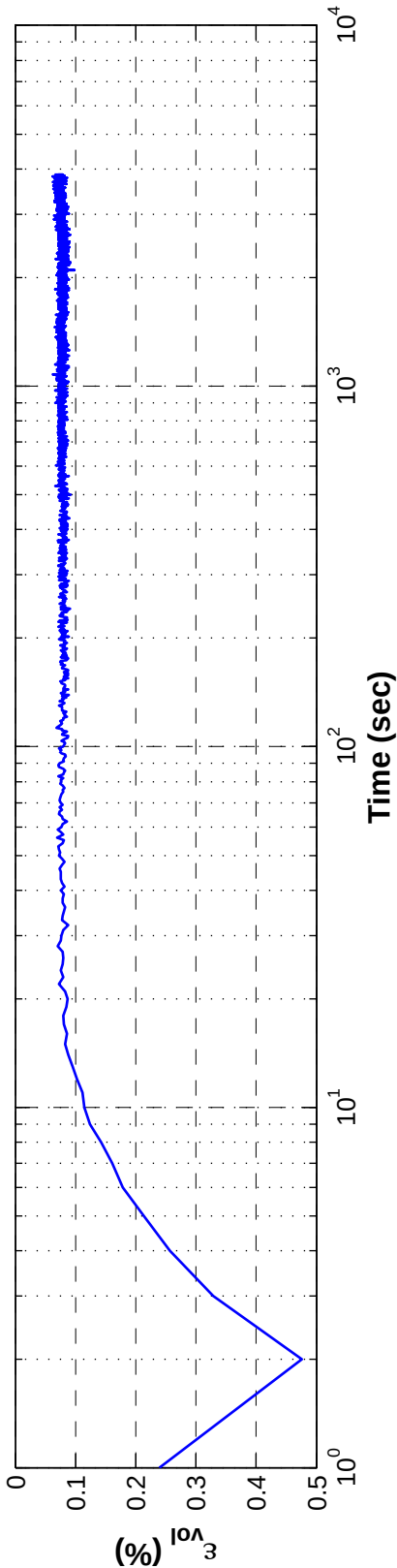
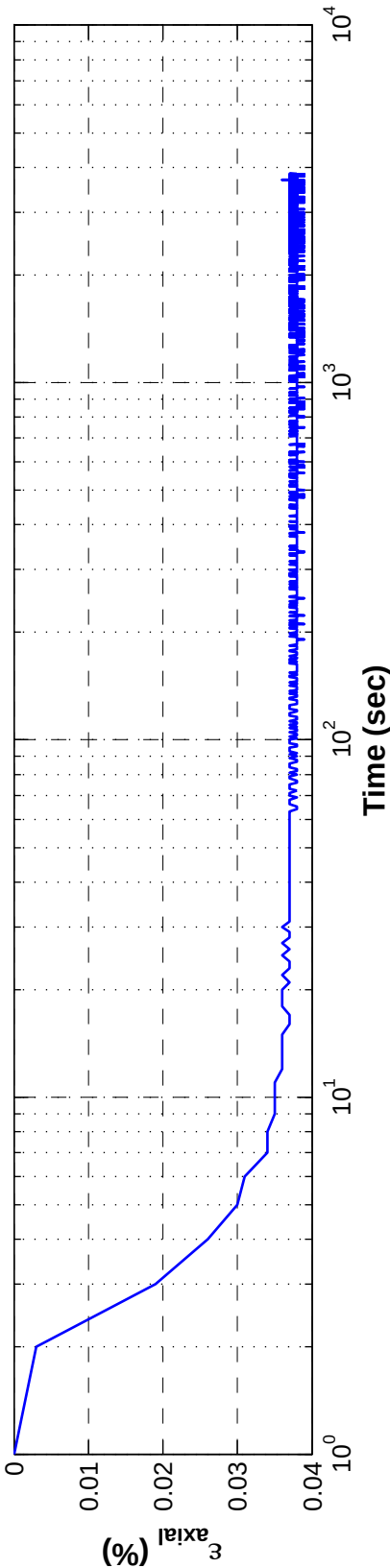
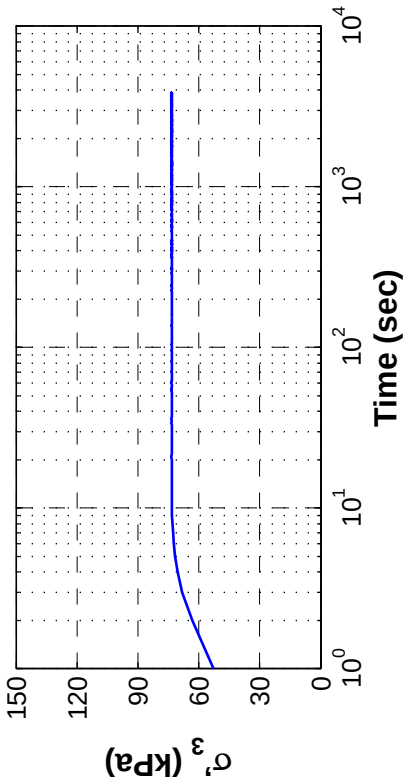


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 14	σ'_c (kPa):	72
Borehole:	BH-2	Loading Freq (Hz):	0.1
Sample No.:	5U	B-Value:	0.973
Sampler Type:	D&M	CSR:	0.3
Spec. Depth (m):	5.17	N to $\epsilon_{Ax-S.A.}$ =3%:	11
Date Tested:	05/08/14	N to $\epsilon_{Ax-D.A.}$ =5%:	15
Date Sampled:	03/25/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	138.276	Gs:	---
Spec. Diam. (mm):	61.17	e_c :	0.78
Dry Mass (g):	613.61	PI (%):	NP
		FC (%):	47

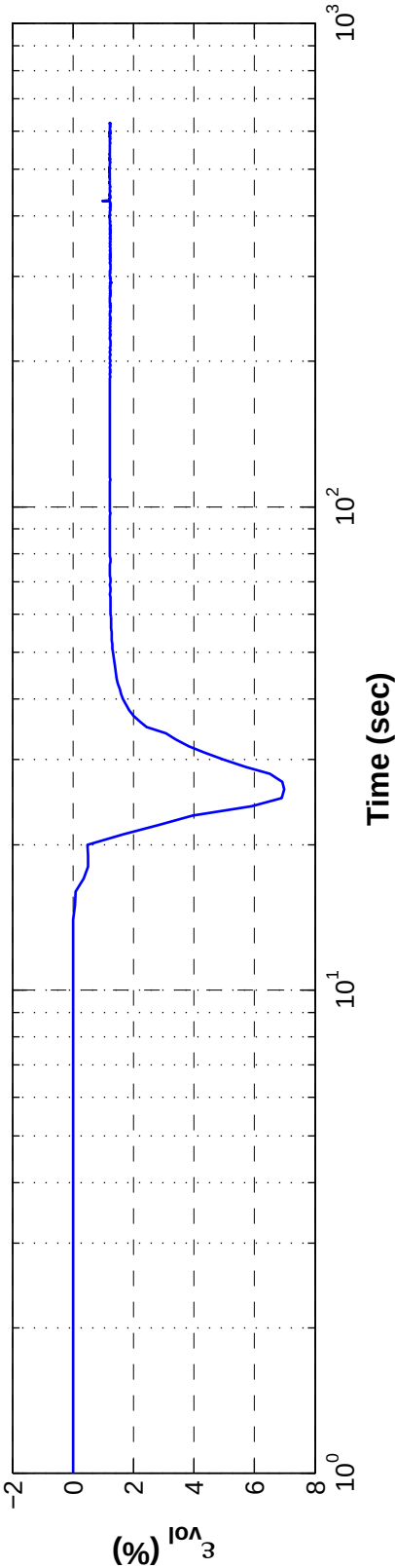
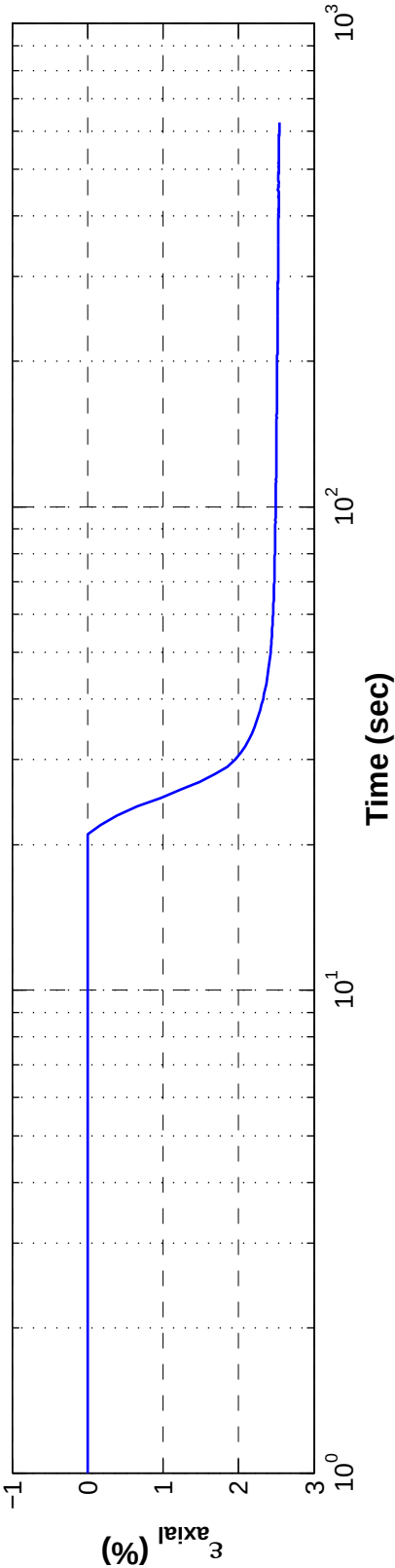
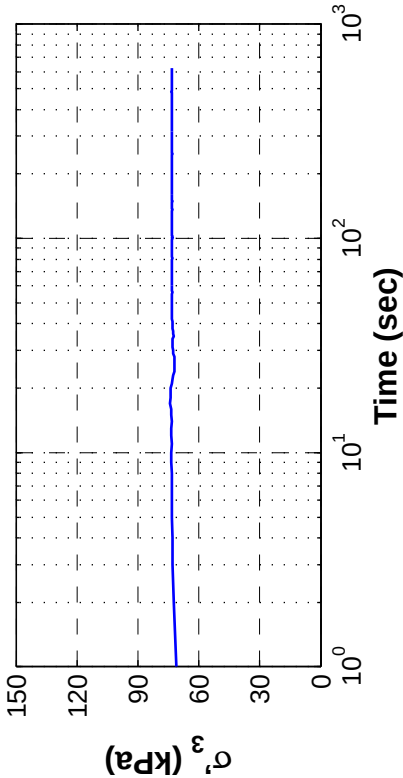
Specimen and Isotropic Consolidation Data

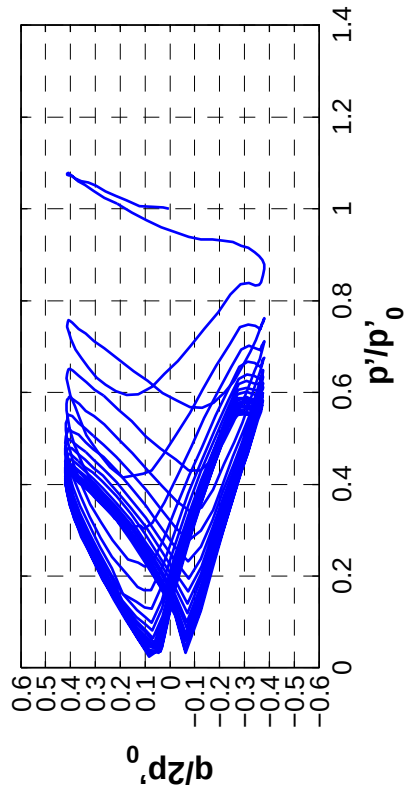
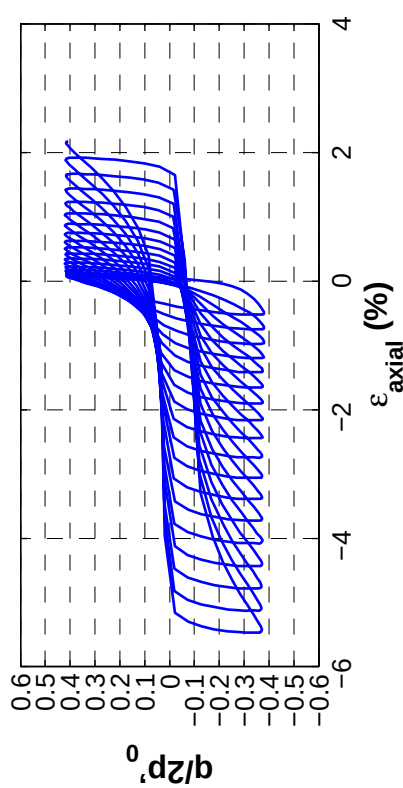
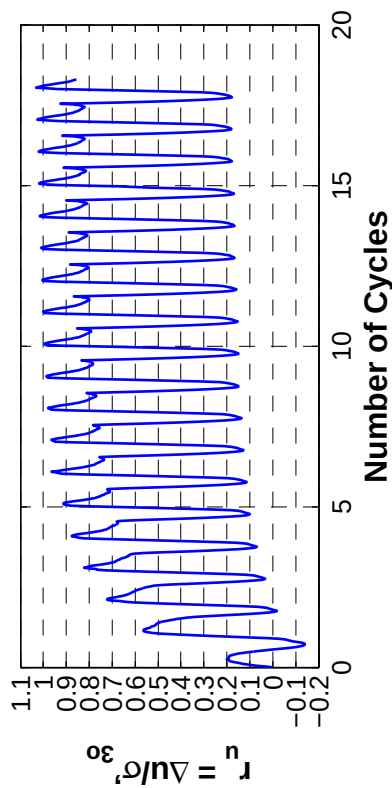
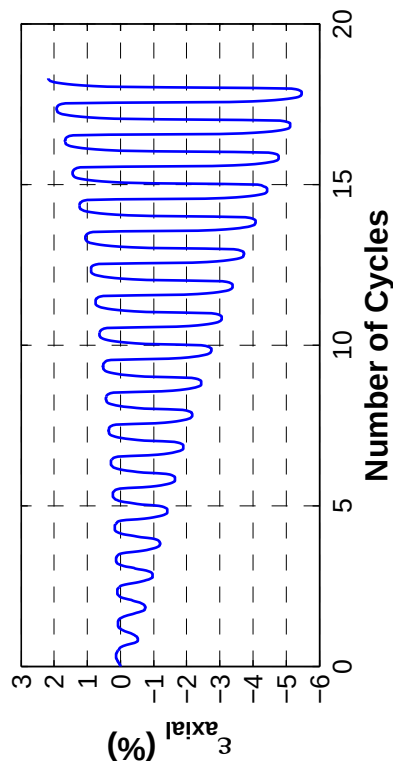
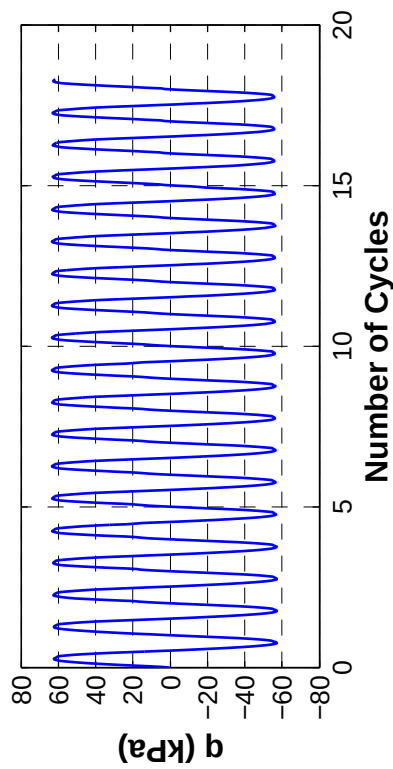
Site: Site 14
Borehole: BH-2
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.17
Date Tested: 05/08/14
Date Sampled: 03/25/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 14
Borehole: BH-2
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.17
Date Tested: 05/08/14
Date Sampled: 03/25/14



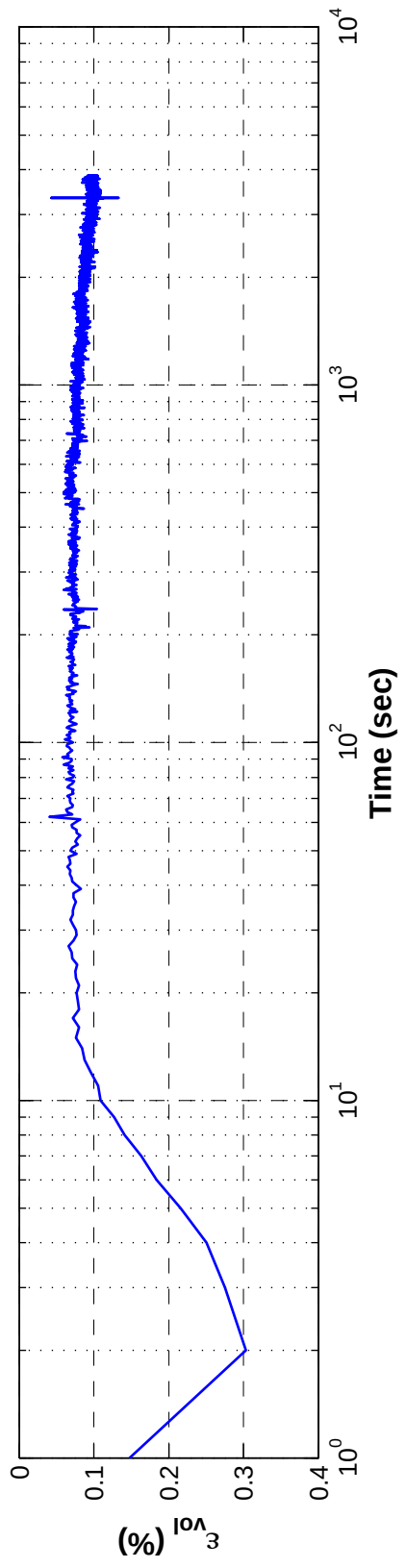
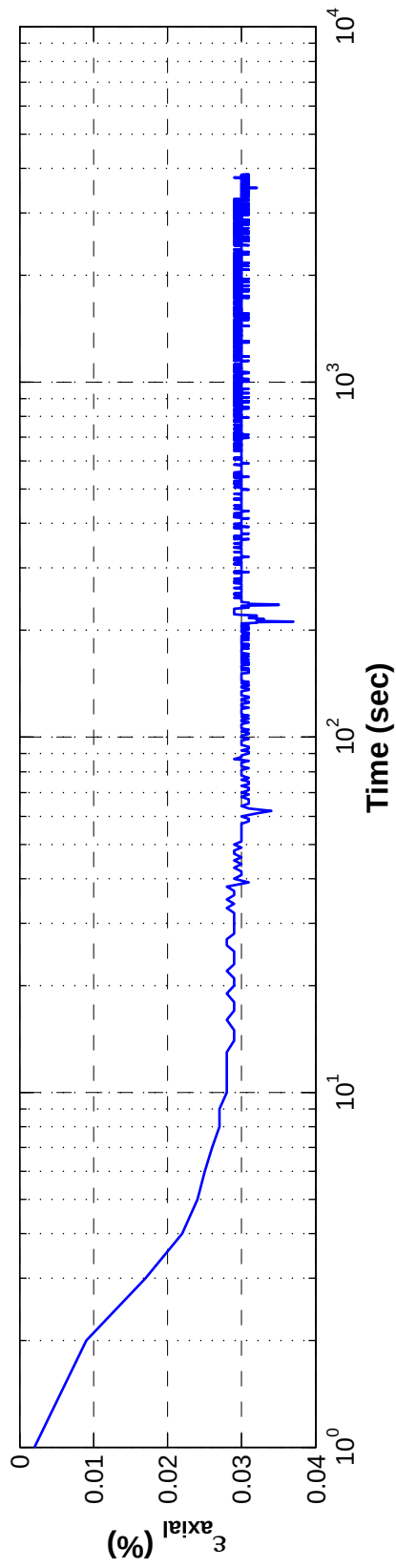
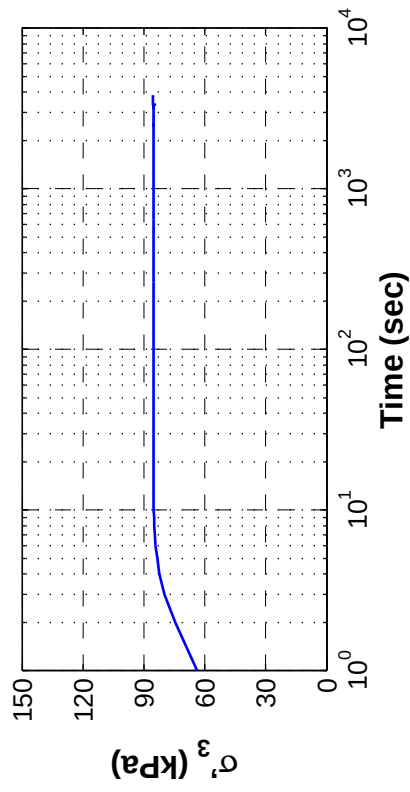


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 14	σ'_c (kPa):	75
Borehole:	BH-2	Loading Freq (Hz):	0.1
Sample No.:	6U	B-Value:	0.968
Sampler Type:	D&M	CSR:	0.36
Spec. Depth (m):	6.67	N to $\epsilon_{Ax-S.A.}$ =3%:	11
Date Tested:	05/17/14	N to $\epsilon_{Ax-D.A.}$ =5%:	14
Date Sampled:	03/25/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	139.086	Gs:	2.69
Spec. Diam. (mm):	61.18	e_c :	0.67
Dry Mass (g):	657.71	PI (%):	NP
		FC (%):	54

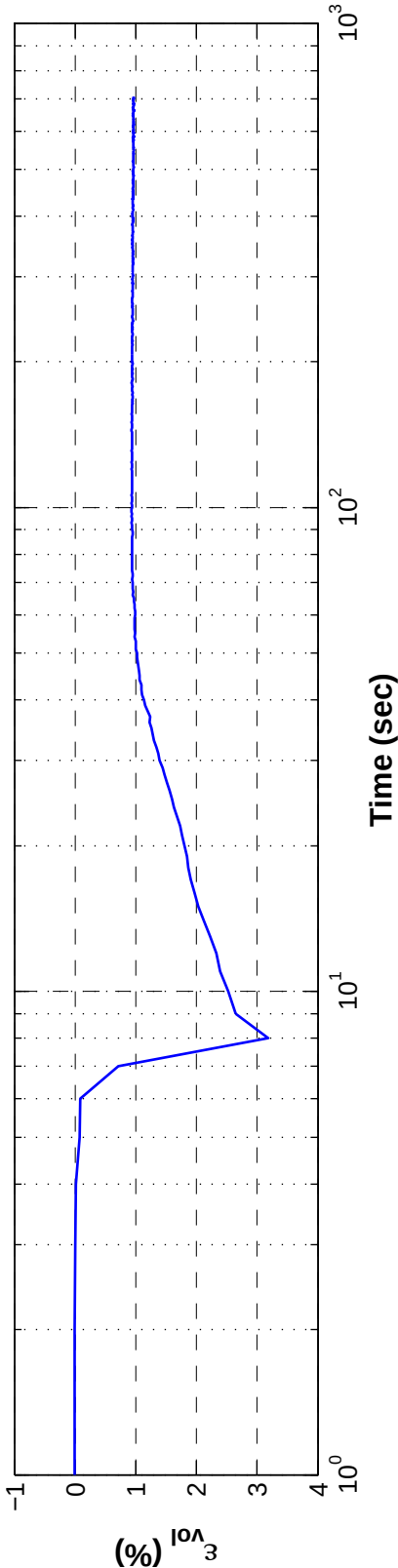
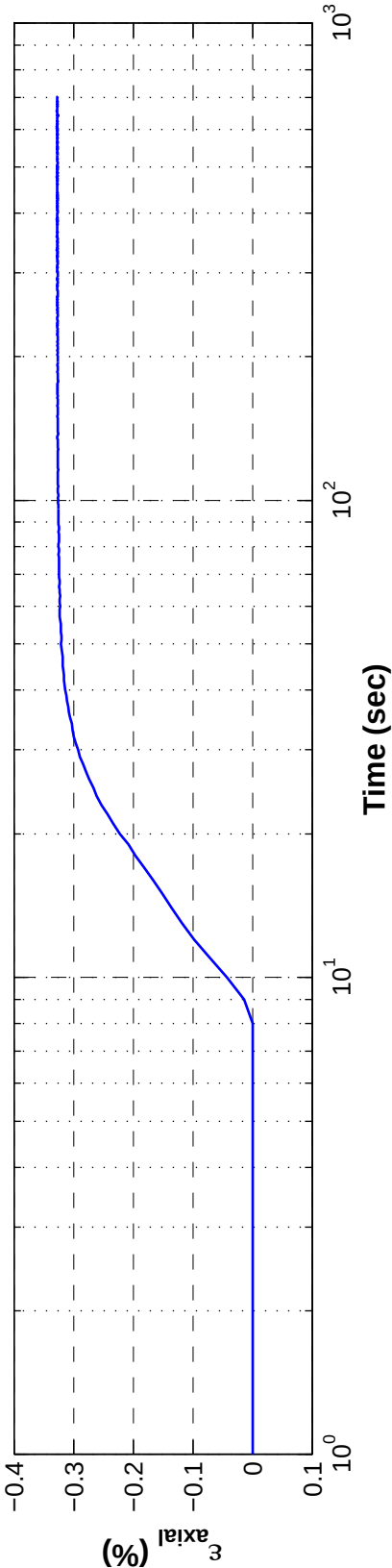
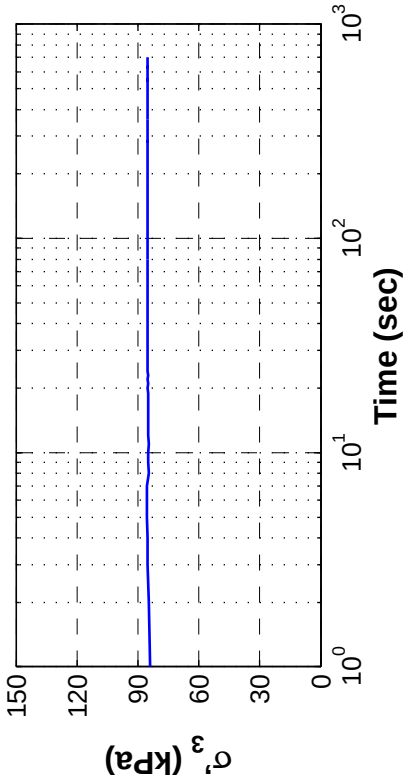
Specimen and Isotropic Consolidation Data

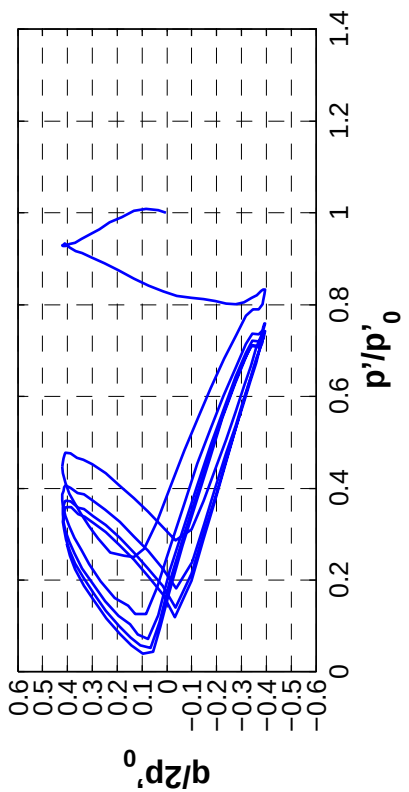
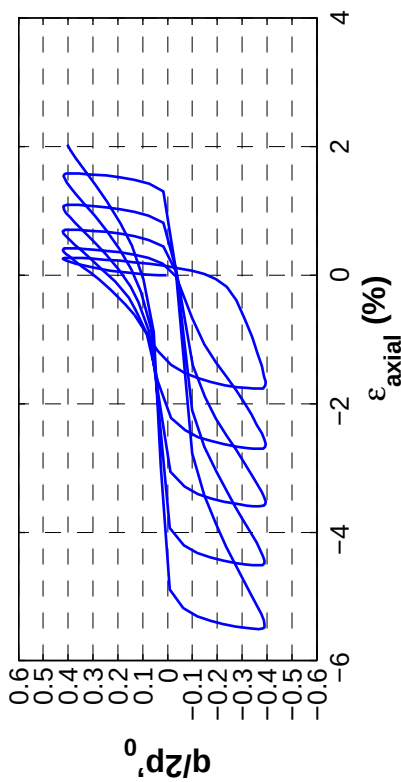
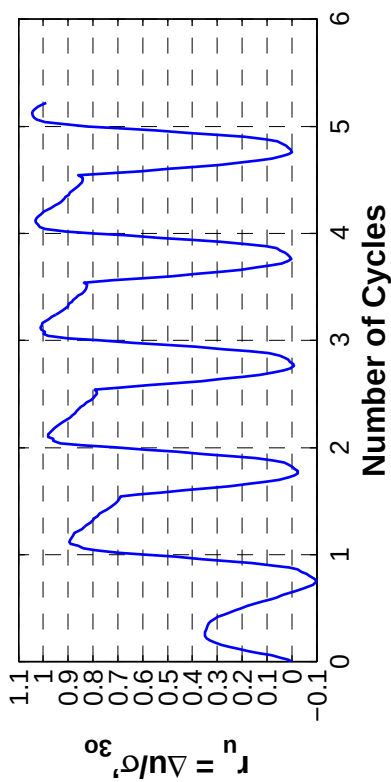
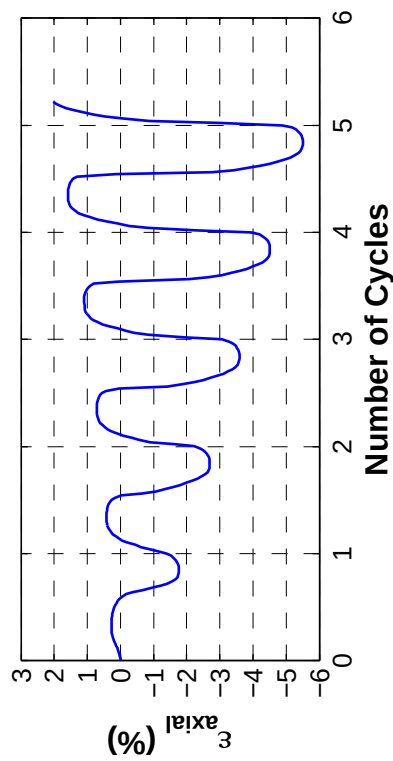
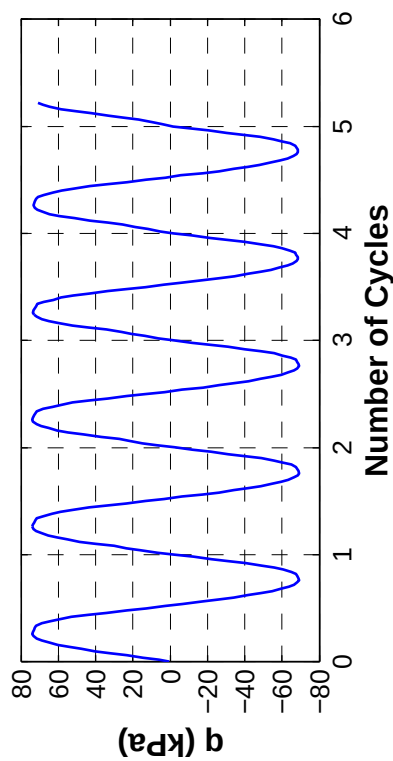
Site: Site 14
Borehole: BH-2
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.67
Date Tested: 05/17/14
Date Sampled: 03/25/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 14
Borehole: BH-2
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.67
Date Tested: 05/17/14
Date Sampled: 03/25/14



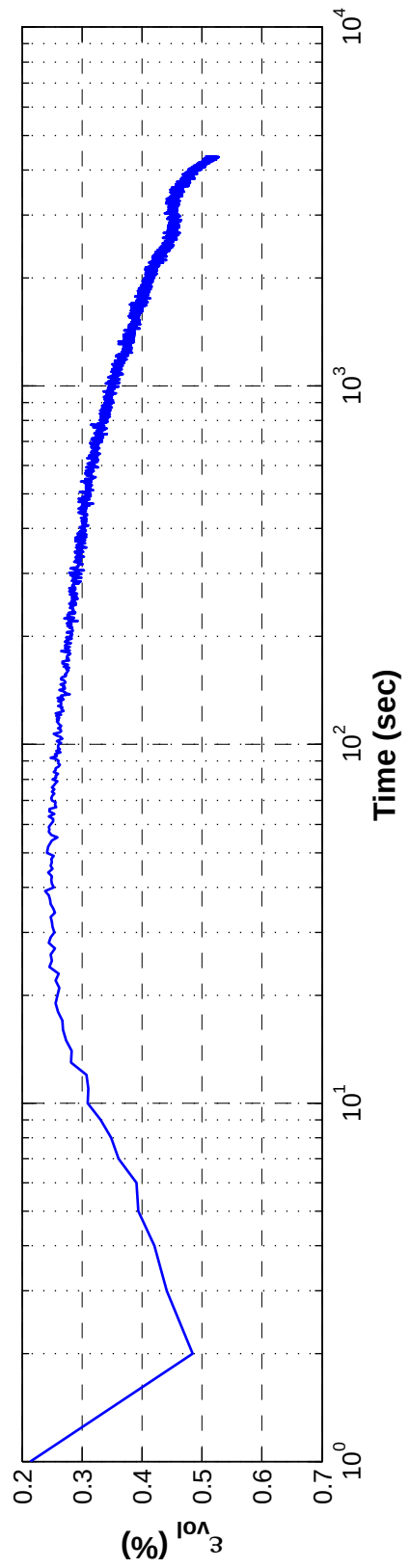
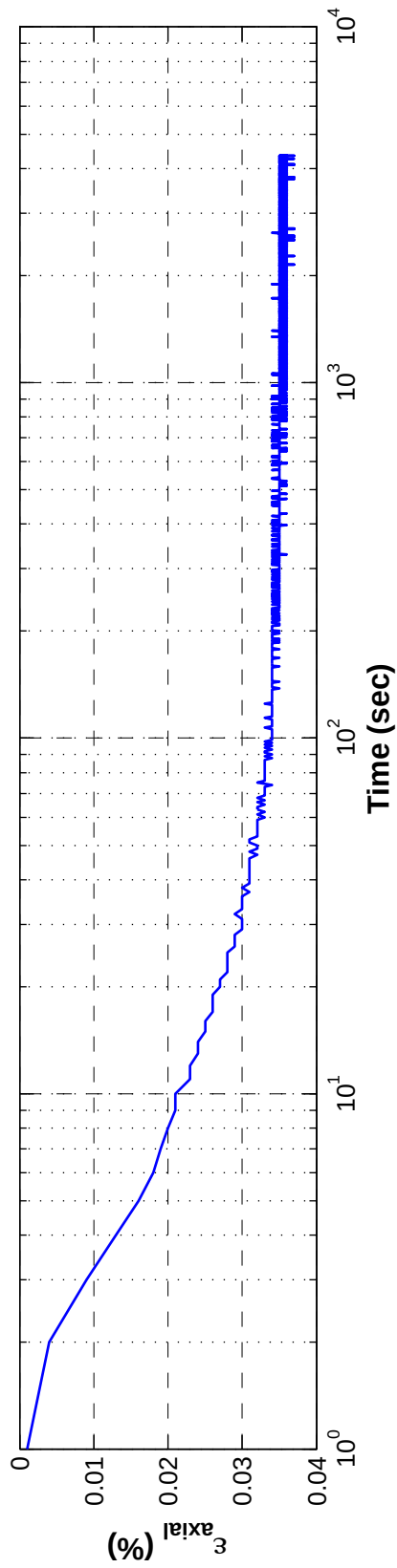
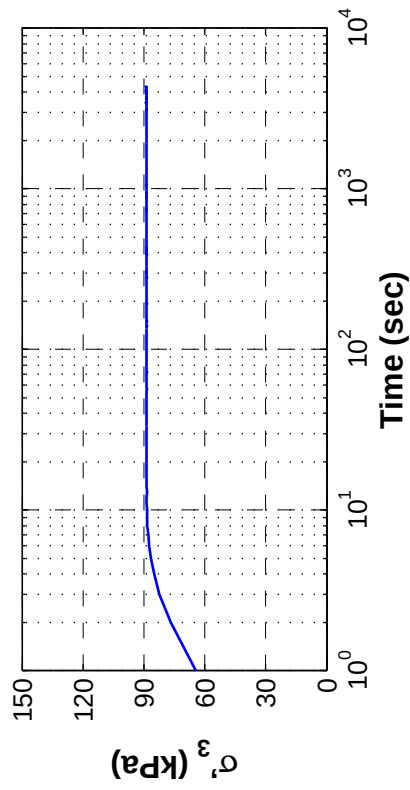


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 14	σ'_c (kPa):	88
Borehole:	BH-2	Loading Freq (Hz):	0.1
Sample No.:	6U	B-Value:	0.98
Sampler Type:	D&M	CSR:	0.42
Spec. Depth (m):	6.825	N to $\epsilon_{Ax-S.A.}$ =3%:	3
Date Tested:	07/02/14	N to $\epsilon_{Ax-D.A.}$ =5%:	4
Date Sampled:	03/25/14	Post-Cyclic Test:	---
Spec. Ht. (mm):	139.976	Gs:	---
Spec. Diam. (mm):	61.00	e_c :	0.67
Dry Mass (g):	656.36	PI (%):	NP
		FC (%):	69

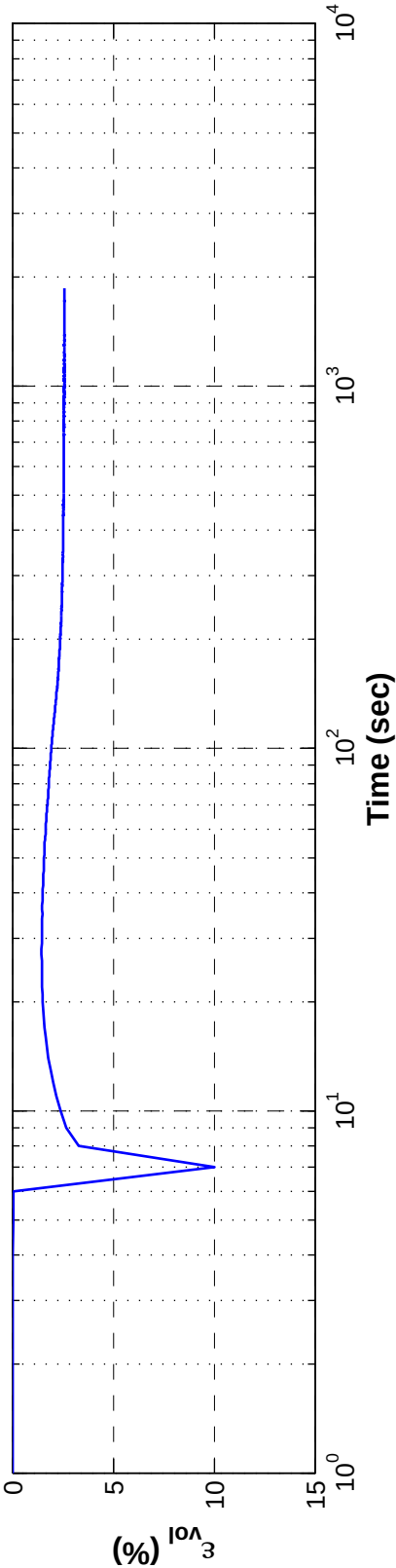
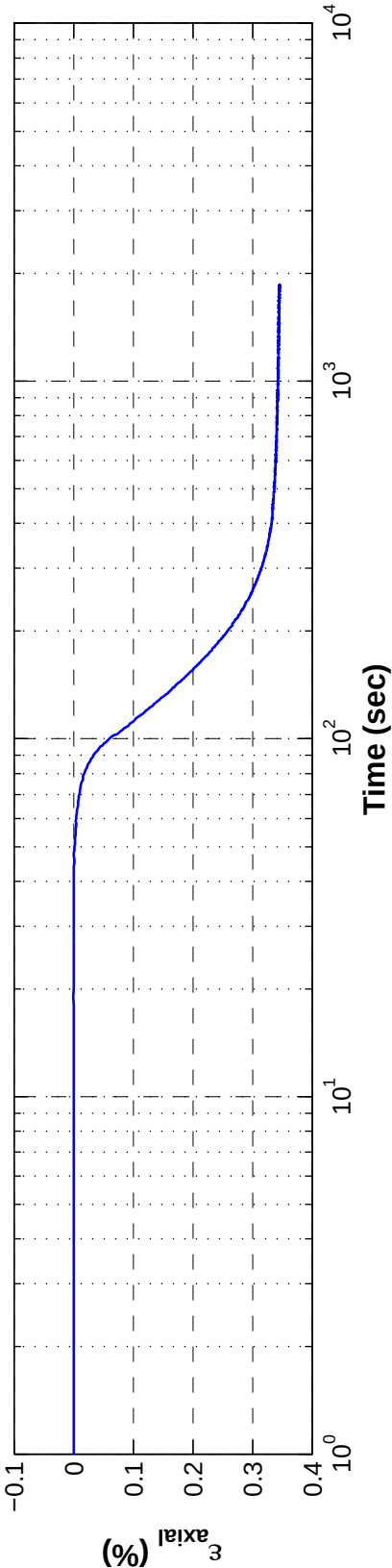
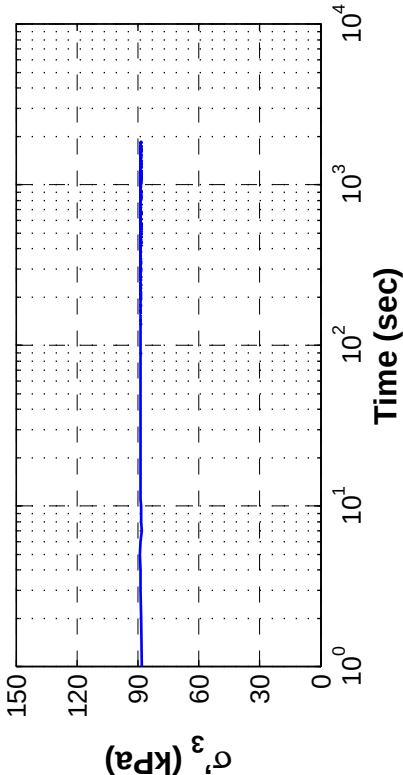
Specimen and Isotropic Consolidation Data

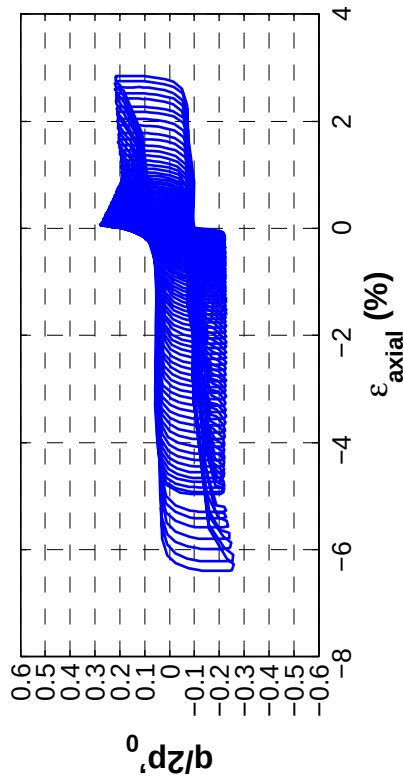
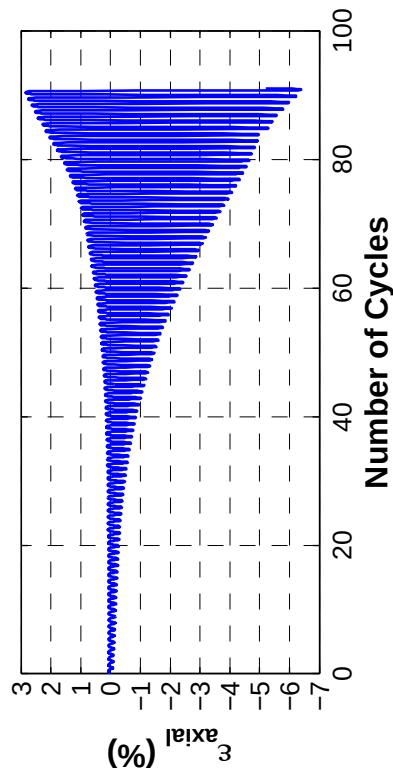
Site: Site 14
Borehole: BH-2
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.825
Date Tested: 07/02/14
Date Sampled: 03/25/14



Specimen and Post-CTX Reconsolidation Data

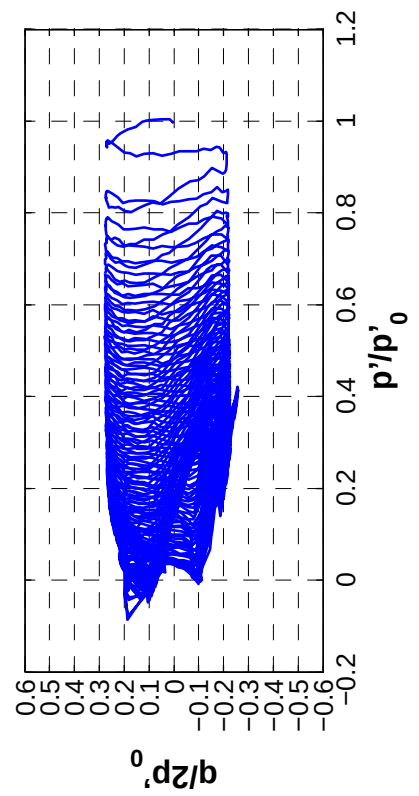
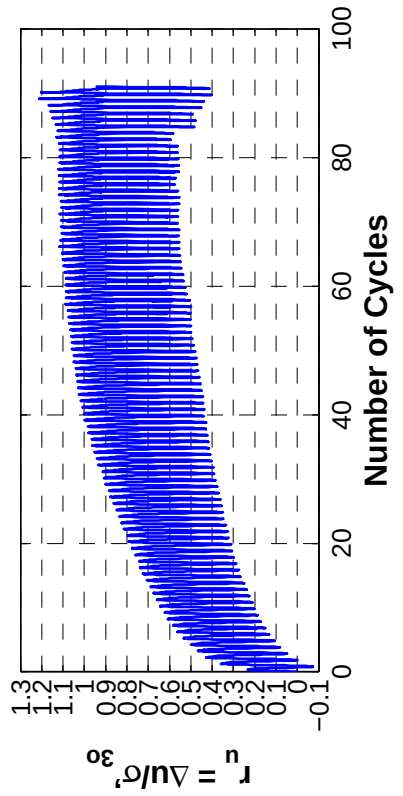
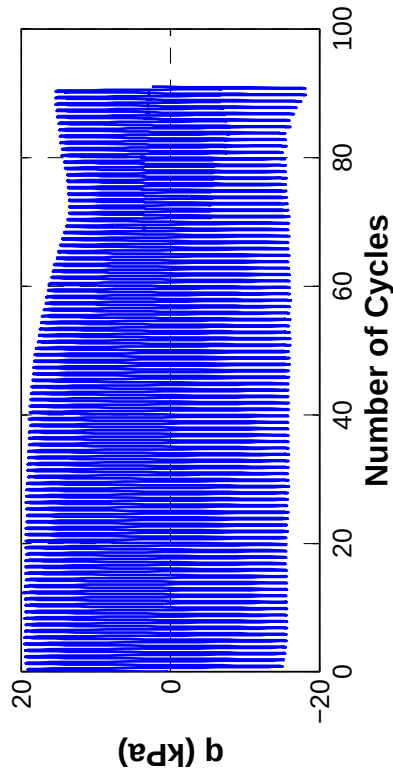
Site: Site 14
Borehole: BH-2
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.825
Date Tested: 07/02/14
Date Sampled: 03/25/14





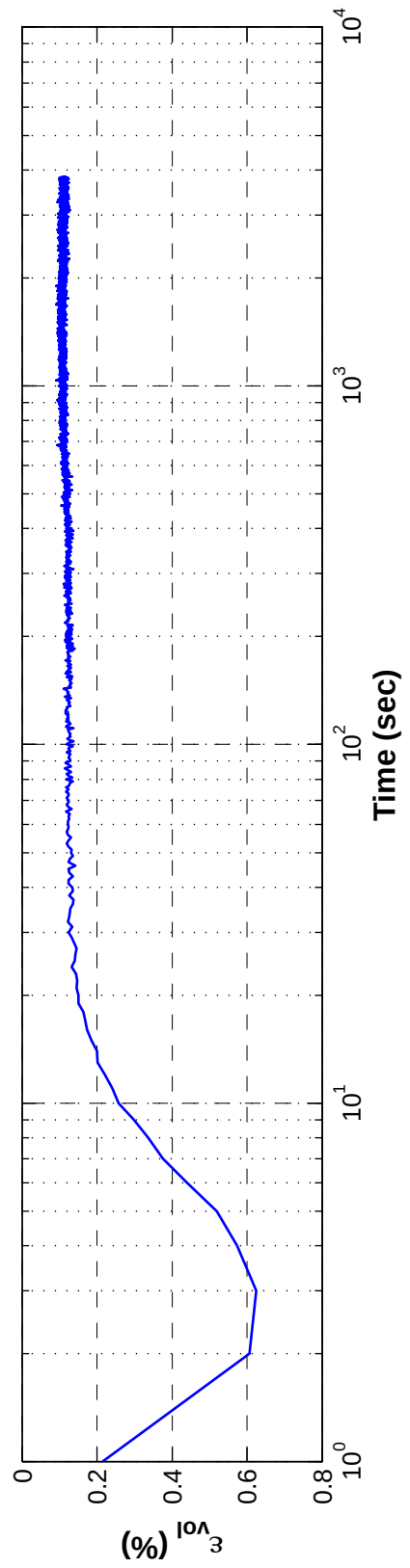
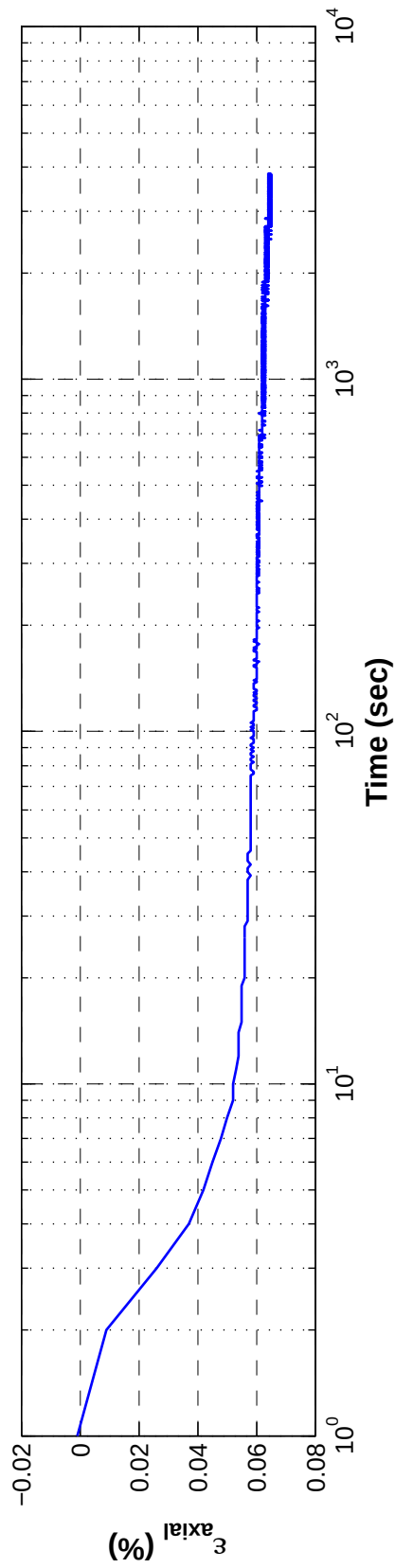
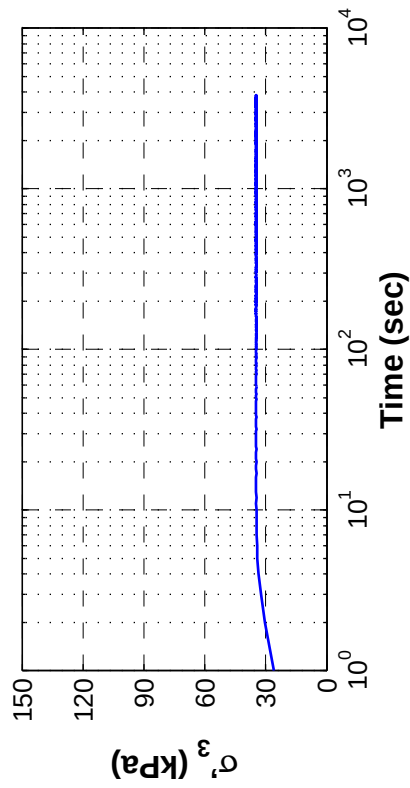
Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 21	σ'_c (kPa):	35
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	2U	B-Value:	0.978
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	1.77	N to $\epsilon_{Ax-S.A.}$ =3%:	67
Date Tested:	08/06/14	N to $\epsilon_{Ax-D.A.}$ =5%:	75
Date Sampled:	06/24/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	140.676	Gs:	2.72
Spec. Diam. (mm):	61.10	e_c :	0.85
Dry Mass (g):	604.75	PI (%):	2
		FC (%):	94



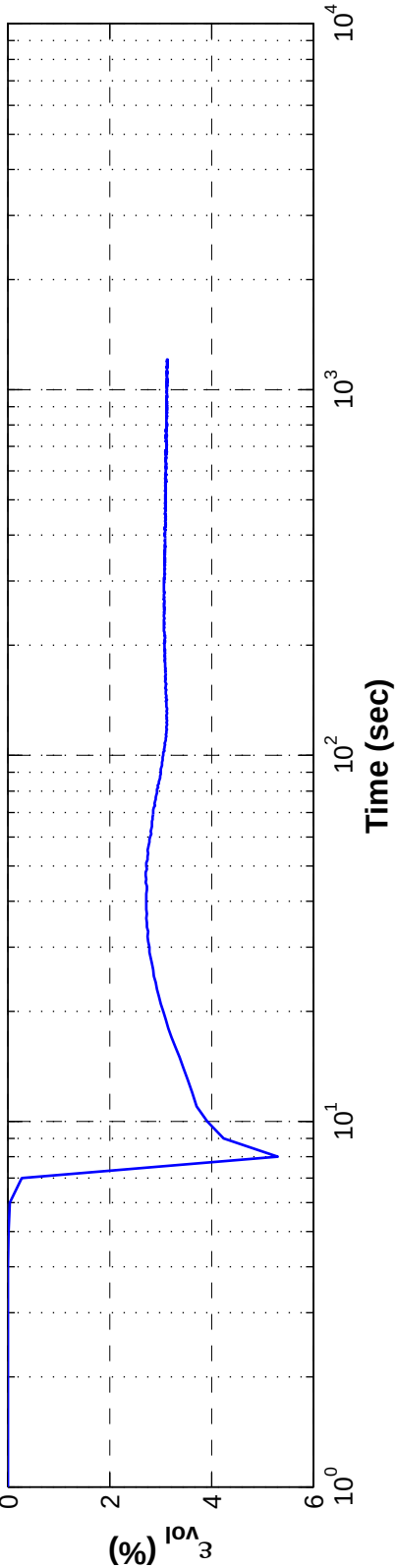
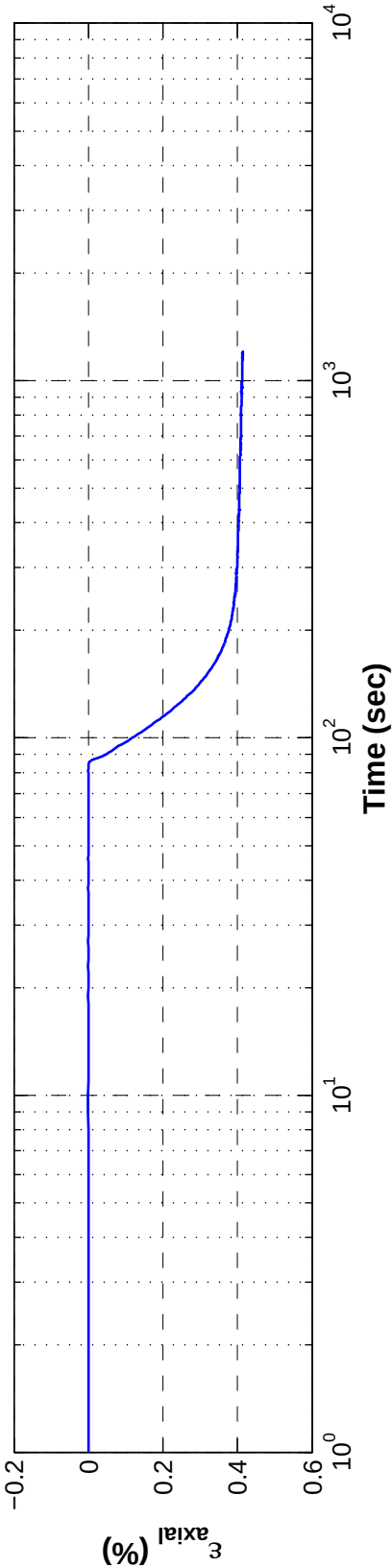
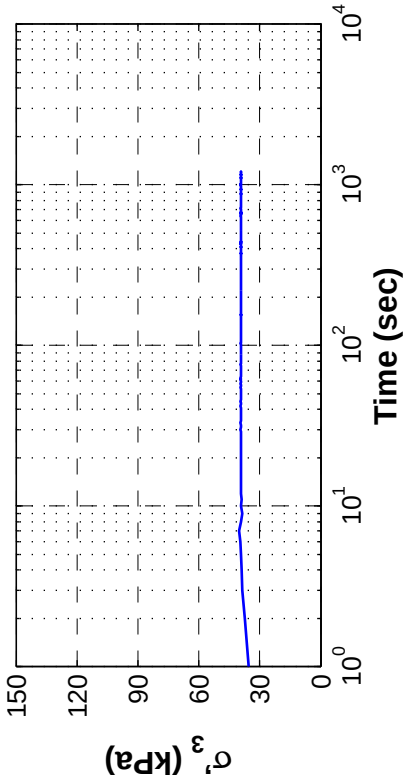
Specimen and Isotropic Consolidation Data

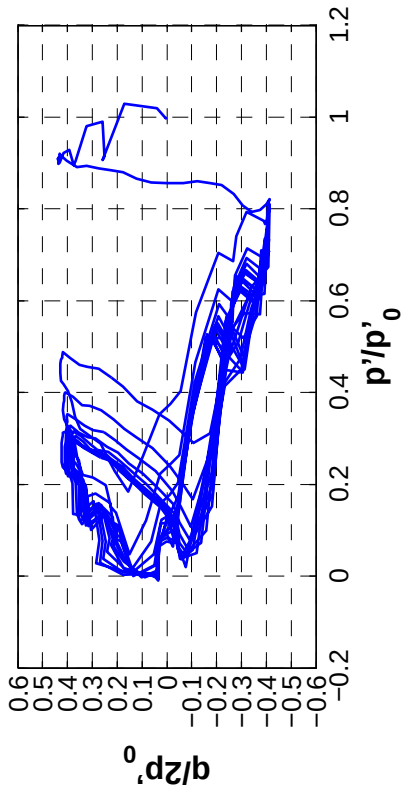
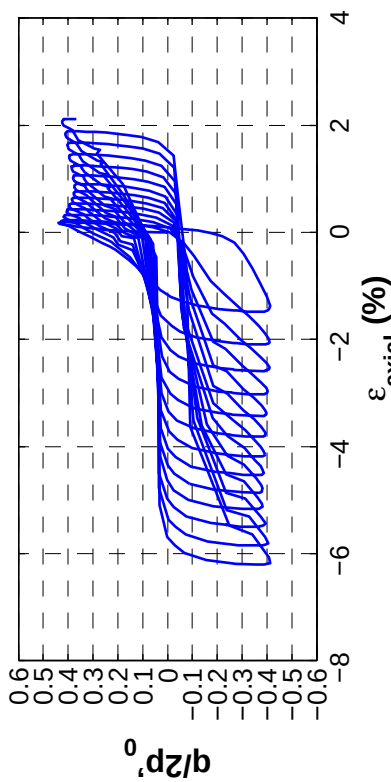
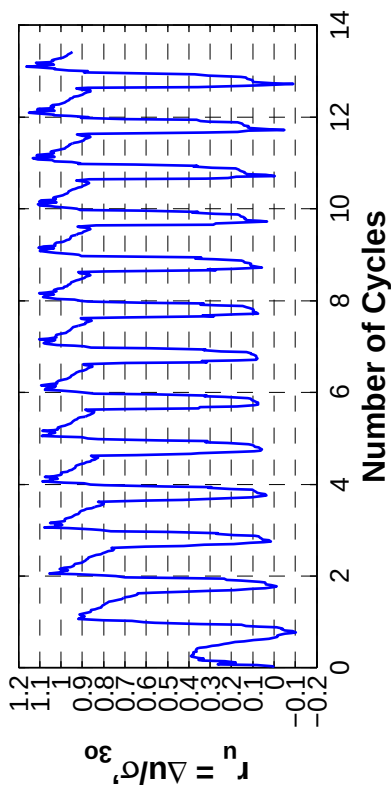
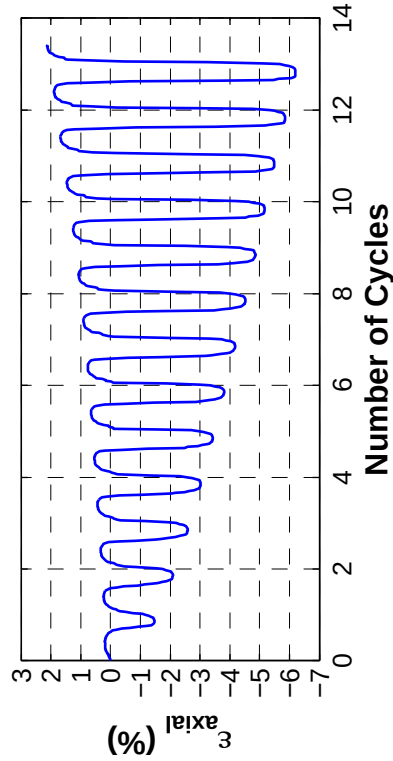
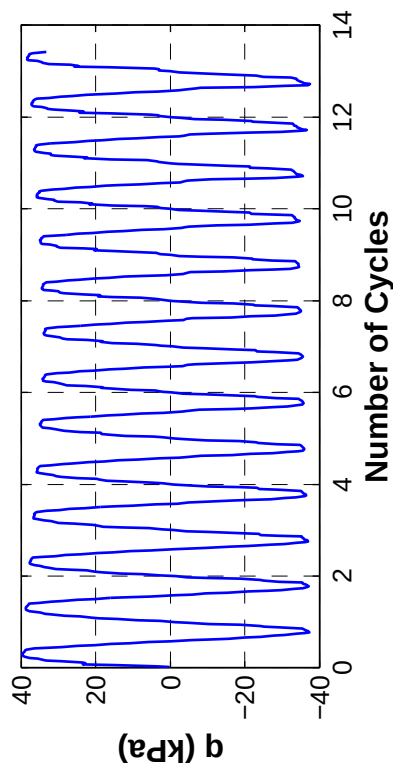
Site: Site 21
Borehole: DM-1
Sample No.: 2U
Sampler Type: D&M
Spec. Depth (m): 1.77
Date Tested: 08/06/14
Date Sampled: 06/24/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 21
Borehole: DM-1
Sample No.: 2U
Sampler Type: D&M
Spec. Depth (m): 1.77
Date Tested: 08/06/14
Date Sampled: 06/24/14



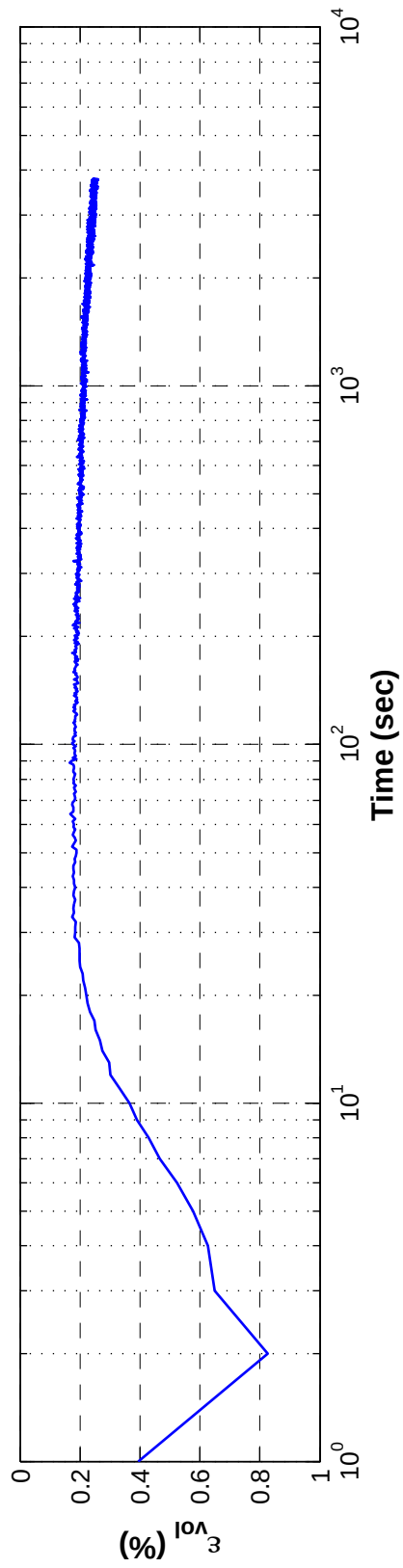
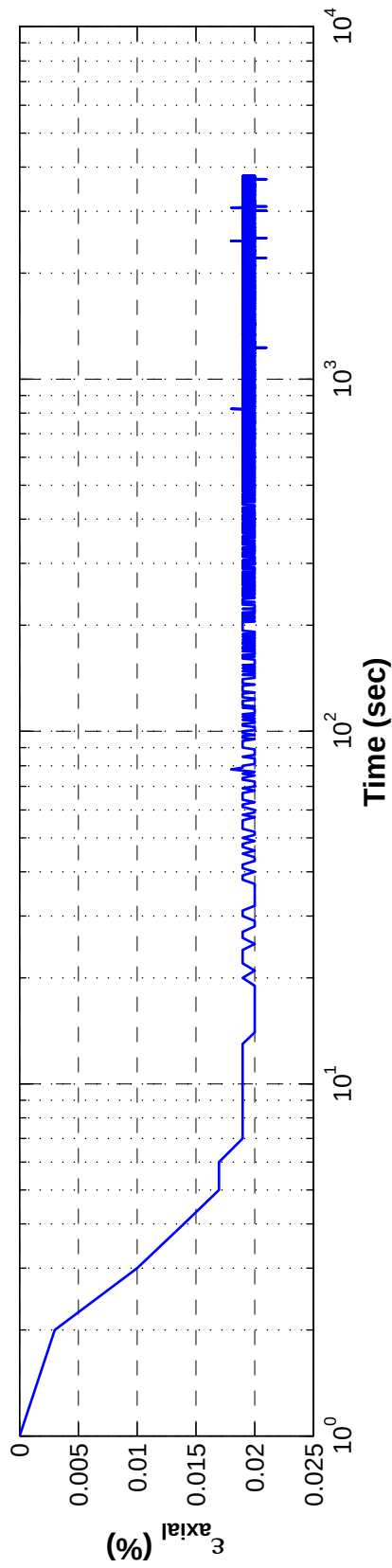
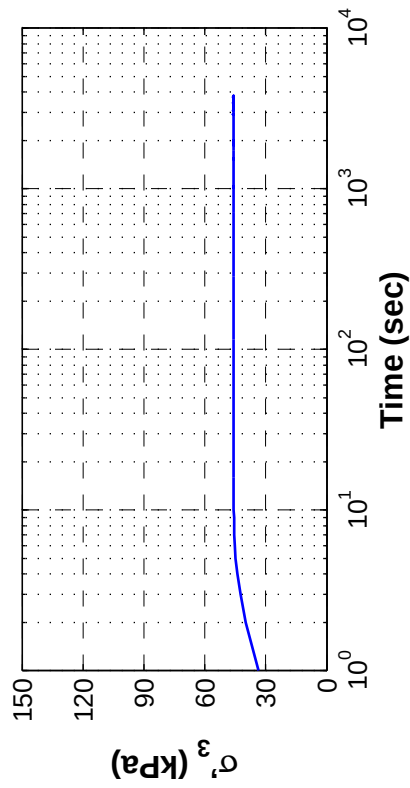


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 21	σ'_c (kPa):	45
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.972
Sampler Type:	D&M	CSR:	0.43
Spec. Depth (m):	2.32	N to $\epsilon_{Ax-S.A.}$ =3%:	4
Date Tested:	08/03/14	N to $\epsilon_{Ax-D.A.}$ =5%:	7.5
Date Sampled:	06/24/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	139.256	Gs:	---
Spec. Diam. (mm):	61.12	e_c :	0.82
Dry Mass (g):	604.44	PI (%):	NP
		FC (%):	61

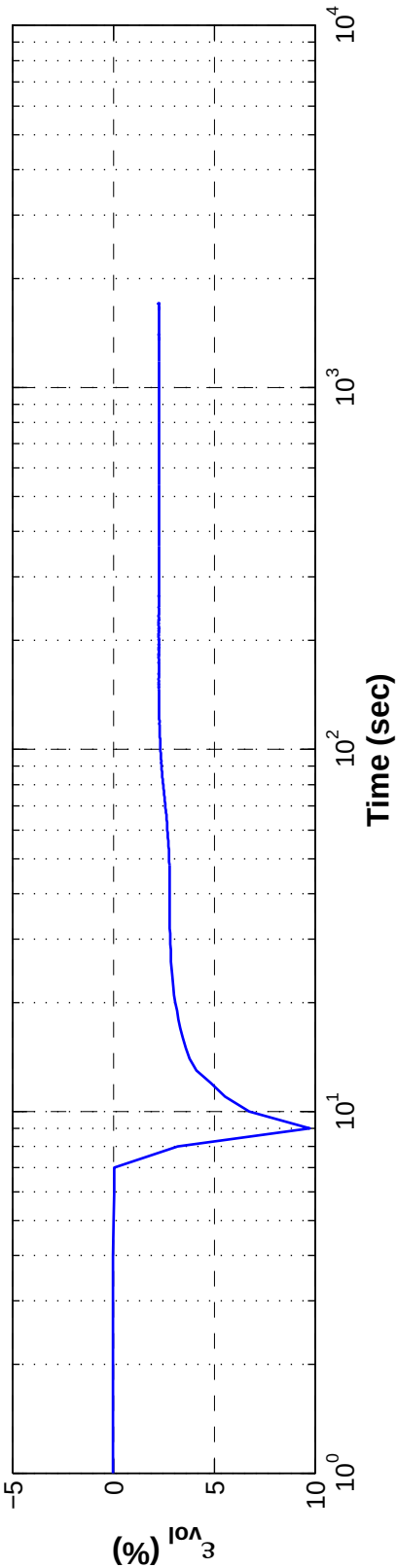
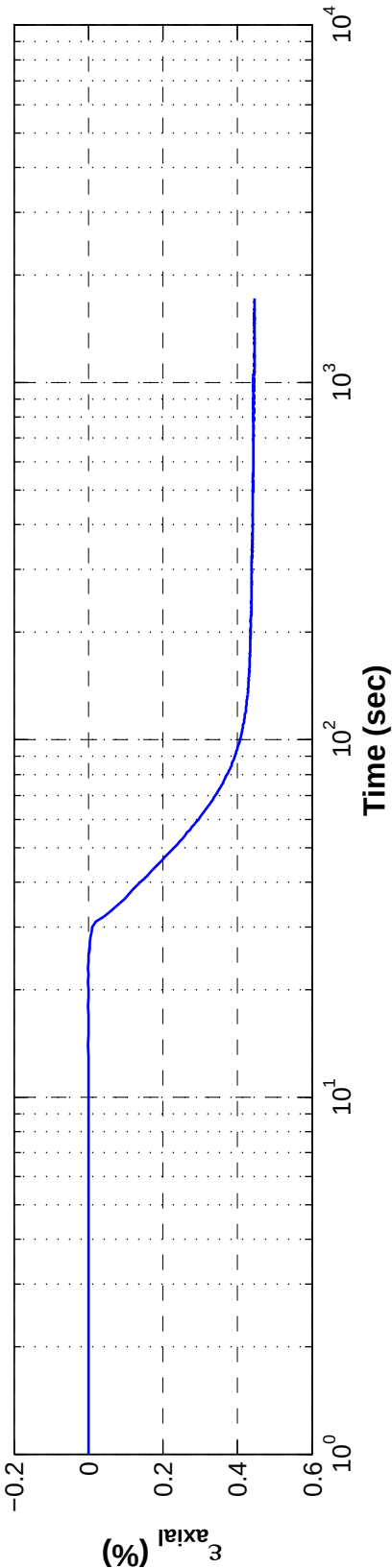
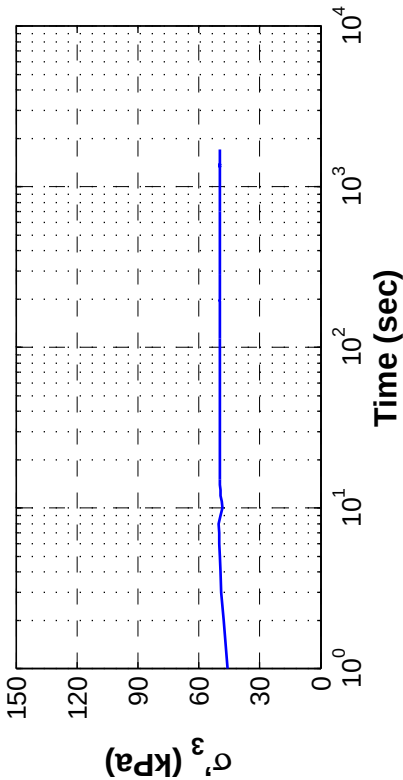
Specimen and Isotropic Consolidation Data

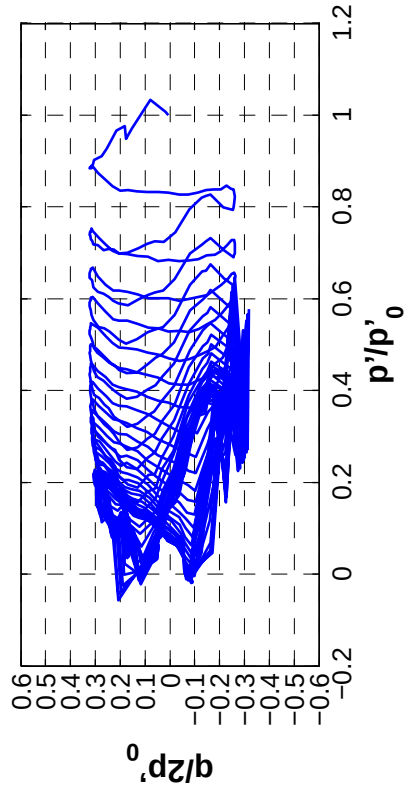
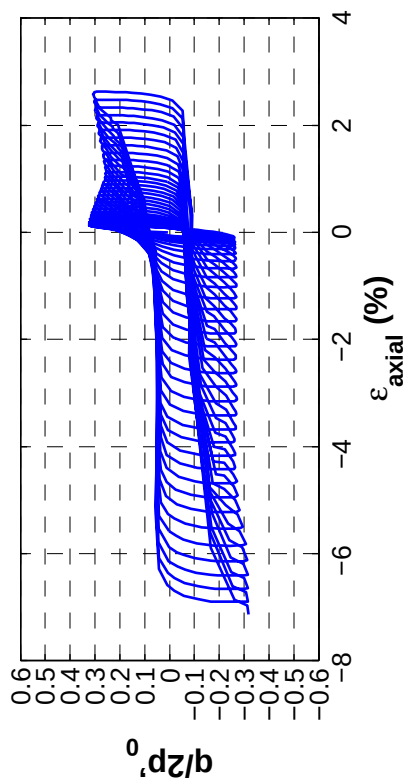
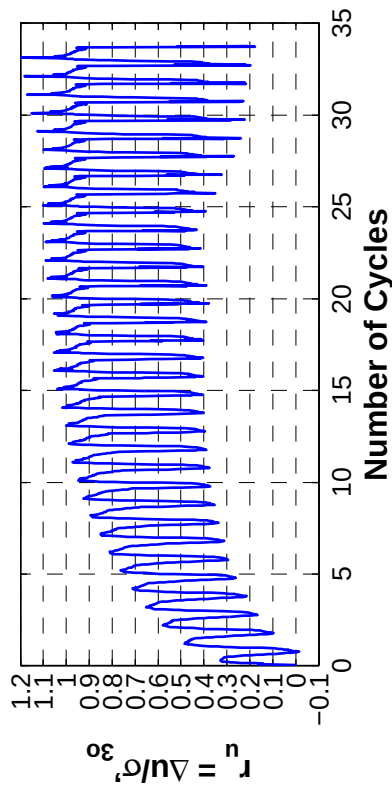
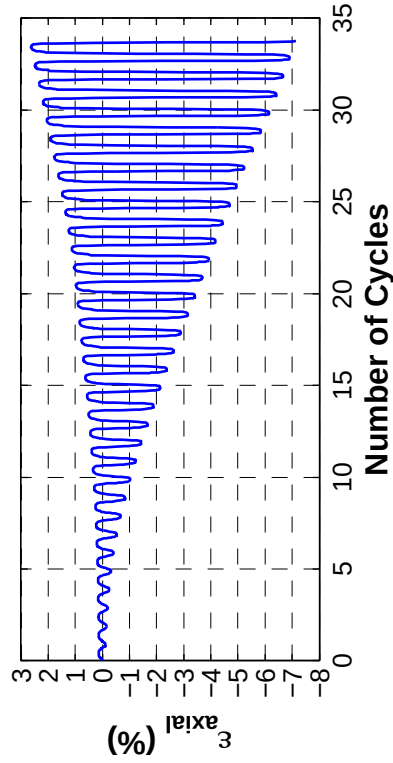
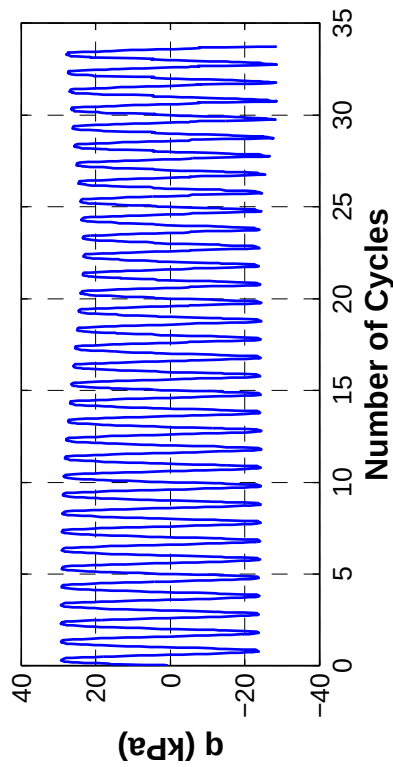
Site: Site 21
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.32
Date Tested: 08/03/14
Date Sampled: 06/24/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 21
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.32
Date Tested: 08/03/14
Date Sampled: 06/24/14



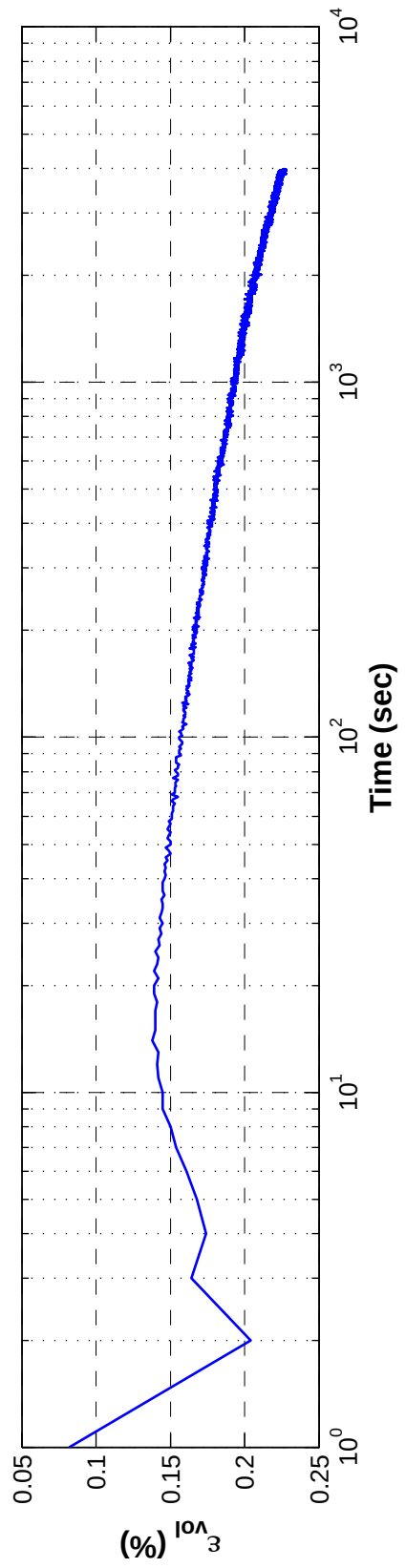
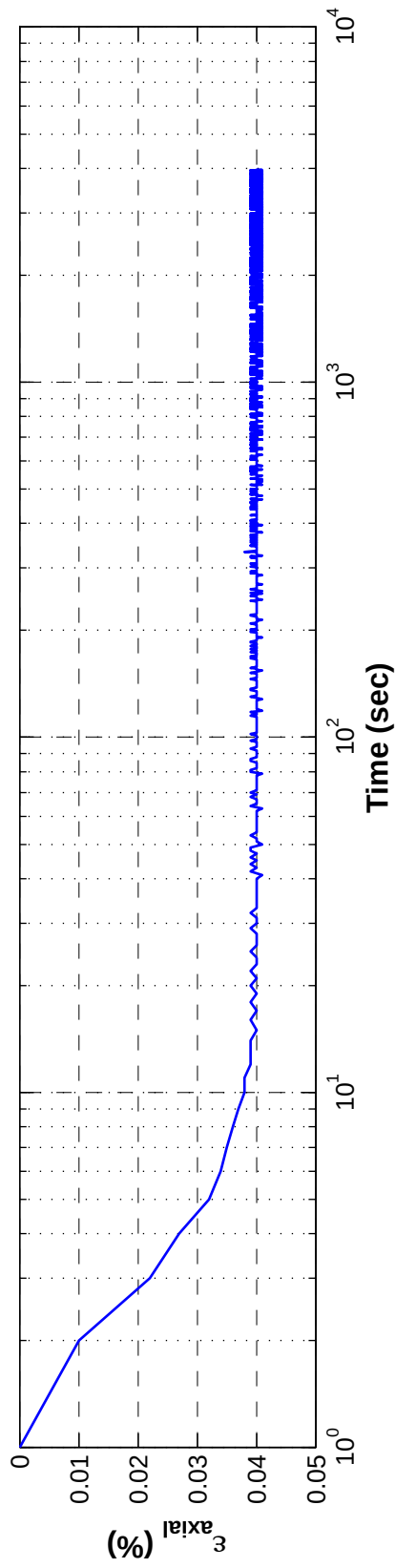
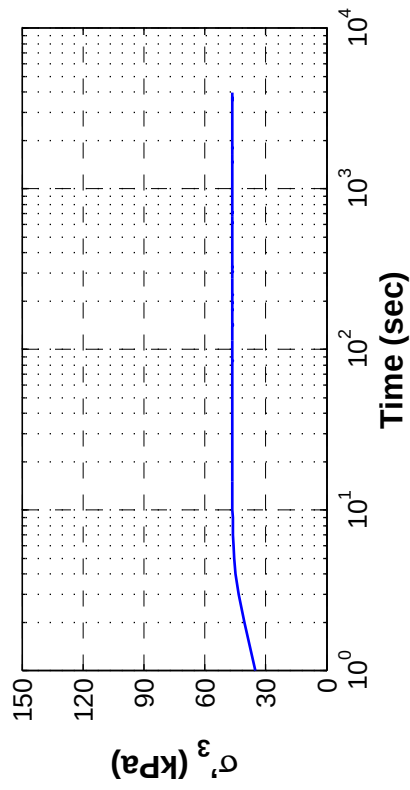


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 21	σ'_c (kPa):	45
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.977
Sampler Type:	D&M	CSR:	0.3
Spec. Depth (m):	2.475	N to $\epsilon_{Ax-S.A.}$ =3%:	19
Date Tested:	08/04/14	N to $\epsilon_{Ax-D.A.}$ =5%:	23
Date Sampled:	06/24/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	132.516	Gs:	2.69
Spec. Diam. (mm):	61.14	e_c :	0.84
Dry Mass (g):	566.41	PI (%):	NP
		FC (%):	72

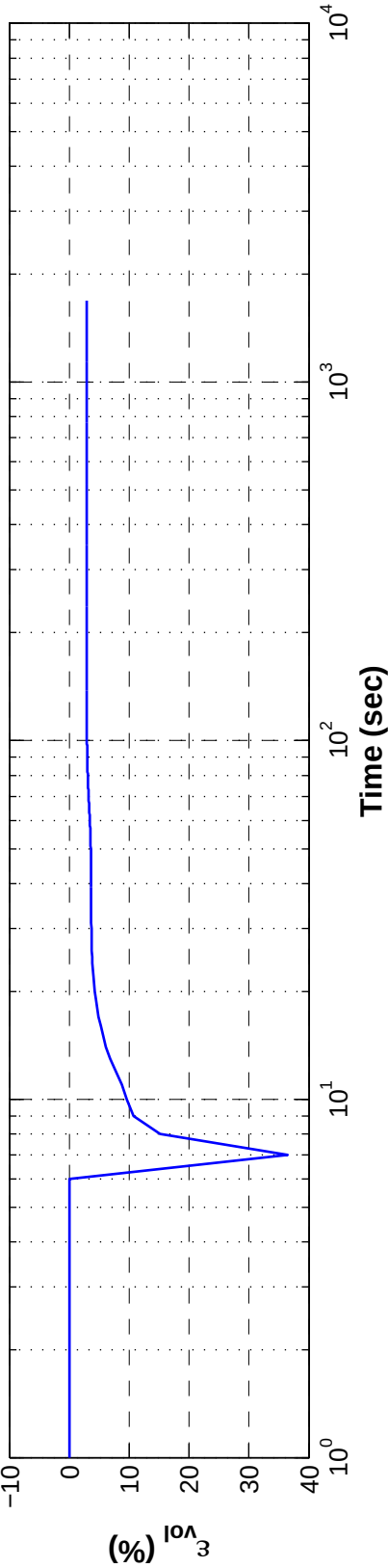
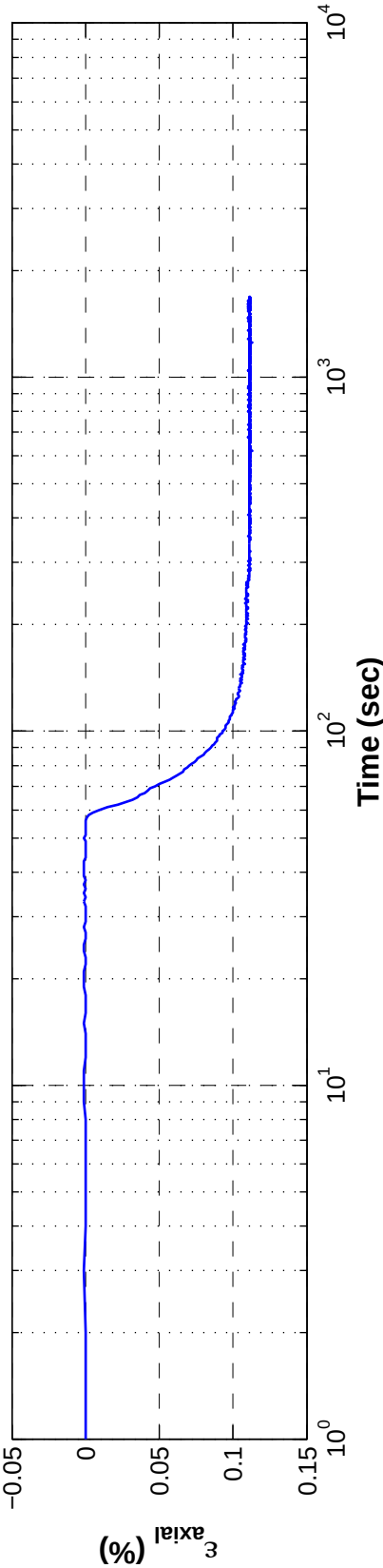
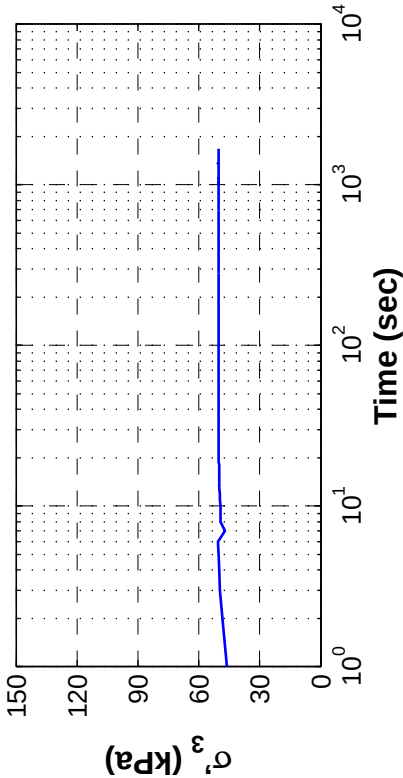
Specimen and Isotropic Consolidation Data

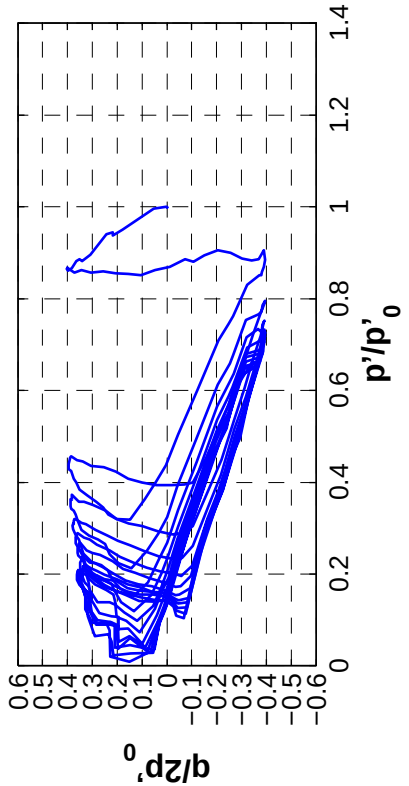
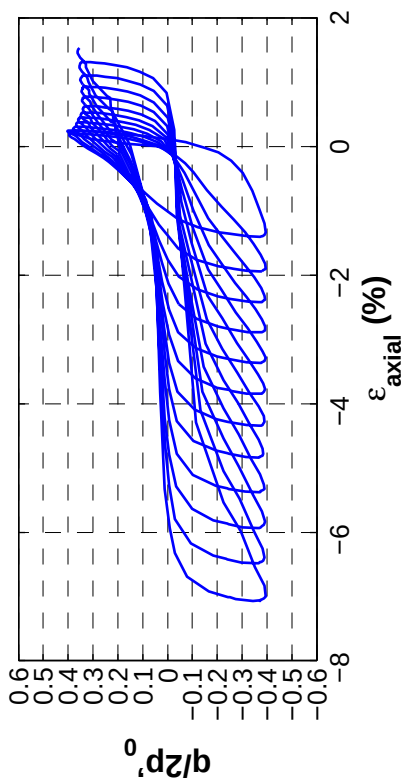
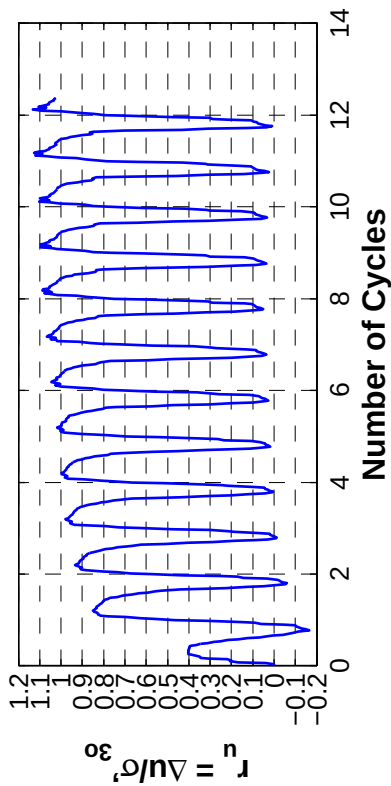
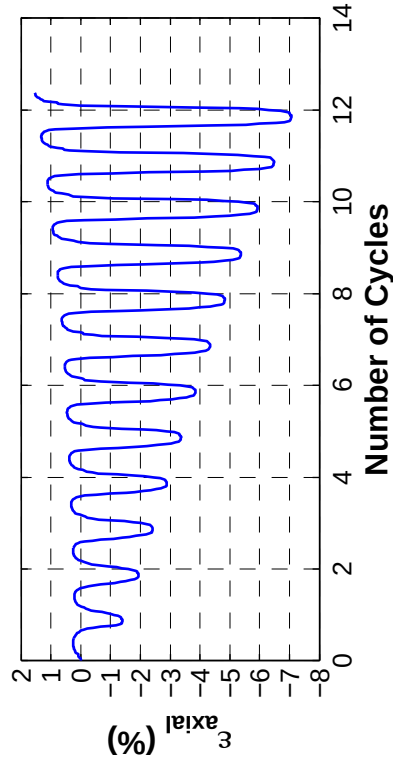
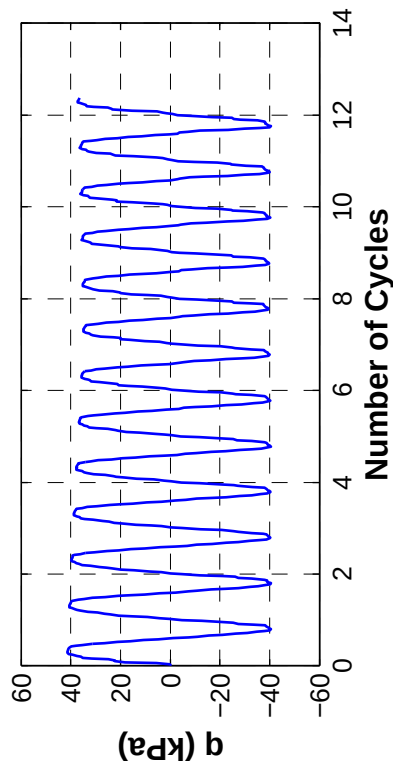
Site: Site 21
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.475
Date Tested: 08/04/14
Date Sampled: 06/24/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 21
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.475
Date Tested: 08/04/14
Date Sampled: 06/24/14



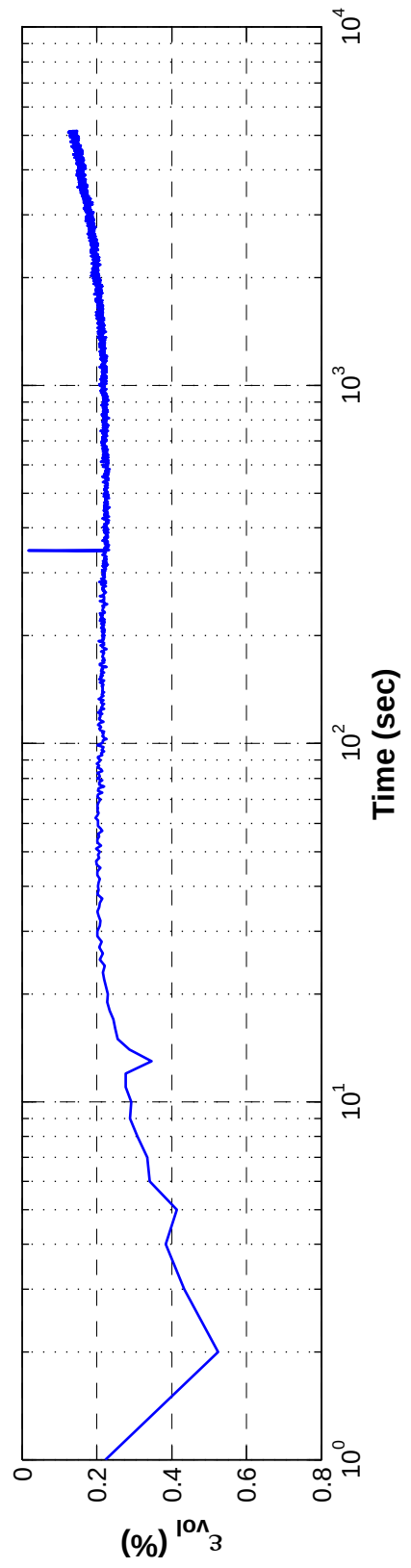
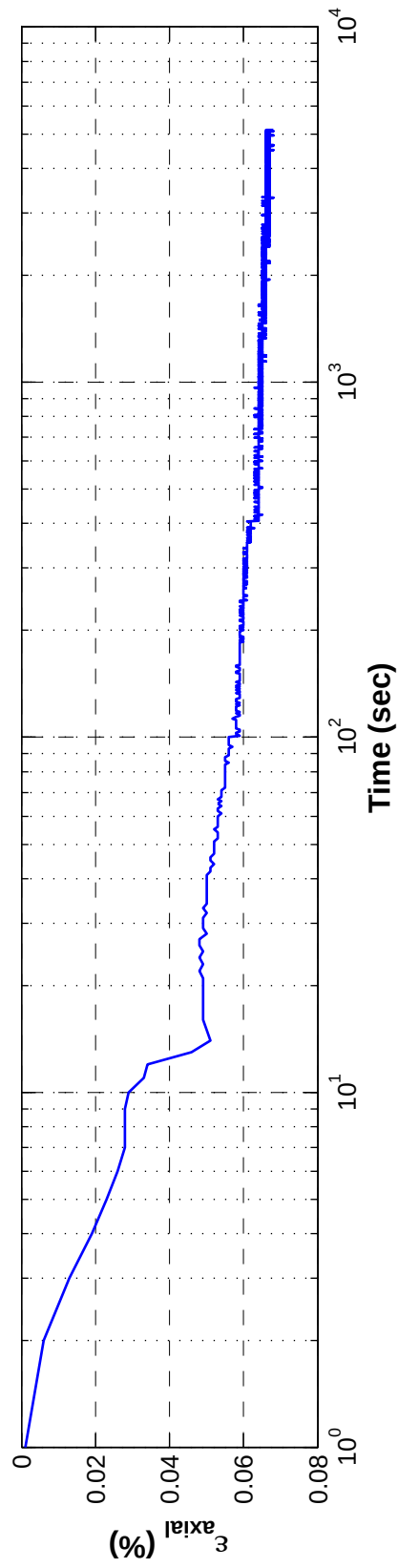
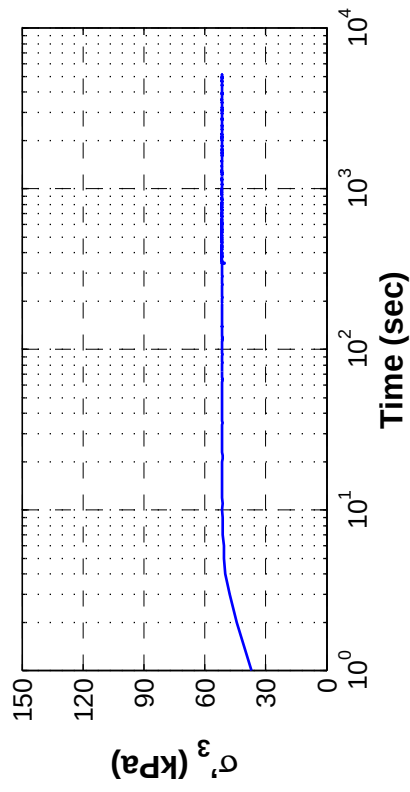


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	51
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.965
Sampler Type:	D&M	CSR:	0.4
Spec. Depth (m):	3.39	N to $\epsilon_{Ax-S.A.}$ =3%:	5
Date Tested:	07/21/14	N to $\epsilon_{Ax-D.A.}$ =5%:	8
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	141.676	Gs:	2.72
Spec. Diam. (mm):	61.05	e_c :	1.00
Dry Mass (g):	563.52	PI (%):	5
		FC (%):	93

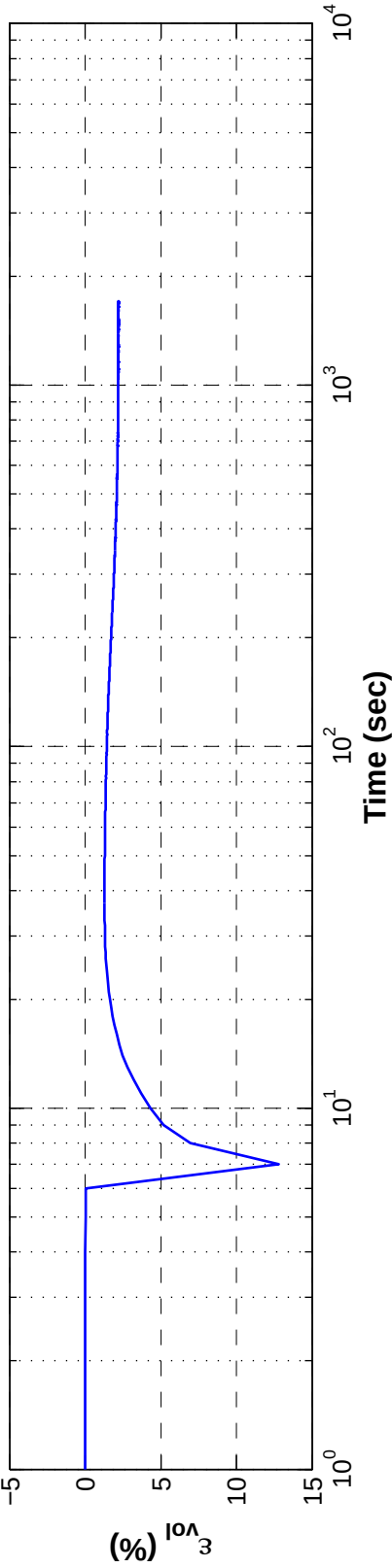
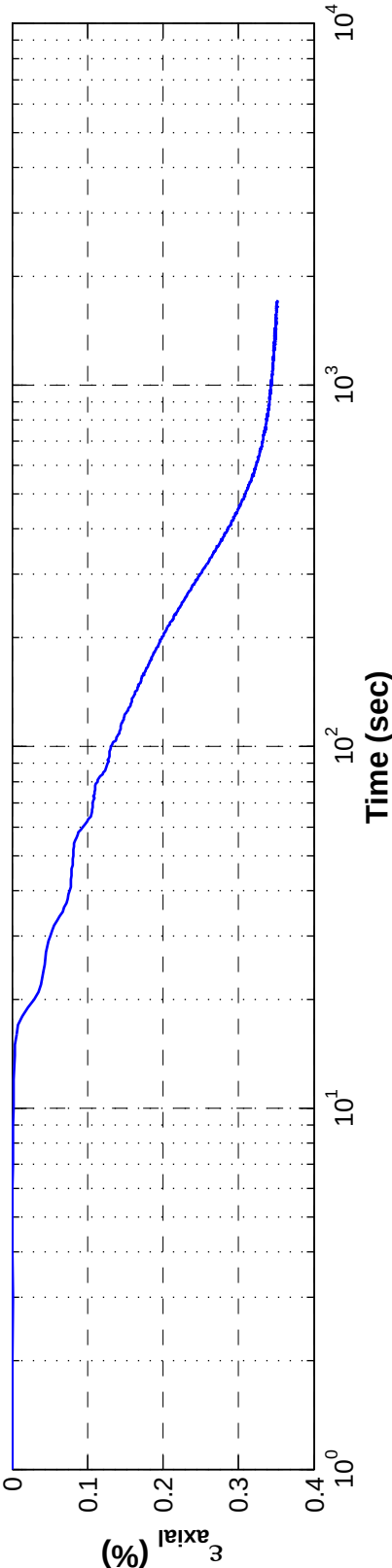
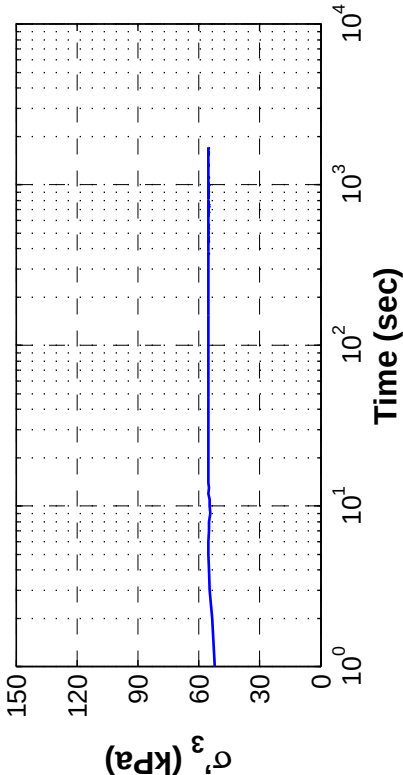
Specimen and Isotropic Consolidation Data

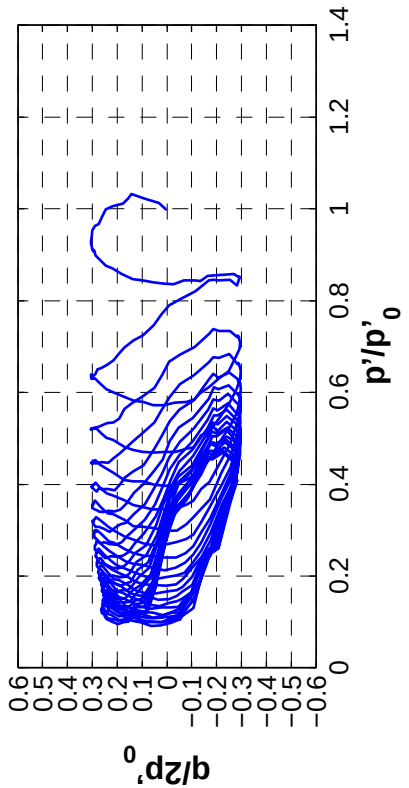
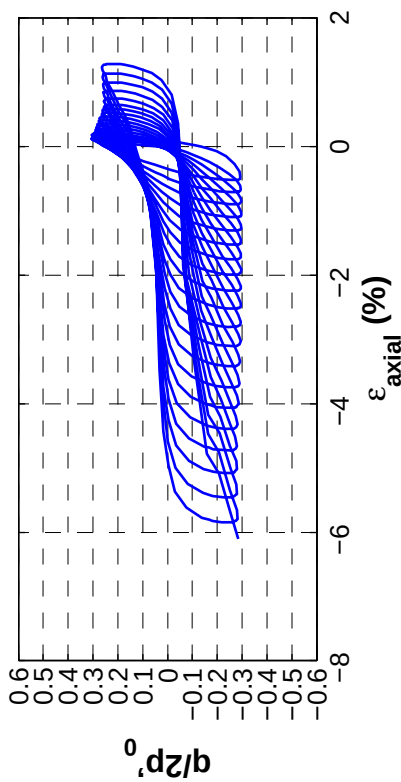
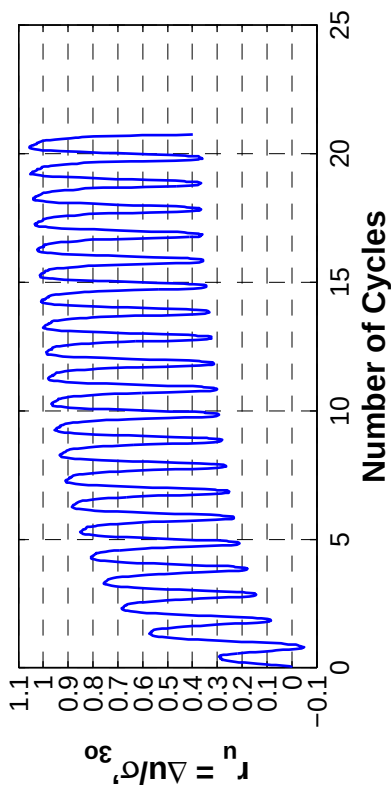
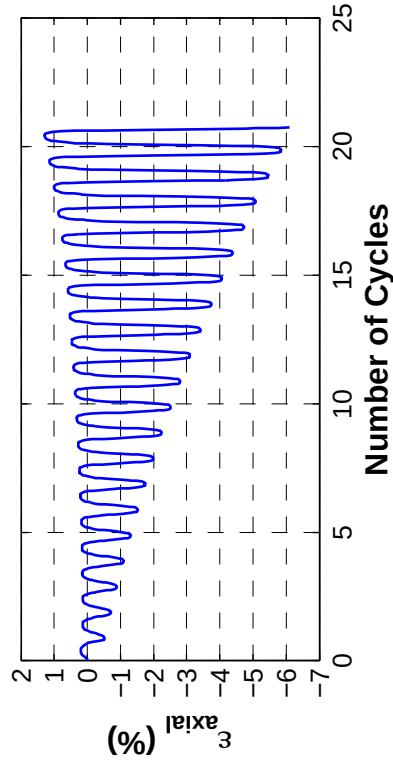
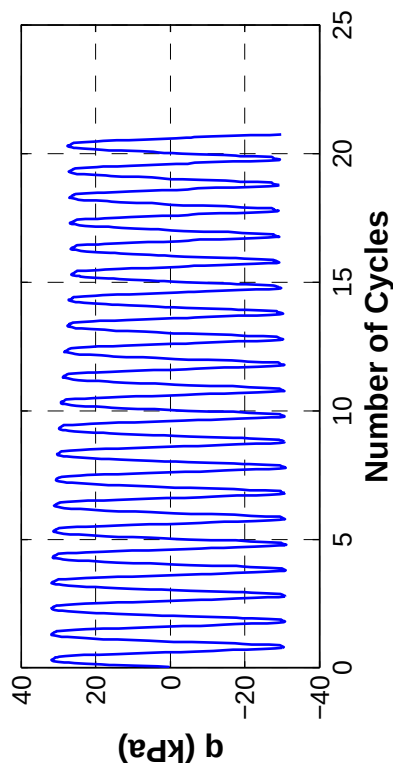
Site: Site 23
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.39
Date Tested: 07/21/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.39
Date Tested: 07/21/14
Date Sampled: 06/21/14



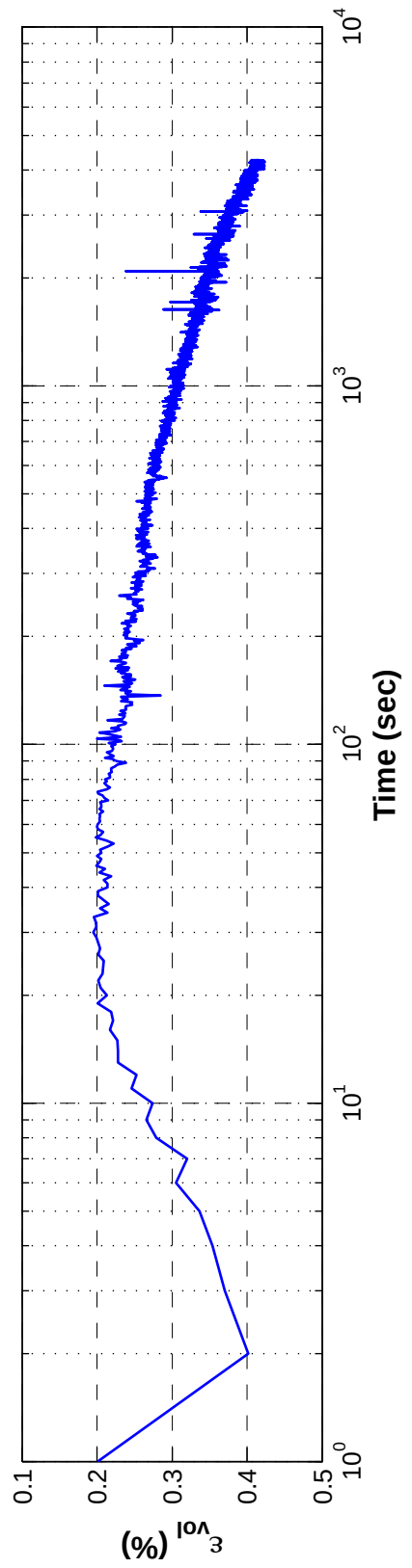
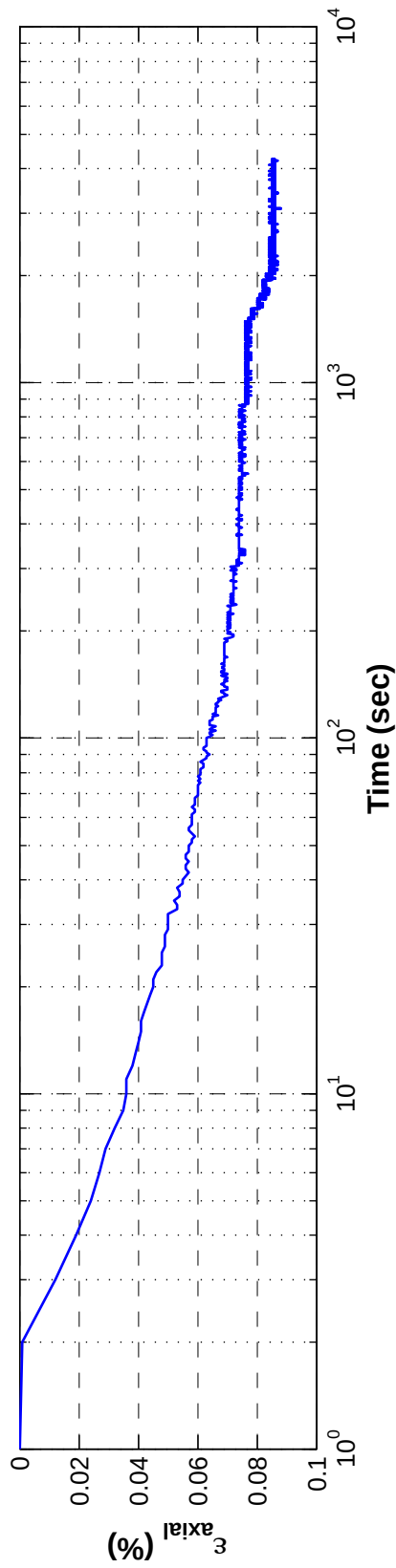
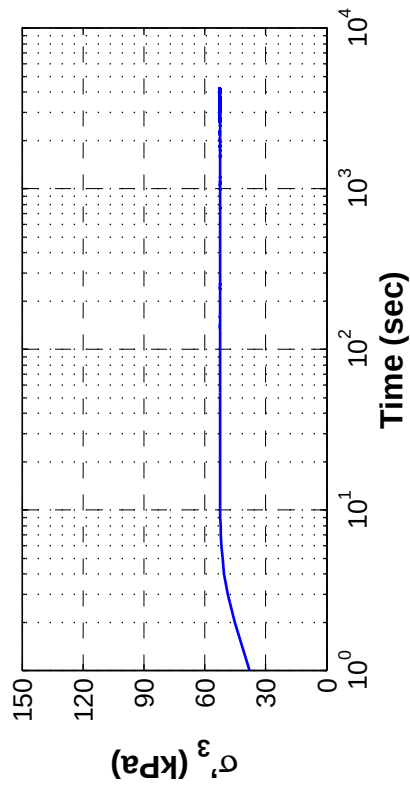


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	52
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.973
Sampler Type:	D&M	CSR:	0.3
Spec. Depth (m):	3.545	N to $\epsilon_{Ax-S.A.}$ =3%:	12
Date Tested:	07/22/14	N to $\epsilon_{Ax-D.A.}$ =5%:	16
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	140.386	Gs:	---
Spec. Diam. (mm):	61.14	e_c :	1.08
Dry Mass (g):	537.13	PI (%):	7
		FC (%):	94

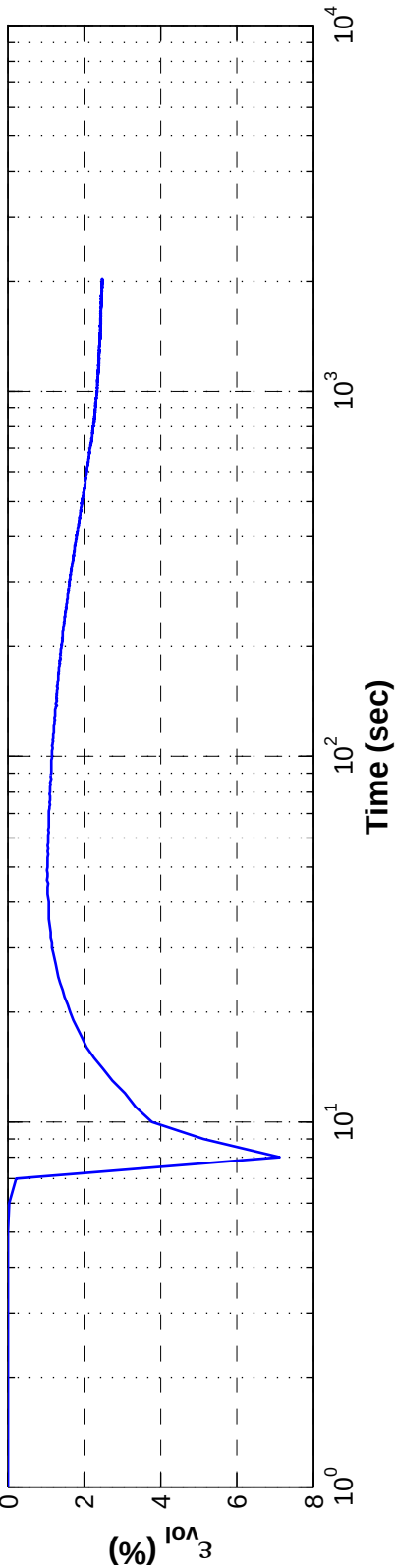
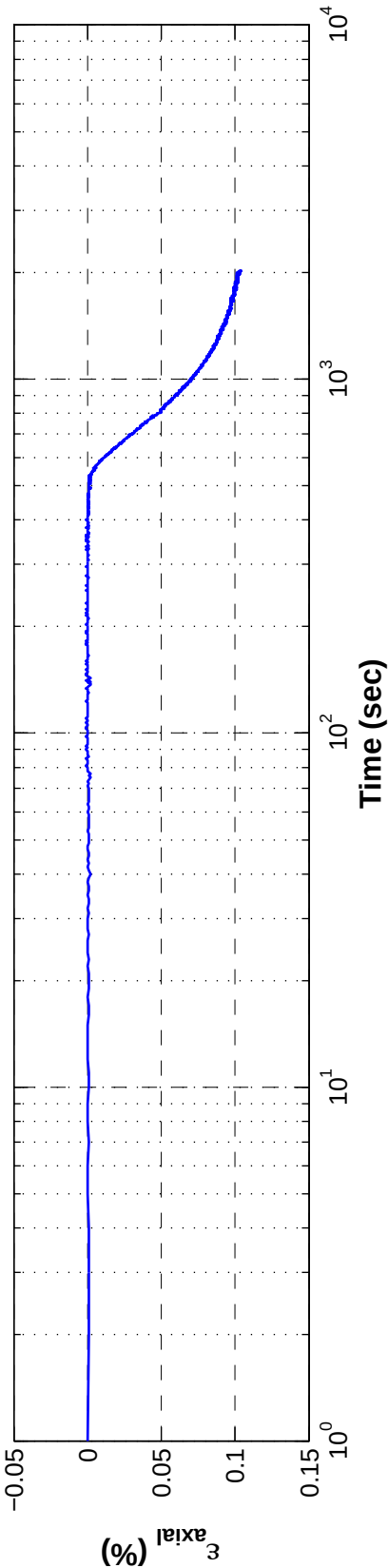
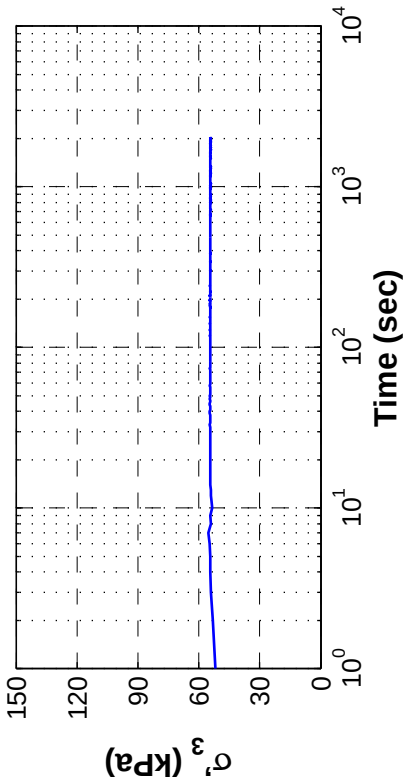
Specimen and Isotropic Consolidation Data

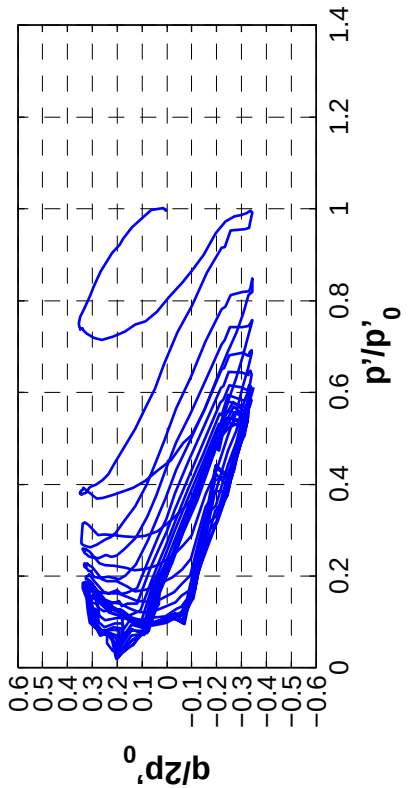
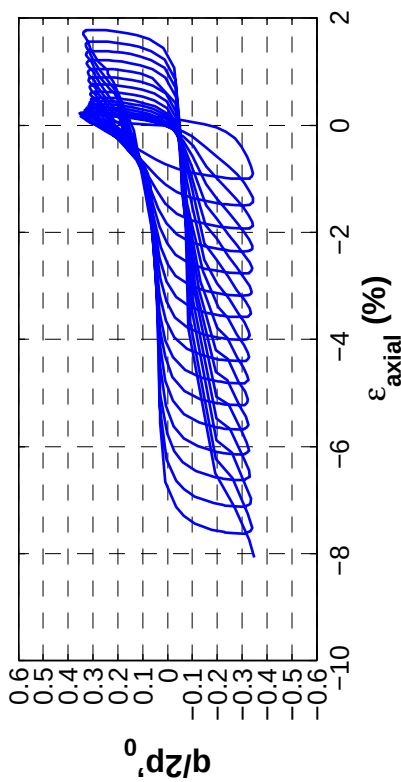
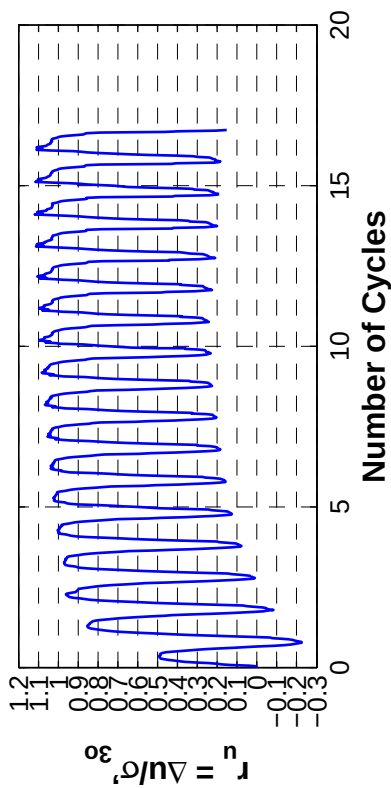
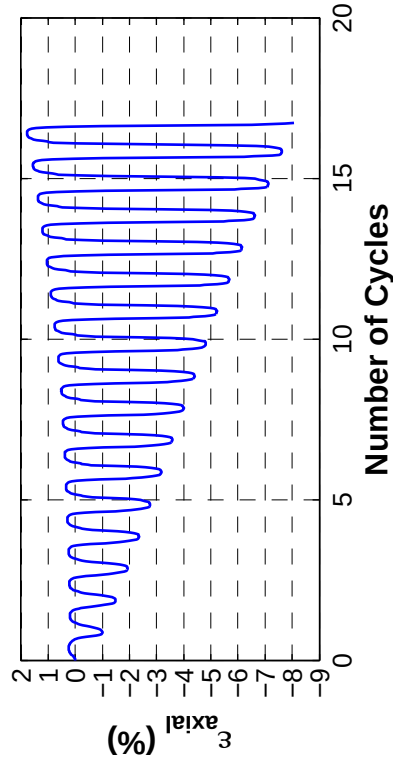
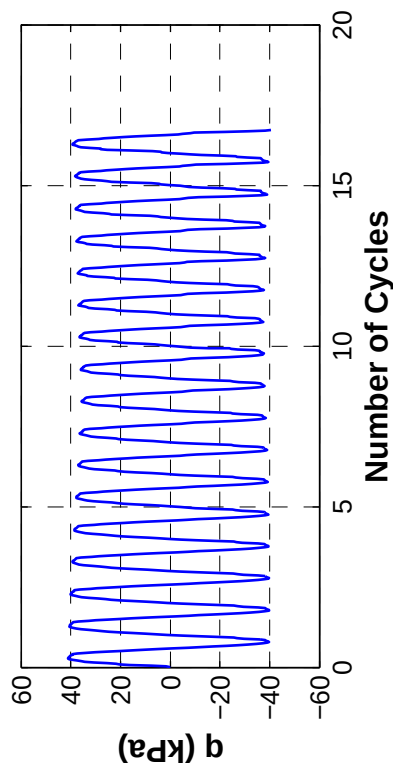
Site: Site 23
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.545
Date Tested: 07/22/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.545
Date Tested: 07/22/14
Date Sampled: 06/21/14



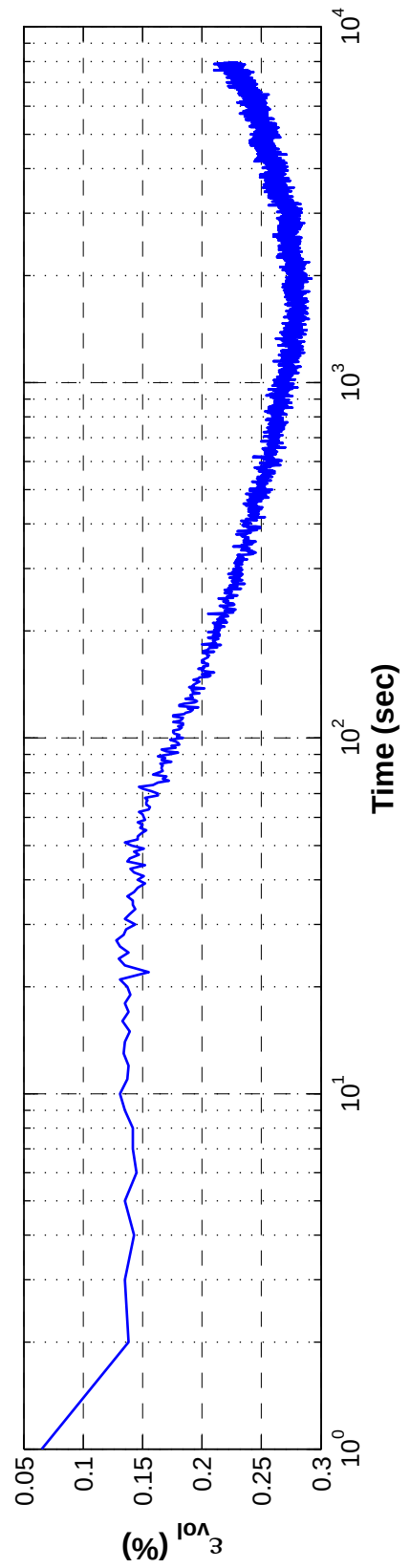
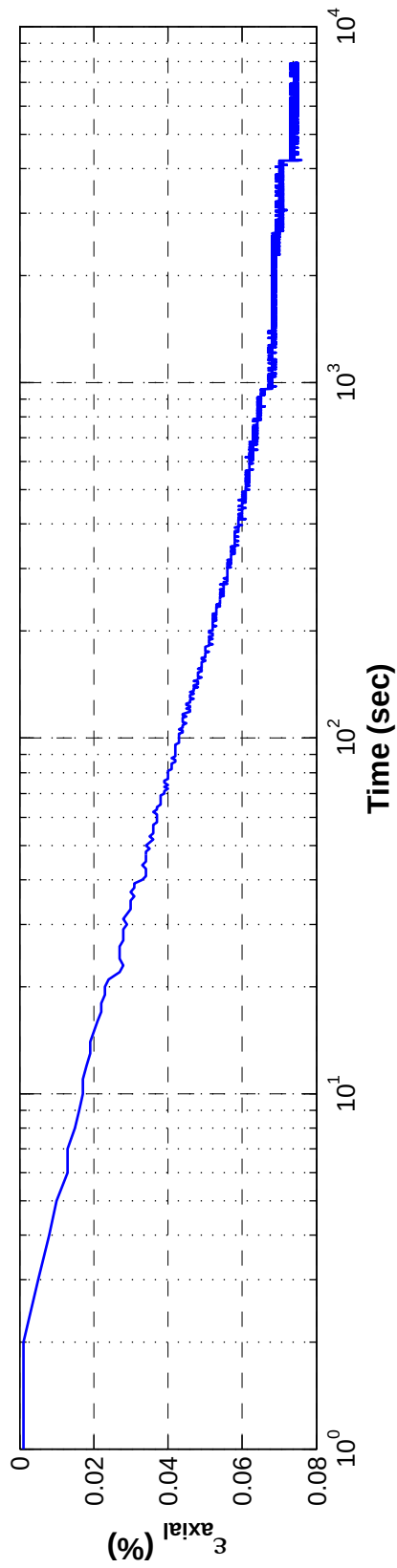
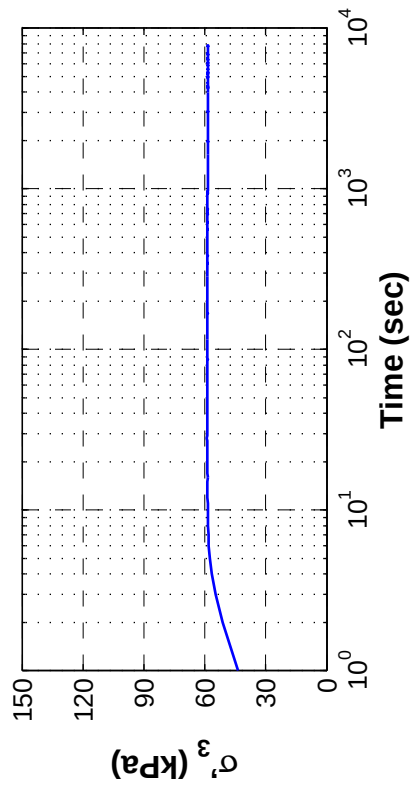


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	58
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	4U	B-Value:	0.986
Sampler Type:	D&M	CSR:	0.35
Spec. Depth (m):	4.125	N to $\epsilon_{Ax-S.A.}$ =3%:	6
Date Tested:	07/18/14	N to $\epsilon_{Ax-D.A.}$ =5%:	10
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	144.576	Gs:	---
Spec. Diam. (mm):	61.08	e_c :	0.98
Dry Mass (g):	576.71	PI (%):	4
		FC (%):	95

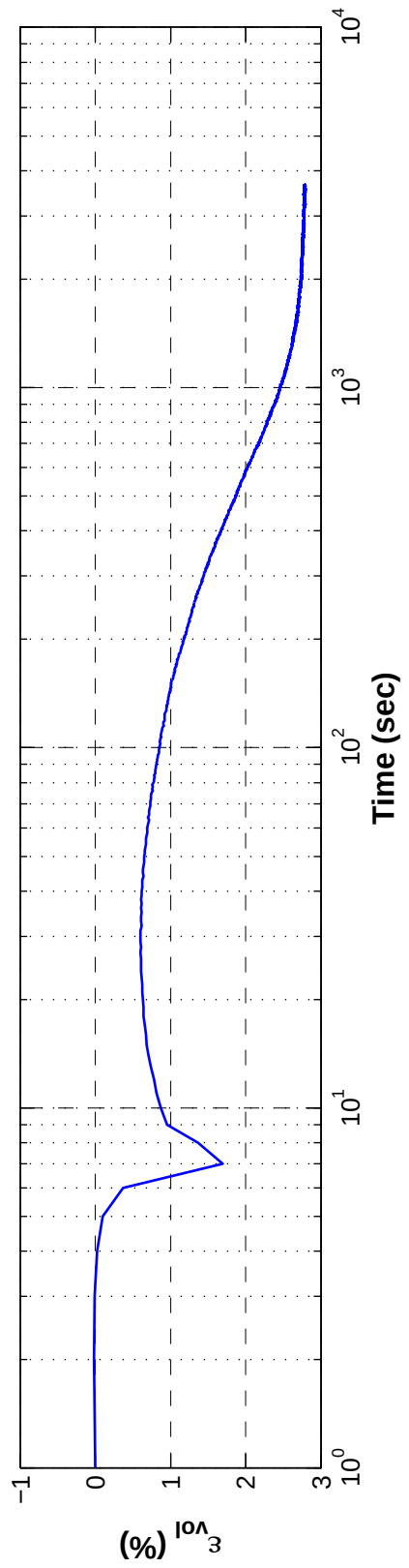
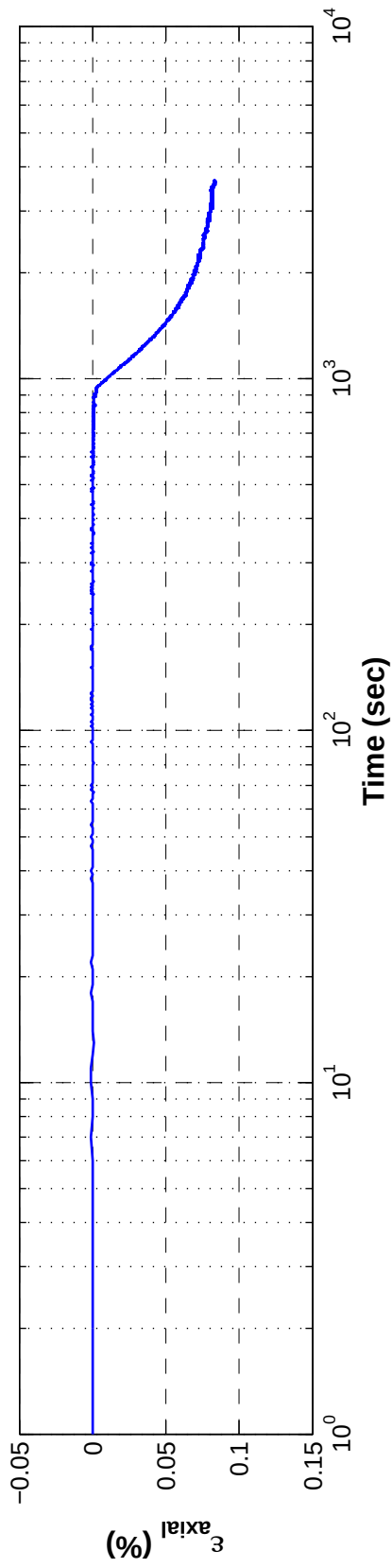
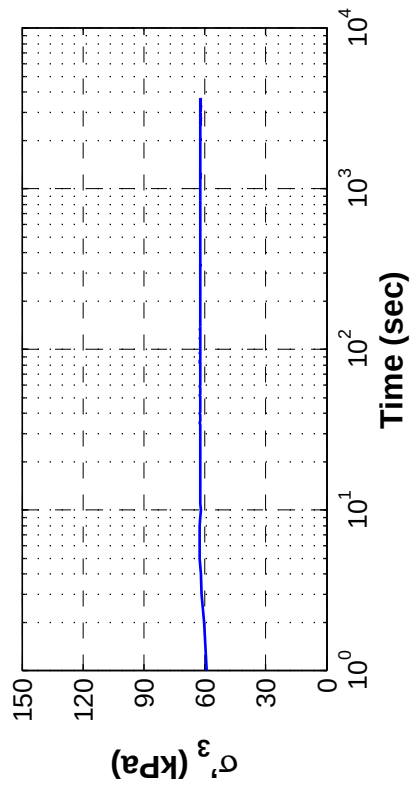
Specimen and Isotropic Consolidation Data

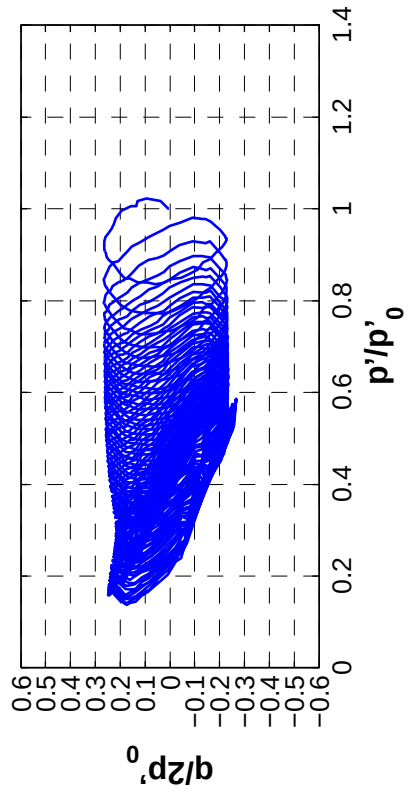
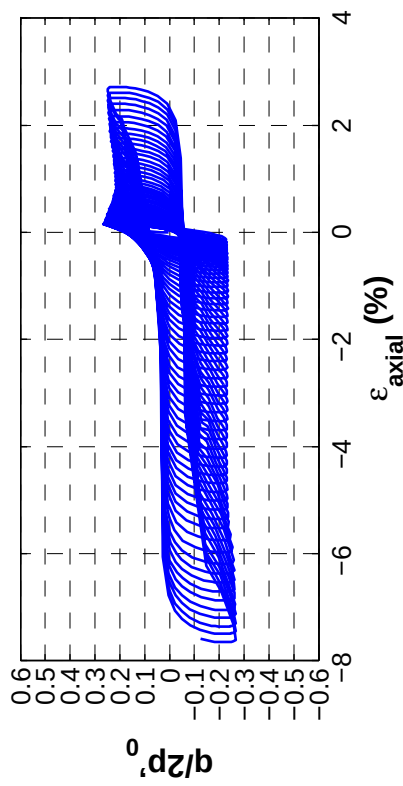
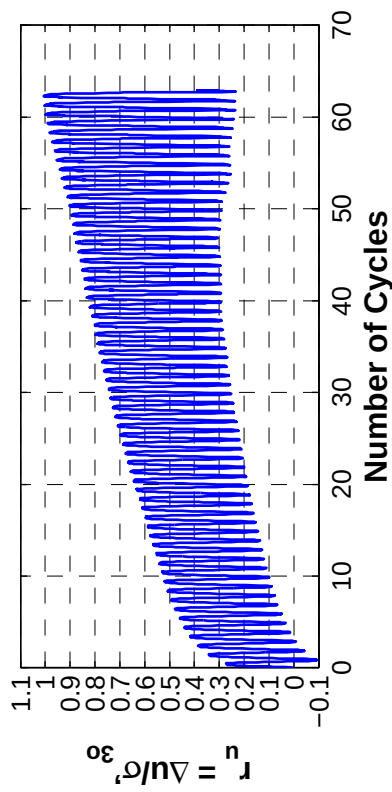
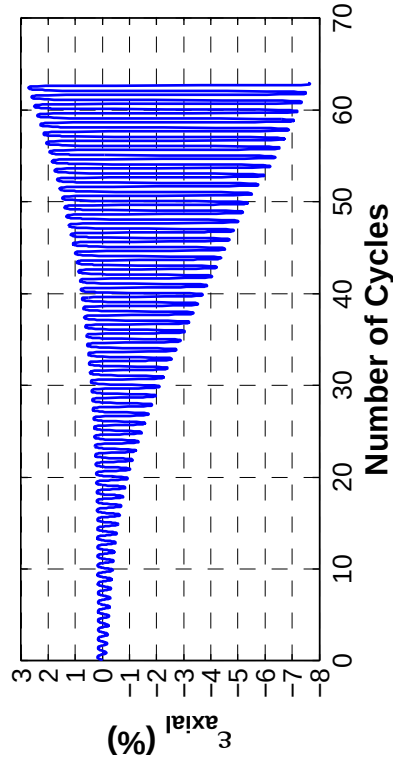
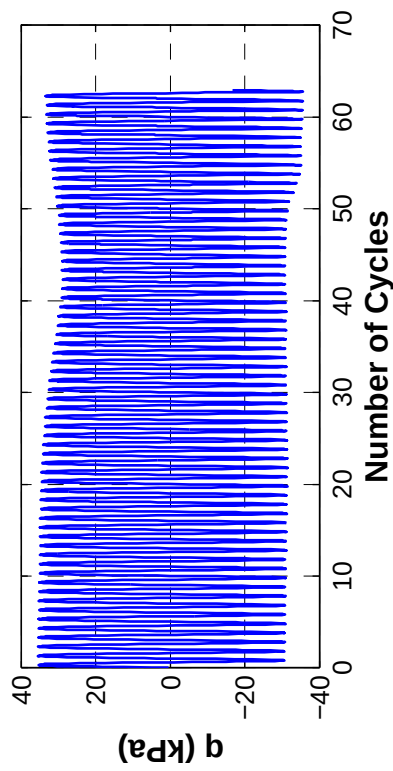
Site: Site 23
Borehole: DM-1
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 4.125
Date Tested: 07/18/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 4.125
Date Tested: 07/18/14
Date Sampled: 06/21/14



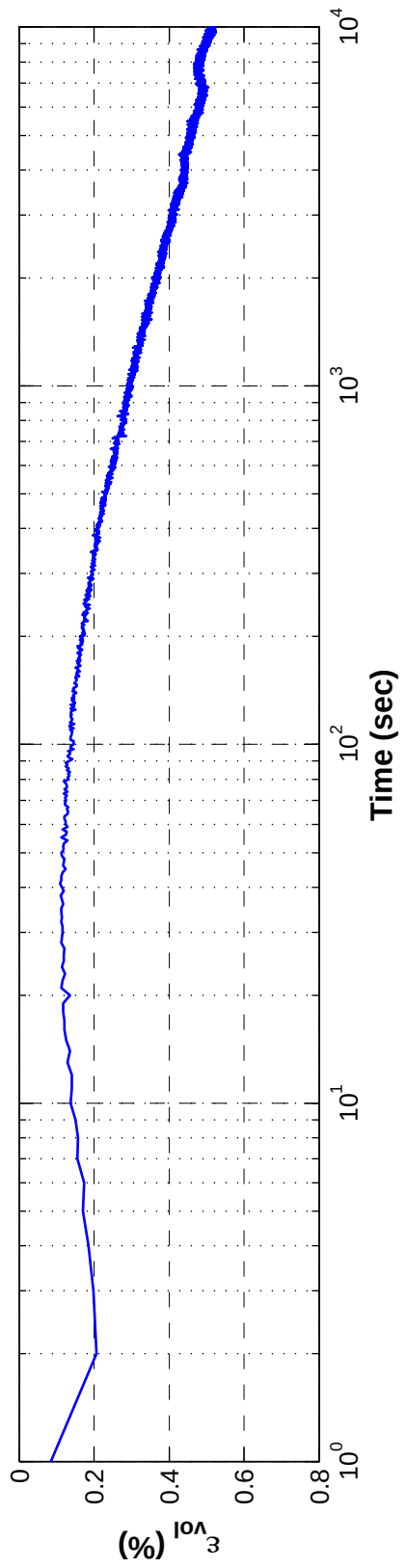
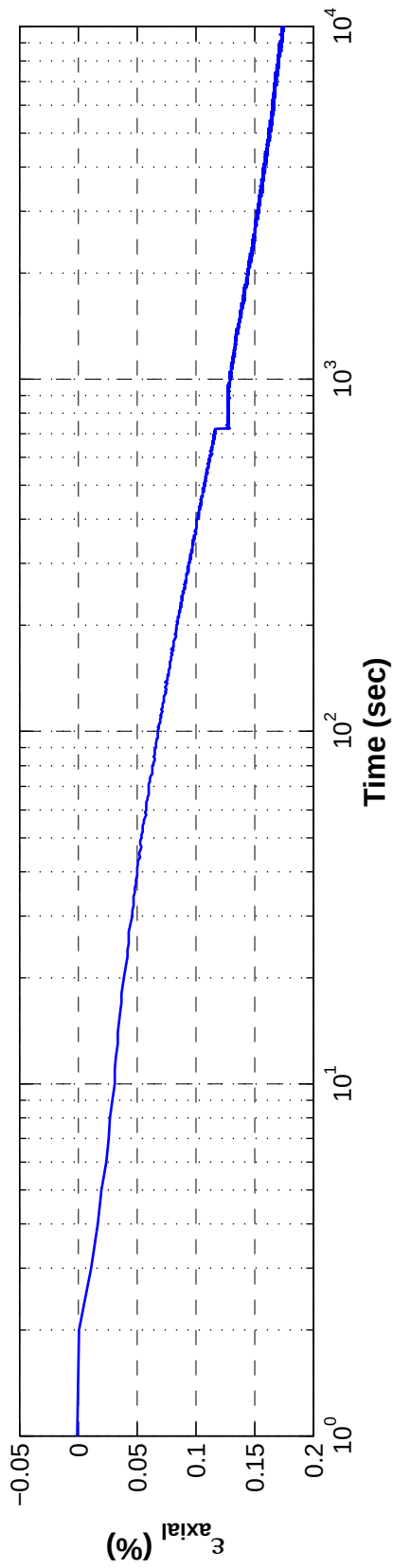
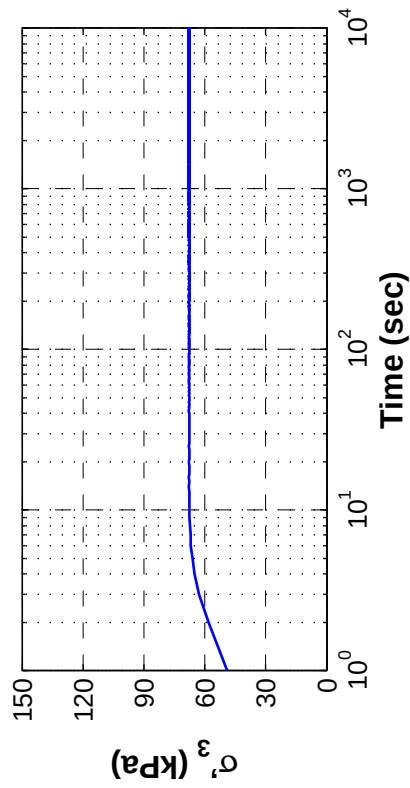


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	67
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	5U	B-Value:	0.985
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	5.07	N to $\epsilon_{Ax-S.A.}$ =3%:	36
Date Tested:	07/29/14	N to $\epsilon_{Ax-D.A.}$ =5%:	43
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	137.866	Gs:	2.72
Spec. Diam. (mm):	61.10	e_c :	1.11
Dry Mass (g):	518.48	PI (%):	9
		FC (%):	94

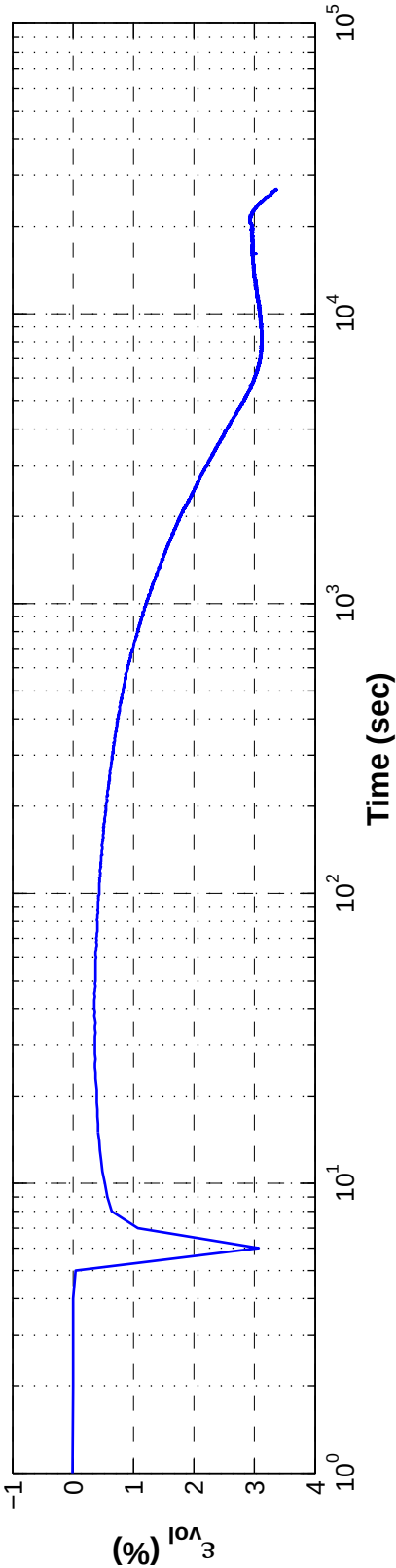
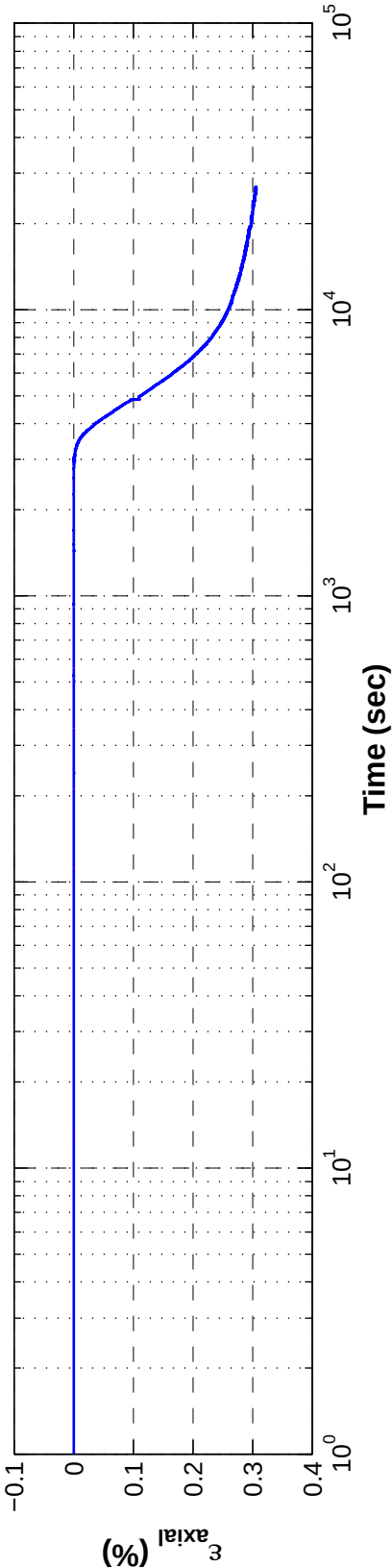
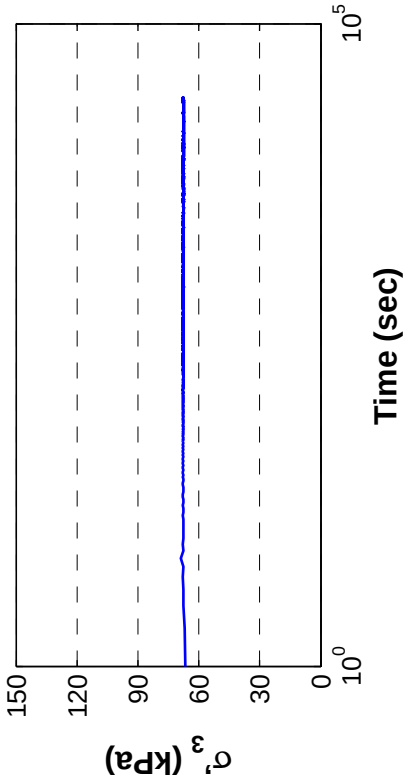
Specimen and Isotropic Consolidation Data

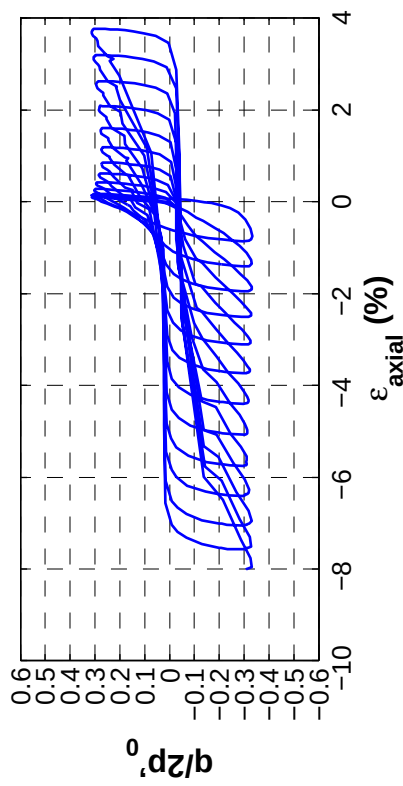
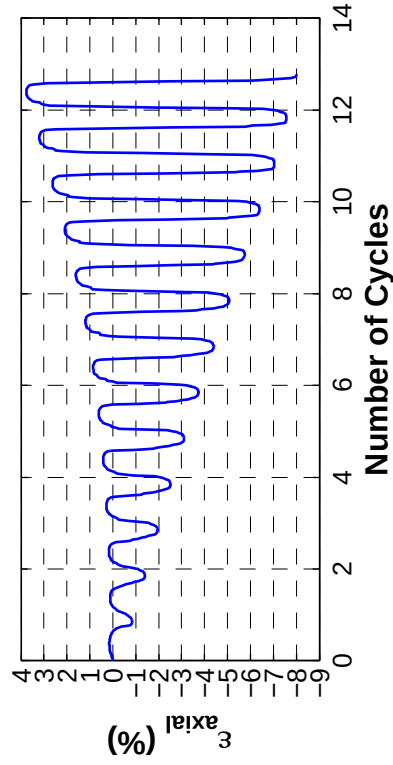
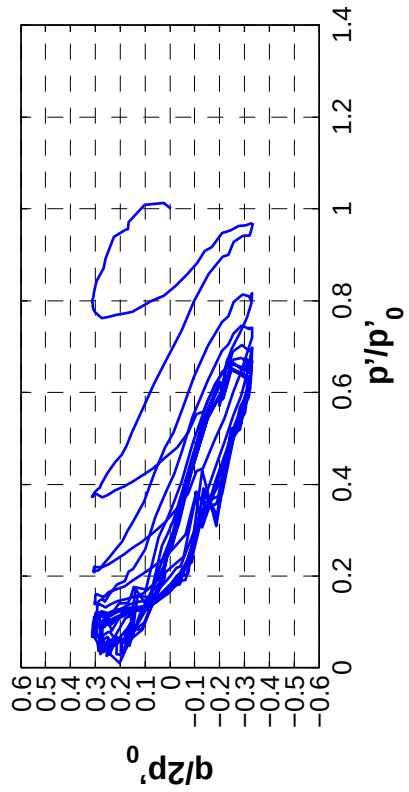
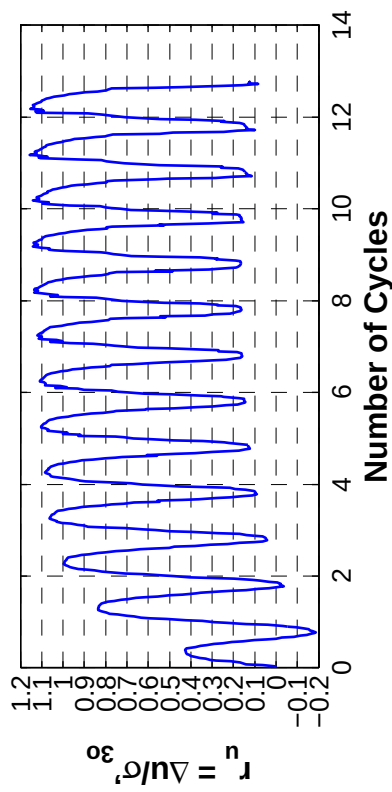
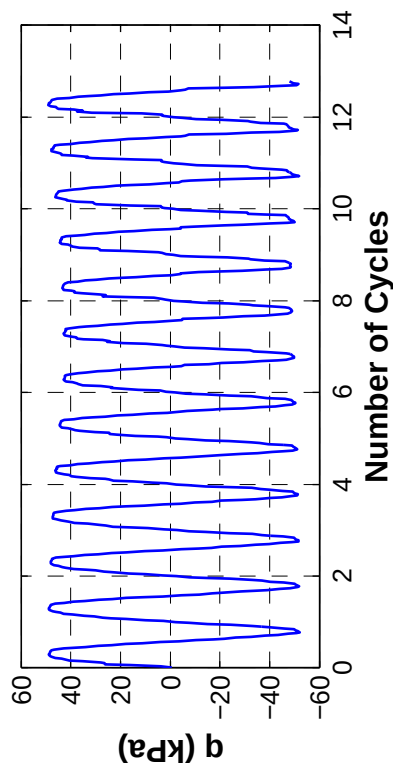
Site: Site 23
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.07
Date Tested: 07/29/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.07
Date Tested: 07/29/14
Date Sampled: 06/21/14



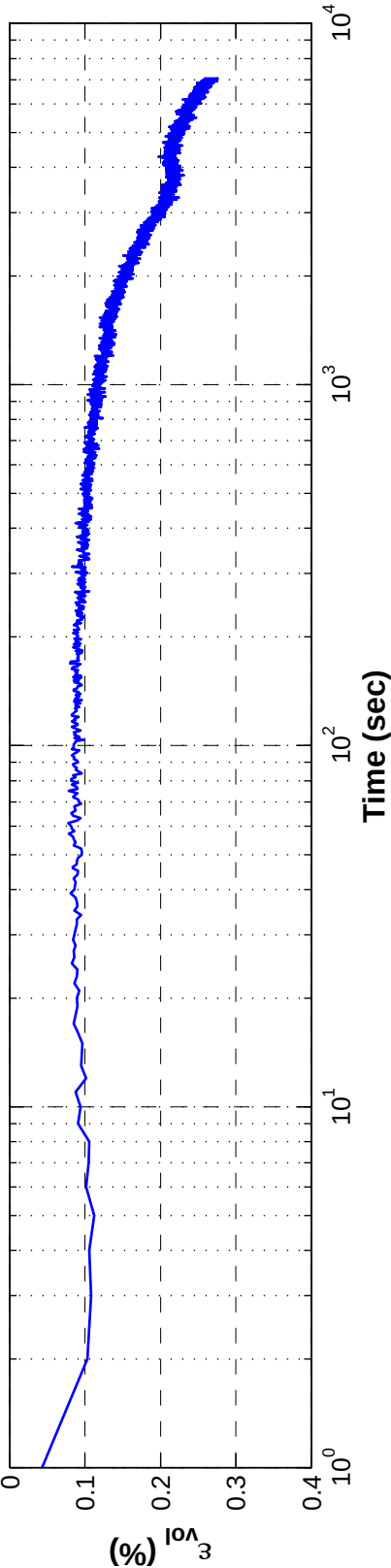
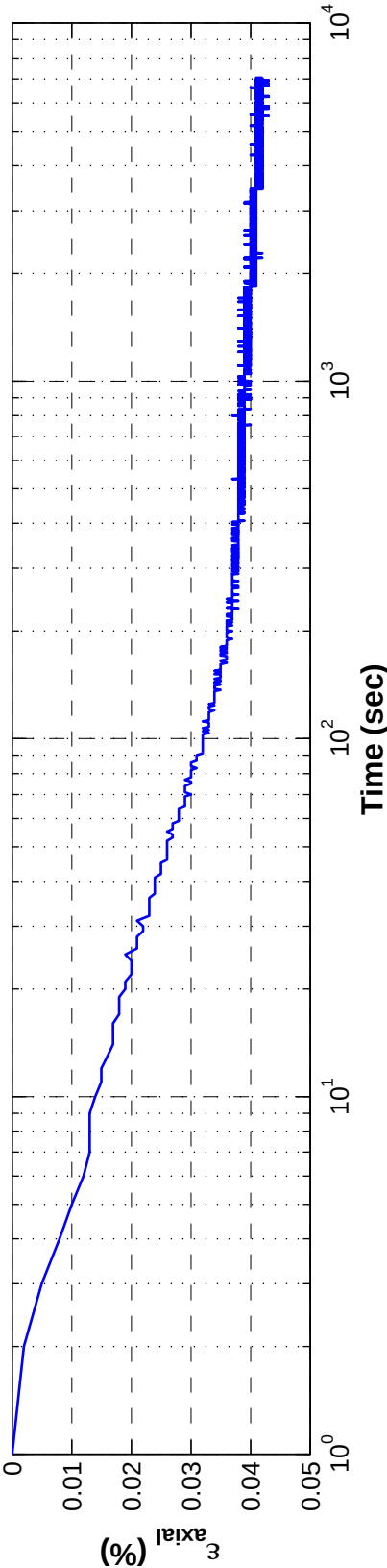
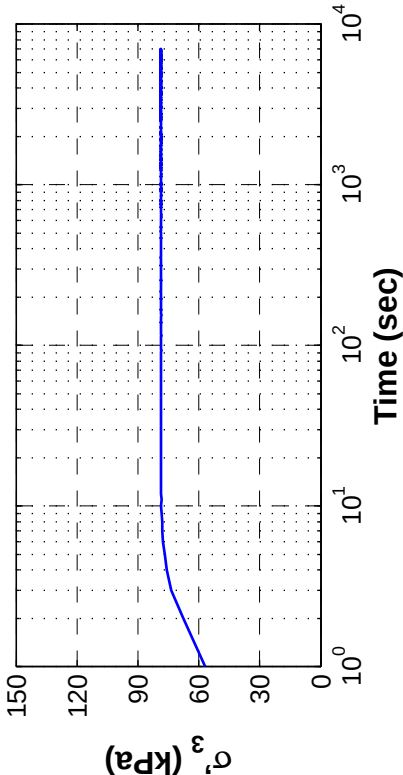


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	78
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	7U	B-Value:	0.917
Sampler Type:	D&M	CSR:	0.32
Spec. Depth (m):	6.27	N to $\epsilon_{Ax-S.A.}$ =3%:	5
Date Tested:	07/25/14	N to $\epsilon_{Ax-D.A.}$ =5%:	7
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	138.116	Gs:	---
Spec. Diam. (mm):	61.18	e_c :	0.71
Dry Mass (g):	638.86	PI (%):	6
		FC (%):	63

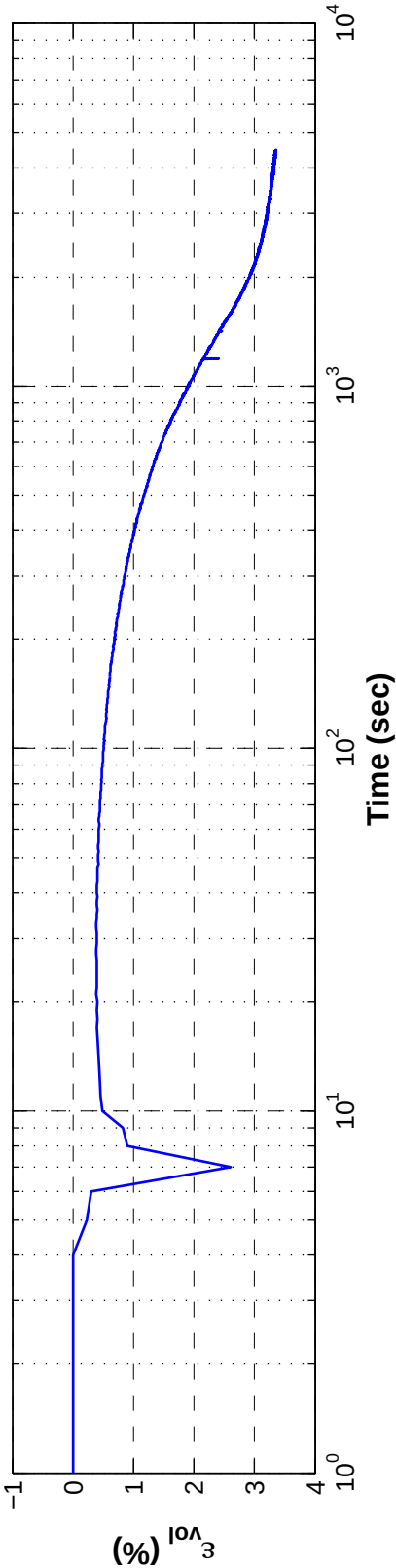
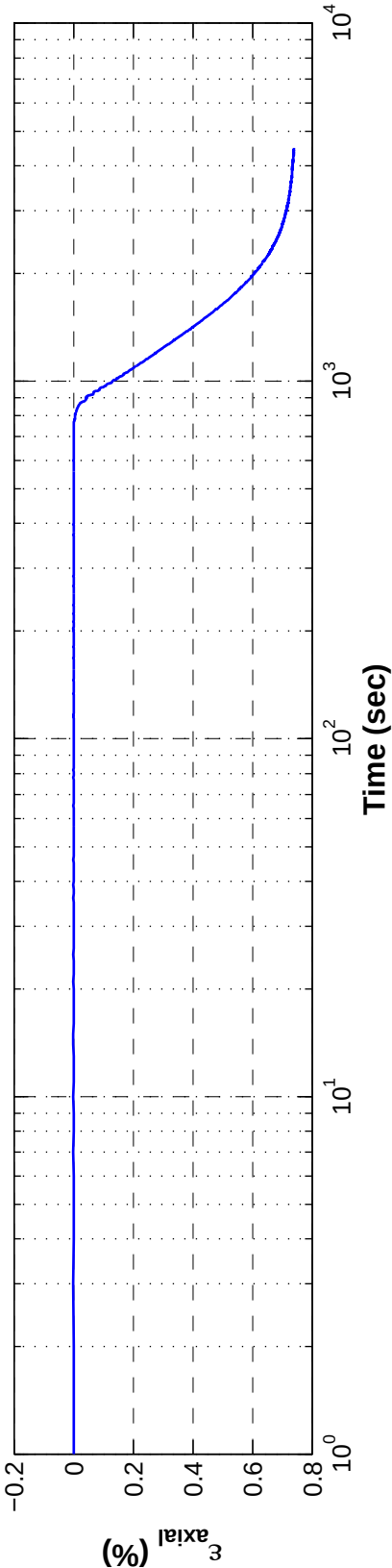
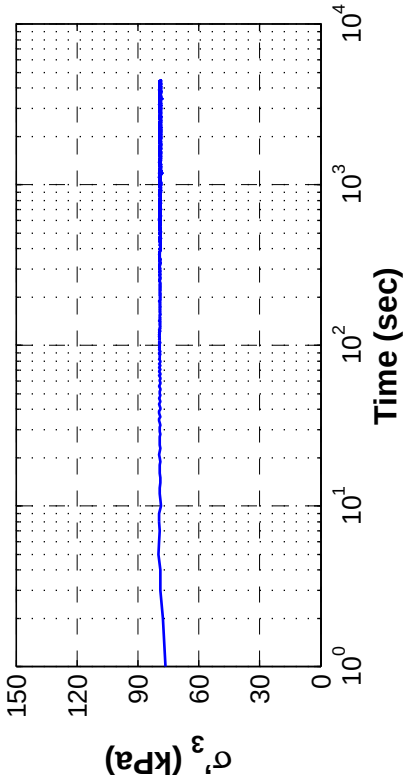
Specimen and Isotropic Consolidation Data

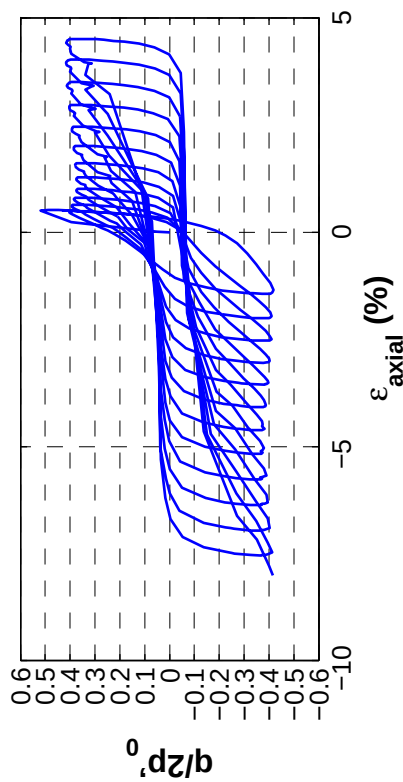
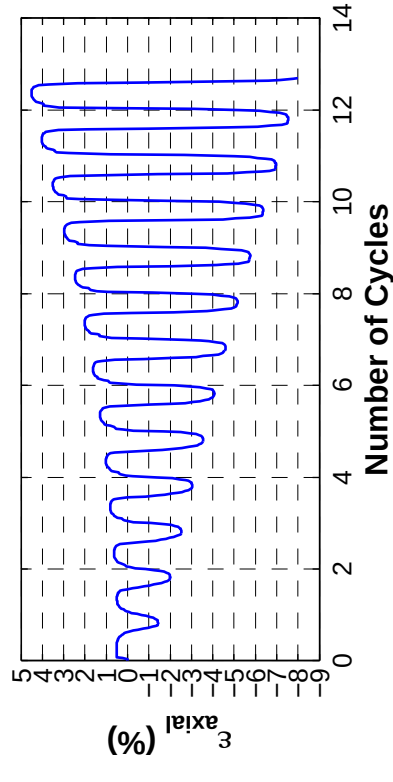
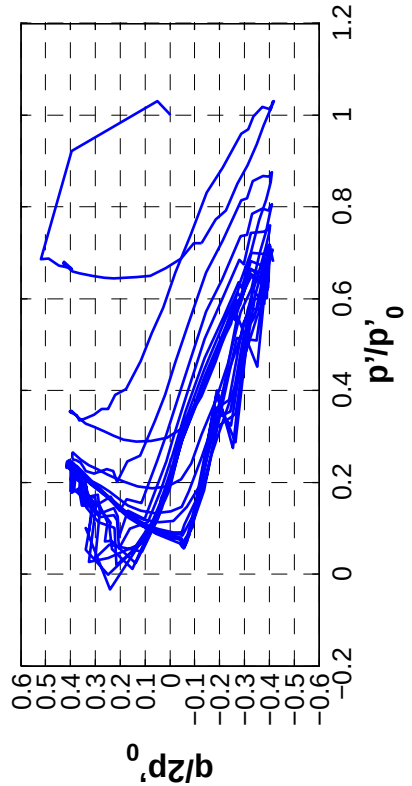
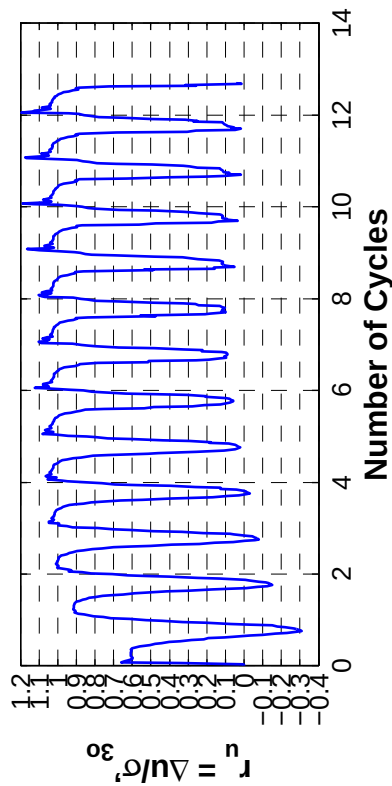
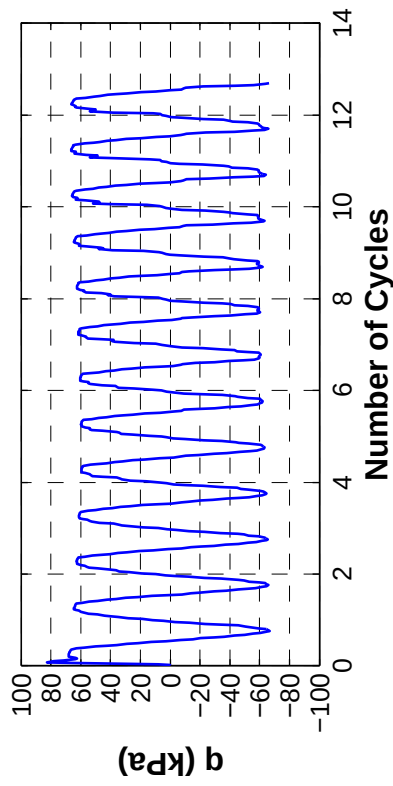
Site: Site 23
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 6.27
Date Tested: 07/25/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 6.27
Date Tested: 07/25/14
Date Sampled: 06/21/14



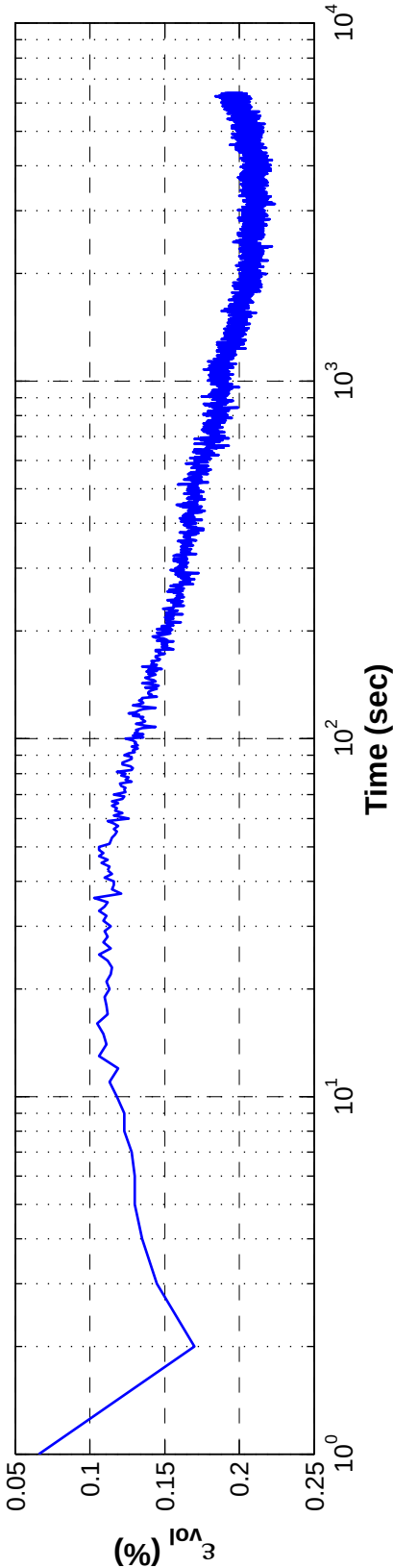
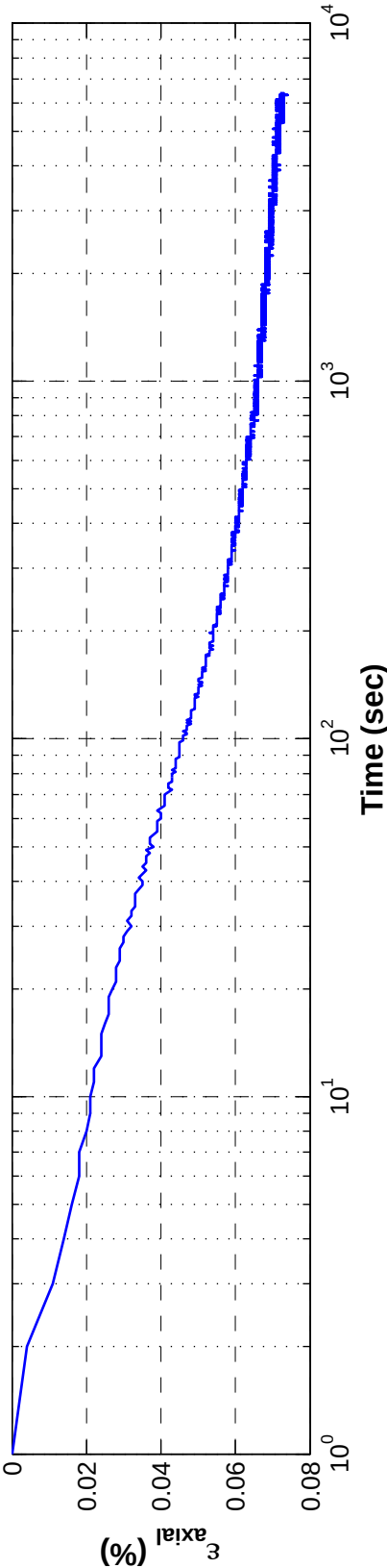
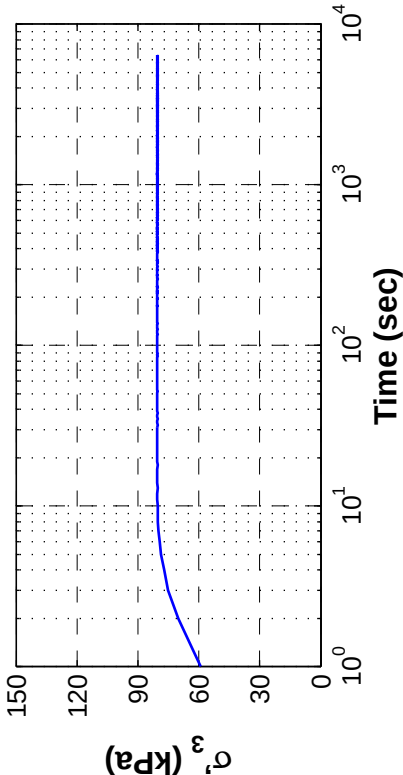


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	80
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	7U	B-Value:	0.972
Sampler Type:	D&M	CSR:	0.4
Spec. Depth (m):	6.425	N to $\epsilon_{Ax-S.A.}$:	3%
Date Tested:	07/30/14	N to $\epsilon_{Ax-D.A.}$:	5%
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	141.936	Gs:	2.69
Spec. Diam. (mm):	61.02	e_c :	0.68
Dry Mass (g):	664.15	PI (%):	7
		FC (%):	73

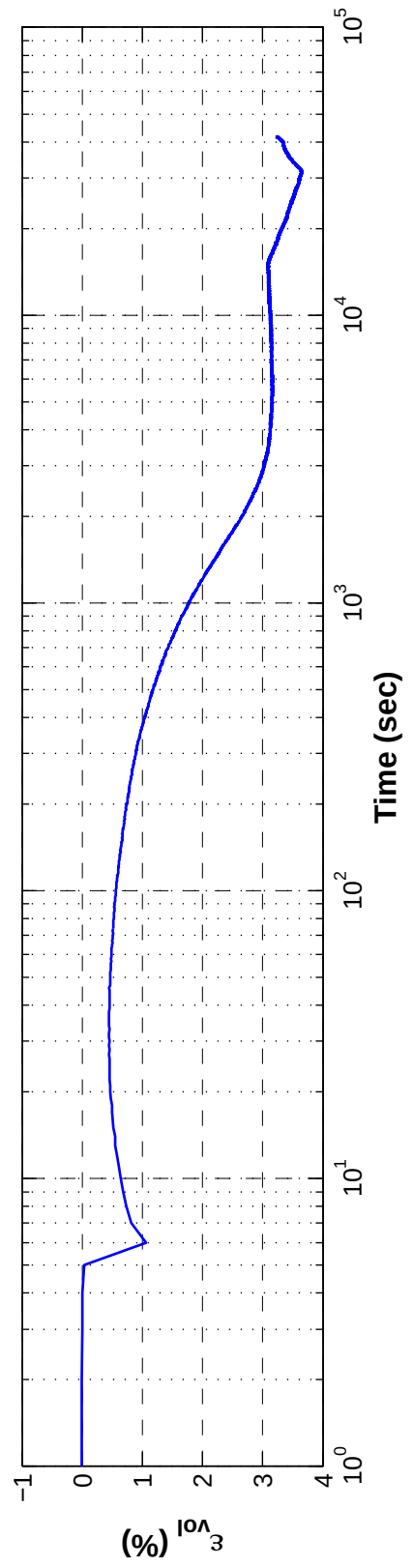
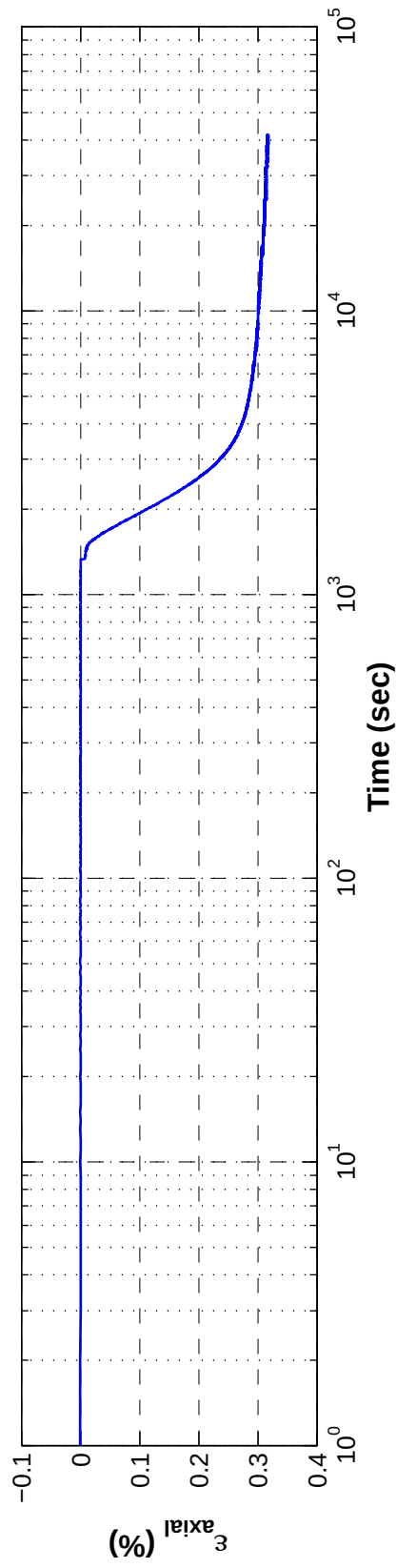
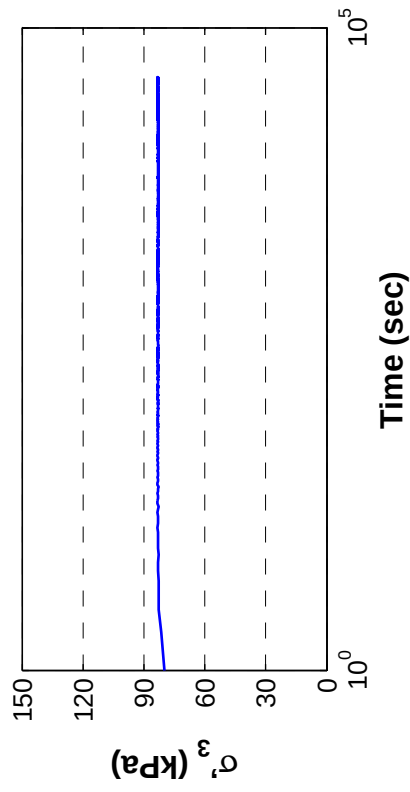
Specimen and Isotropic Consolidation Data

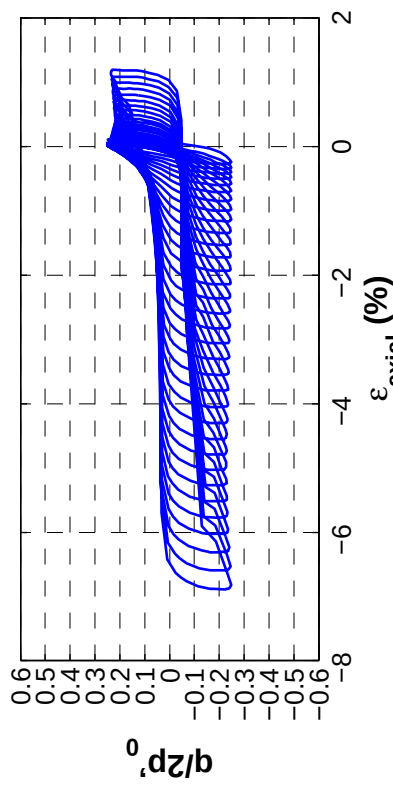
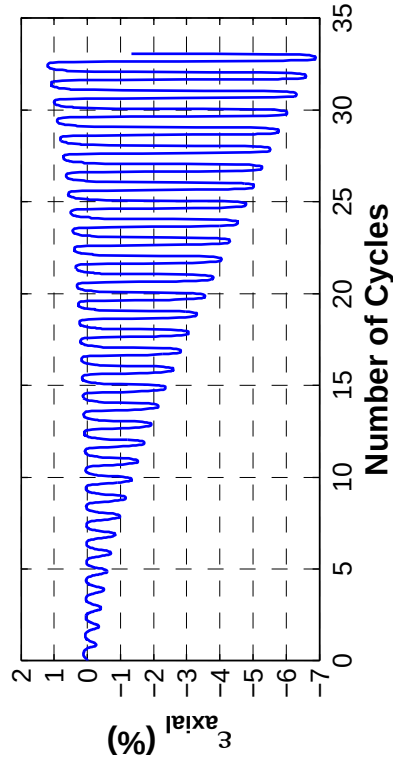
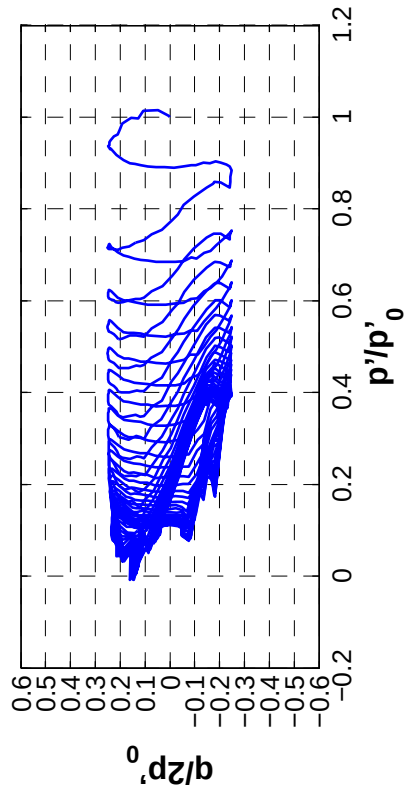
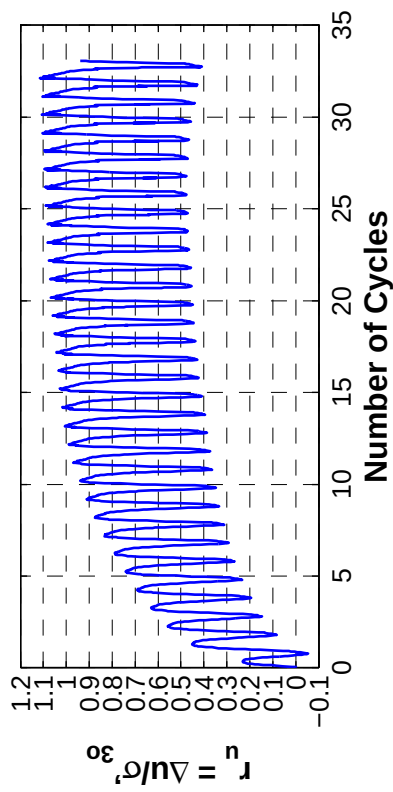
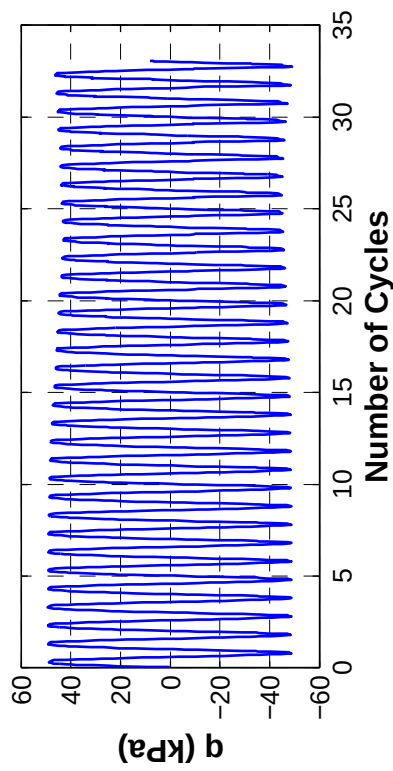
Site: Site 23
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 6.425
Date Tested: 07/30/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 6.425
Date Tested: 07/30/14
Date Sampled: 06/21/14



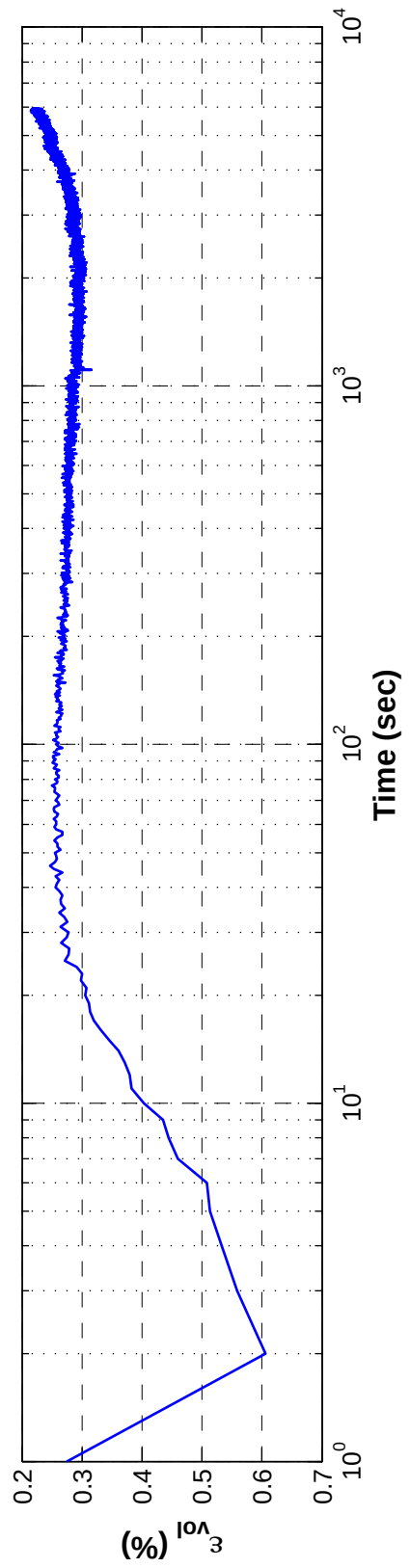
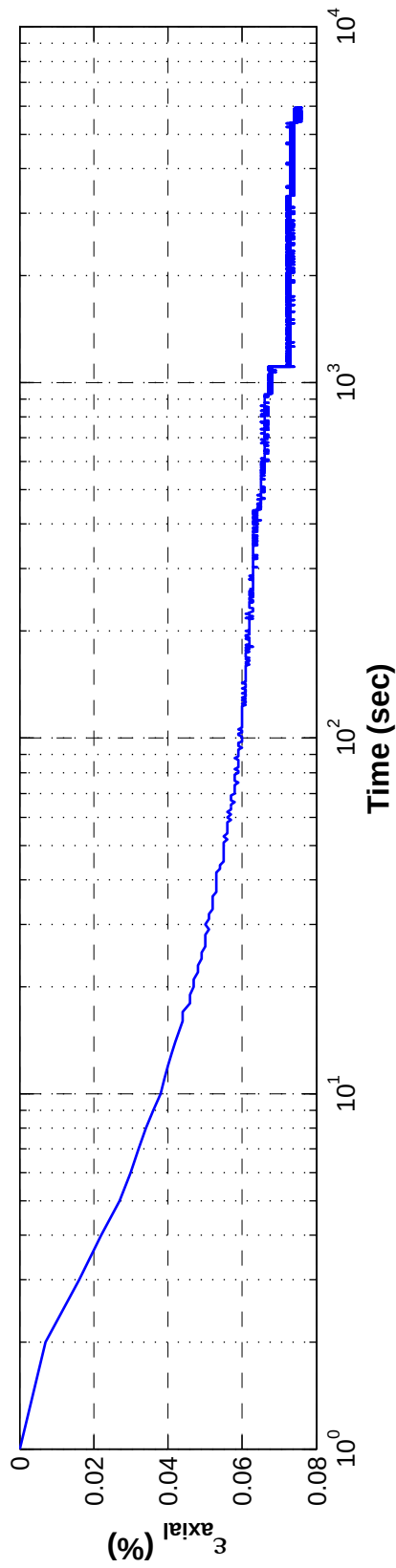
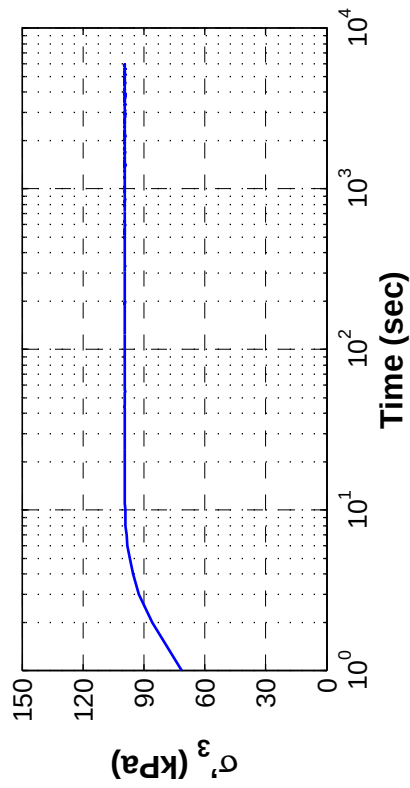


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 23	σ'_c (kPa):	98
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	8Ub	B-Value:	0.967
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	8.37	N to $\epsilon_{Ax-S.A.}$ =3%:	18
Date Tested:	08/01/14	N to $\epsilon_{Ax-D.A.}$ =5%:	25
Date Sampled:	06/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	140.516	Gs:	2.67
Spec. Diam. (mm):	60.84	e_c :	0.76
Dry Mass (g):	620.81	PI (%):	NP
		FC (%):	63

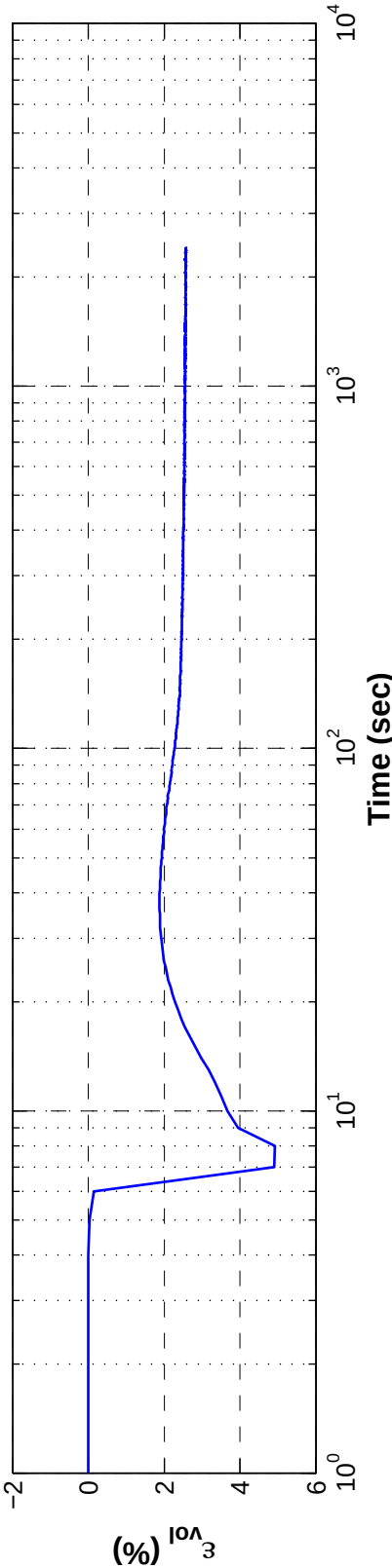
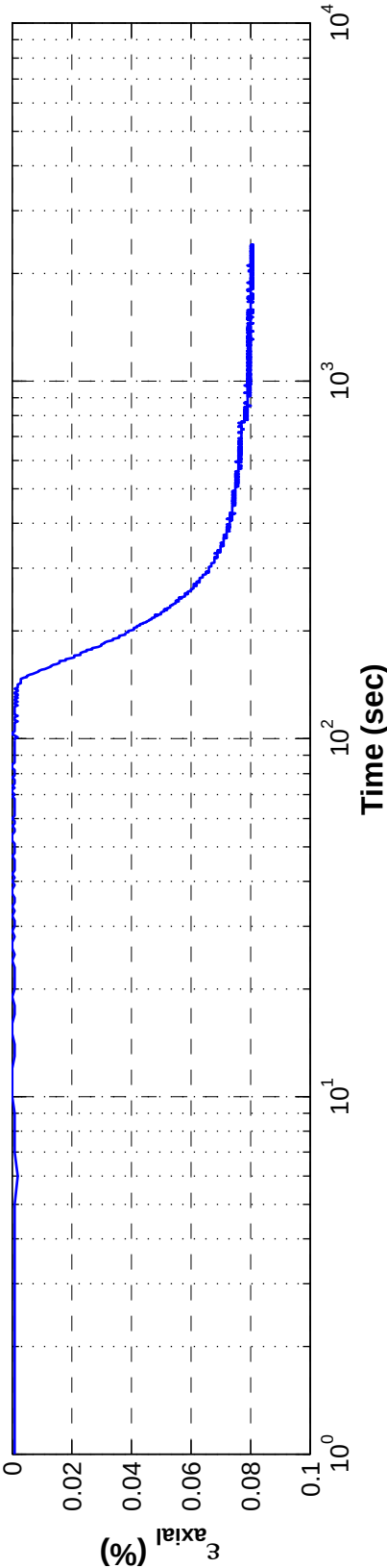
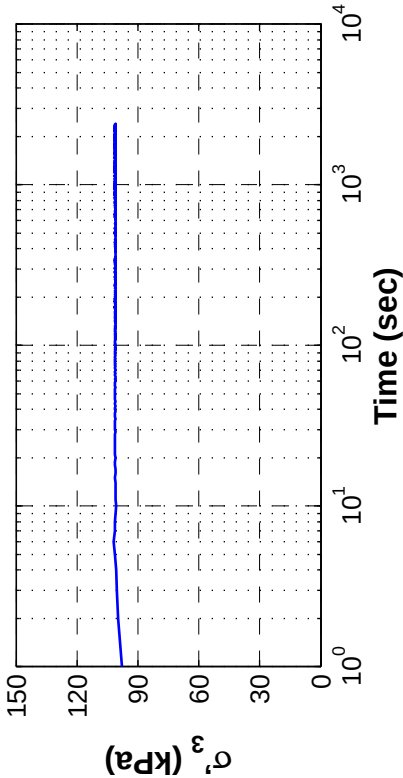
Specimen and Isotropic Consolidation Data

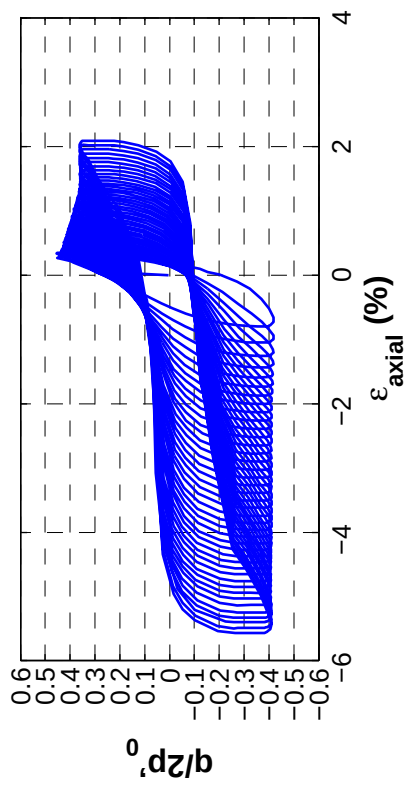
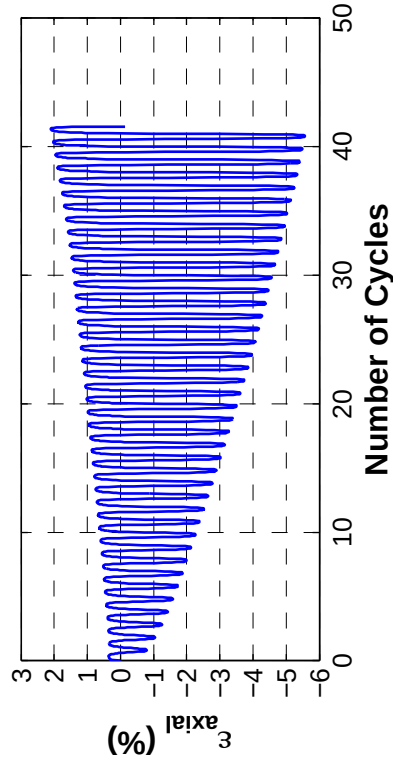
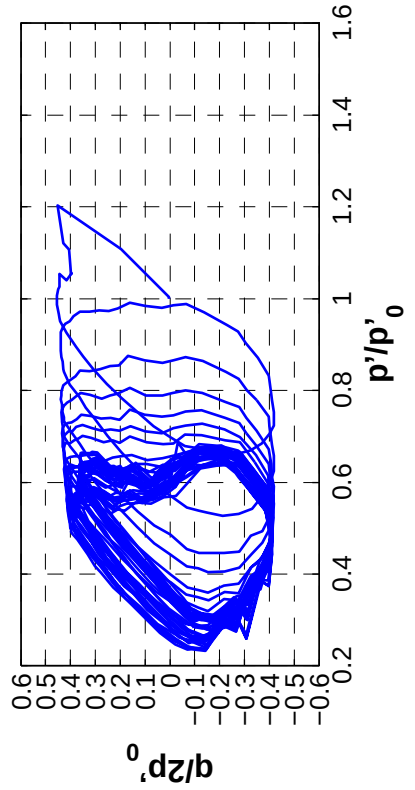
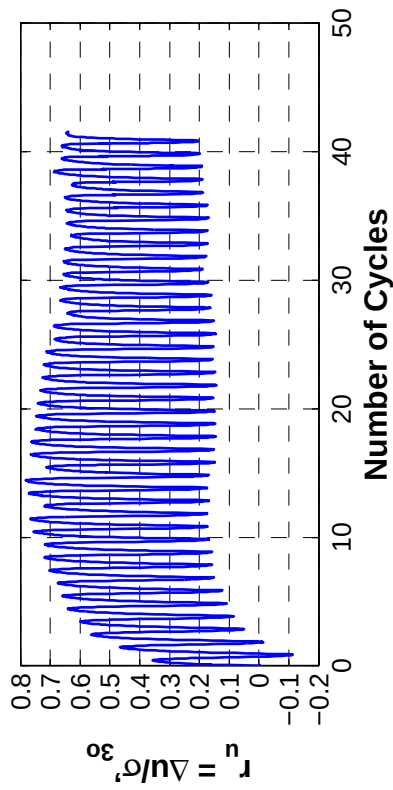
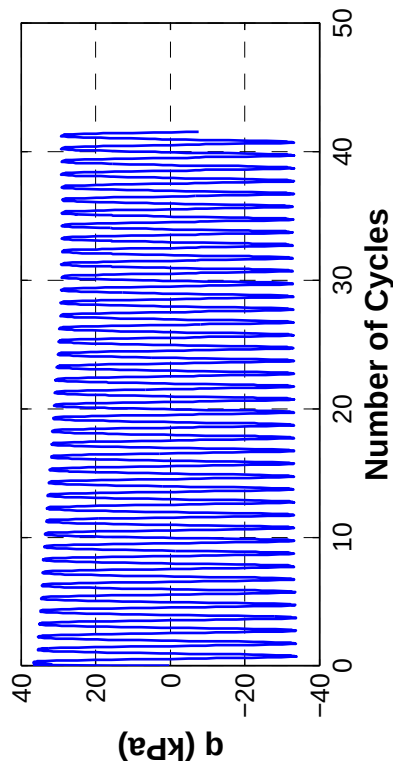
Site: Site 23
Borehole: DM-1
Sample No.: 8Ub
Sampler Type: D&M
Spec. Depth (m): 8.37
Date Tested: 08/01/14
Date Sampled: 06/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 23
Borehole: DM-1
Sample No.: 8Ub
Sampler Type: D&M
Spec. Depth (m): 8.37
Date Tested: 08/01/14
Date Sampled: 06/21/14



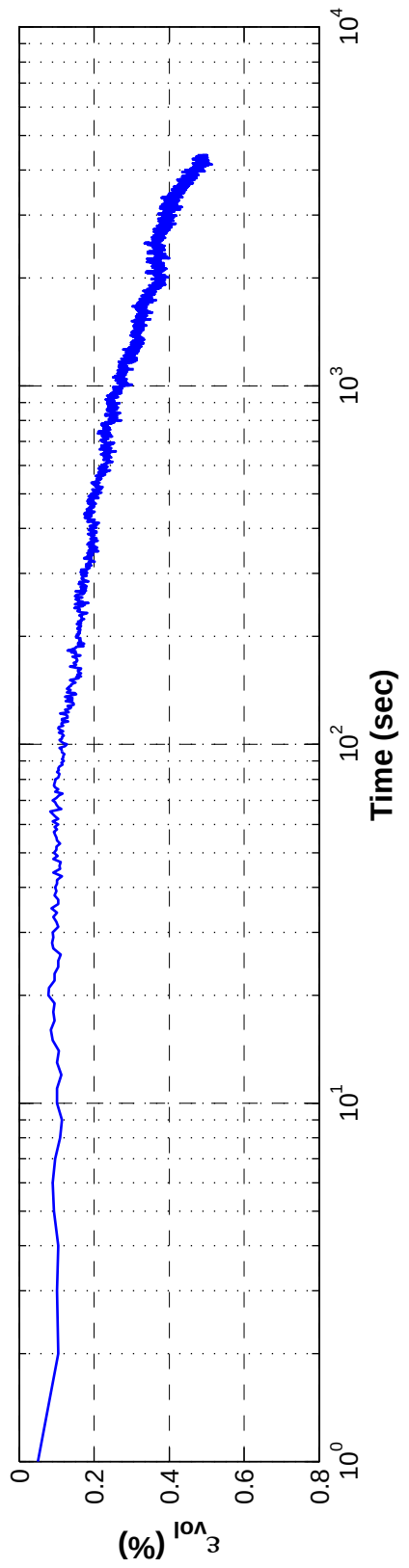
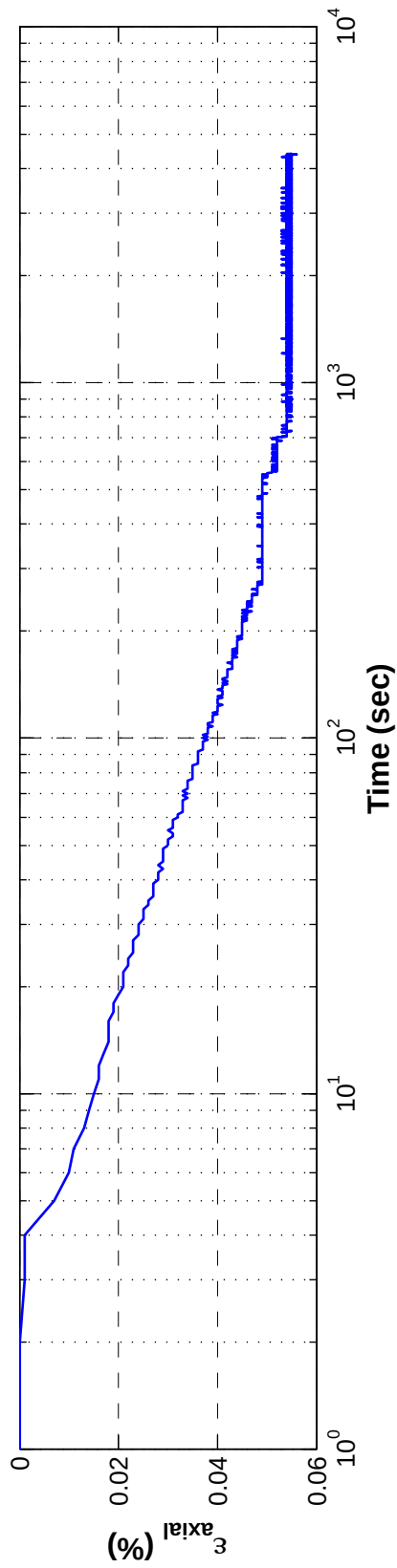
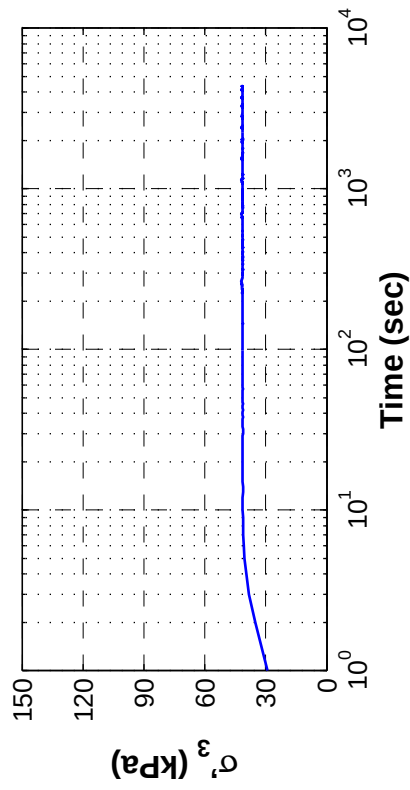


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	40
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	2U	B-Value:	0.997
Sampler Type:	D&M	CSR:	0.42
Spec. Depth (m):	2.125	N to $\epsilon_{Ax-S.A.}$ =3%:	16
Date Tested:	11/16/14	N to $\epsilon_{Ax-D.A.}$ =5%:	24
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	135.88	Gs:	2.67
Spec. Diam. (mm):	61.023	e_c :	0.93
Dry Mass (g):	546.58	PI (%):	15
		FC (%):	92

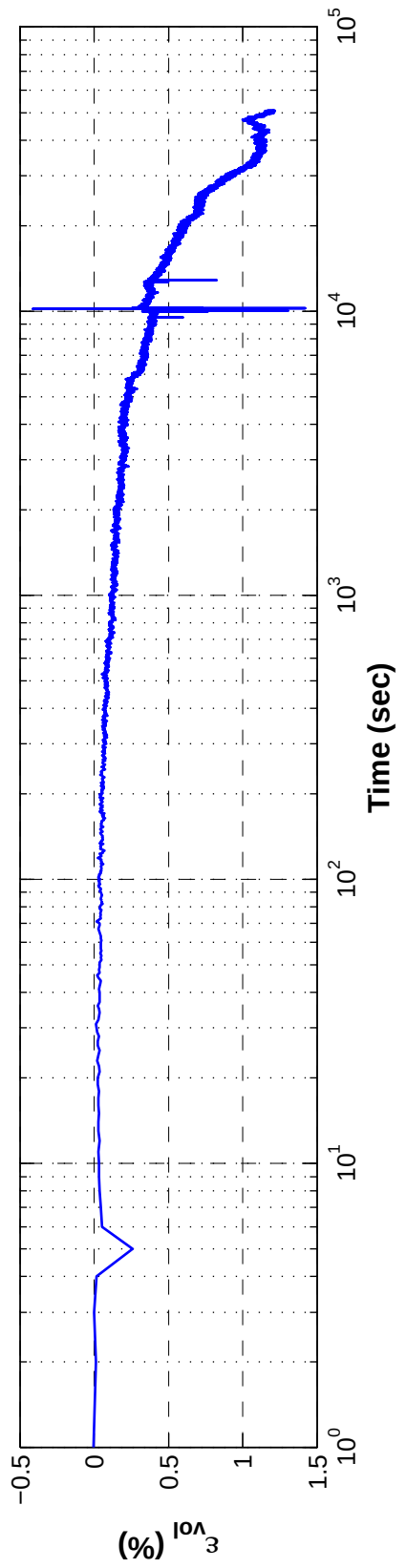
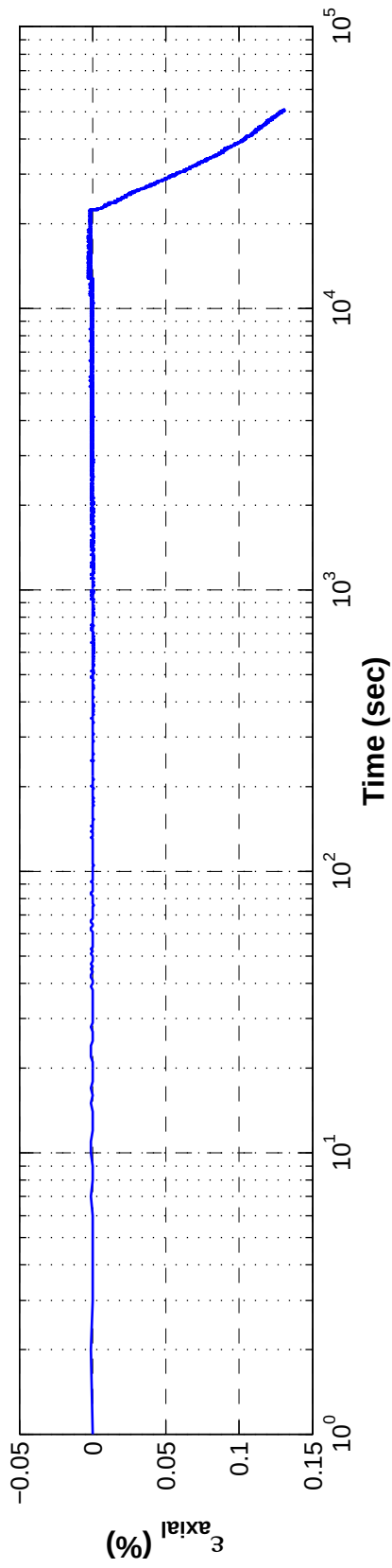
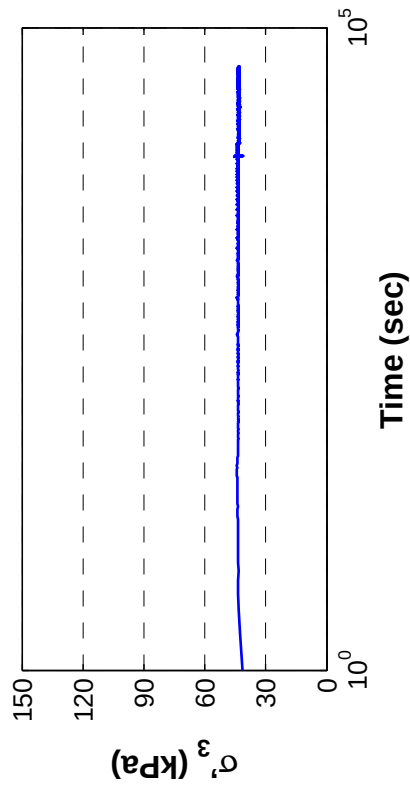
Specimen and Isotropic Consolidation Data

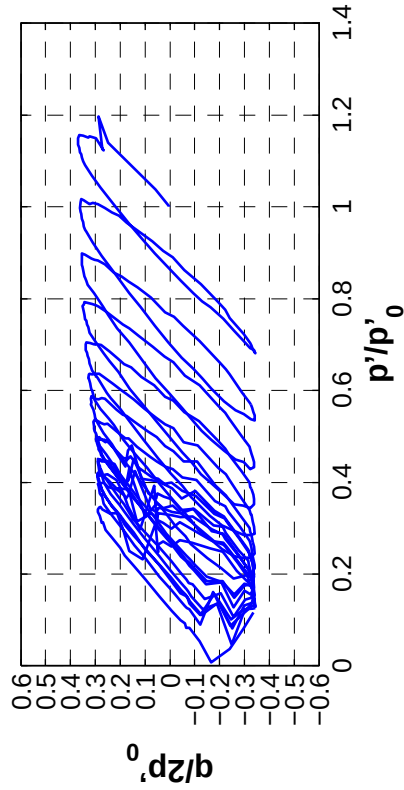
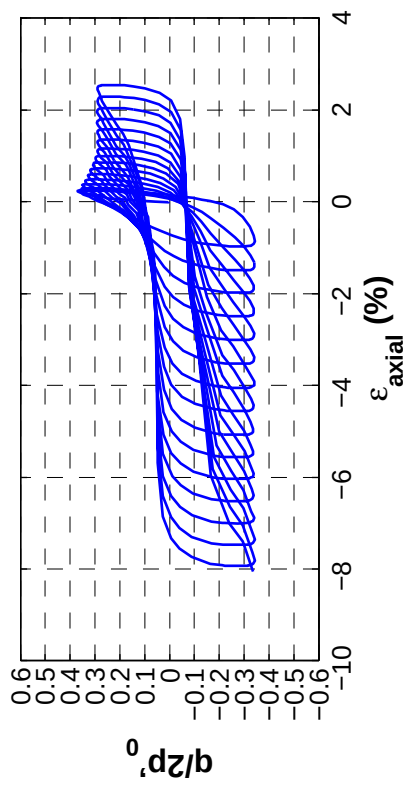
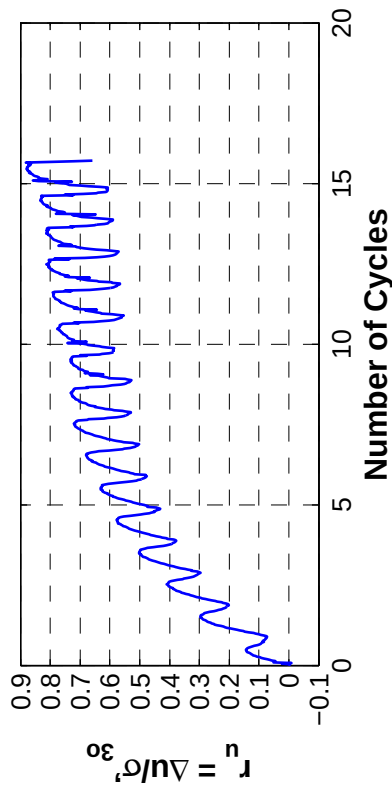
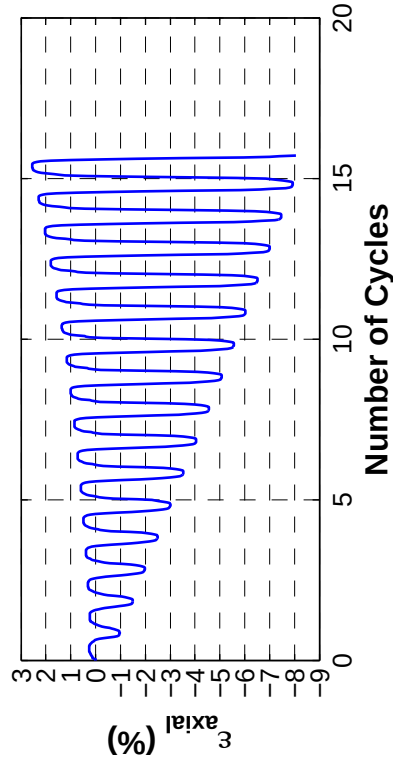
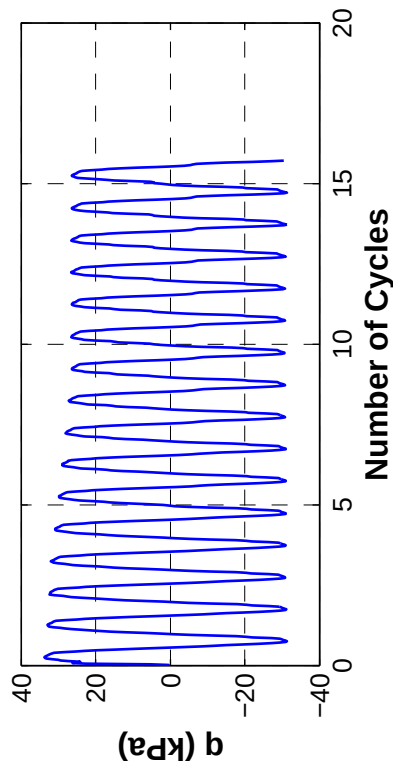
Site: Site 33
Borehole: DM-1
Sample No.: 2U
Sampler Type: D&M
Spec. Depth (m): 2.125
Date Tested: 11/16/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 2U
Sampler Type: D&M
Spec. Depth (m): 2.125
Date Tested: 11/16/14
Date Sampled: 10/21/14



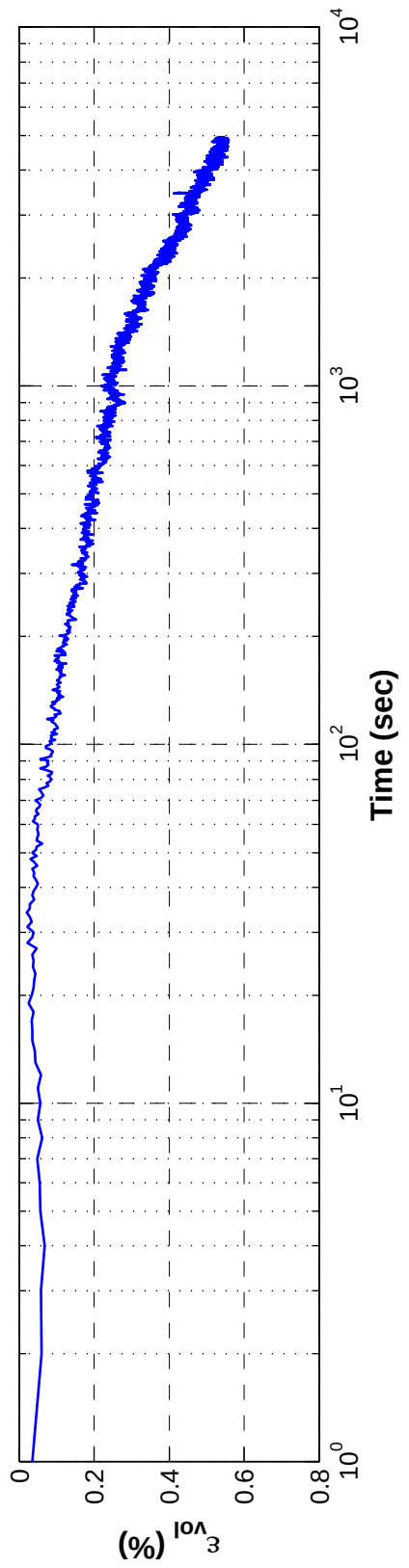
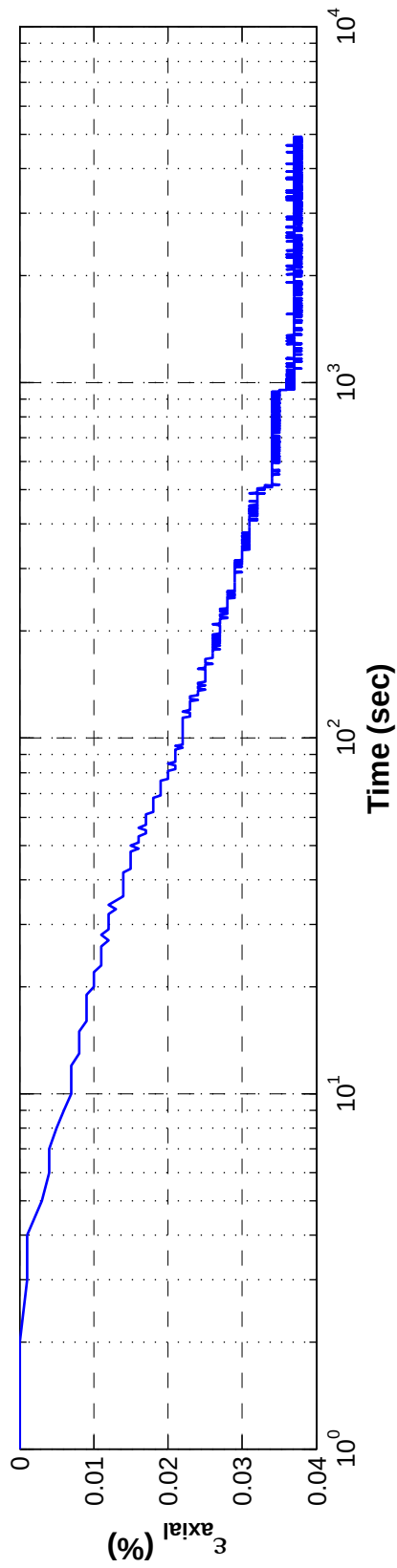
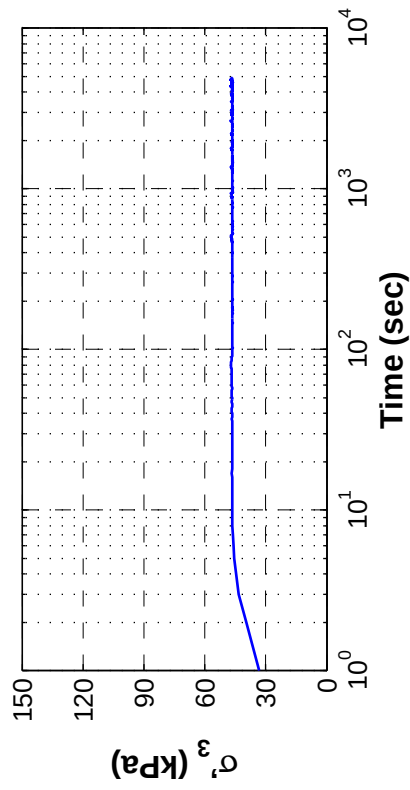


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	45
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.99
Sampler Type:	D&M	CSR:	0.35
Spec. Depth (m):	2.57	N to $\epsilon_{Ax-S.A.}$ =3%:	5
Date Tested:	11/13/14	N to $\epsilon_{Ax-D.A.}$ =5%:	8
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	135.11	Gs:	2.70
Spec. Diam. (mm):	60.978	e_c :	0.86
Dry Mass (g):	570.40	PI (%):	12
		FC (%):	100

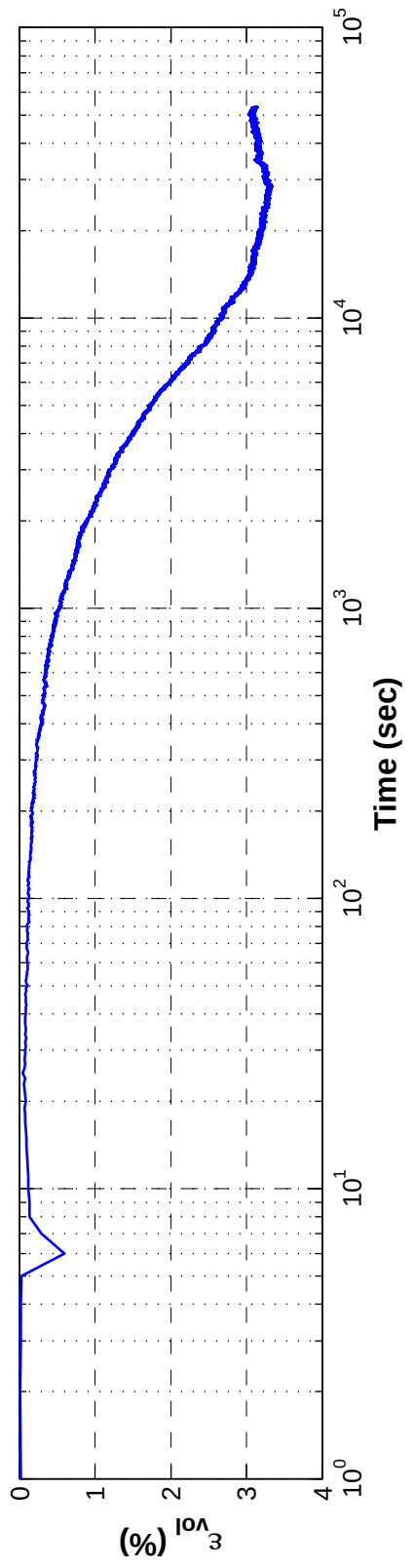
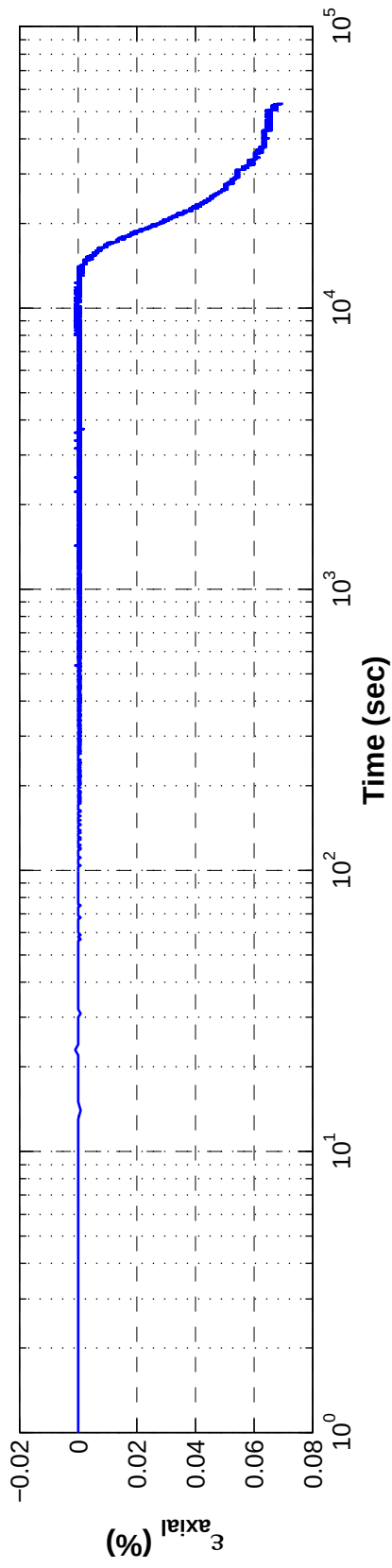
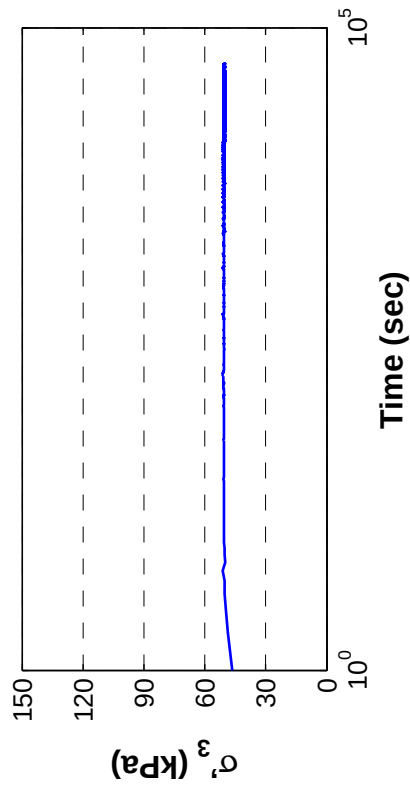
Specimen and Isotropic Consolidation Data

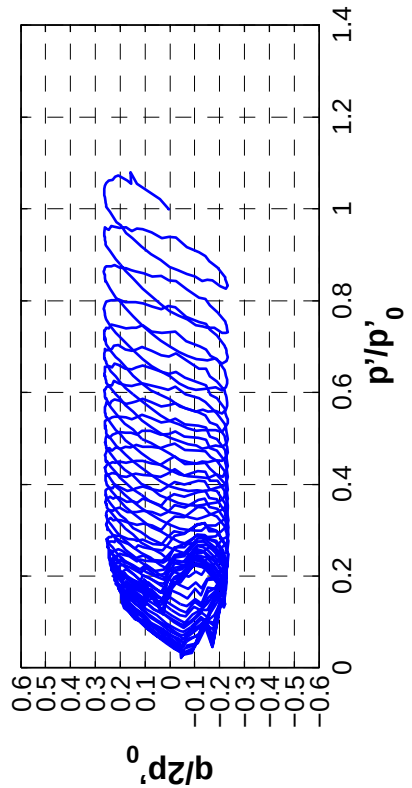
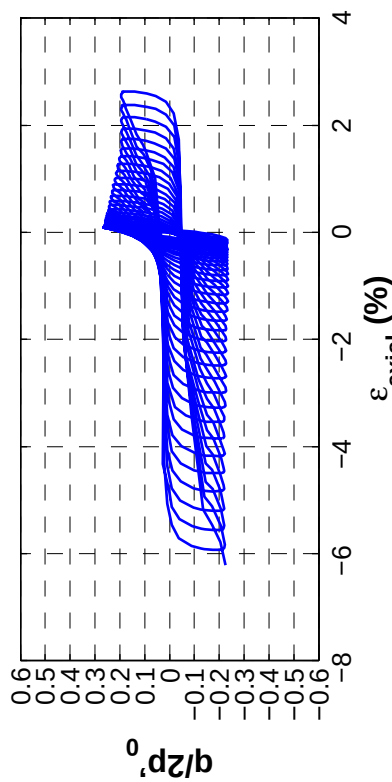
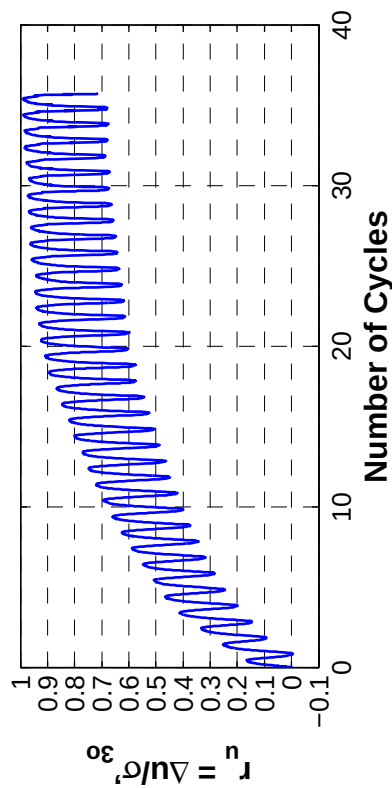
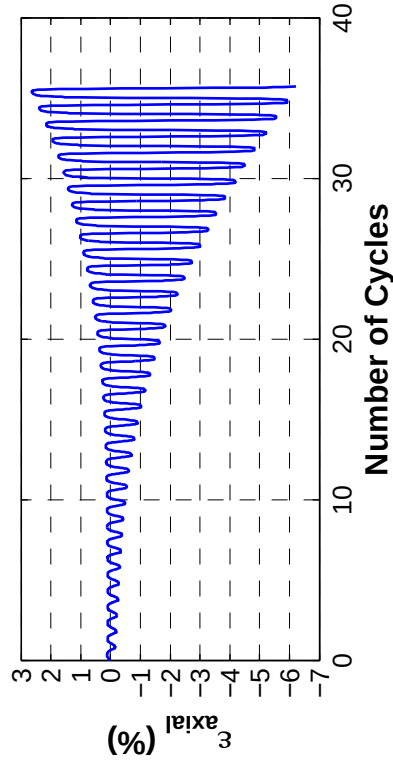
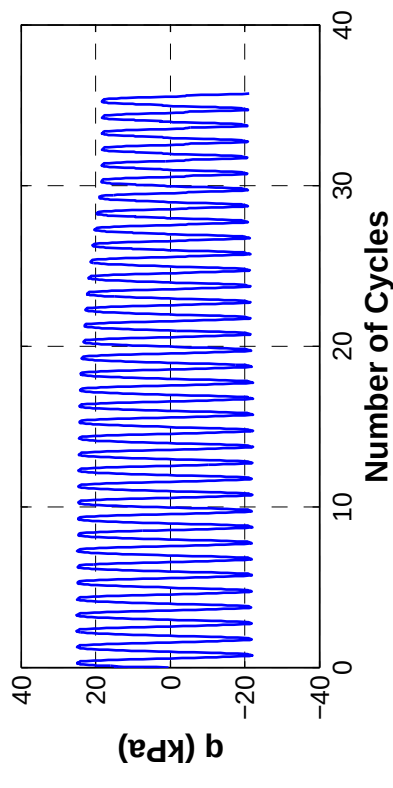
Site: Site 33
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.57
Date Tested: 11/13/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.57
Date Tested: 11/13/14
Date Sampled: 10/21/14



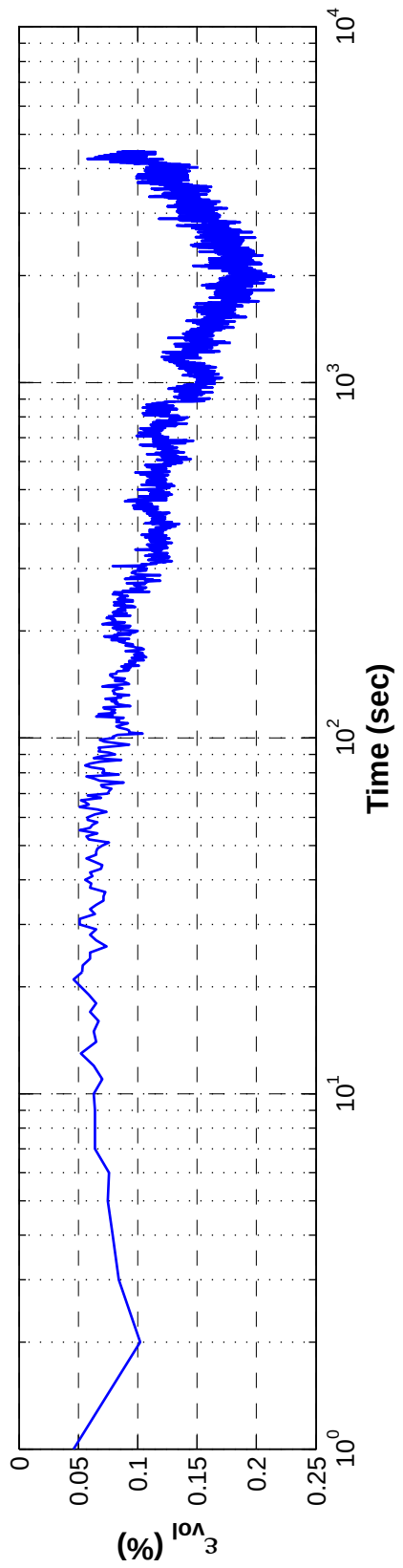
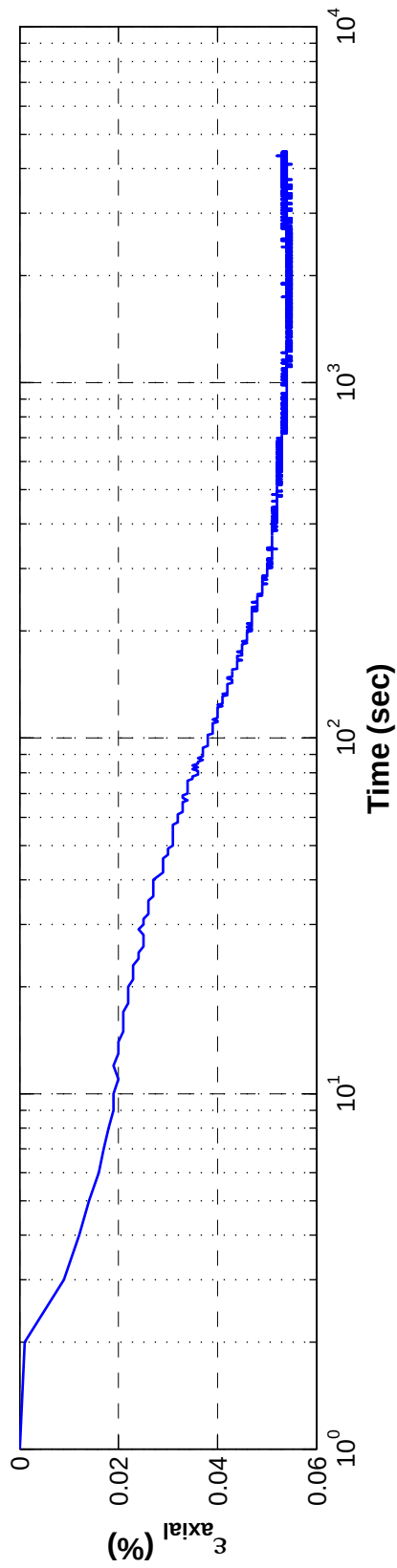
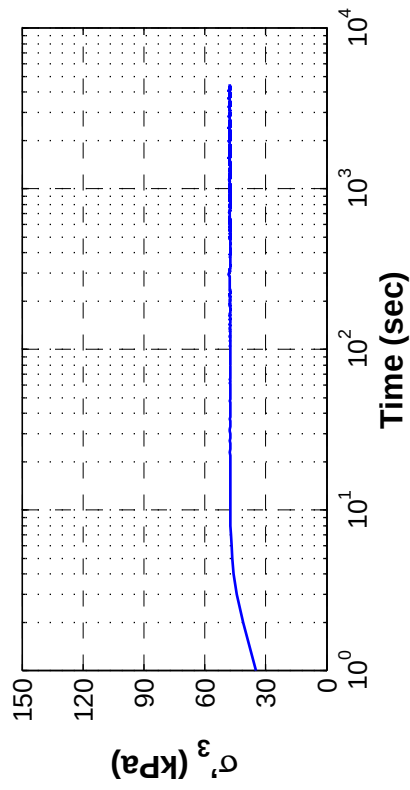


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	47
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.97
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	2.725	N to $\epsilon_{Ax-S.A.}$ =3%:	27
Date Tested:	11/14/13	N to $\epsilon_{Ax-D.A.}$ =5%:	29
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	134.19	Gs:	---
Spec. Diam. (mm):	61.241	e_c :	0.88
Dry Mass (g):	566.09	PI (%):	5
		FC (%):	98

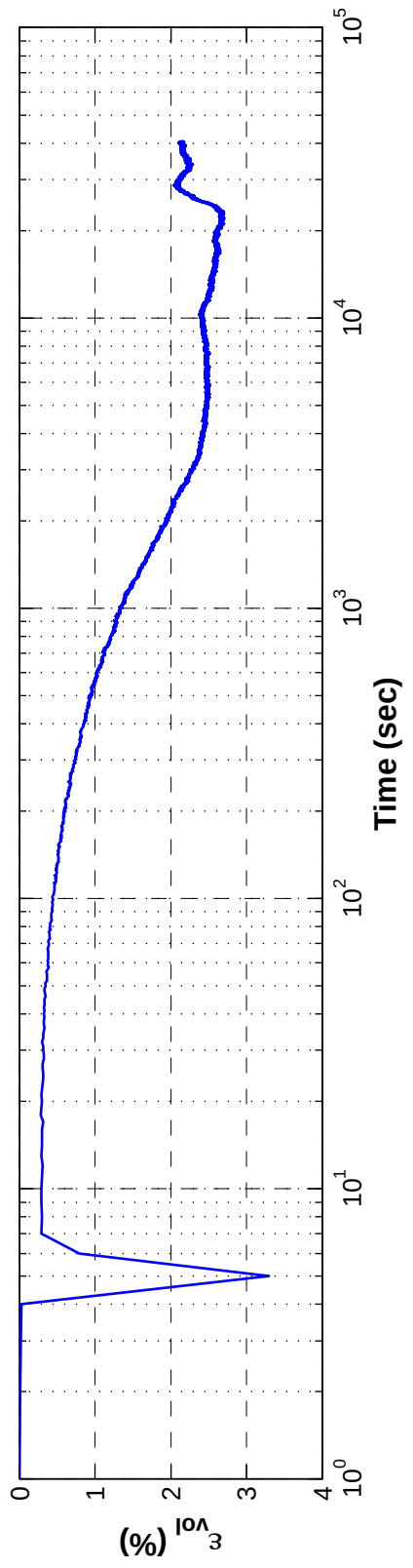
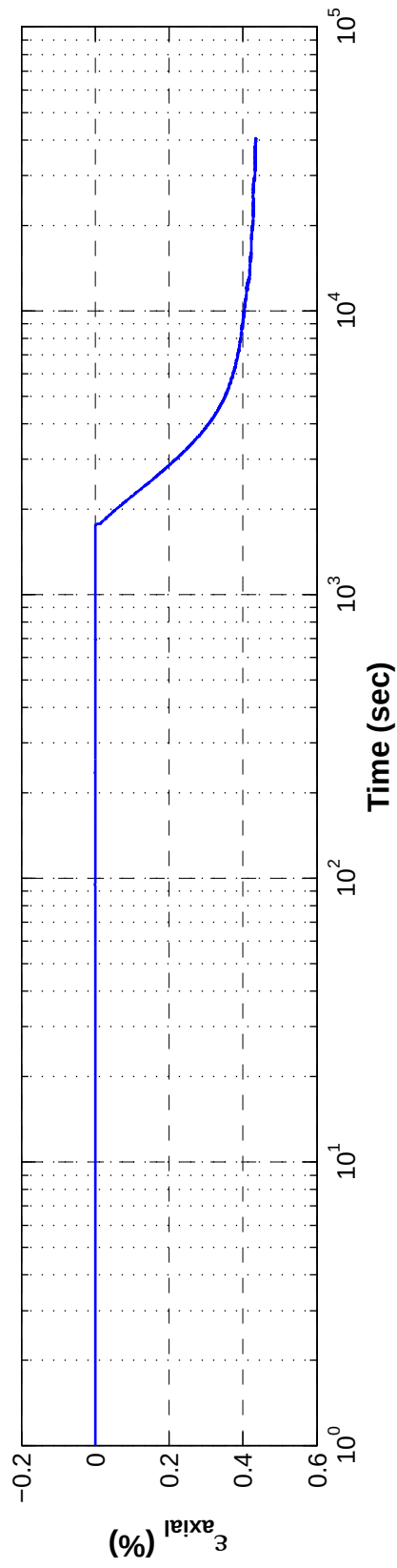
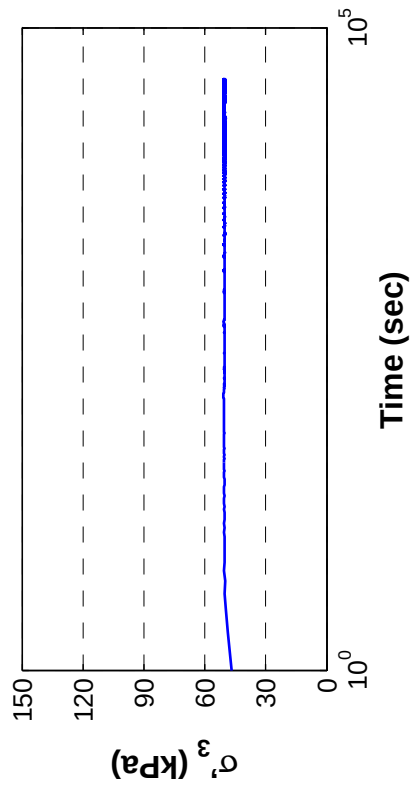
Specimen and Isotropic Consolidation Data

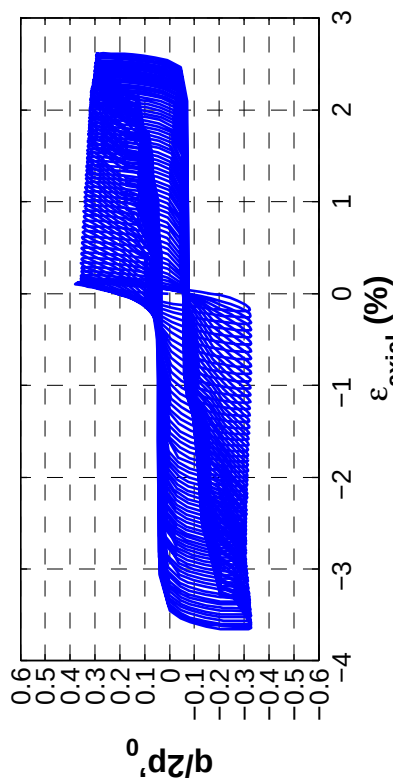
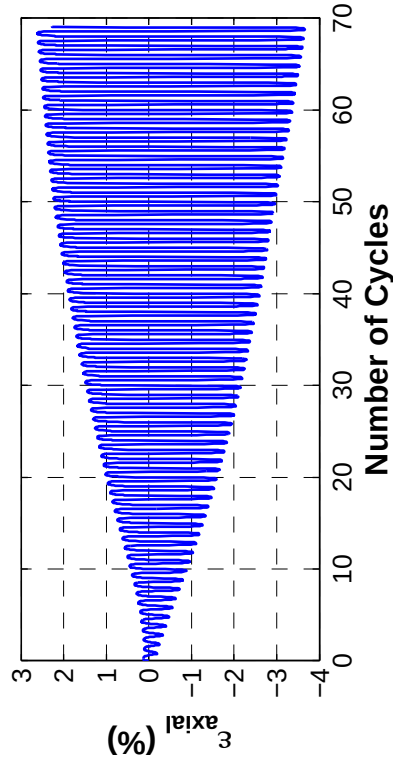
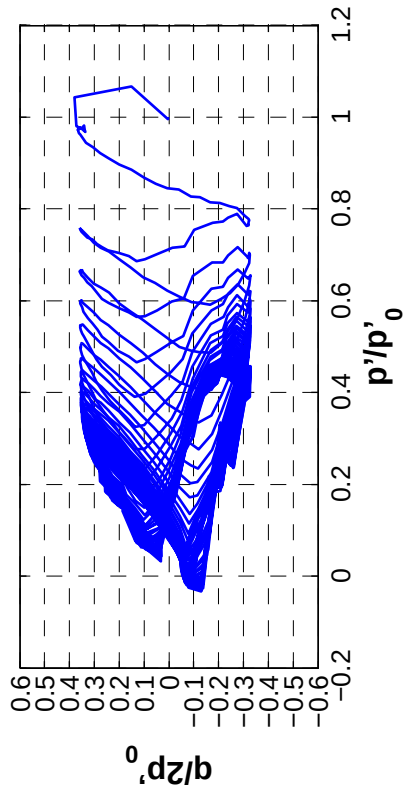
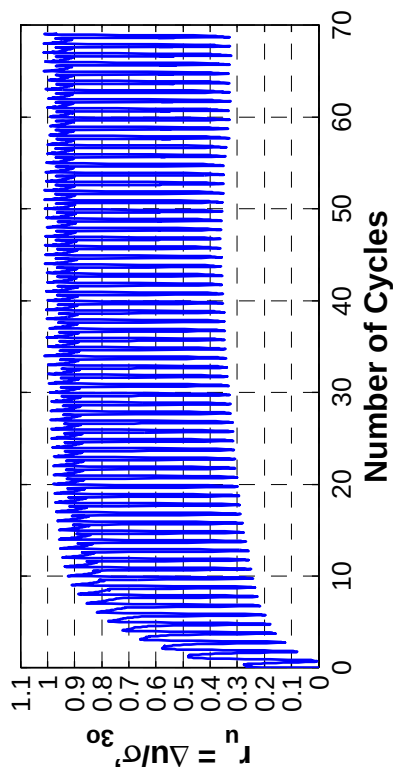
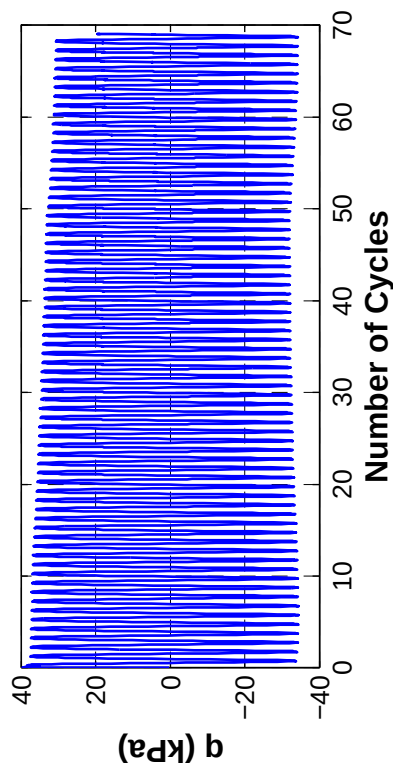
Site: Site 33
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.725
Date Tested: 11/14/13
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.725
Date Tested: 11/14/13
Date Sampled: 10/21/14



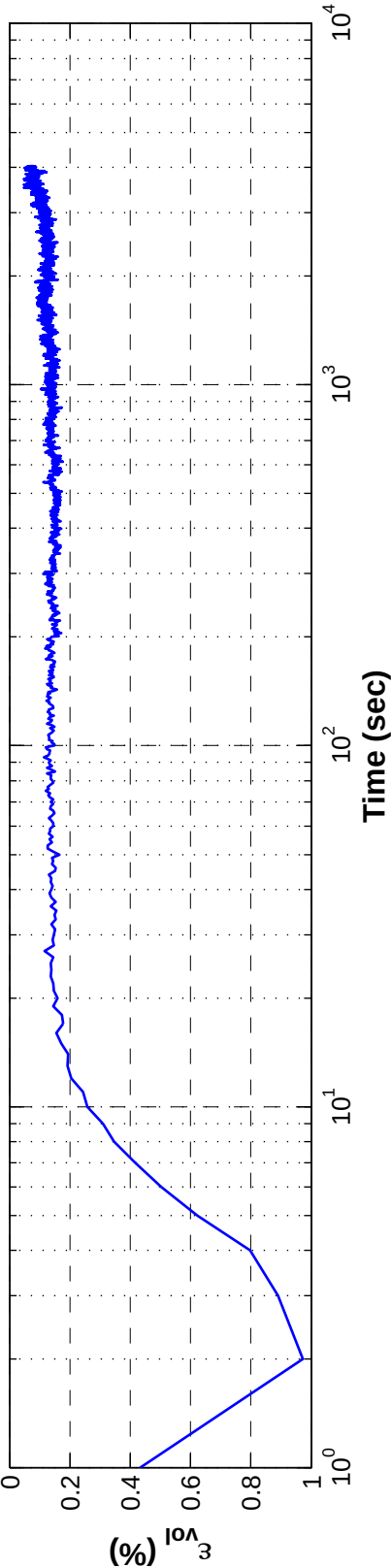
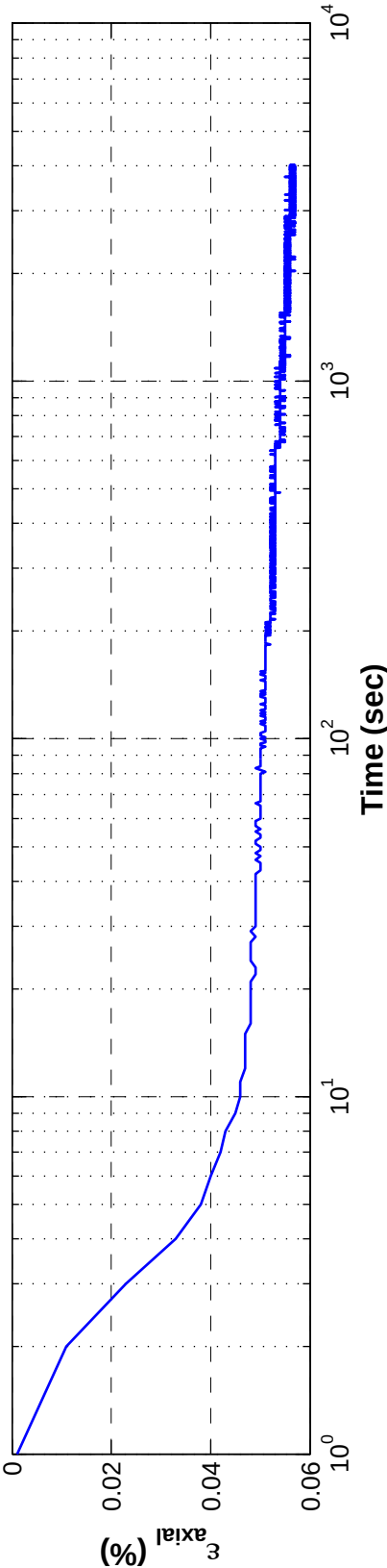
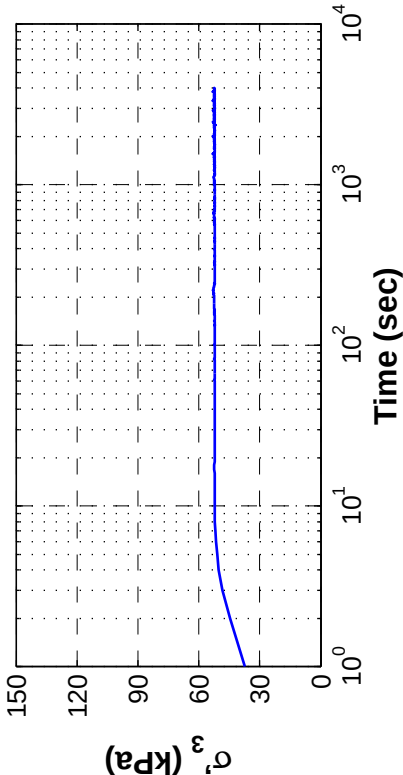


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	52
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	4U	B-Value:	0.963
Sampler Type:	D&M	CSR:	0.35
Spec. Depth (m):	3.22	N to $\epsilon_{Ax-S.A.}$ =3%:	52
Date Tested:	11/17/14	N to $\epsilon_{Ax-D.A.}$ =5%:	48
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	134.39	Gs:	2.68
Spec. Diam. (mm):	61.436	e_c :	0.73
Dry Mass (g):	614.72	PI (%):	NP
		FC (%):	11

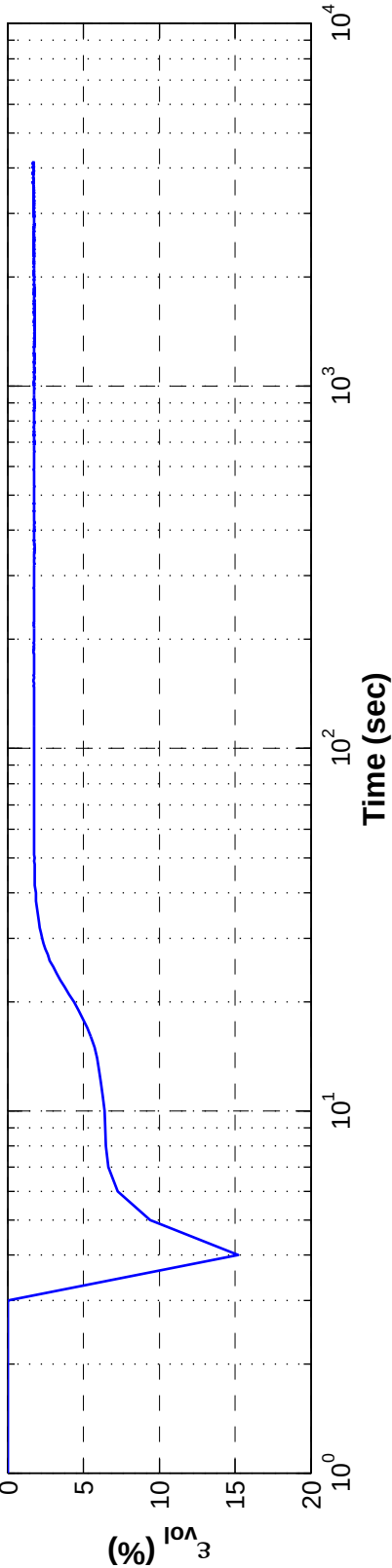
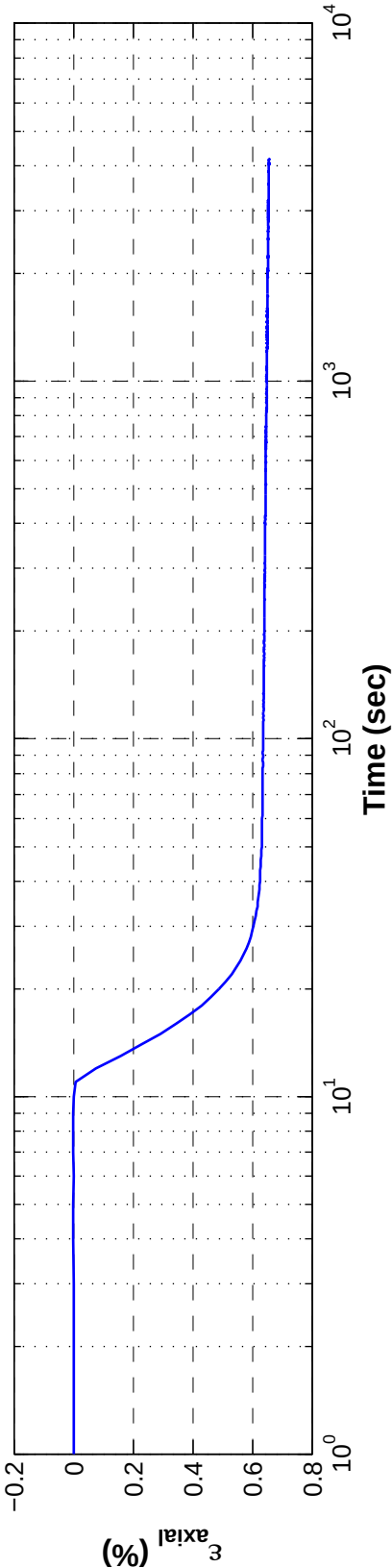
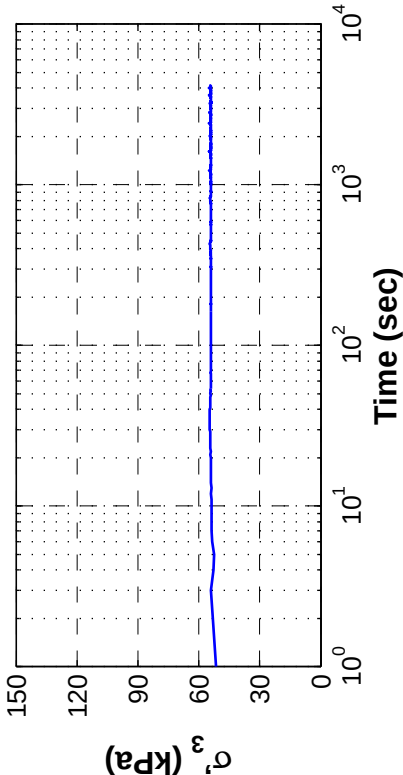
Specimen and Isotropic Consolidation Data

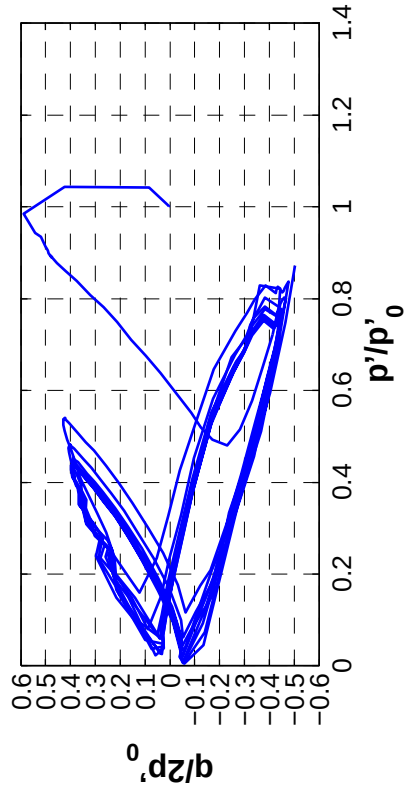
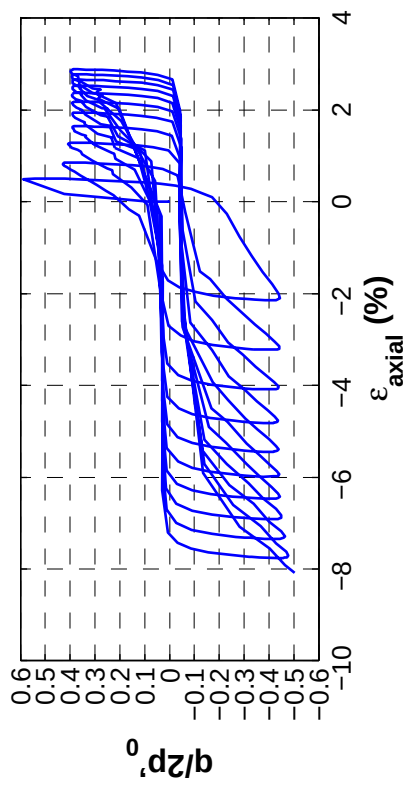
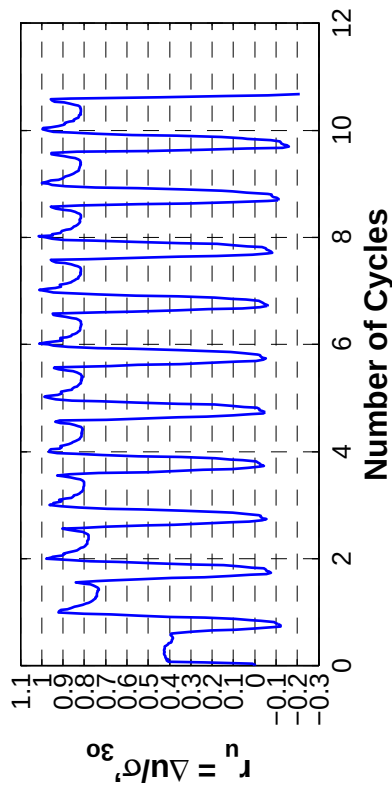
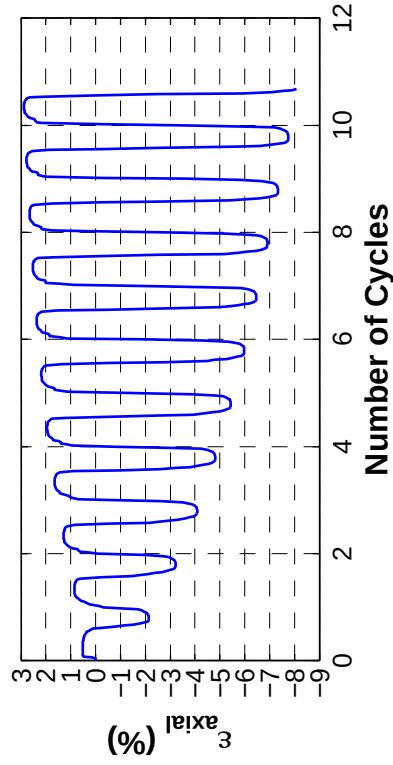
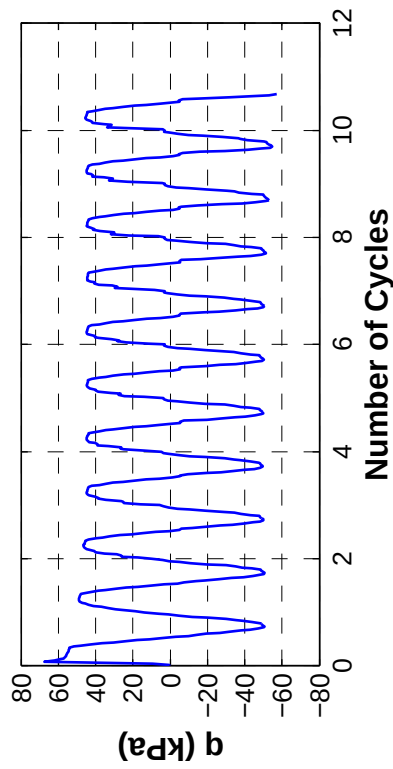
Site: Site 33
Borehole: DM-1
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 3.22
Date Tested: 11/17/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 3.22
Date Tested: 11/17/14
Date Sampled: 10/21/14



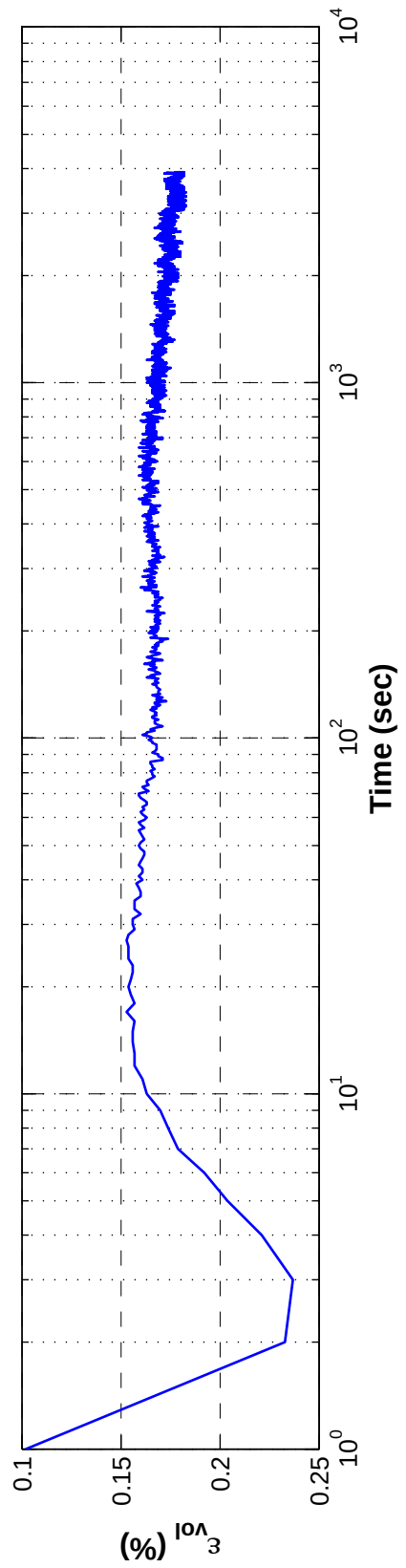
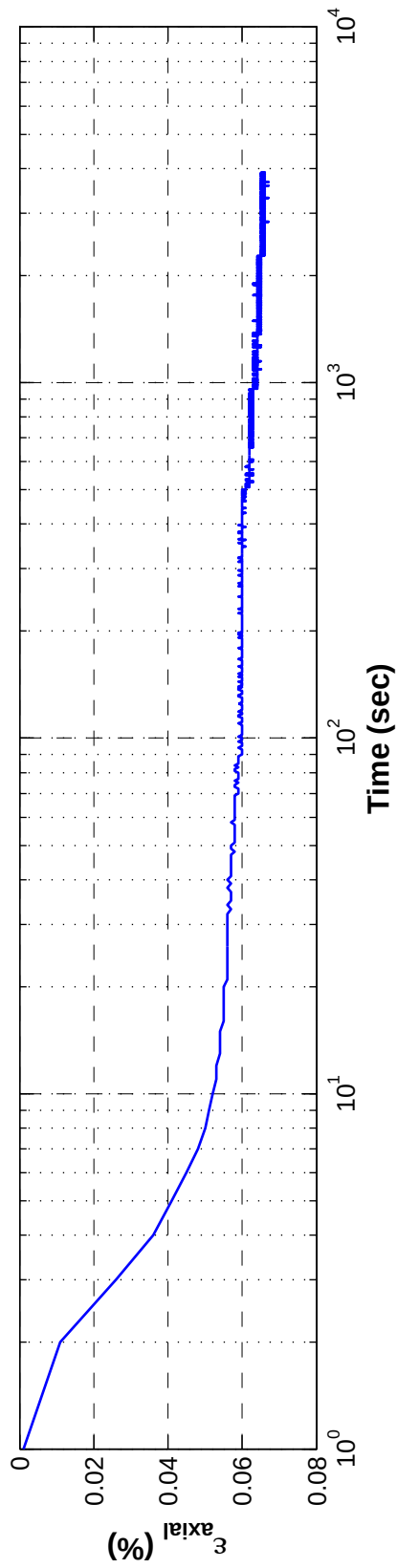
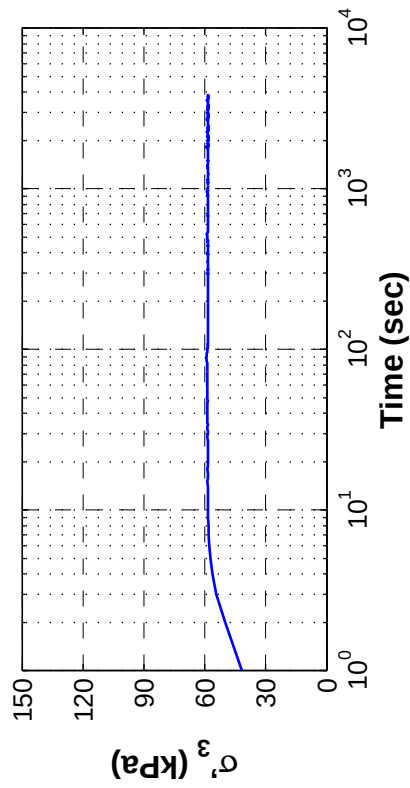


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	57
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	5U	B-Value:	0.976
Sampler Type:	D&M	CSR:	0.43
Spec. Depth (m):	3.82	N to $\epsilon_{Ax-S.A.}$ =3%:	2
Date Tested:	11/18/14	N to $\epsilon_{Ax-D.A.}$ =5%:	3
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	129.25	Gs:	2.69
Spec. Diam. (mm):	61.291	e_c :	0.87
Dry Mass (g):	548.56	PI (%):	NP
		FC (%):	10

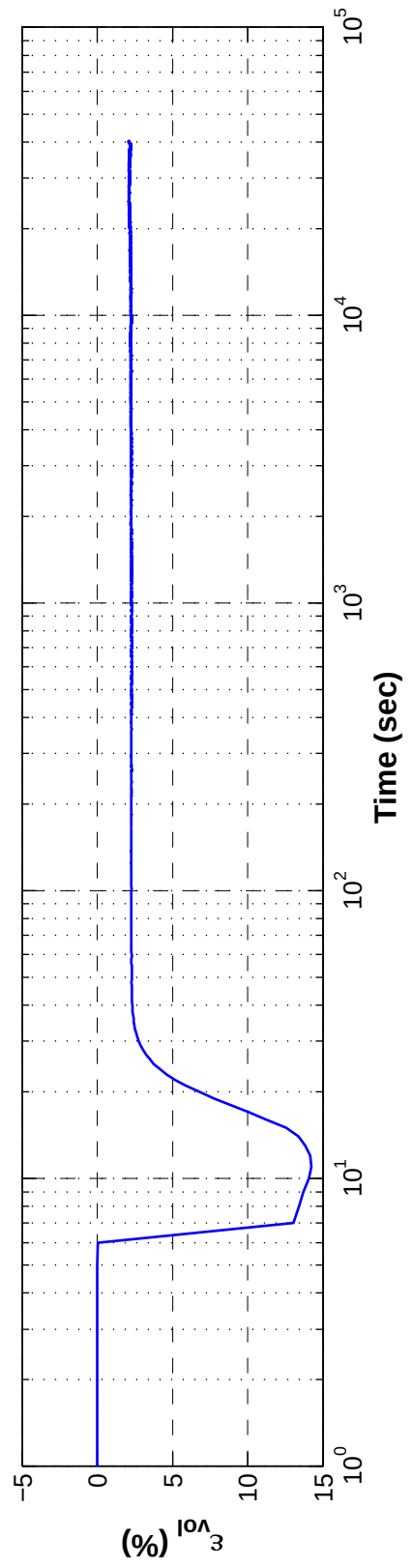
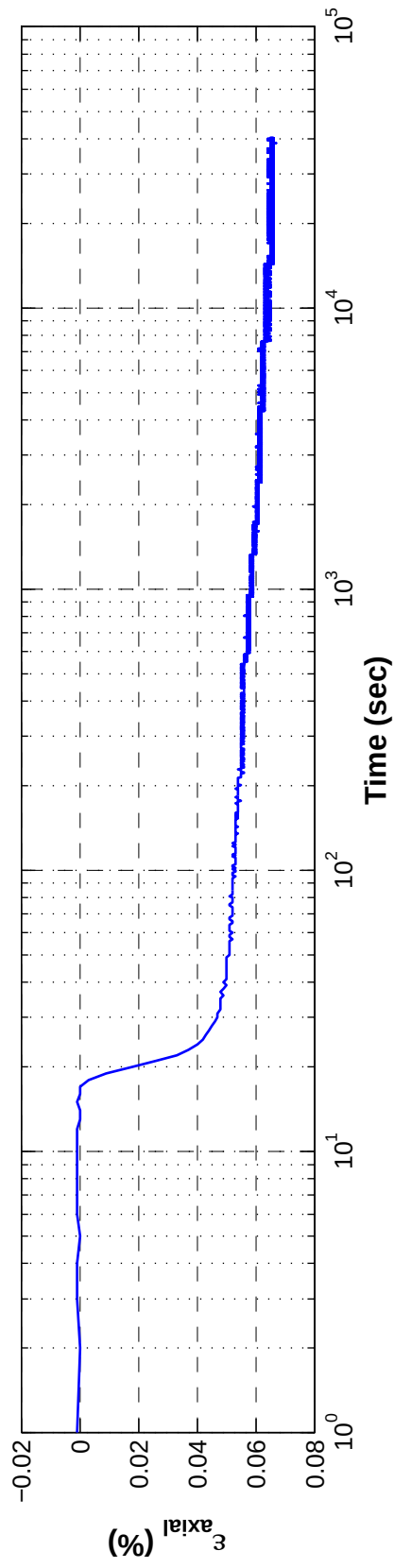
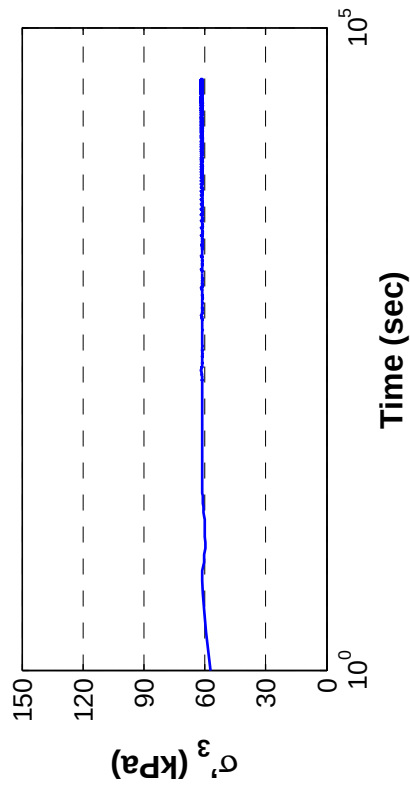
Specimen and Isotropic Consolidation Data

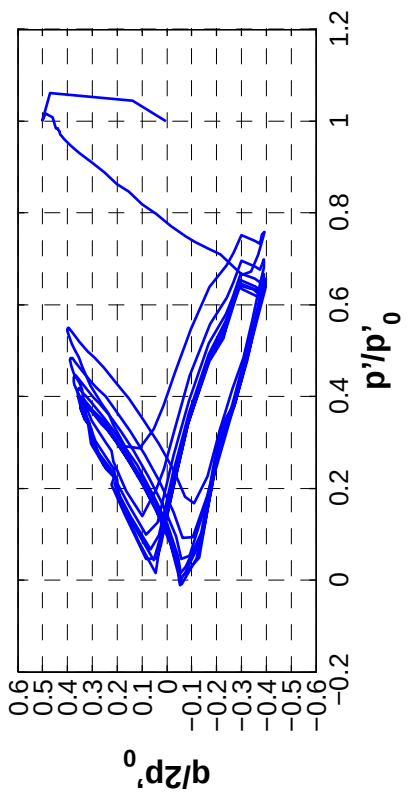
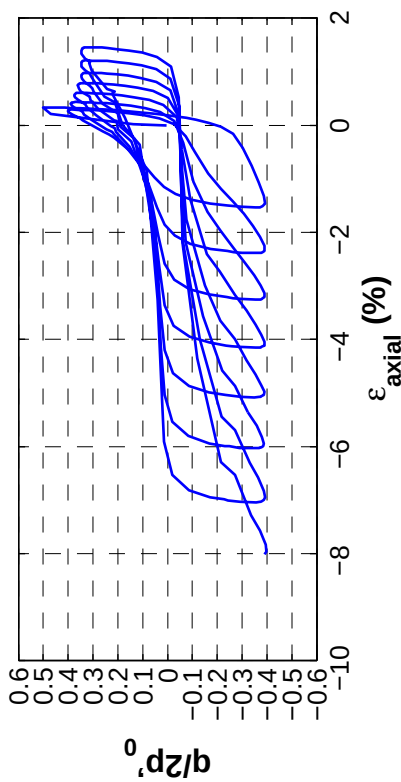
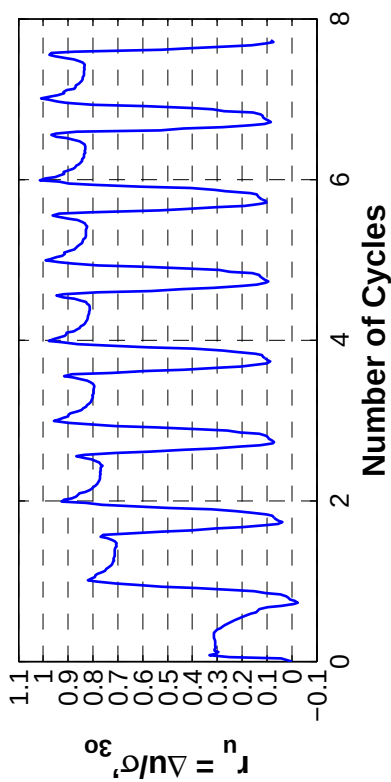
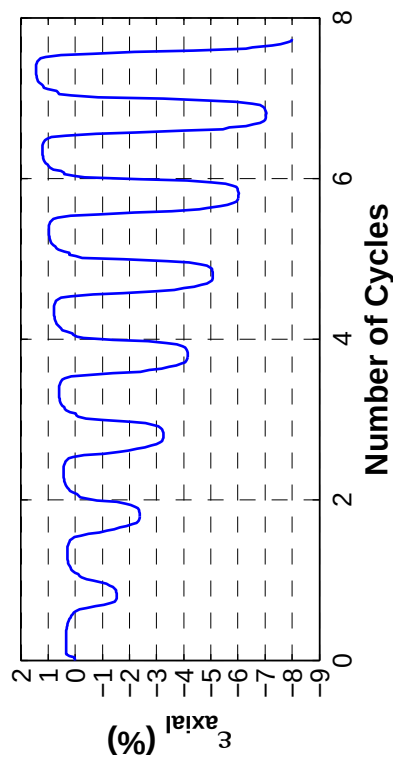
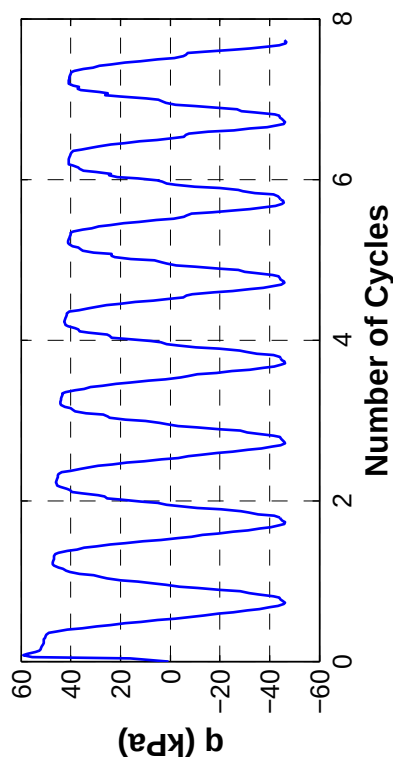
Site: Site 33
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 3.82
Date Tested: 11/18/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 3.82
Date Tested: 11/18/14
Date Sampled: 10/21/14



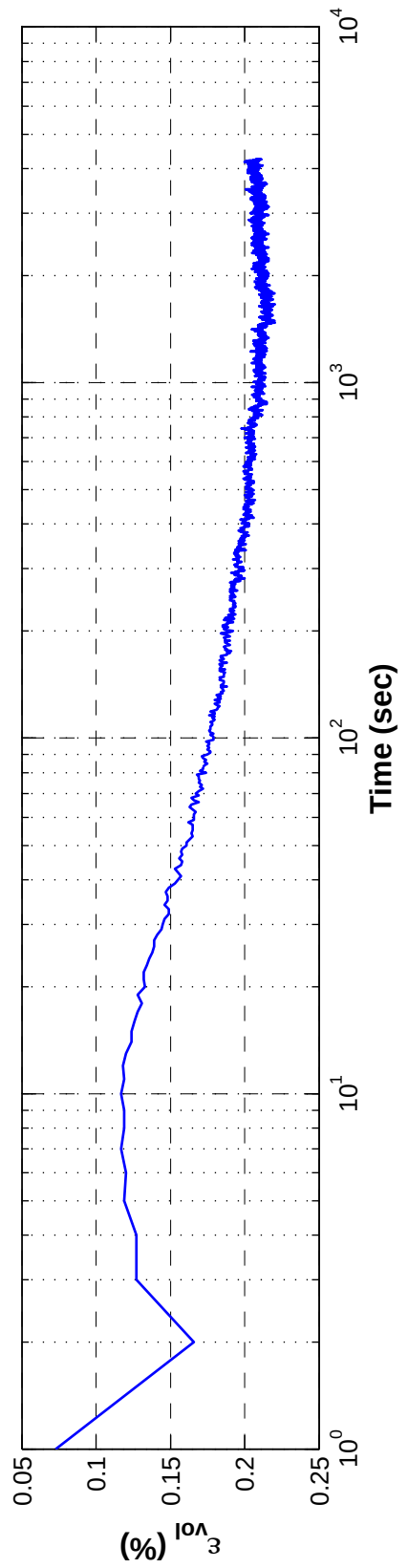
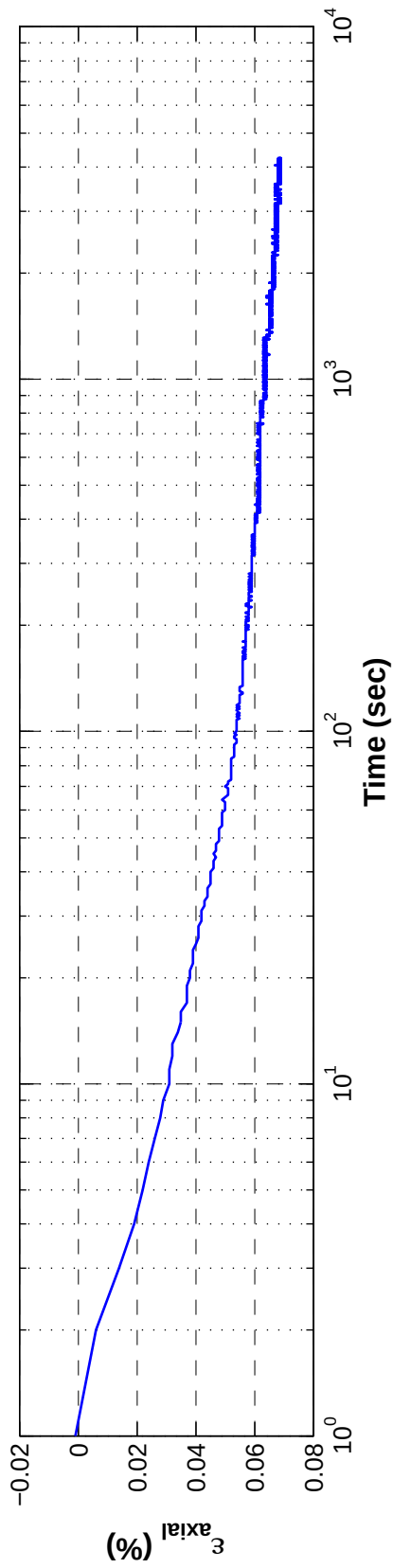
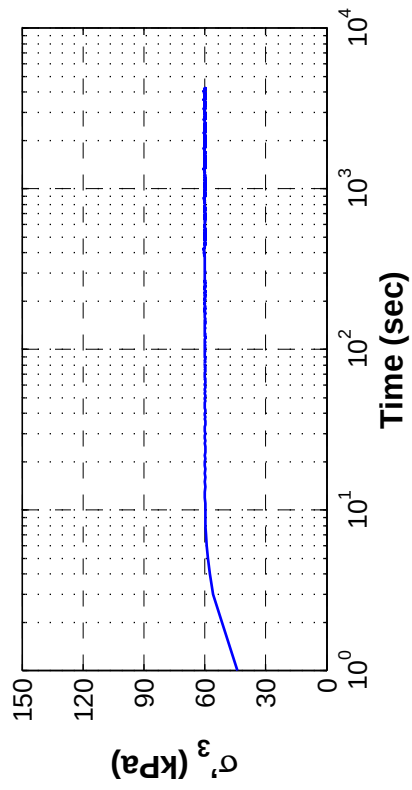


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	59
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	5U	B-Value:	0.976
Sampler Type:	D&M	CSR:	0.39
Spec. Depth (m):	3.975	N to $\epsilon_{Ax-S.A.}$ =3%:	3
Date Tested:	11/19/14	N to $\epsilon_{Ax-D.A.}$ =5%:	5
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	130.2	Gs:	---
Spec. Diam. (mm):	61.24	e_c :	0.87
Dry Mass (g):	549.57	PI (%):	NP
		FC (%):	49,82,12

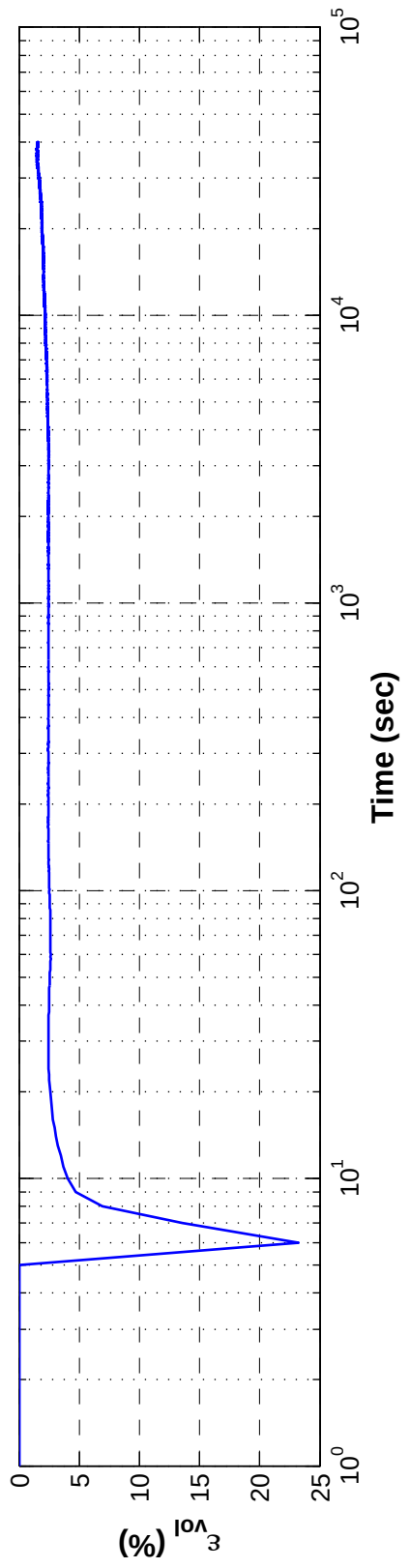
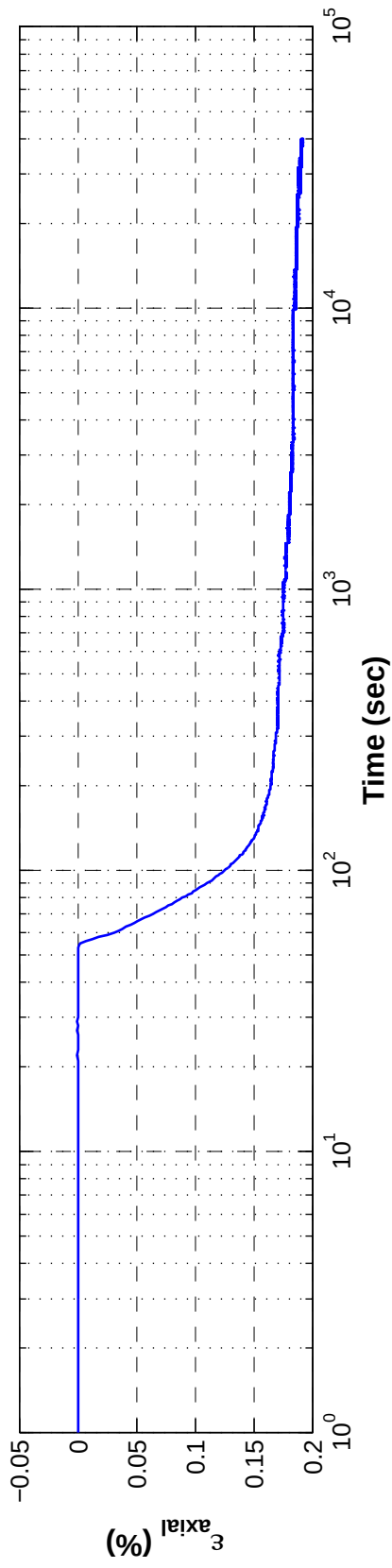
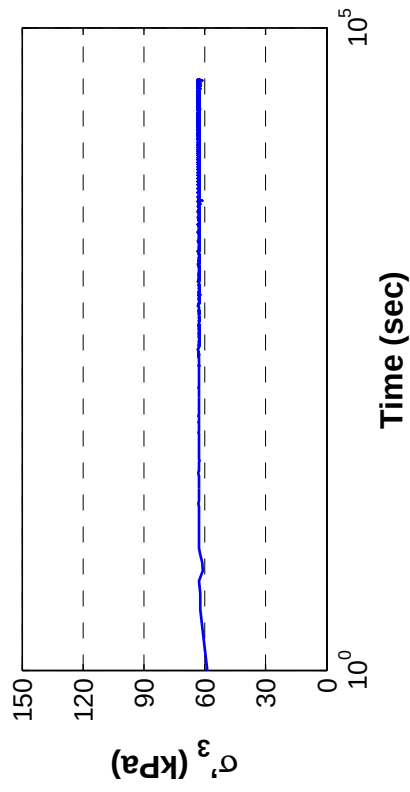
Specimen and Isotropic Consolidation Data

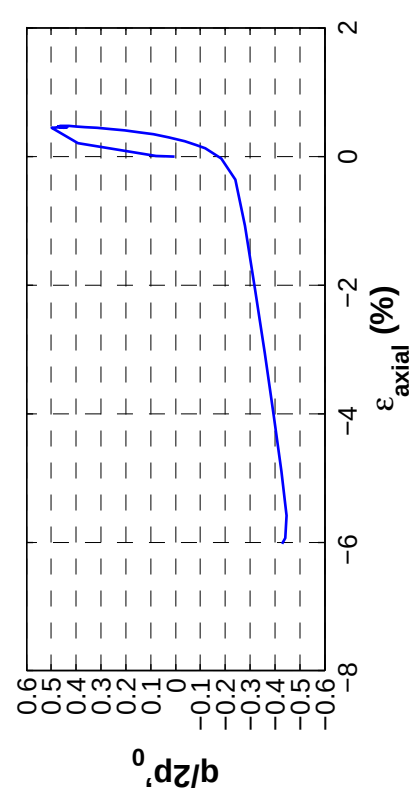
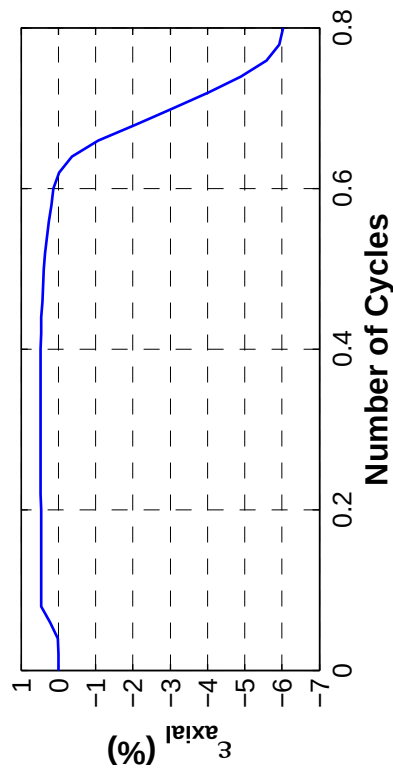
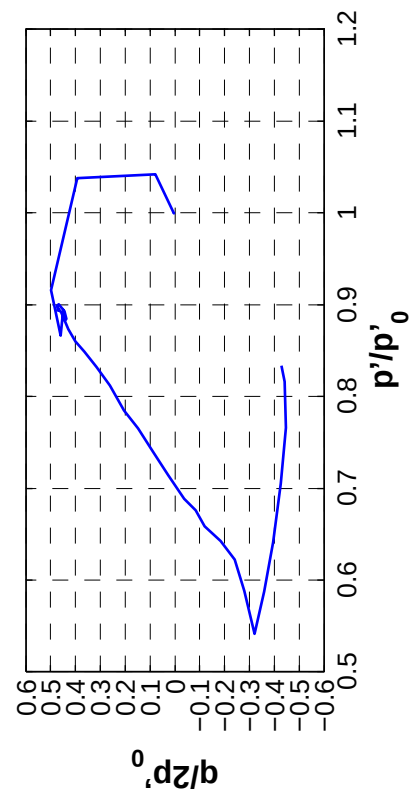
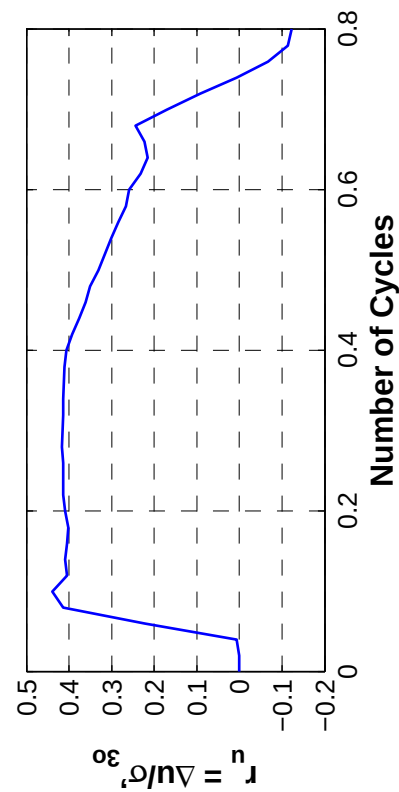
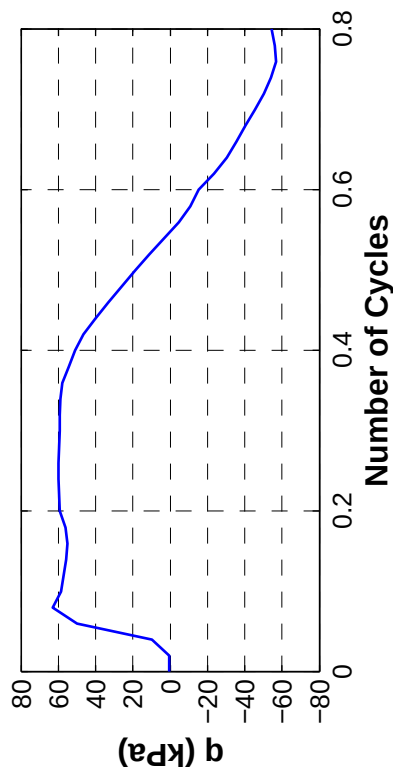
Site: Site 33
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 3.975
Date Tested: 11/19/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 3.975
Date Tested: 11/19/14
Date Sampled: 10/21/14



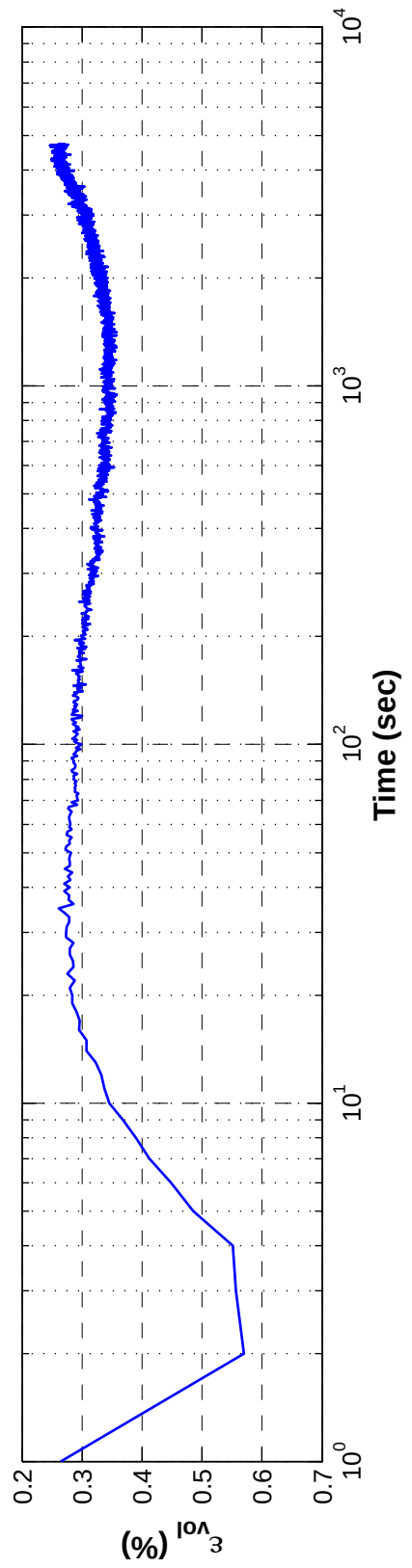
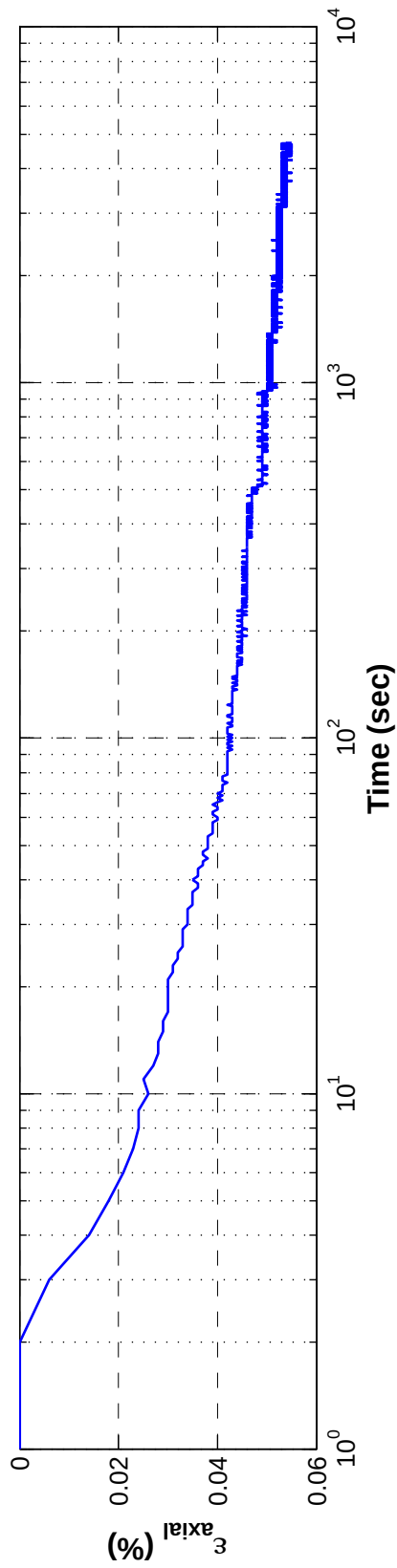
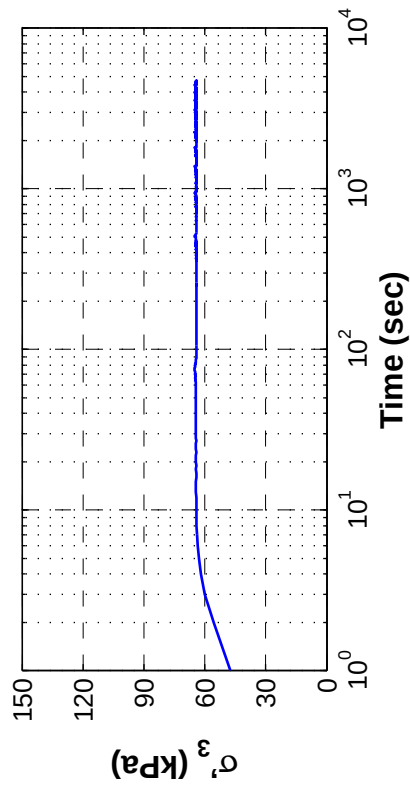


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	63
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	6U	B-Value:	0.983
Sampler Type:	D&M	CSR:	0.47
Spec. Depth (m):	4.52	N to $\epsilon_{Ax-S.A.}$ =3%:	1
Date Tested:	11/10/14	N to $\epsilon_{Ax-D.A.}$ =5%:	1
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	135.14	Gs:	2.69
Spec. Diam. (mm):	60.979	e_c :	0.97
Dry Mass (g):	536.20	PI (%):	1
		FC (%):	87

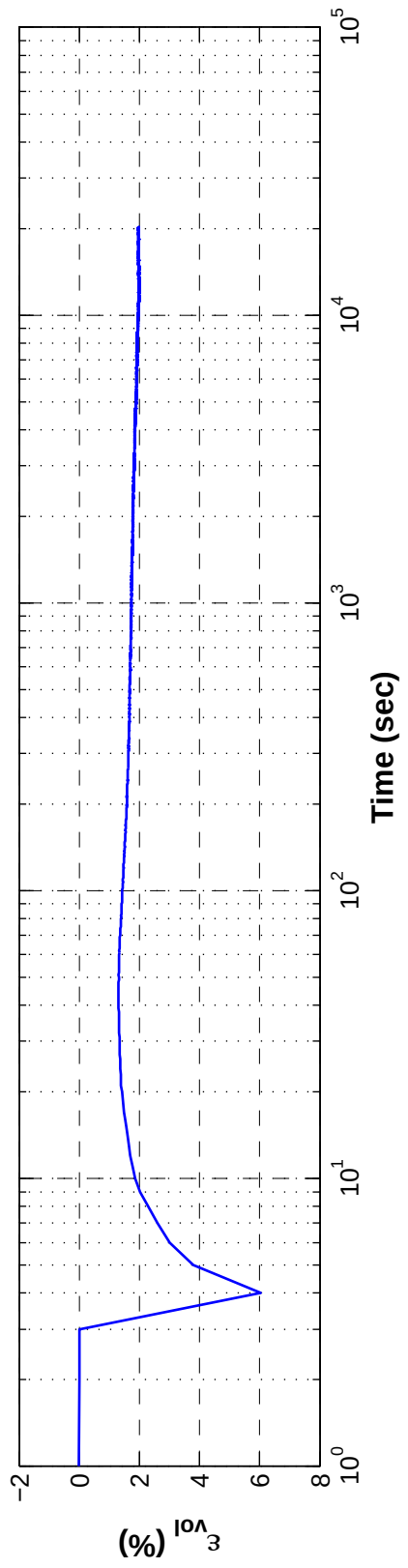
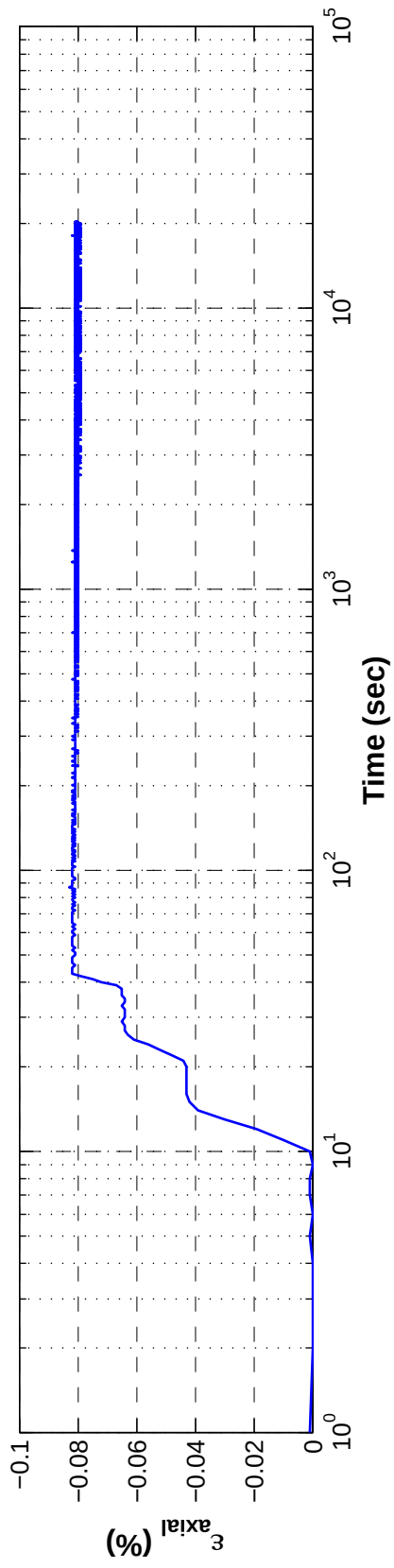
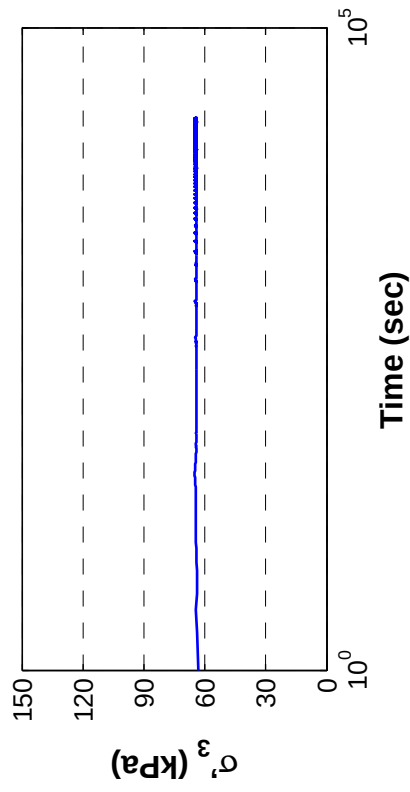
Specimen and Isotropic Consolidation Data

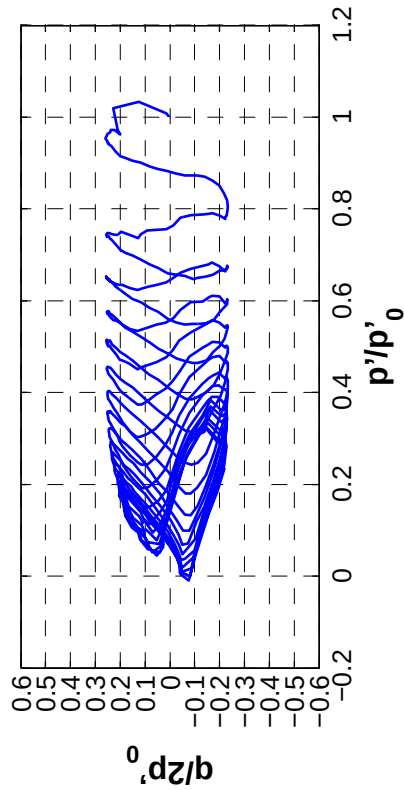
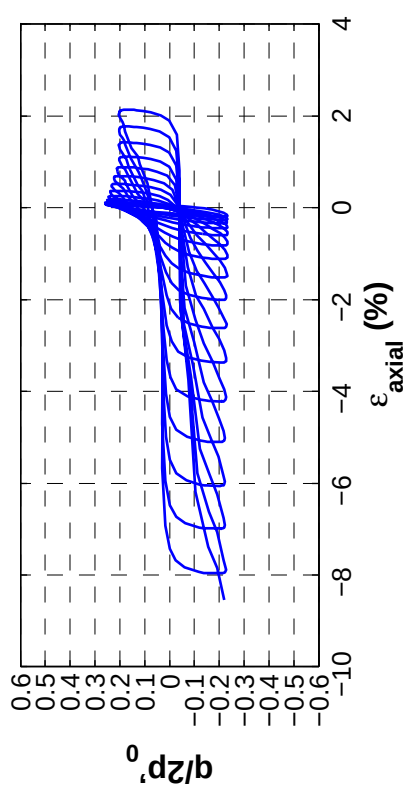
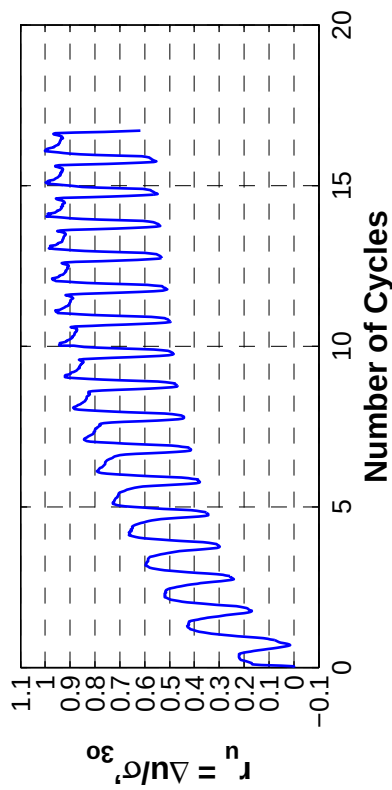
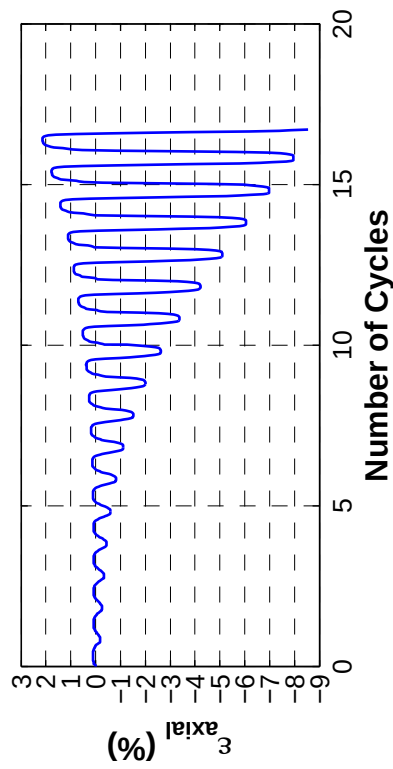
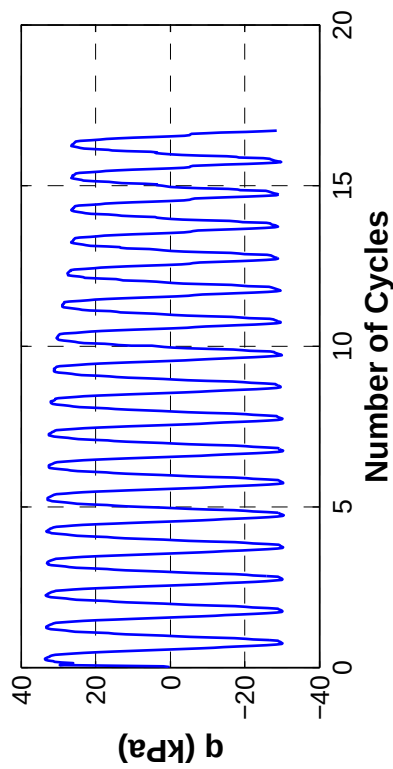
Site: Site 33
Borehole: DM-1
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 4.52
Date Tested: 11/10/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 4.52
Date Tested: 11/10/14
Date Sampled: 10/21/14



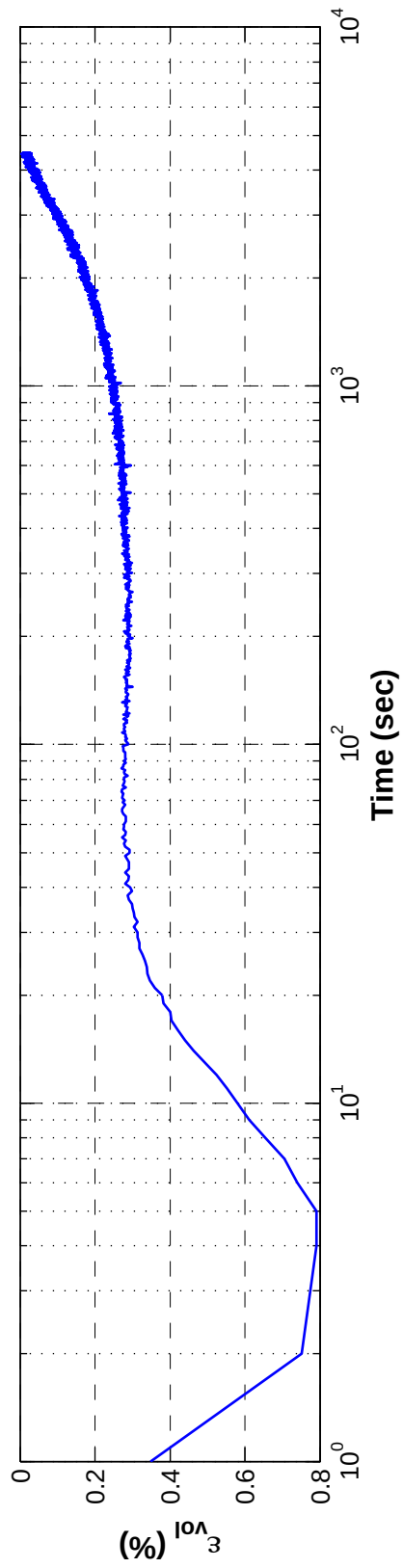
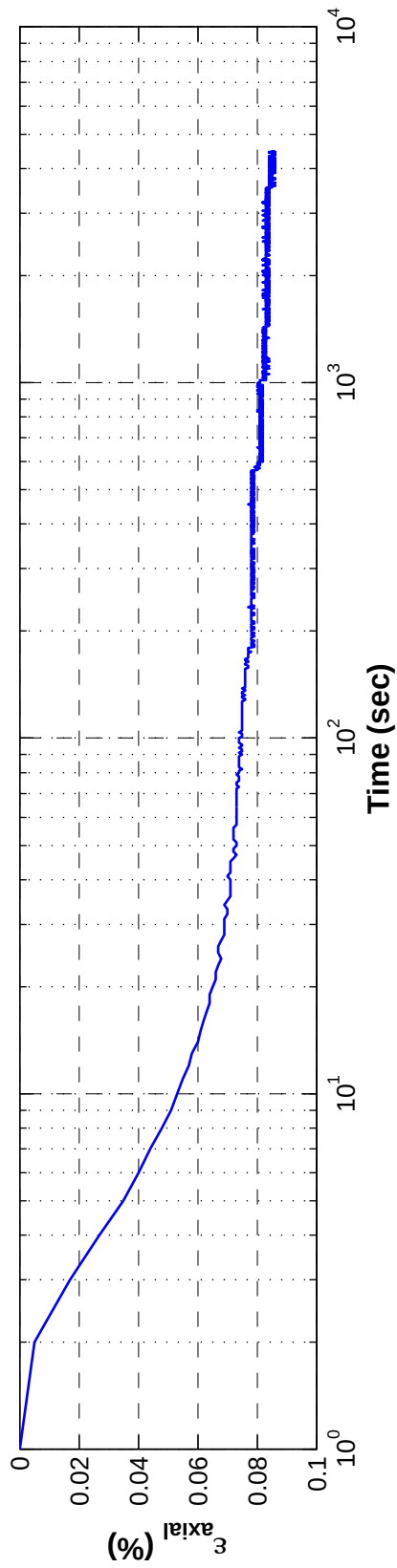
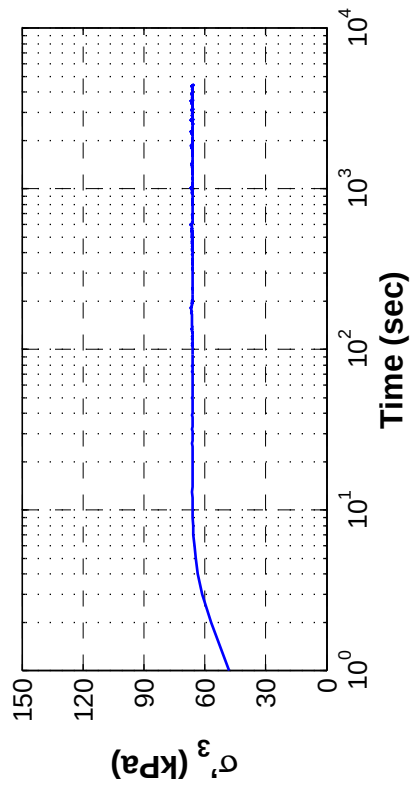


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	65
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	6U	B-Value:	0.975
Sampler Type:	D&M	CSR:	0.25
Spec. Depth (m):	4.675	N to $\epsilon_{Ax-S.A.}$ =3%:	11
Date Tested:	11/11/14	N to $\epsilon_{Ax-D.A.}$ =5%:	13
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	136.81	Gs:	---
Spec. Diam. (mm):	61.198	e_c :	0.96
Dry Mass (g):	550.68	PI (%):	NP
		FC (%):	47.78

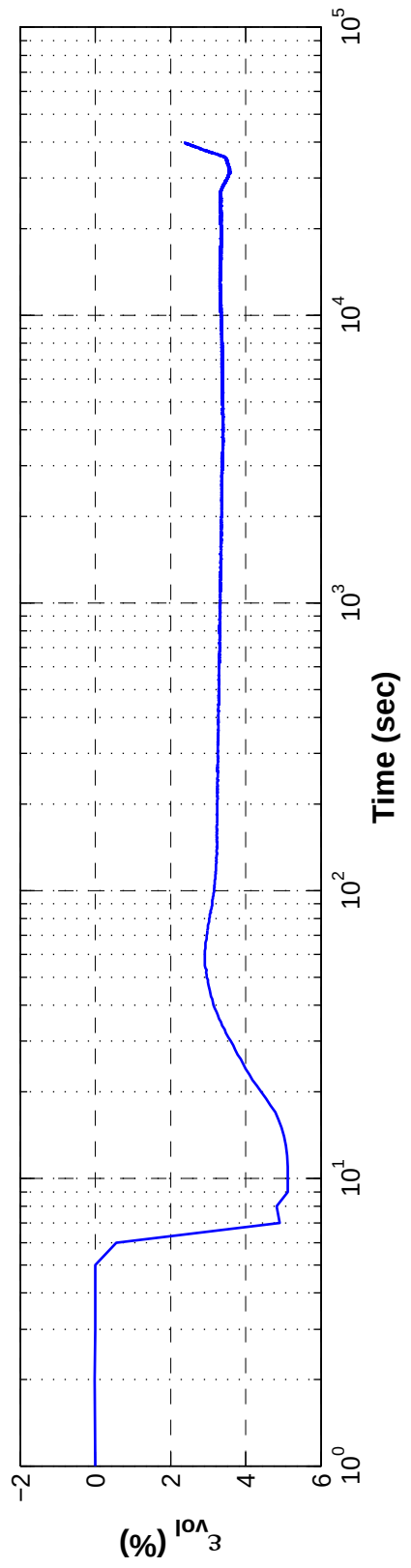
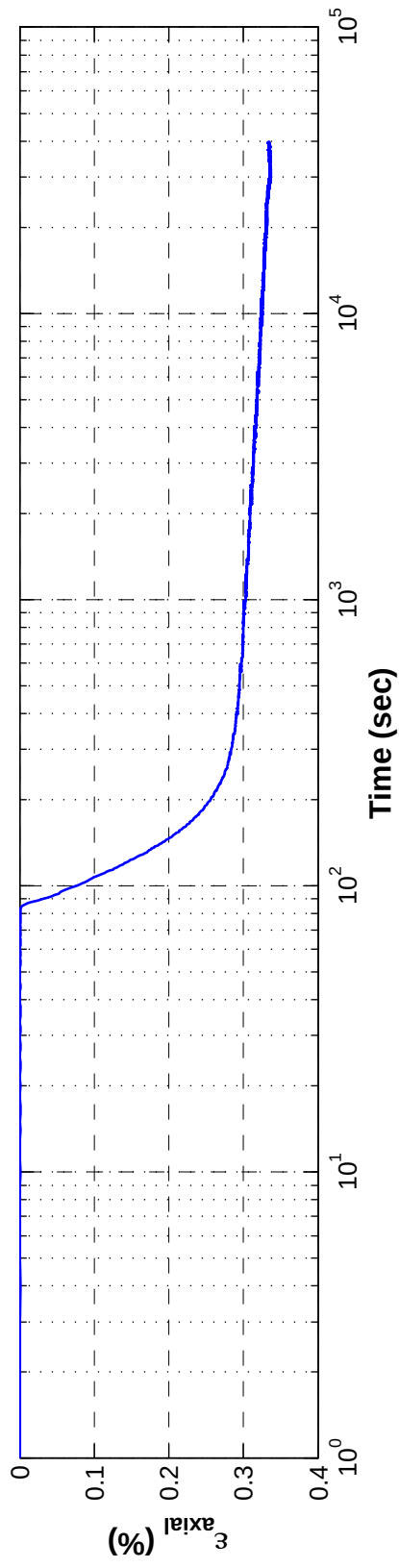
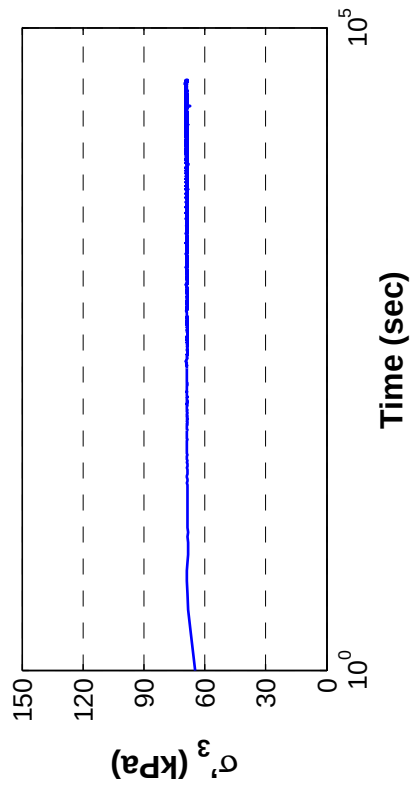
Specimen and Isotropic Consolidation Data

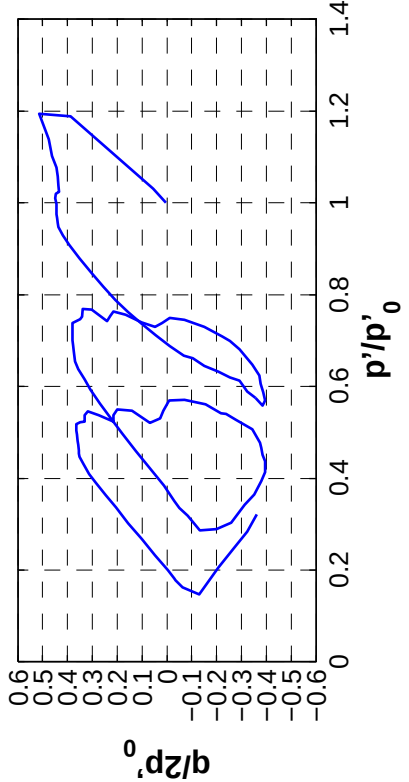
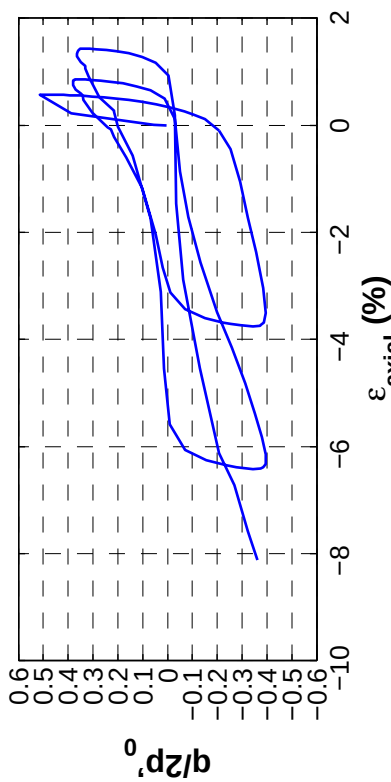
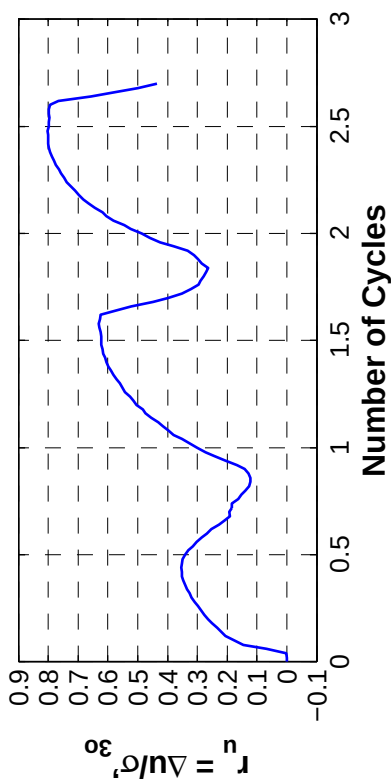
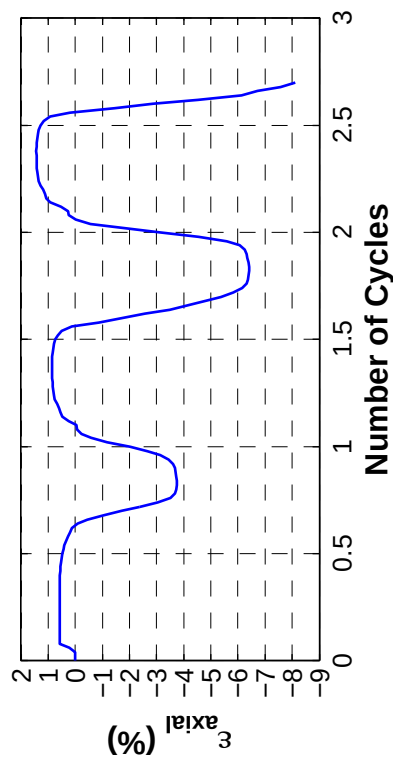
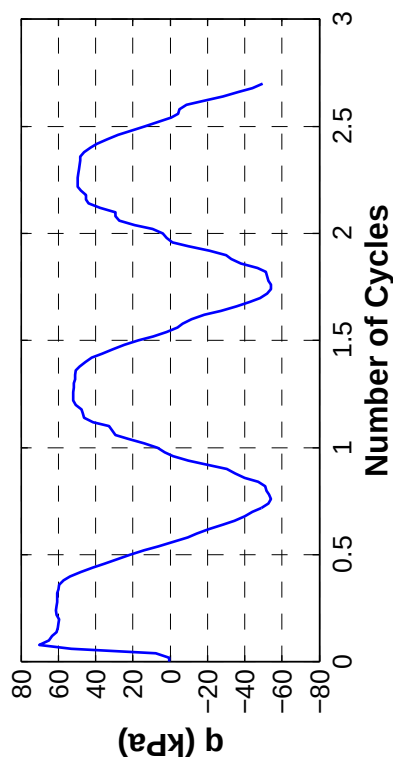
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Borehole: DM-1
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 4.675
Date Tested: 11/11/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 4.675
Date Tested: 11/11/14
Date Sampled: 10/21/14



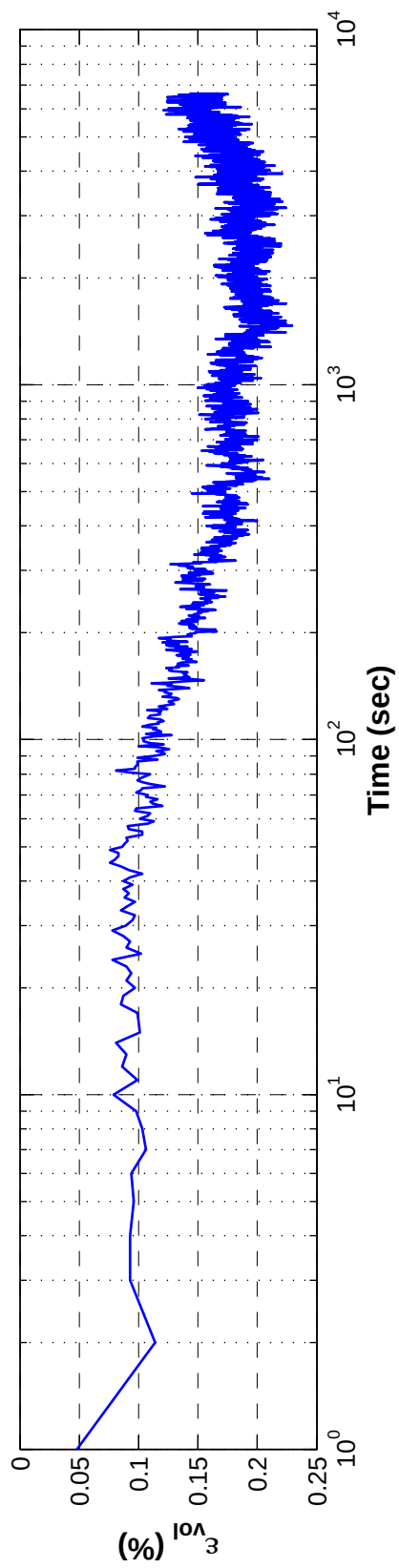
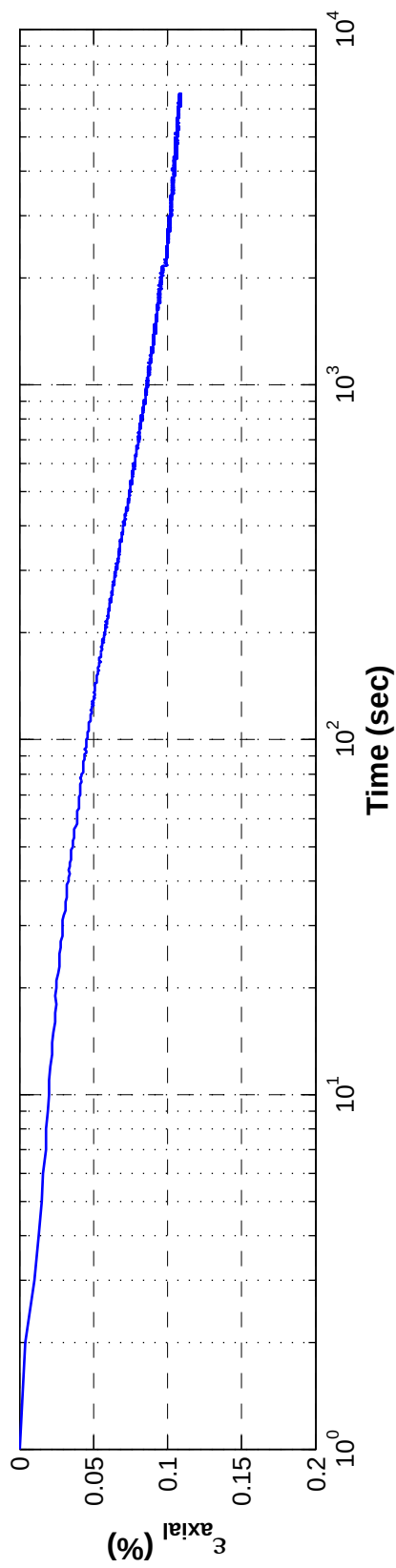
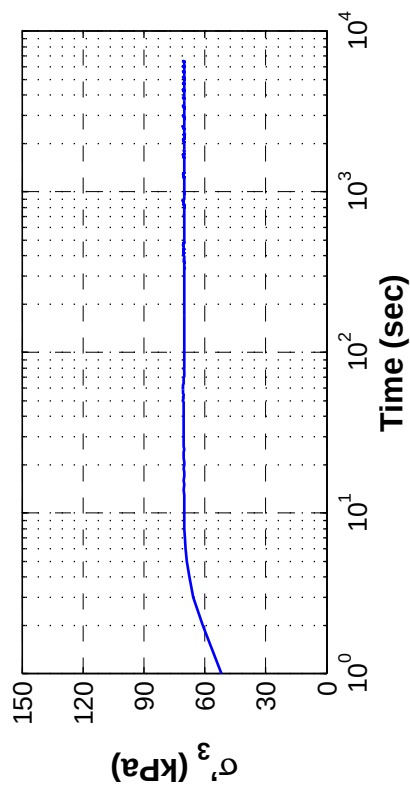


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	68
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	7U	B-Value:	0.979
Sampler Type:	D&M	CSR:	0.42
Spec. Depth (m):	5.12	N to $\epsilon_{Ax-S.A.}$ =3%:	1
Date Tested:	11/21/14	N to $\epsilon_{Ax-D.A.}$ =5%:	2
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	136.87	Gs:	2.68
Spec. Diam. (mm):	61.1	e_c :	0.97
Dry Mass (g):	547.38	PI (%):	---
		FC (%):	83

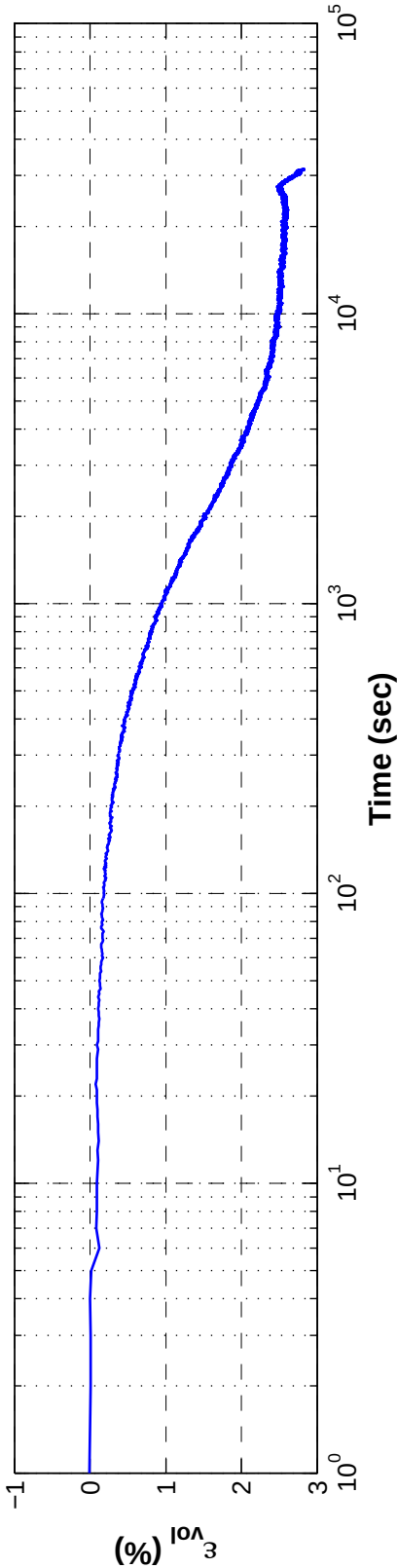
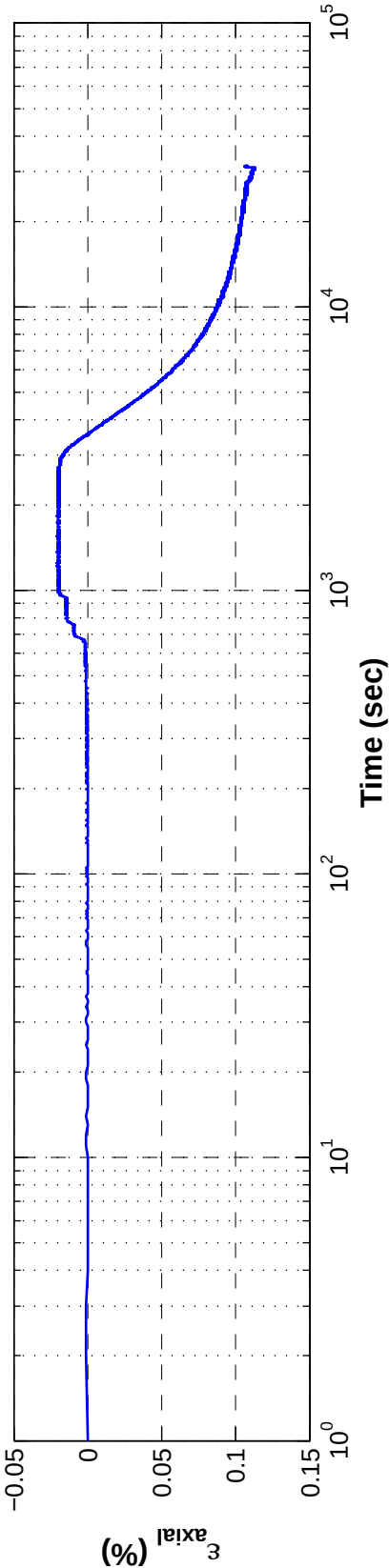
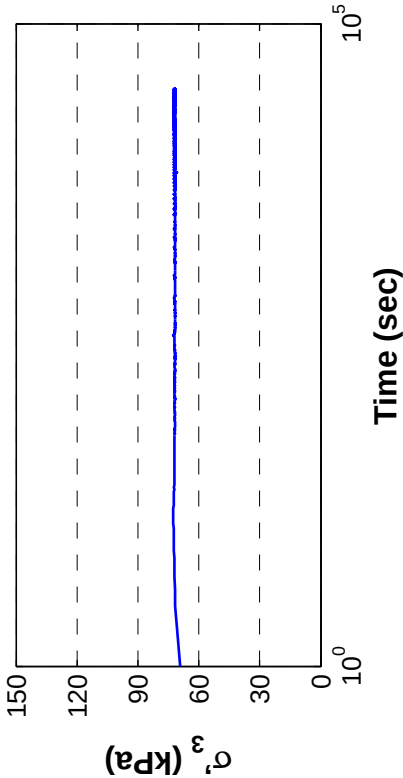
Specimen and Isotropic Consolidation Data

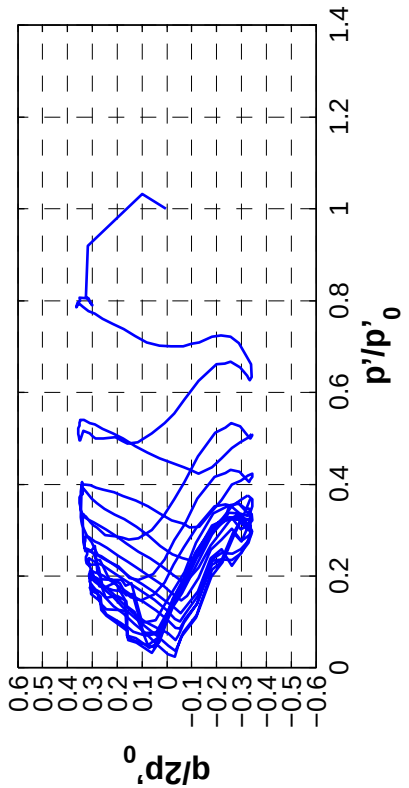
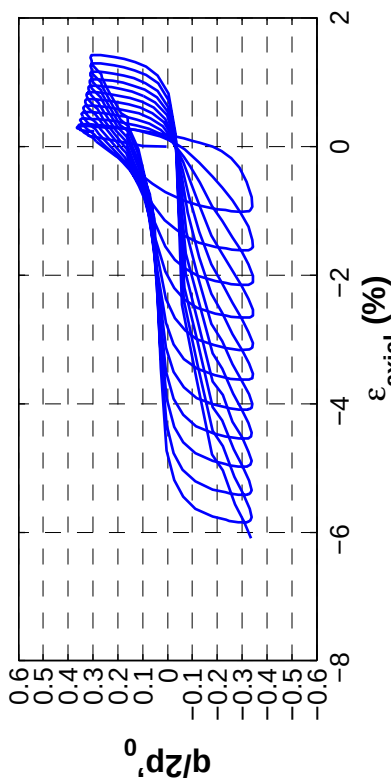
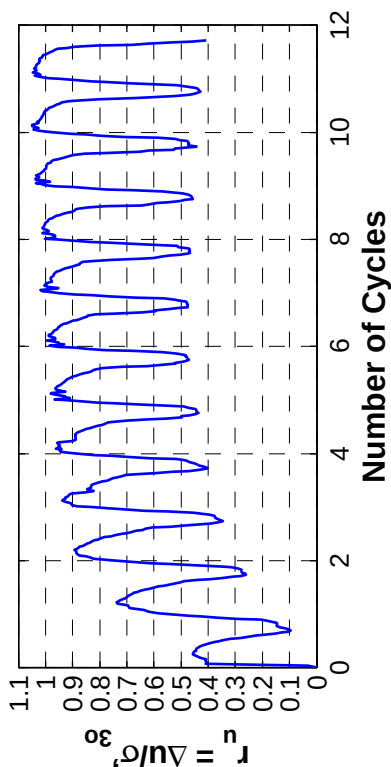
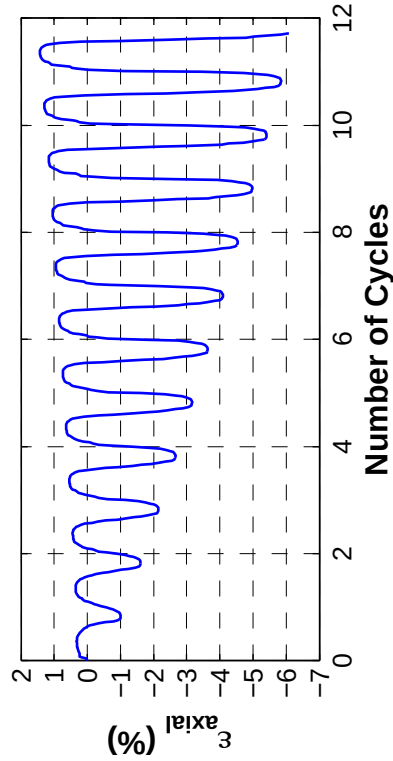
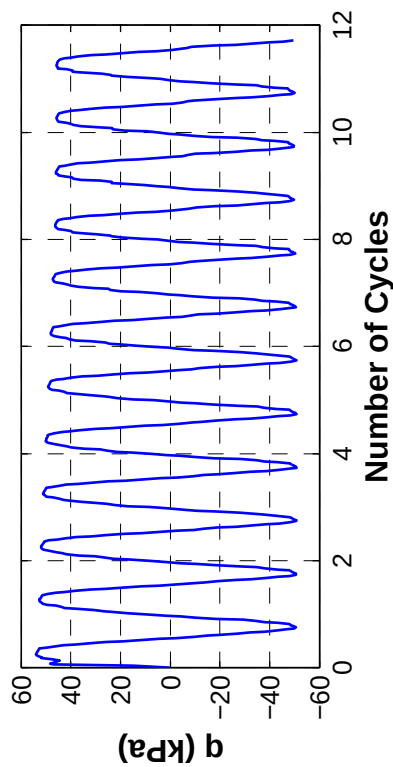
Site: Site 33
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 5.12
Date Tested: 11/21/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 5.12
Date Tested: 11/21/14
Date Sampled: 10/21/14



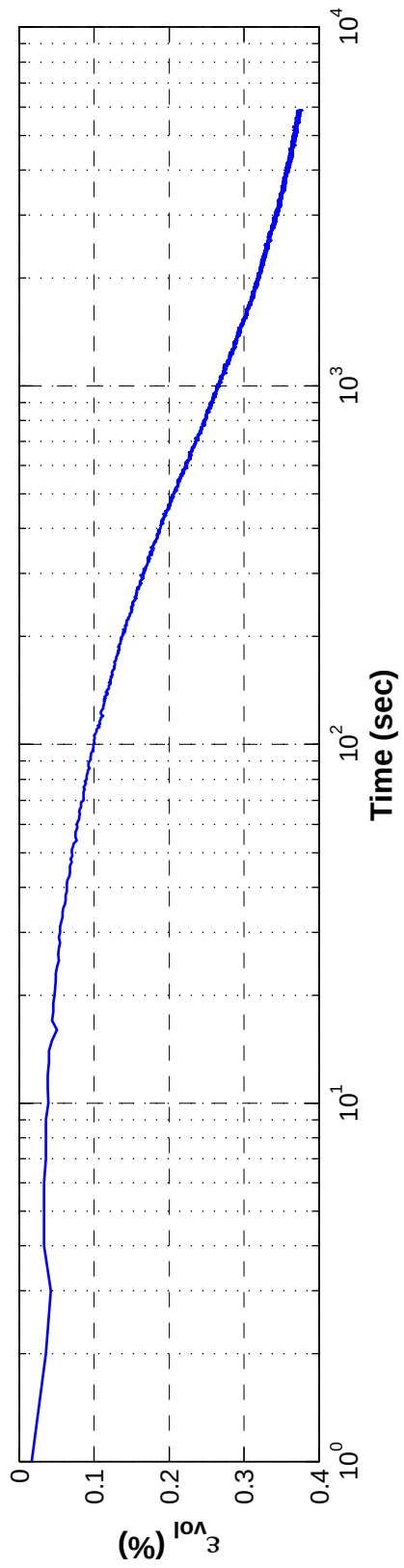
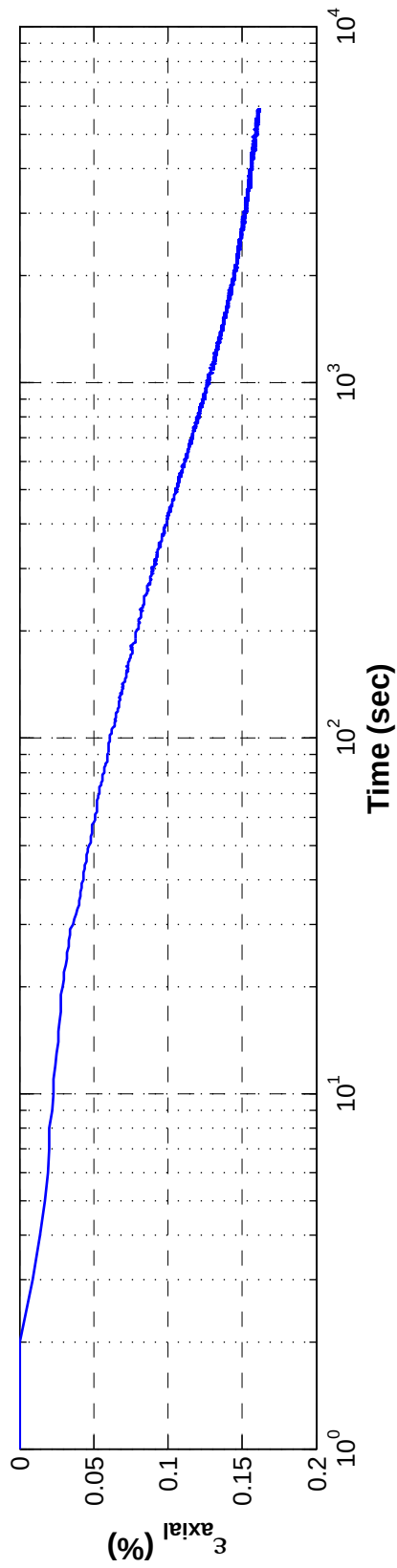
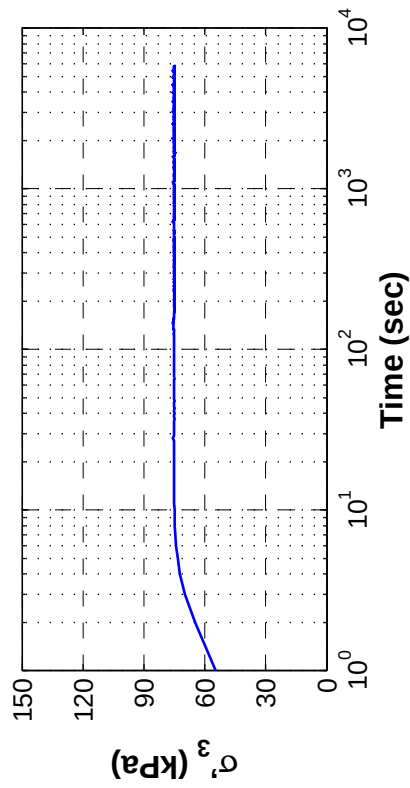


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	74
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	8U	B-Value:	0.988
Sampler Type:	D&M	CSR:	0.35
Spec. Depth (m):	5.72	N to $\epsilon_{Ax-S.A.}$ =3%:	5
Date Tested:	11/6/14	N to $\epsilon_{Ax-D.A.}$ =5%:	7.5
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	131.75	Gs:	2.67
Spec. Diam. (mm):	61.047	e_c :	0.92
Dry Mass (g):	534.17	PI (%):	10
		FC (%):	100

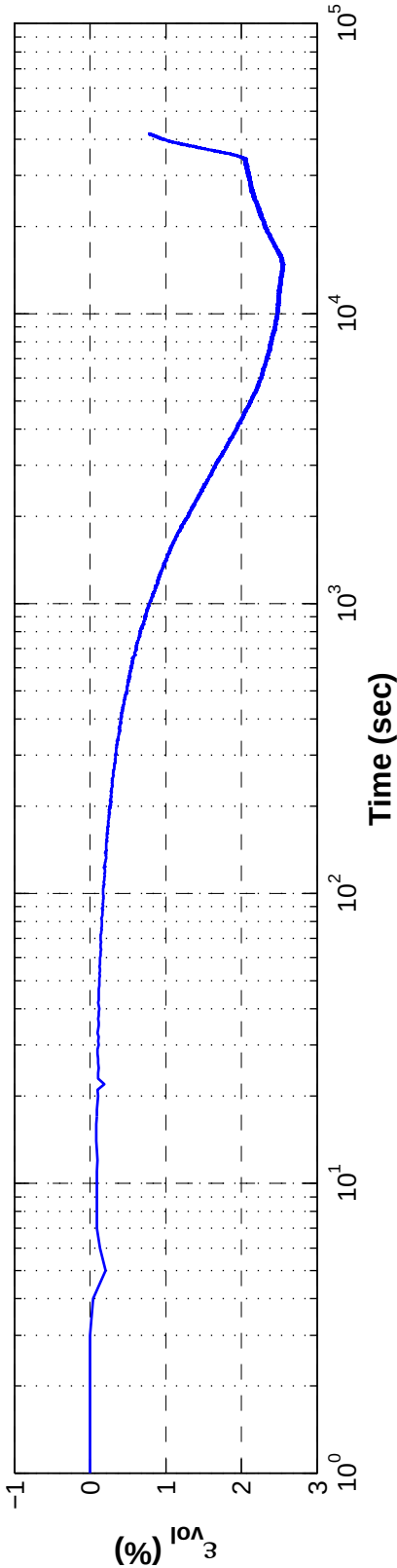
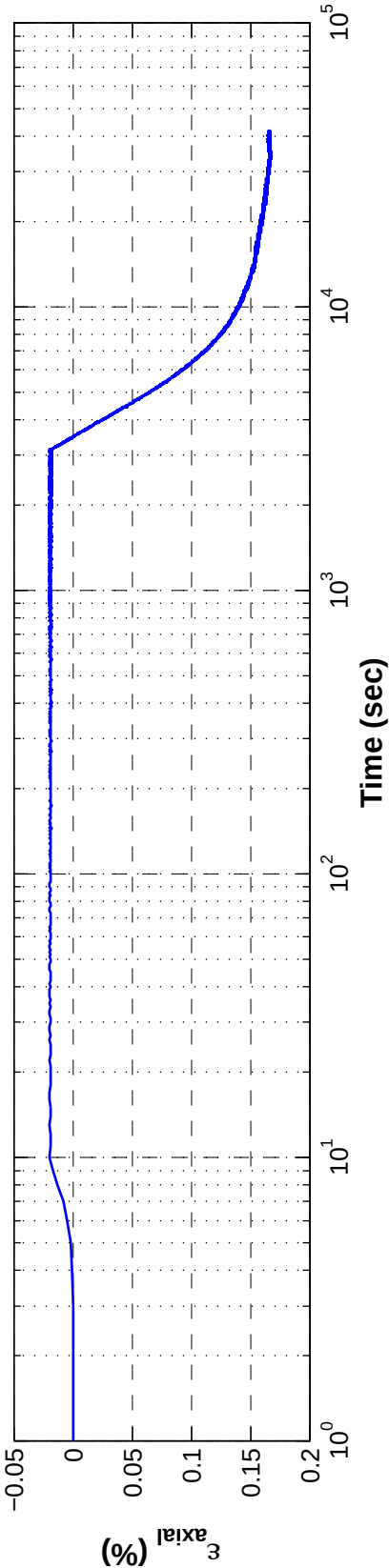
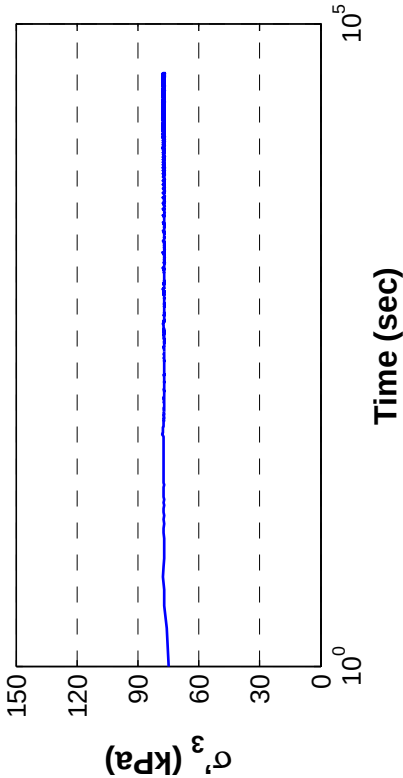
Specimen and Isotropic Consolidation Data

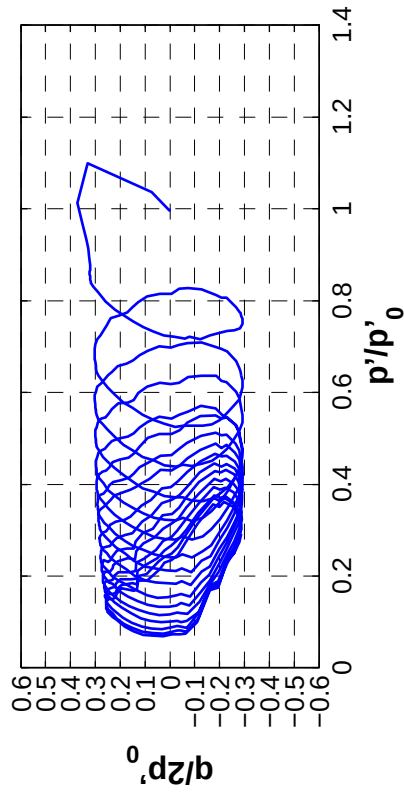
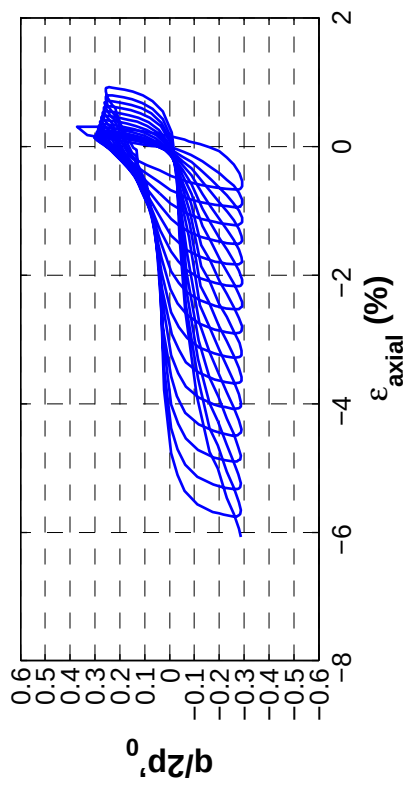
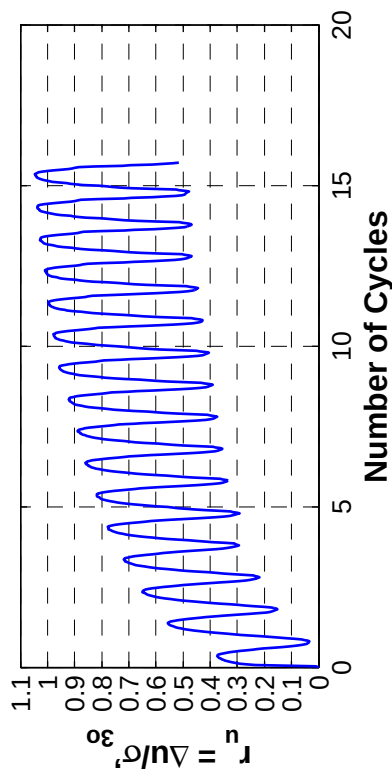
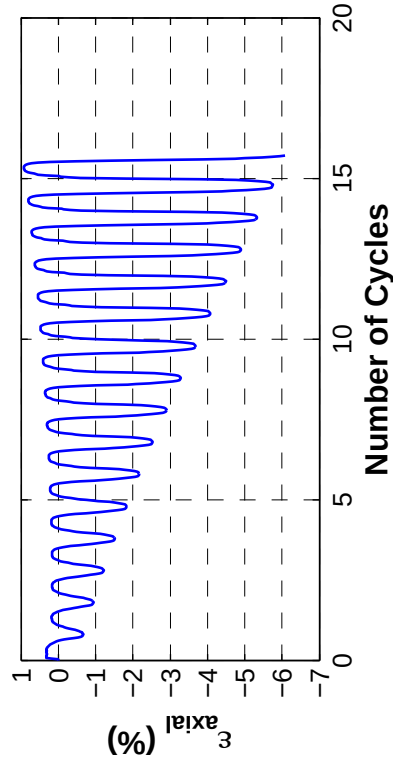
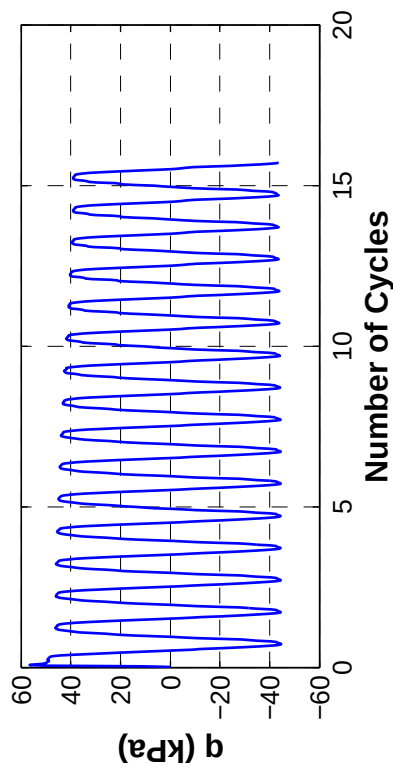
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Borehole: DM-1
Sample No.: 8U
Sampler Type: D&M
Spec. Depth (m): 5.72
Date Tested: 11/6/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 8U
Sampler Type: D&M
Spec. Depth (m): 5.72
Date Tested: 11/6/14
Date Sampled: 10/21/14



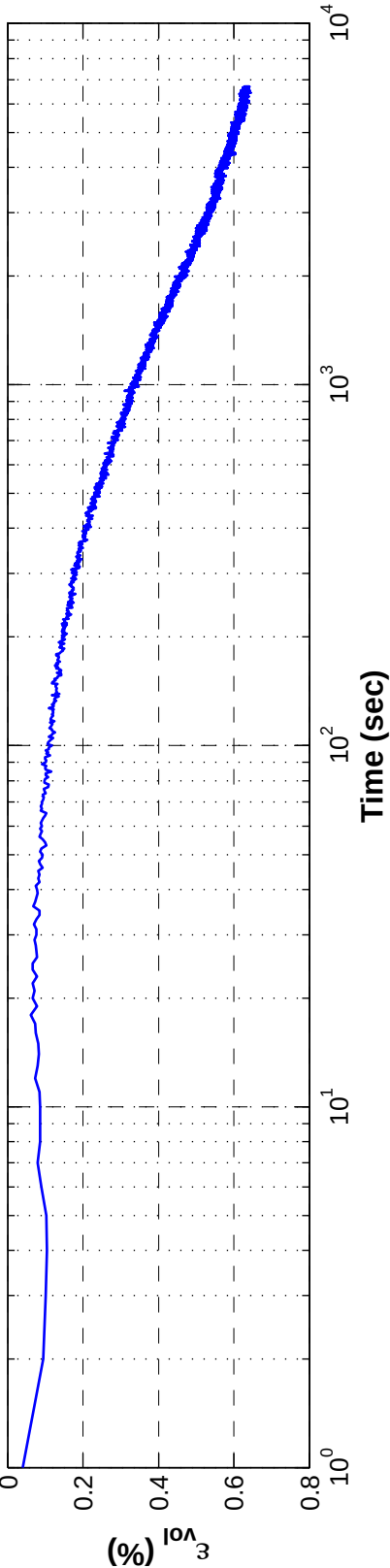
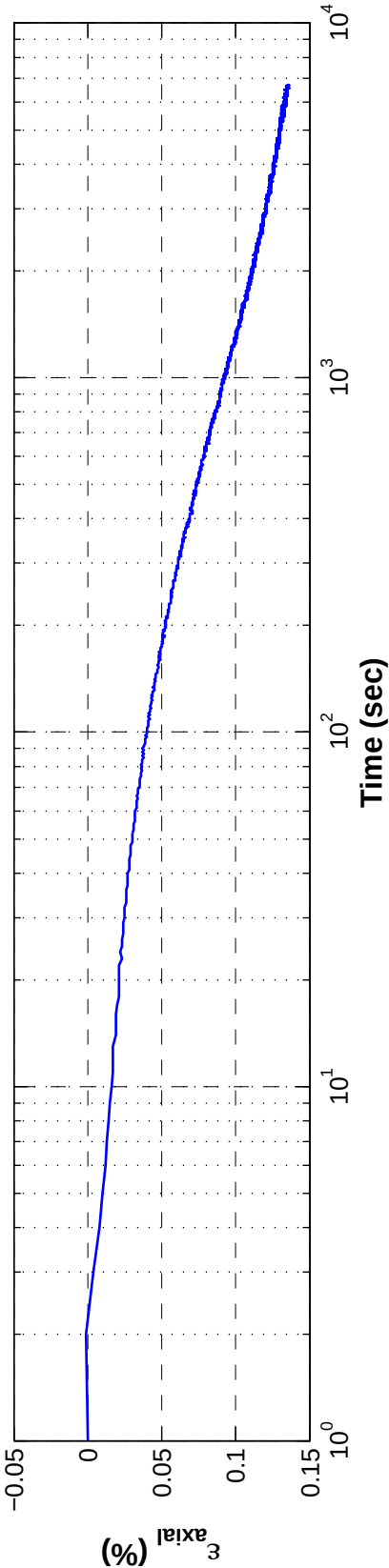
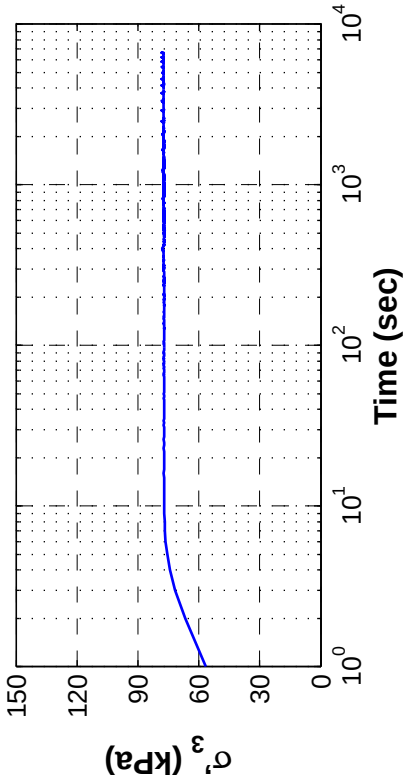


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	Site 33	σ'_c (kPa):	76
Borehole:	DM-1	Loading Freq (Hz):	1
Sample No.:	8U	B-Value:	0.994
Sampler Type:	D&M	CSR:	0.3
Spec. Depth (m):	5.875	N to $\varepsilon_{Ax-S.A.}$ =3%:	9
Date Tested:	11/8/14	N to $\varepsilon_{Ax-D.A.}$ =5%:	12
Date Sampled:	10/21/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	135.36	Gs:	---
Spec. Diam. (mm):	61.058	e_c :	1.00
Dry Mass (g):	524.83	PI (%):	10
		FC (%):	100

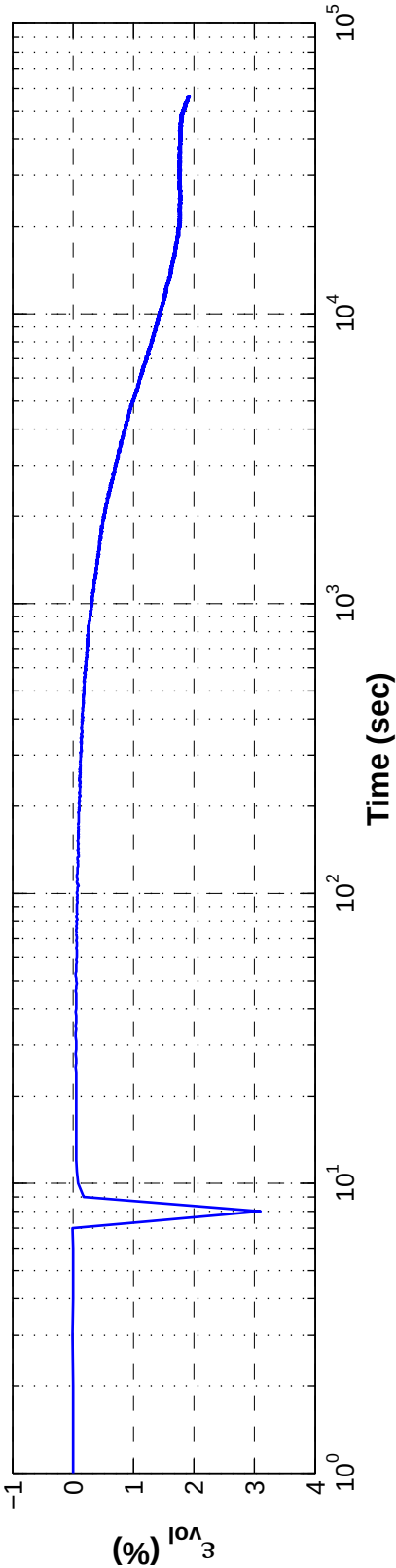
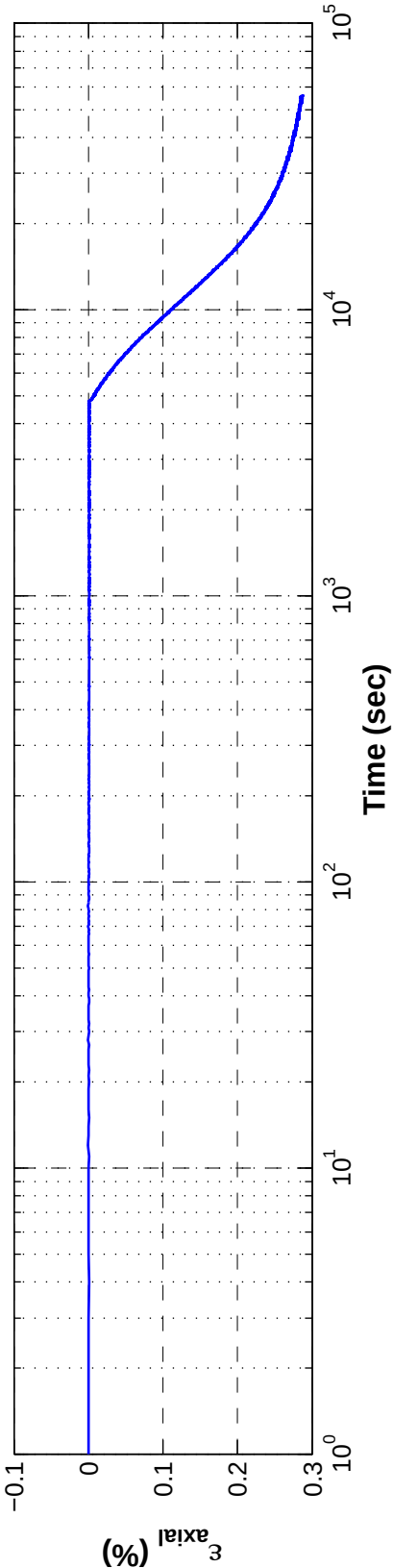
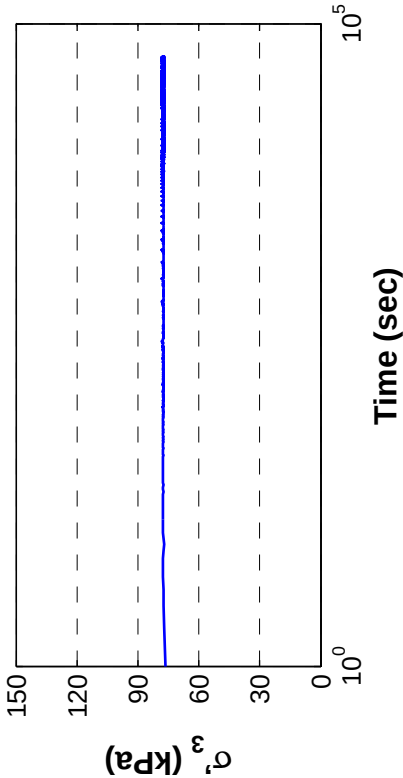
Specimen and Isotropic Consolidation Data

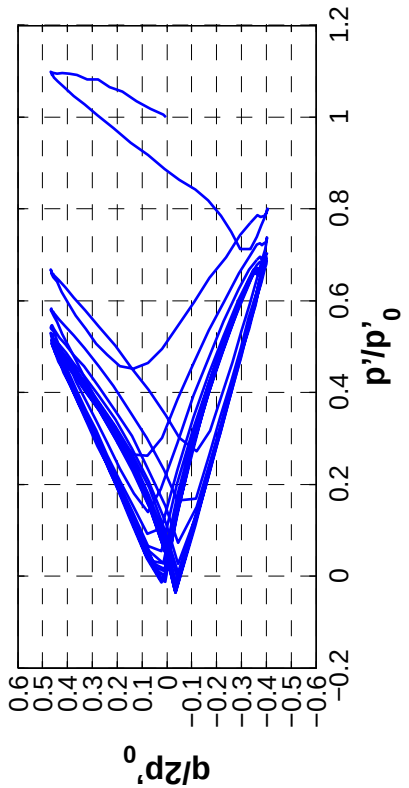
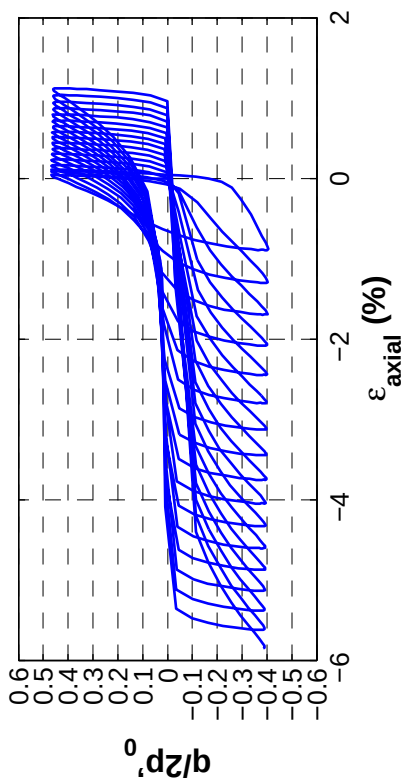
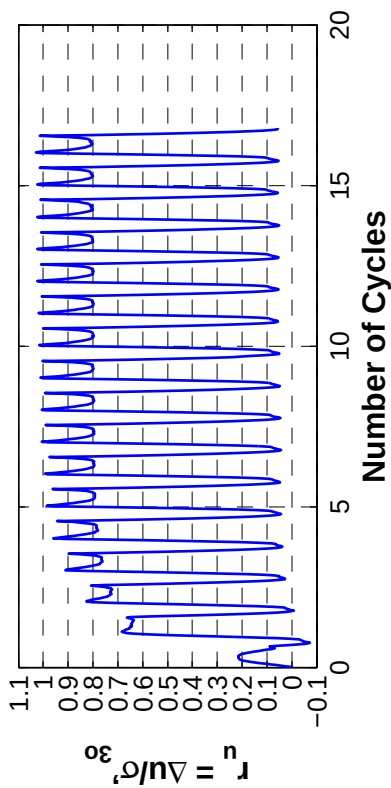
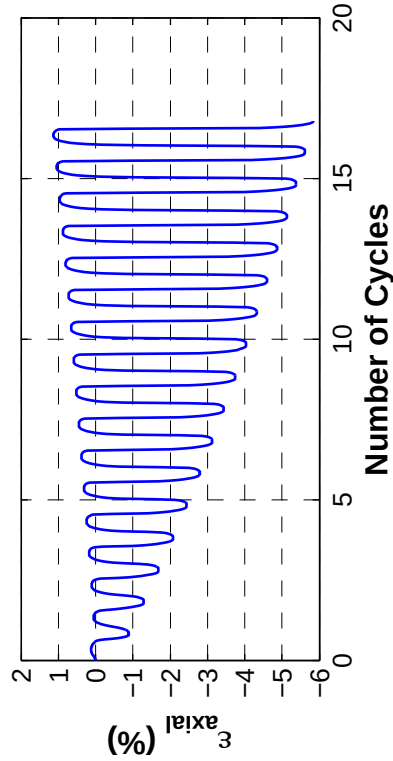
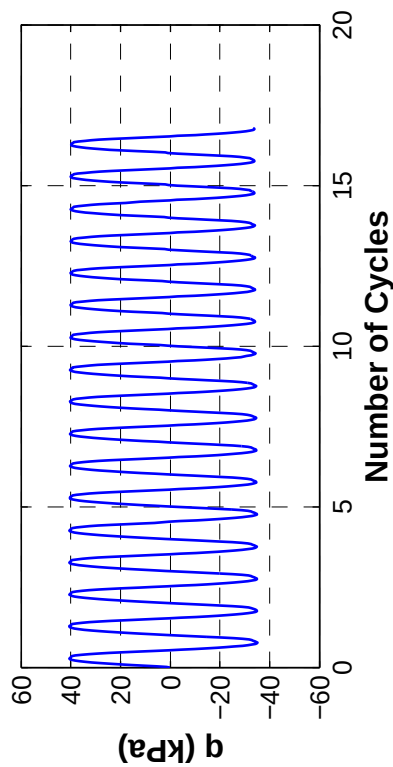
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Borehole: DM-1
Sample No.: 8U
Sampler Type: D&M
Spec. Depth (m): 5.875
Date Tested: 11/8/14
Date Sampled: 10/21/14



Specimen and Post-CTX Reconsolidation Data

Site: Site 33
Borehole: DM-1
Sample No.: 8U
Sampler Type: D&M
Spec. Depth (m): 5.875
Date Tested: 11/8/14
Date Sampled: 10/21/14



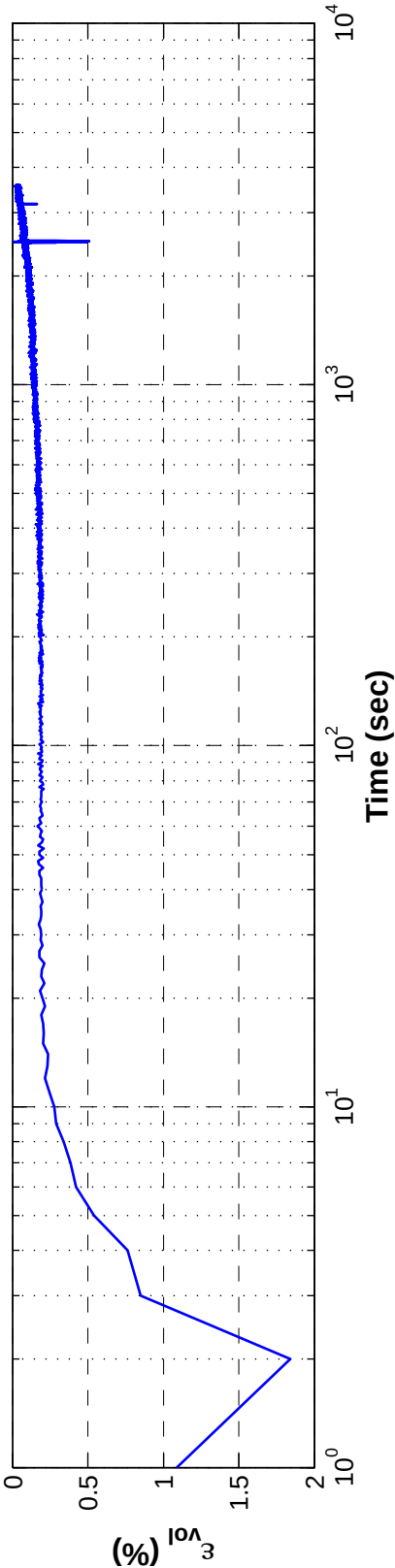
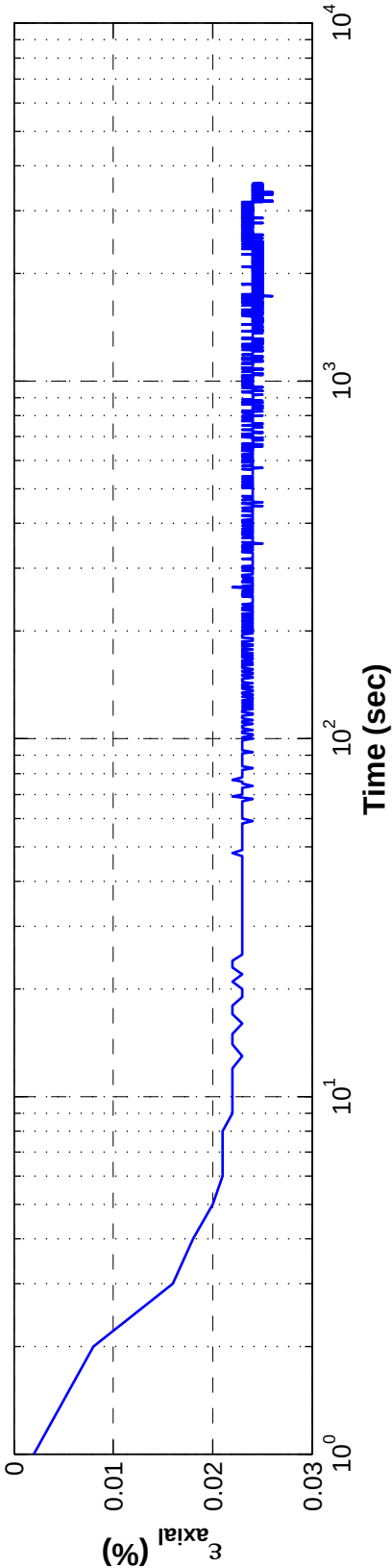
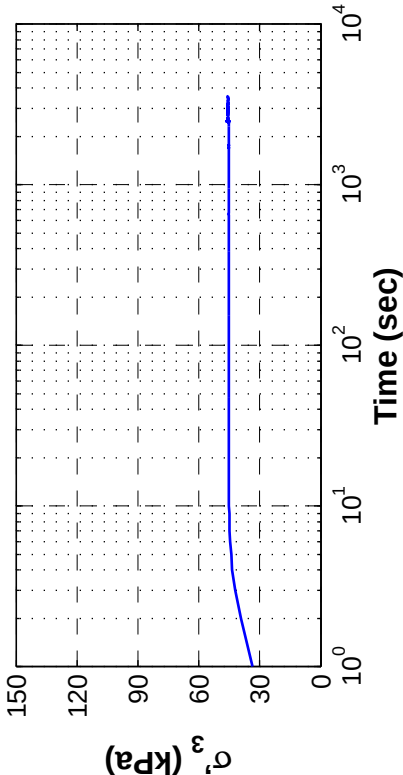


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-3	σ'_c (kPa):	43
Borehole:	BH-1	Loading Freq (Hz):	0.1
Sample No.:	3U	B-Value:	0.974
Sampler Type:	D&M	CSR:	0.44
Spec. Depth (m):	3.575	N to $\epsilon_{Ax-S.A.}$ =3%:	7
Date Tested:	06/30/14	N to $\epsilon_{Ax-D.A.}$ =5%:	12
Date Sampled:	05/20/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	136.676	Gs:	2.69
Spec. Diam. (mm):	61.26	e_c :	0.78
Dry Mass (g):	610.70	PI (%):	NP
		FC (%):	7

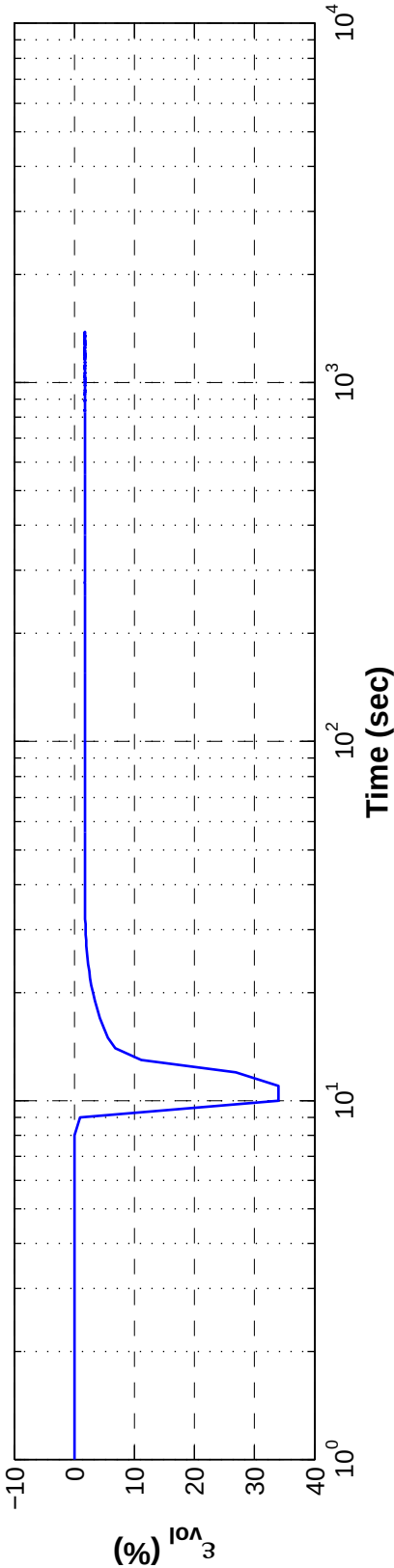
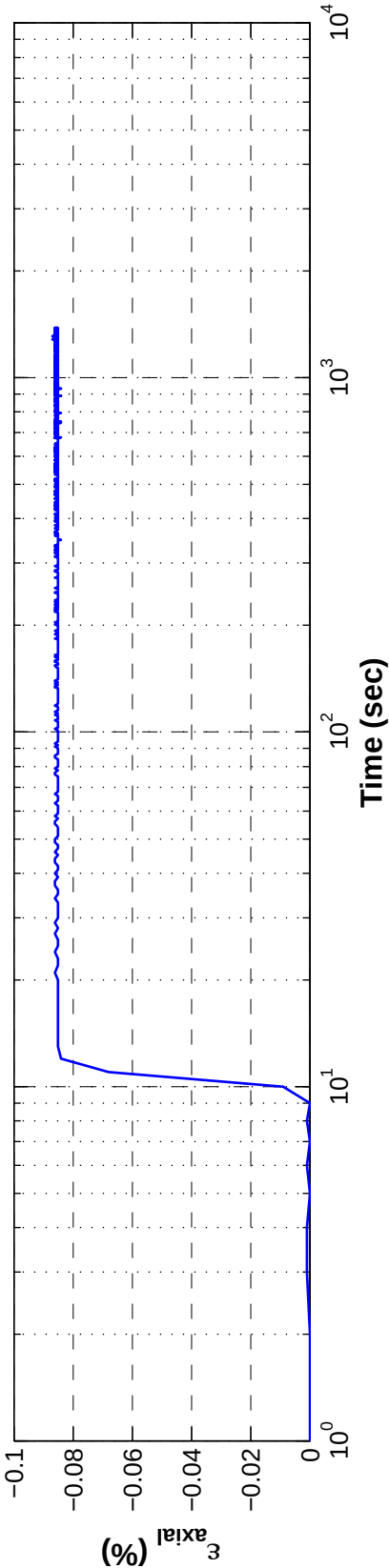
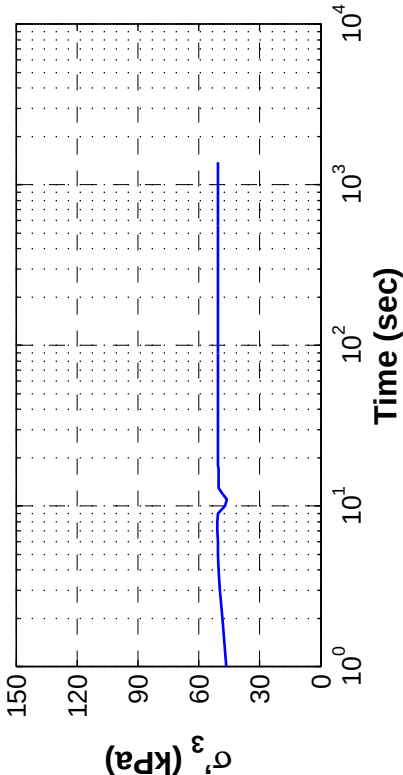
Specimen and Isotropic Consolidation Data

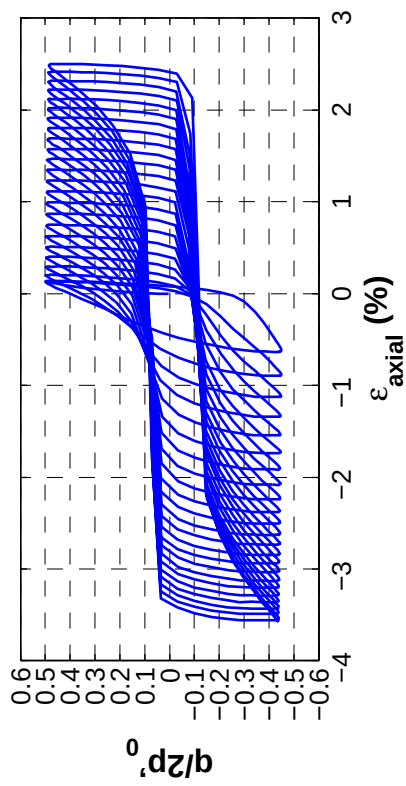
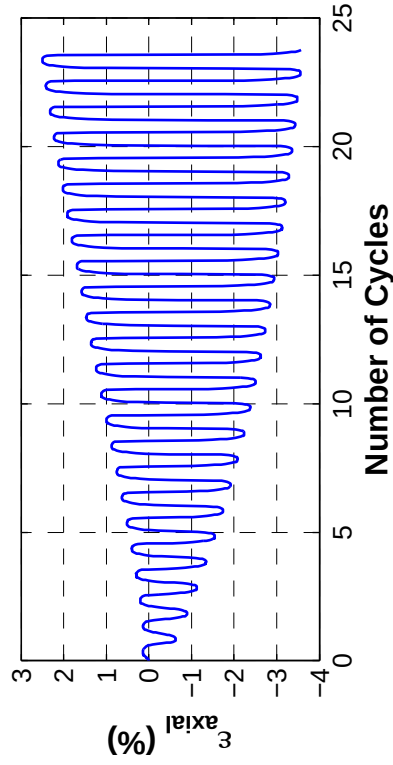
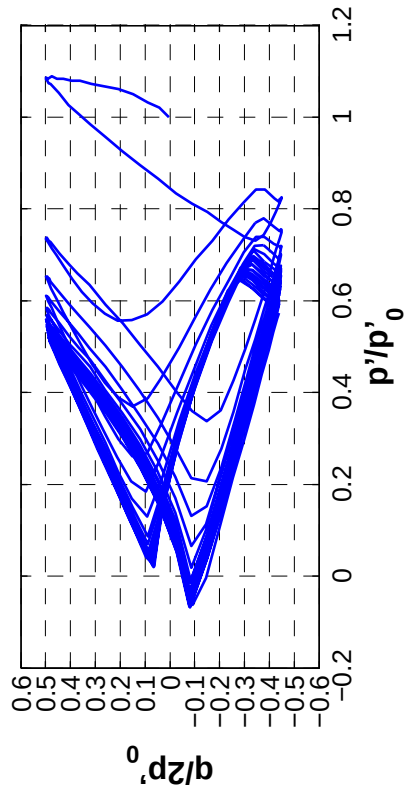
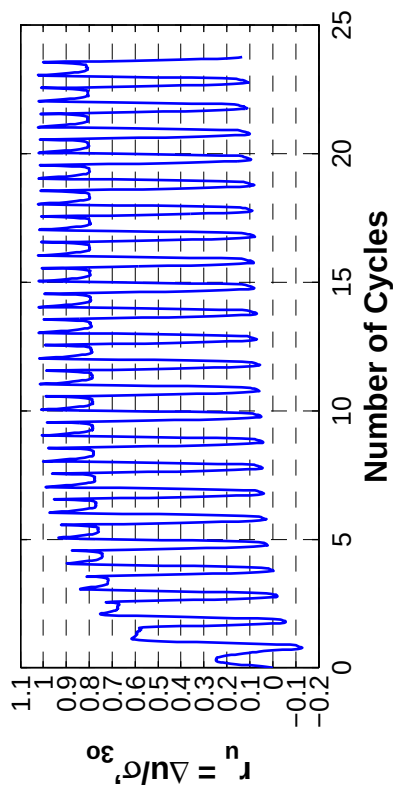
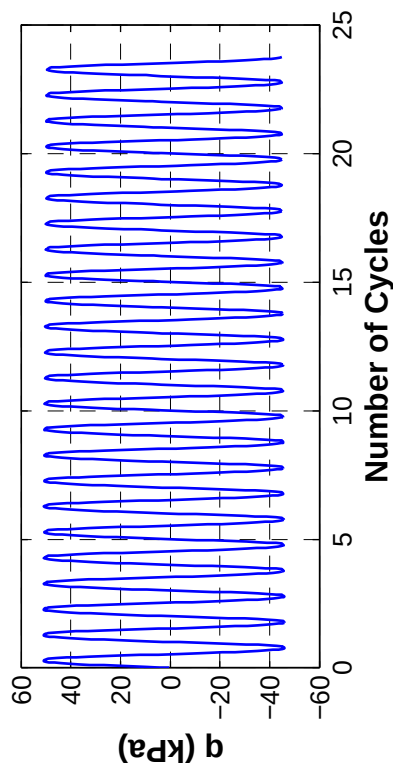
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Borehole: BH-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.575
Date Tested: 06/30/14
Date Sampled: 05/20/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-3
Borehole: BH-1
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 3.575
Date Tested: 06/30/14
Date Sampled: 05/20/14



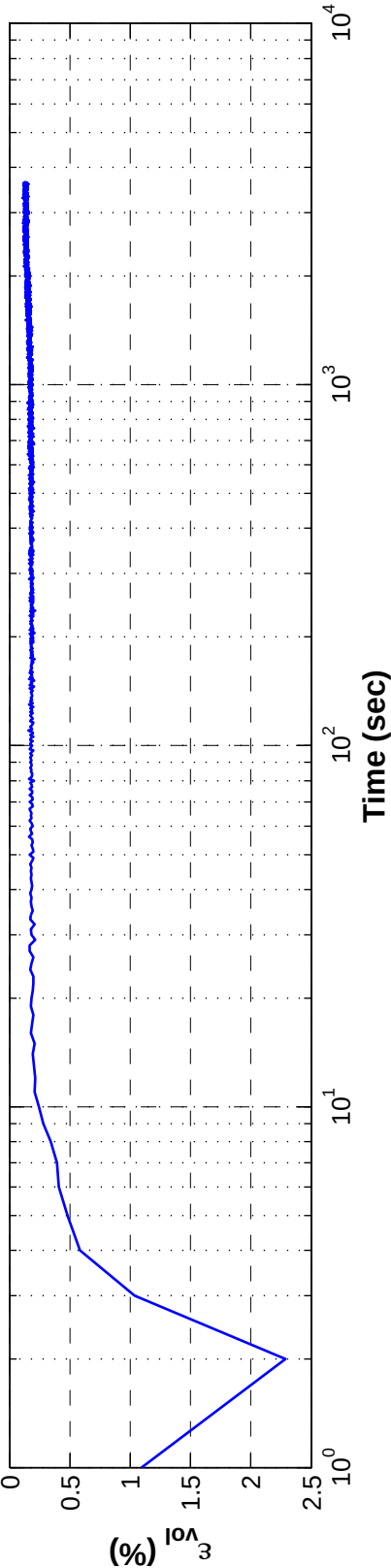
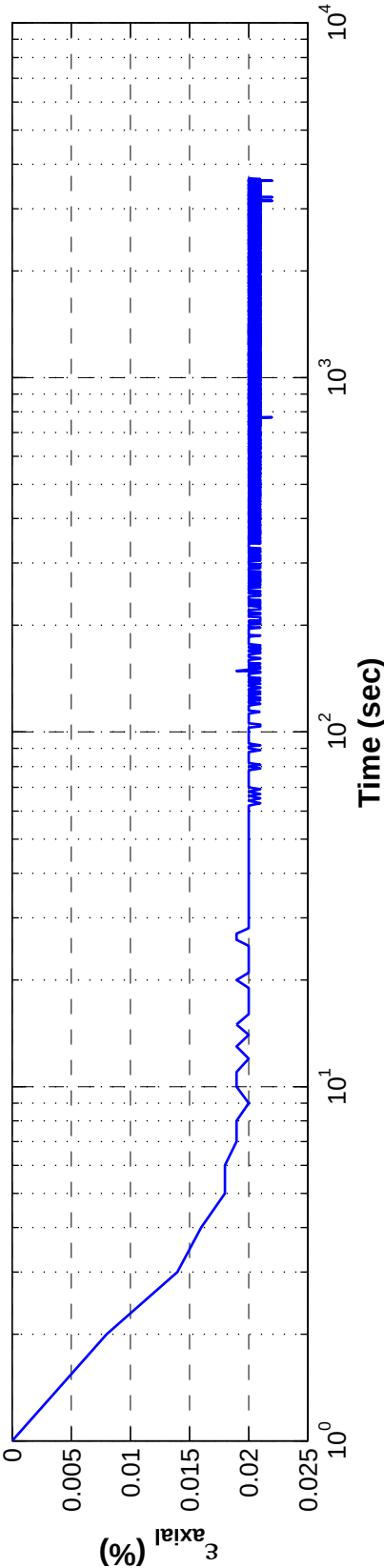
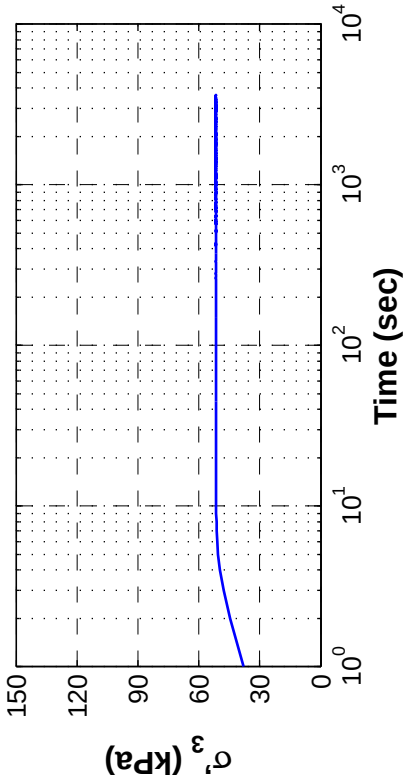


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-3	σ'_c (kPa):	51
Borehole:	BH-1	Loading Freq (Hz):	0.1
Sample No.:	4U	B-Value:	0.976
Sampler Type:	D&M	CSR:	0.49
Spec. Depth (m):	4.17	N to $\epsilon_{Ax-S.A.}$ =3%:	16
Date Tested:	07/08/14	N to $\epsilon_{Ax-D.A.}$ =5%:	18
Date Sampled:	05/20/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	142.936	Gs:	2.68
Spec. Diam. (mm):	61.21	e_c :	0.72
Dry Mass (g):	656.41	PI (%):	NP
		FC (%):	2

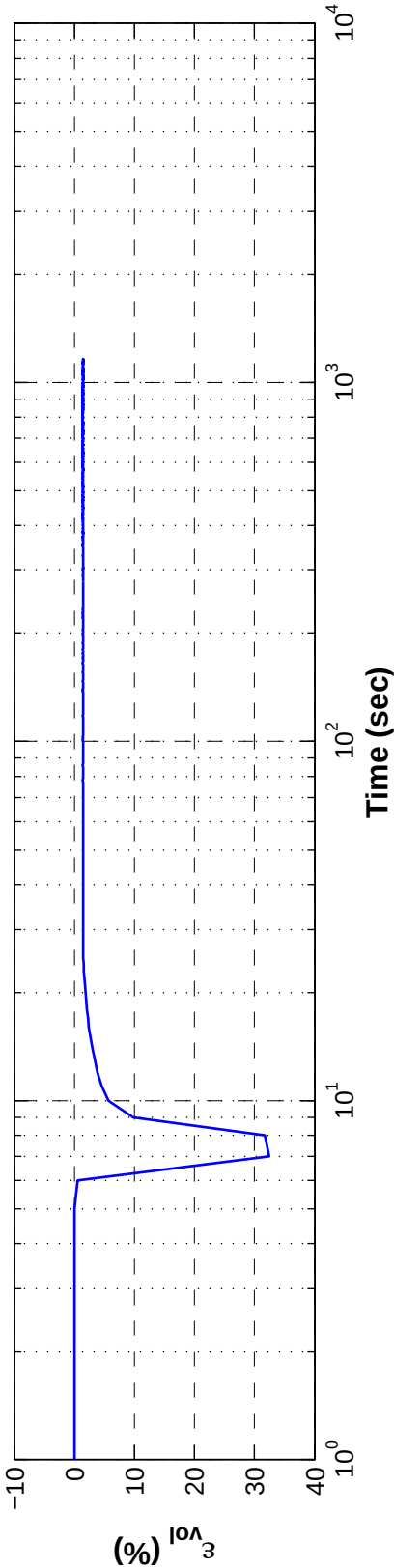
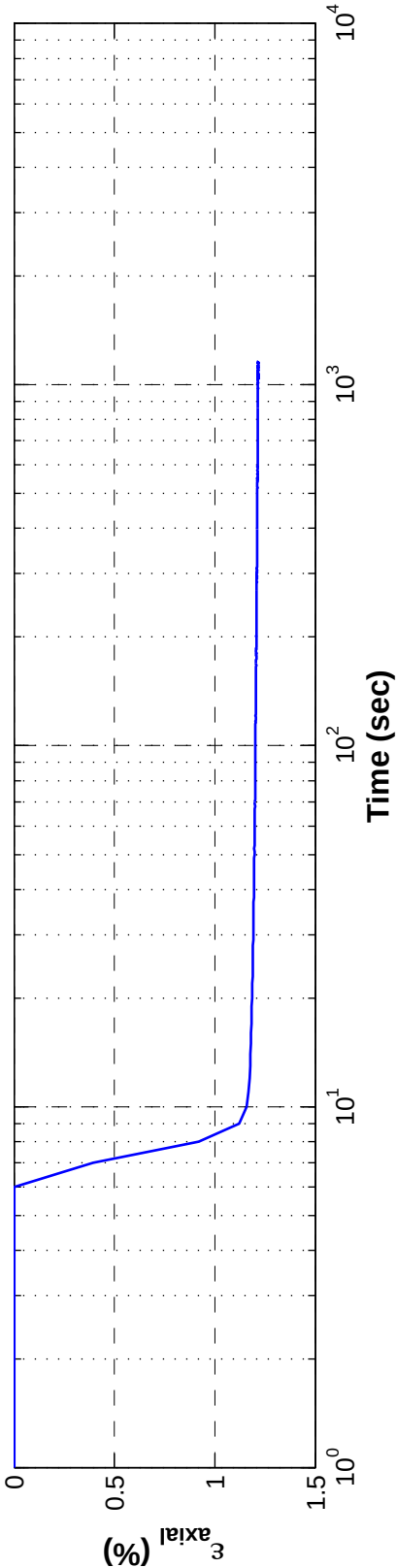
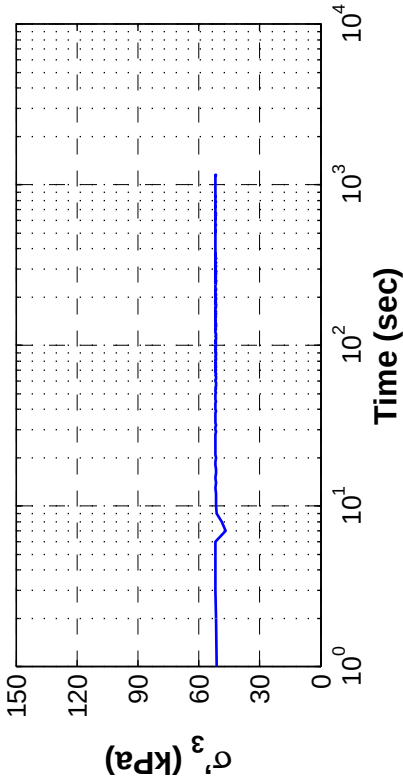
Specimen and Isotropic Consolidation Data

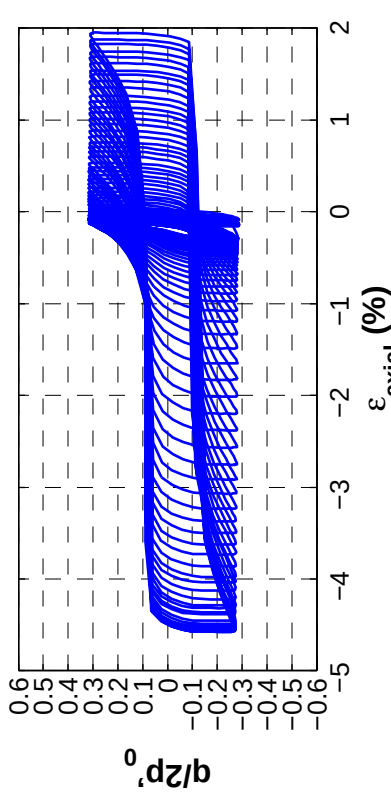
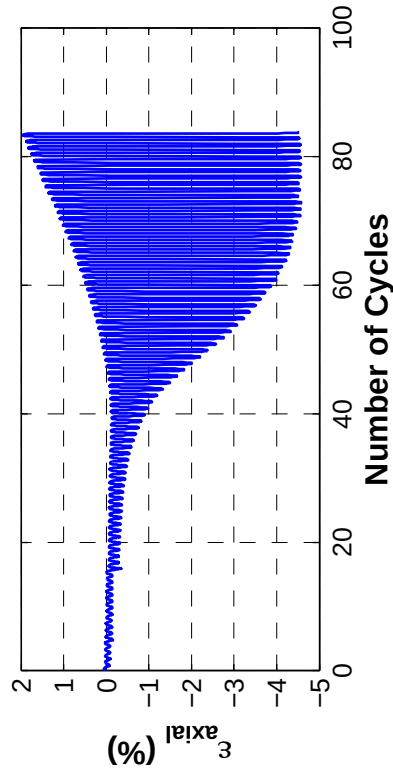
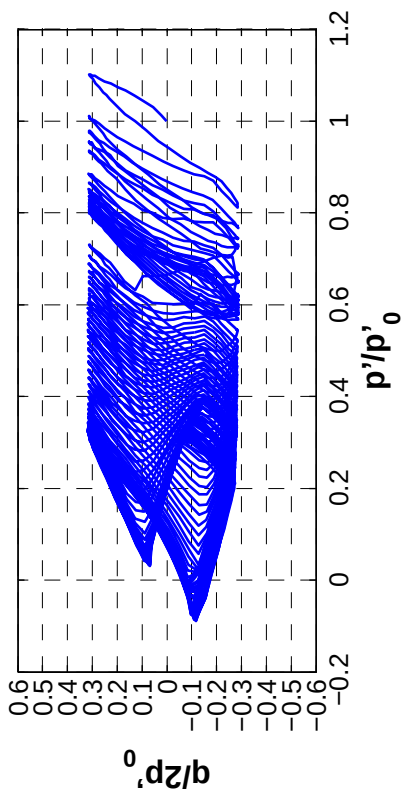
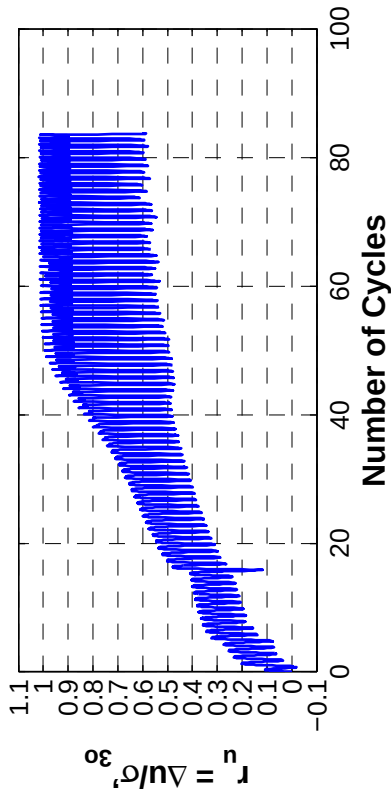
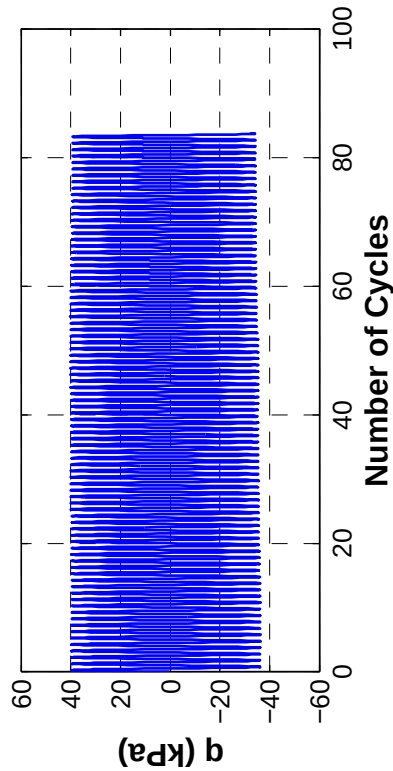
Site: EQC-3
Borehole: BH-1
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 4.17
Date Tested: 07/08/14
Date Sampled: 05/20/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-3
Borehole: BH-1
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 4.17
Date Tested: 07/08/14
Date Sampled: 05/20/14



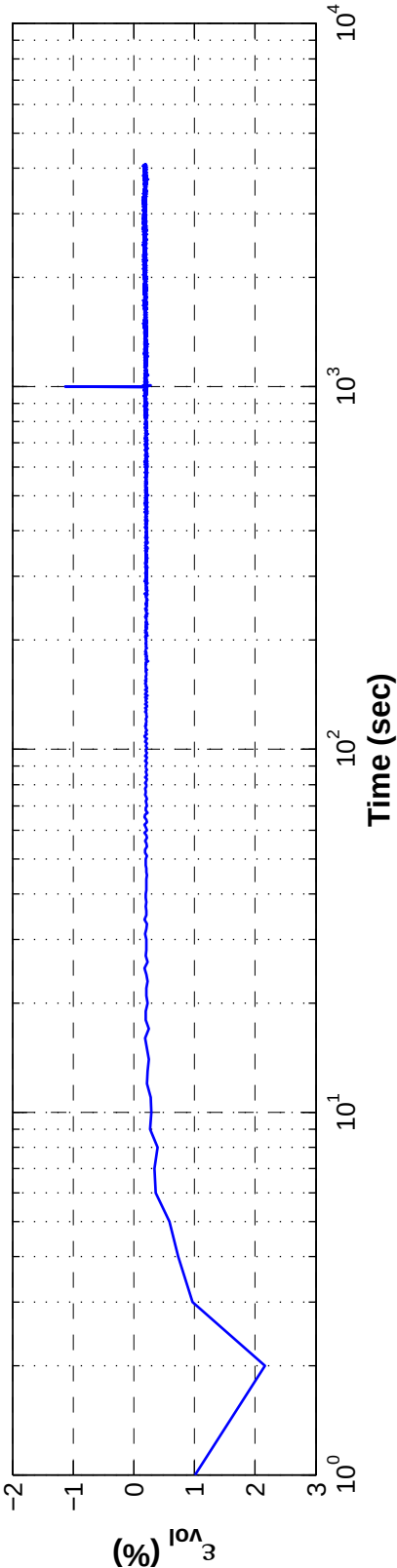
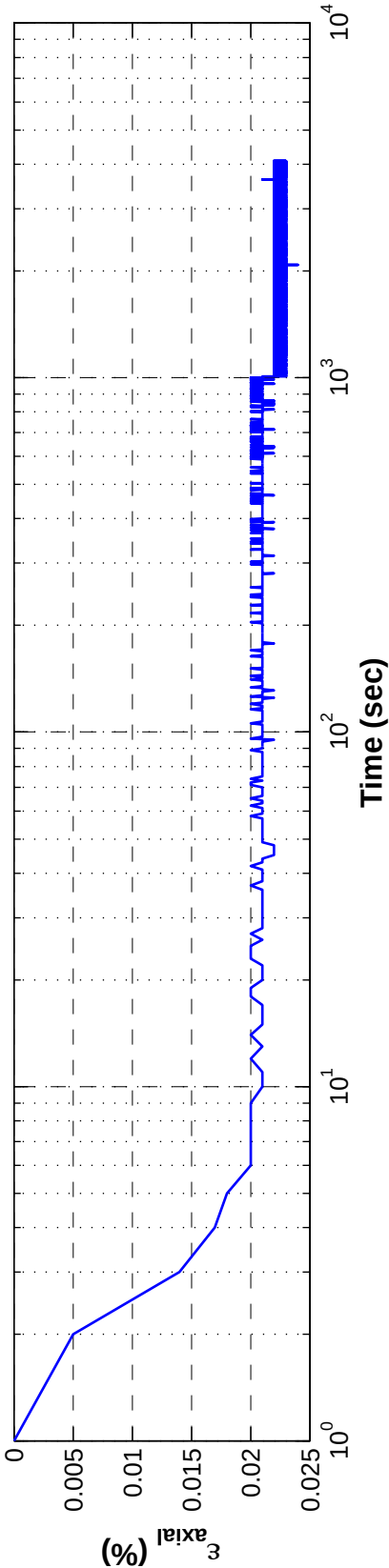
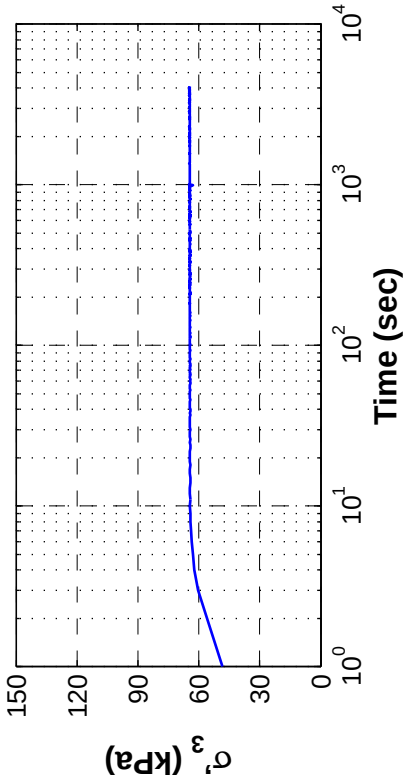


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-3	σ'_c (kPa):	63
Borehole:	BH-1	Loading Freq (Hz):	0.1
Sample No.:	5U	B-Value:	0.955
Sampler Type:	D&M	CSR:	0.3
Spec. Depth (m):	5.67	N to $\epsilon_{Ax-S.A.}$ =3%:	54
Date Tested:	06/26/14	N to $\epsilon_{Ax-D.A.}$ =5%:	66
Date Sampled:	05/20/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	143.396	Gs:	---
Spec. Diam. (mm):	61.22	e_c :	0.7
Dry Mass (g):	661.93	PI (%):	NP
		FC (%):	2

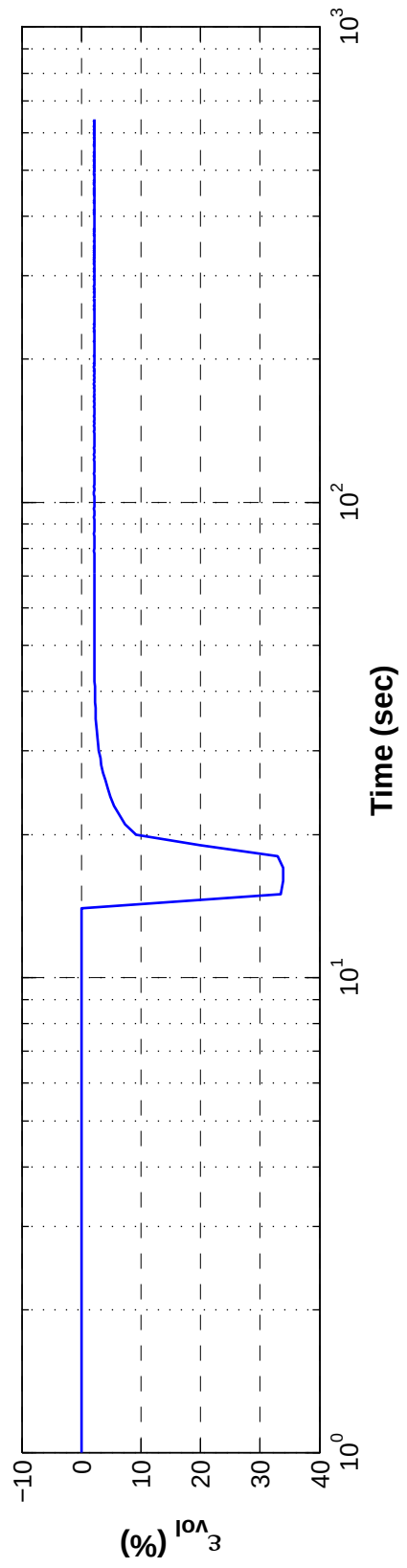
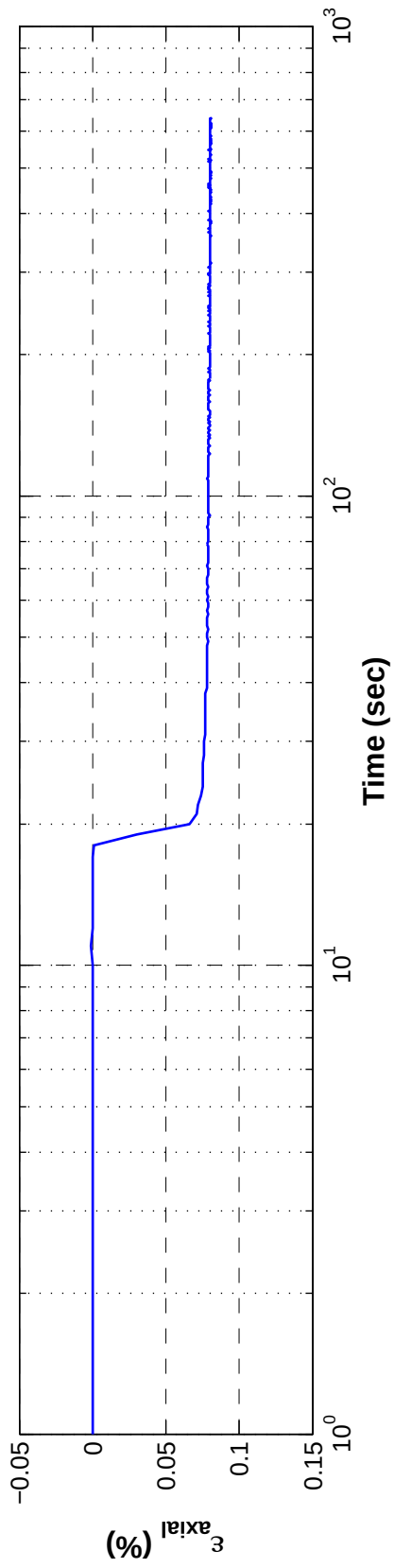
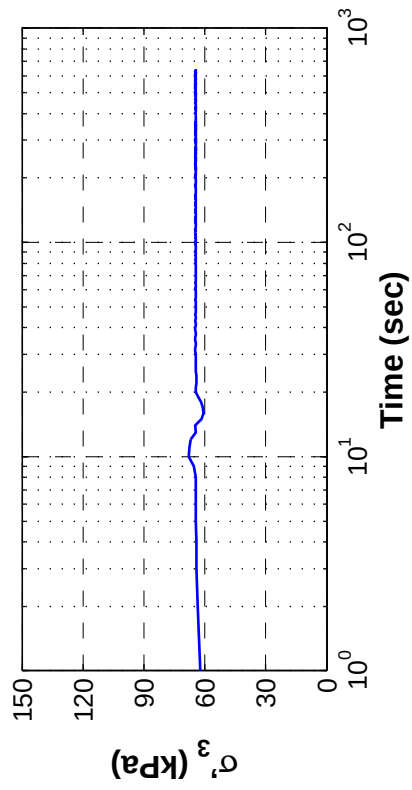
Specimen and Isotropic Consolidation Data

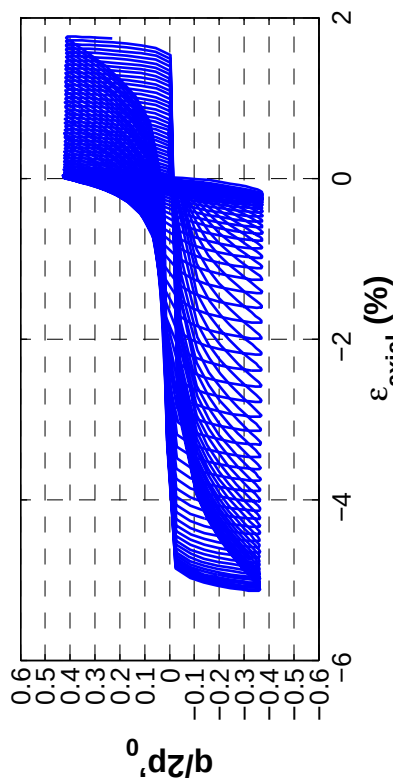
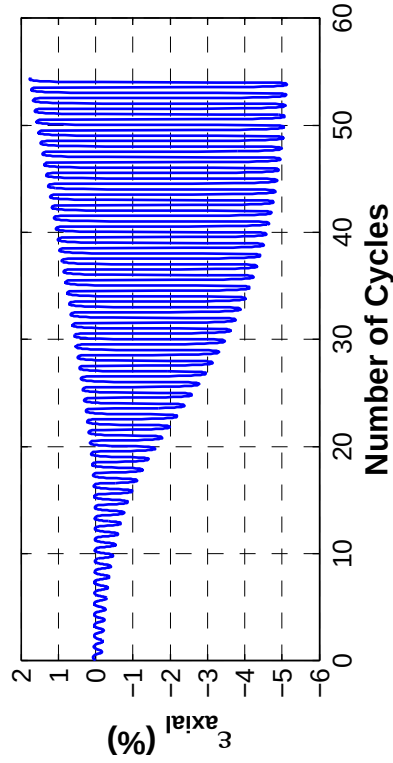
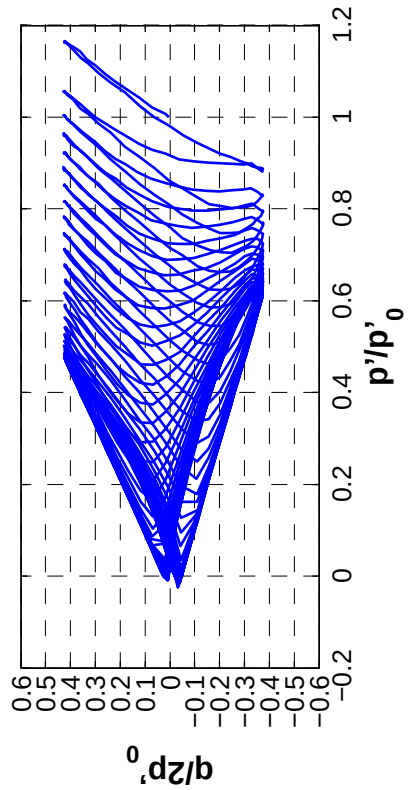
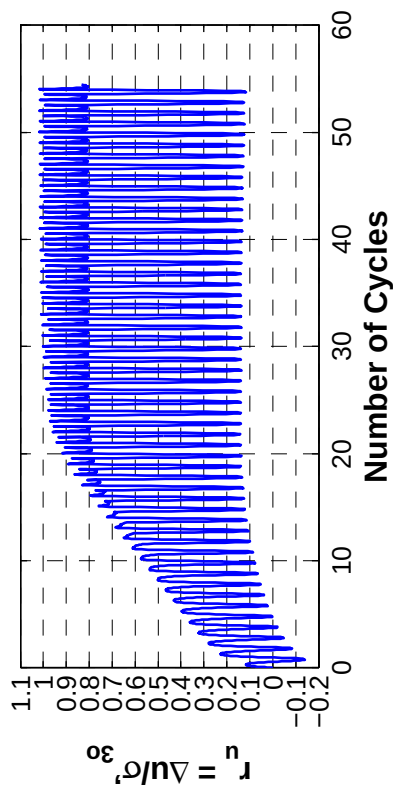
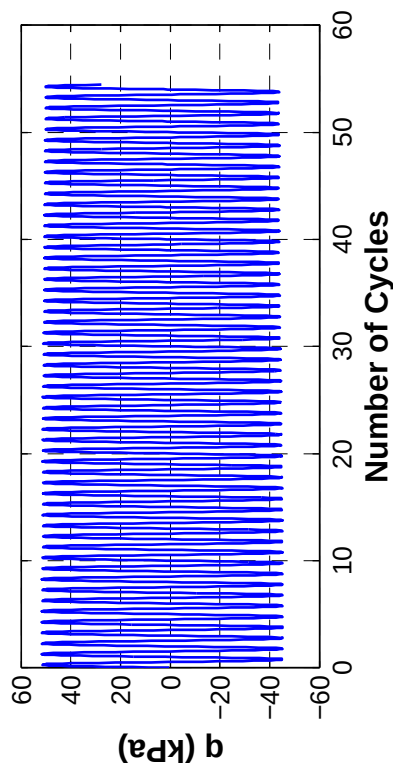
Site: EQC-3
Borehole: BH-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.67
Date Tested: 06/26/14
Date Sampled: 05/20/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-3
Borehole: BH-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.67
Date Tested: 06/26/14
Date Sampled: 05/20/14



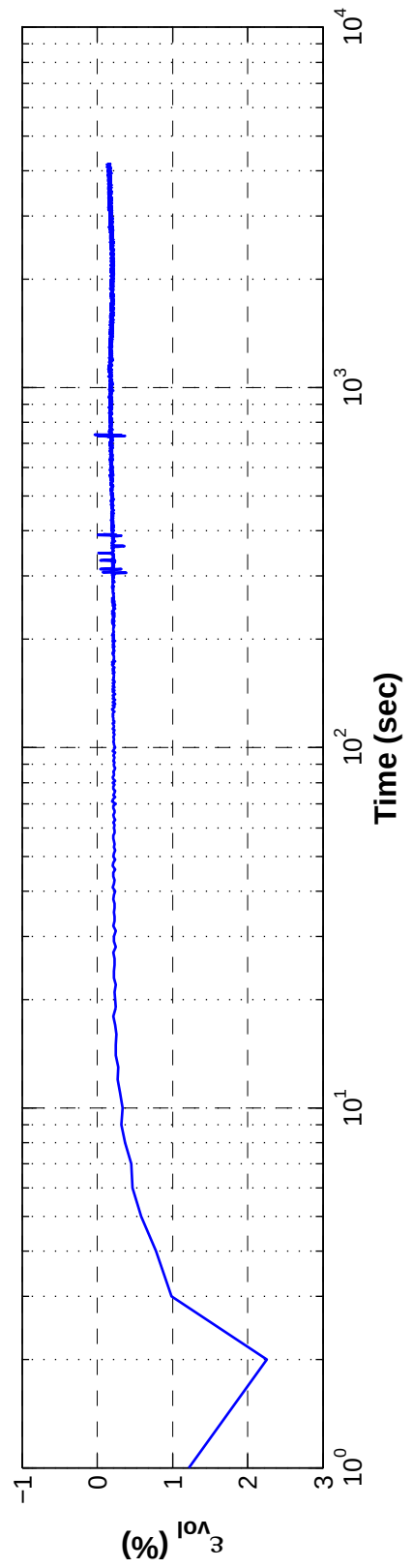
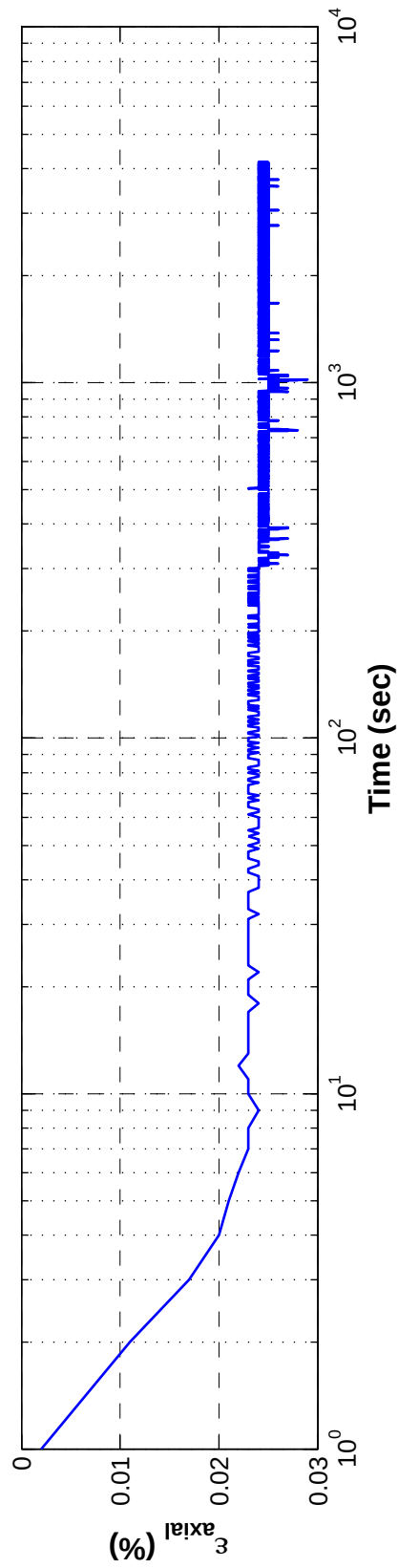
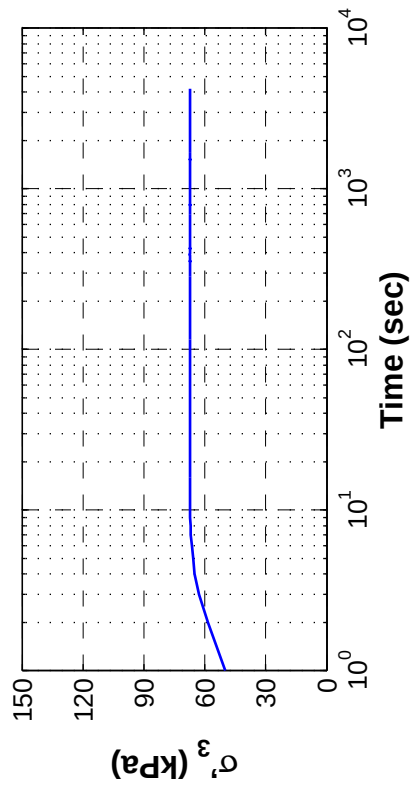


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-3	σ'_c (kPa):	60
Borehole:	BH-1	Loading Freq (Hz):	0.1
Sample No.:	5U	B-Value:	0.962
Sampler Type:	D&M	CSR:	0.41
Spec. Depth (m):	5.825	N to $\epsilon_{Ax-S.A.}$ =3%:	28
Date Tested:	06/27/14	N to $\epsilon_{Ax-D.A.}$ =5%:	36
Date Sampled:	05/20/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	141.606	Gs:	2.68
Spec. Diam. (mm):	61.00	e_c :	0.69
Dry Mass (g):	657.09	PI (%):	NP
		FC (%):	2

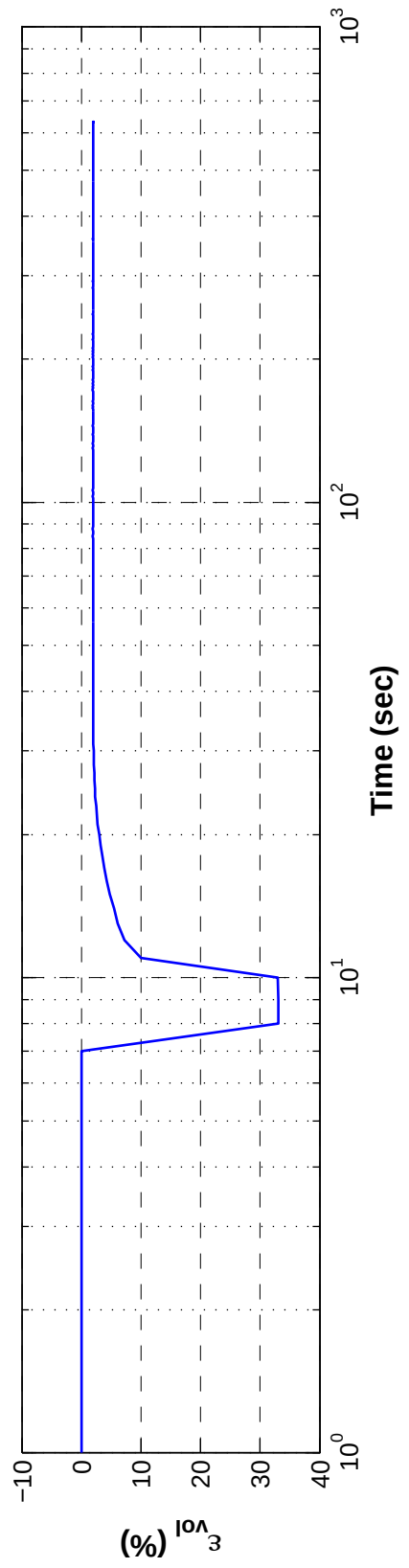
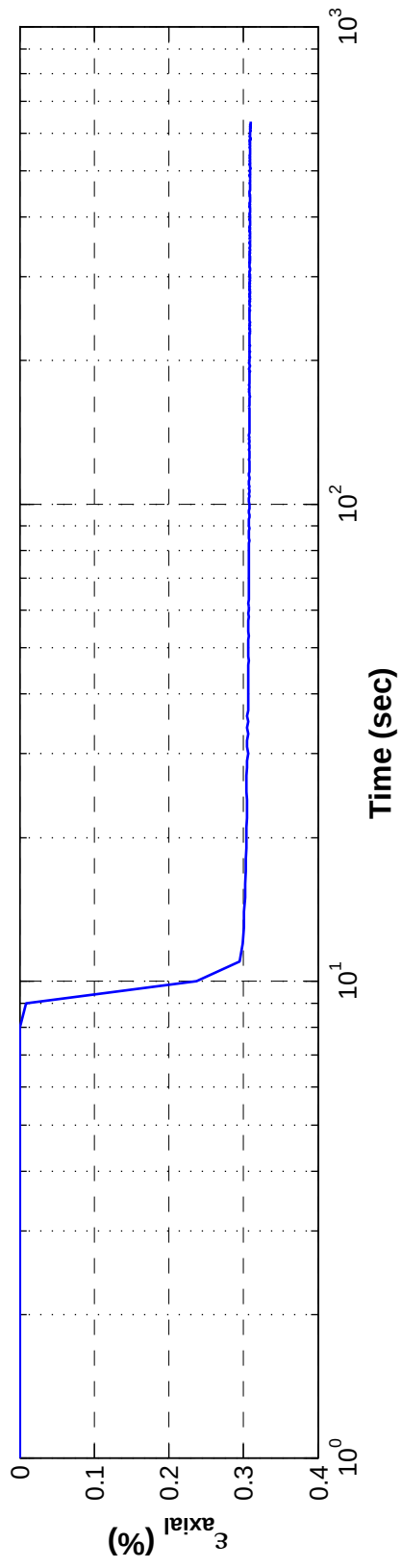
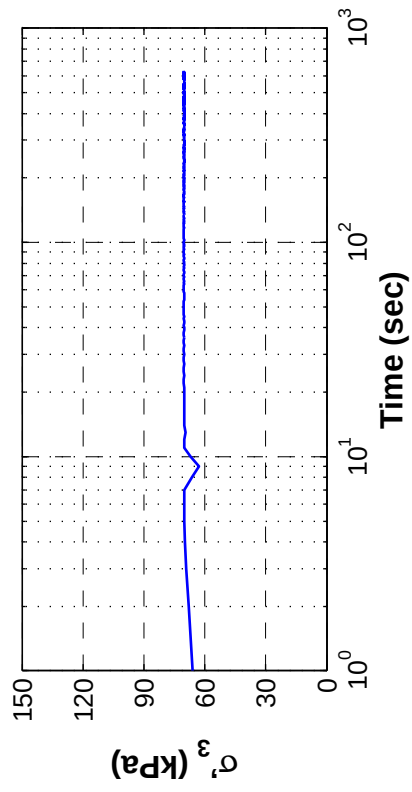
Specimen and Isotropic Consolidation Data

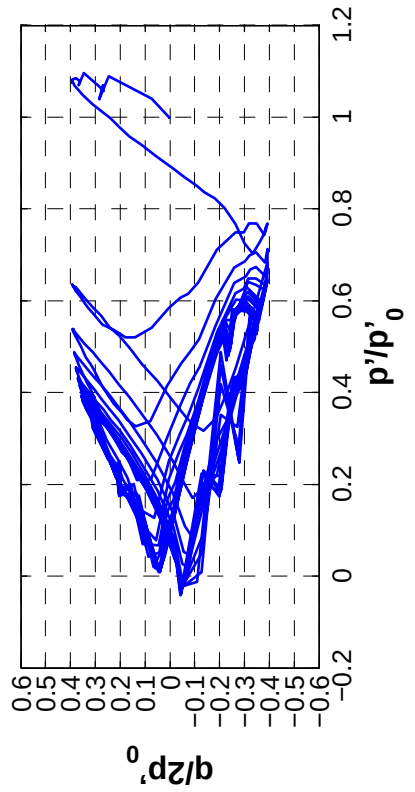
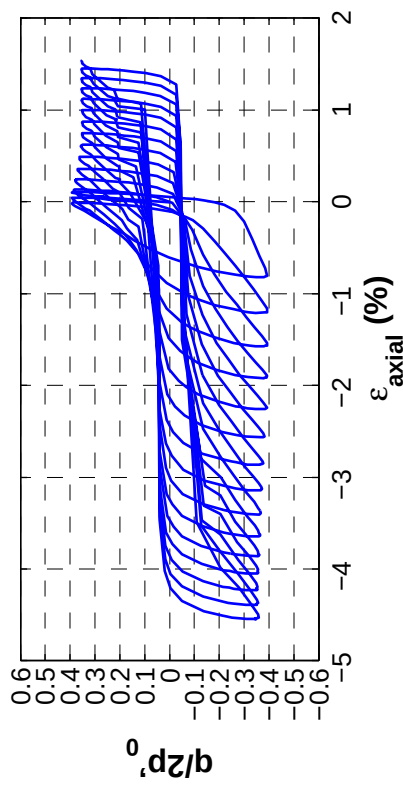
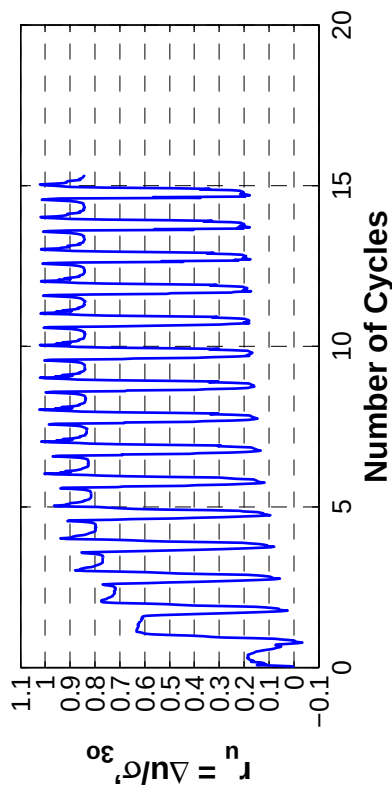
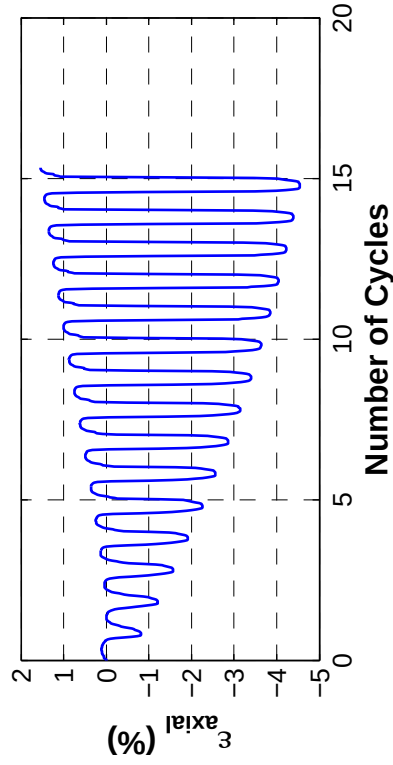
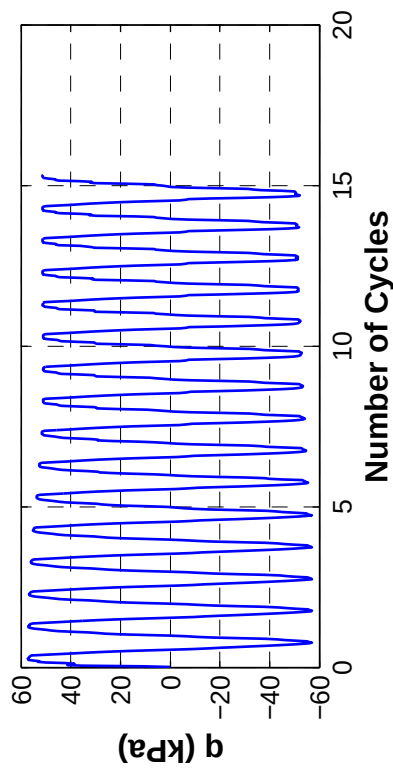
Site: EQC-3
Borehole: BH-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.825
Date Tested: 06/27/14
Date Sampled: 05/20/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-3
Borehole: BH-1
Sample No.: 5U
Sampler Type: D&M
Spec. Depth (m): 5.825
Date Tested: 06/27/14
Date Sampled: 05/20/14



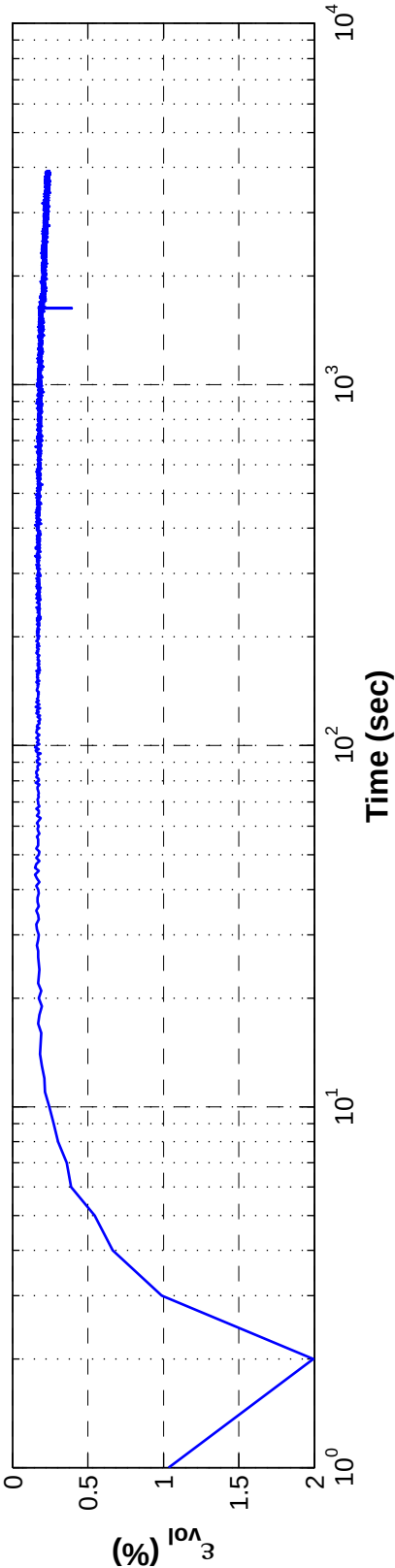
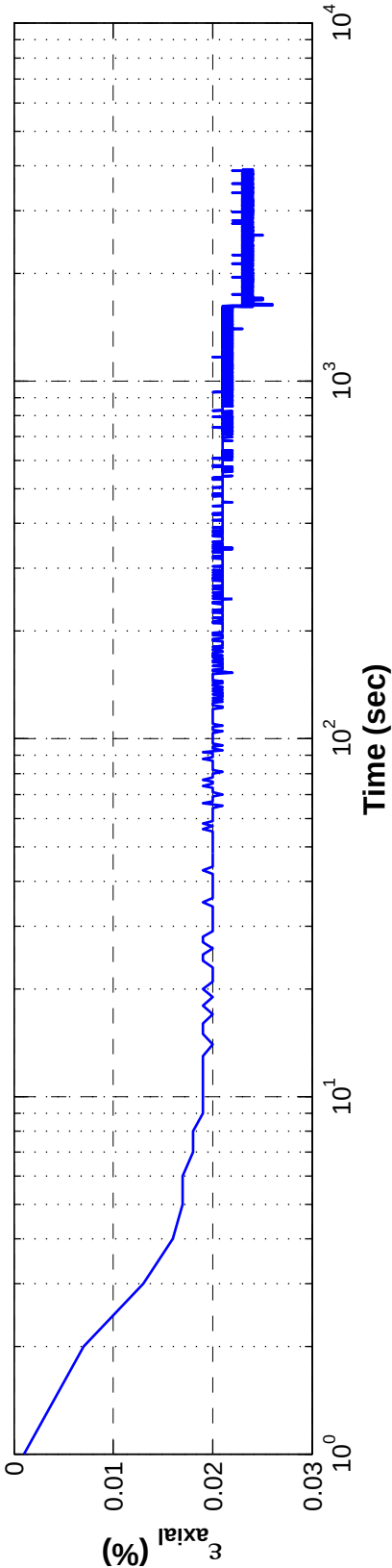
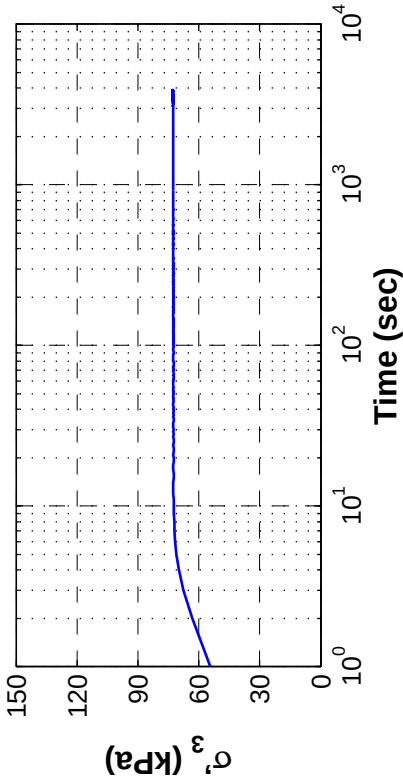


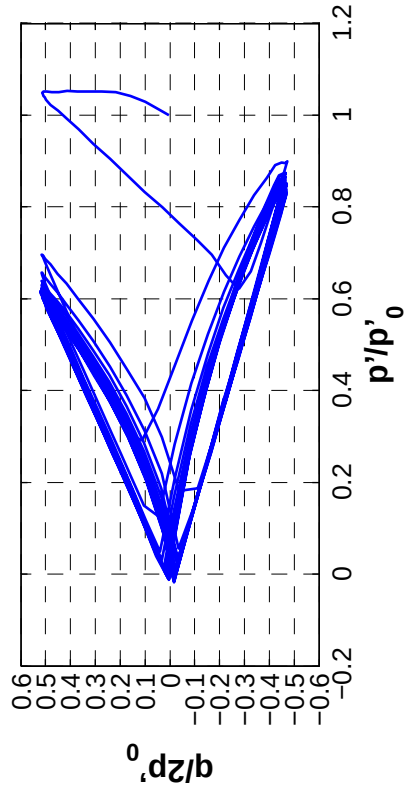
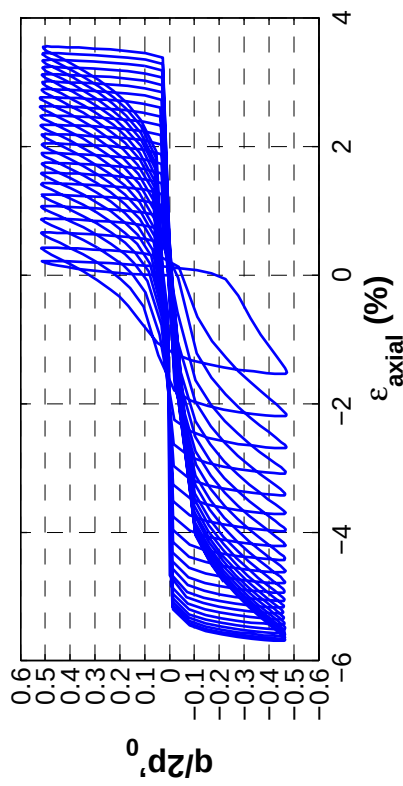
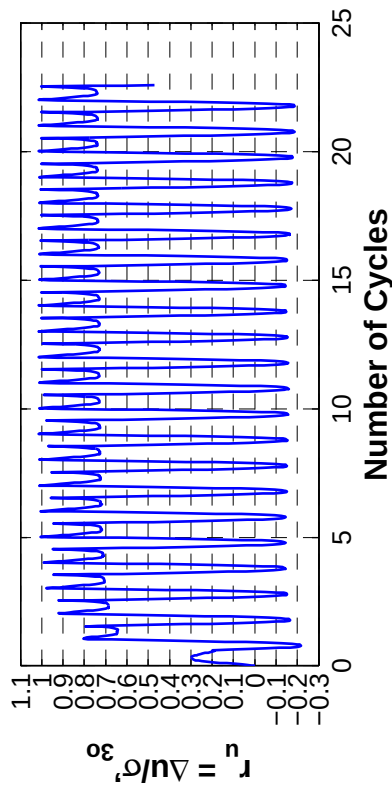
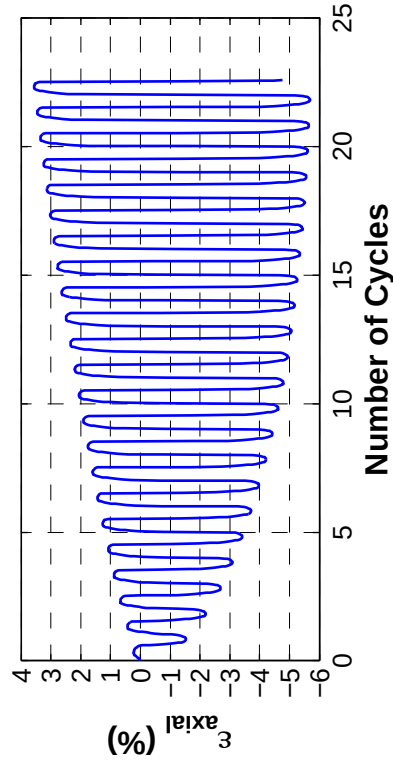
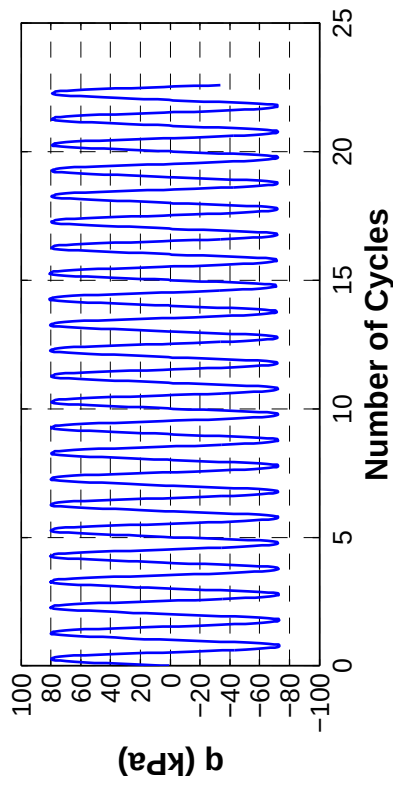
Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-3	σ'_c (kPa):	73
Borehole:	BH-1	Loading Freq (Hz):	1
Sample No.:	6U	B-Value:	0.973
Sampler Type:	D&M	CSR:	0.4
Spec. Depth (m):	6.45	N to $\epsilon_{Ax-S.A.}$ =3%:	8
Date Tested:	07/07/14	N to $\epsilon_{Ax-D.A.}$ =5%:	12
Date Sampled:	05/20/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	135.666	Gs:	2.68
Spec. Diam. (mm):	61.10	e_c :	0.72
Dry Mass (g):	619.17	PI (%):	NP
		FC (%):	1

Specimen and Isotropic Consolidation Data

Site: EQC-3
Borehole: BH-1
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.45
Date Tested: 07/07/14
Date Sampled: 05/20/14



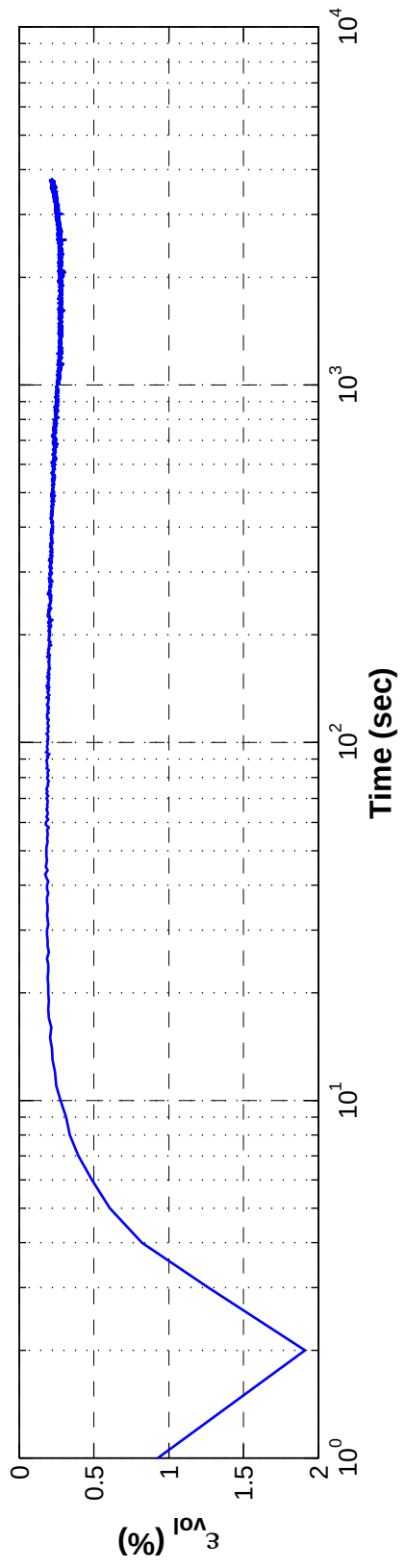
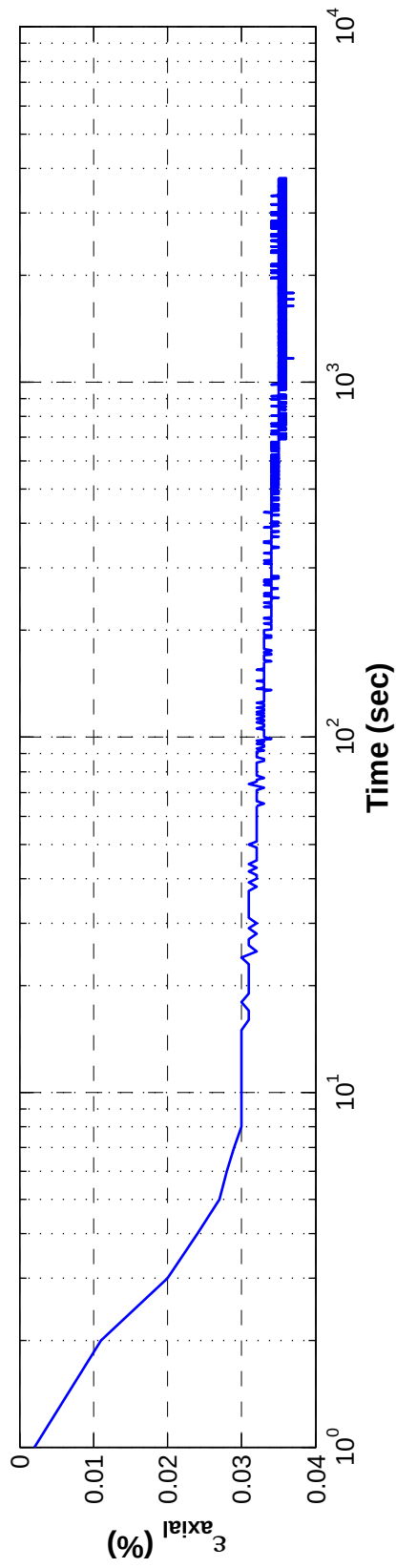
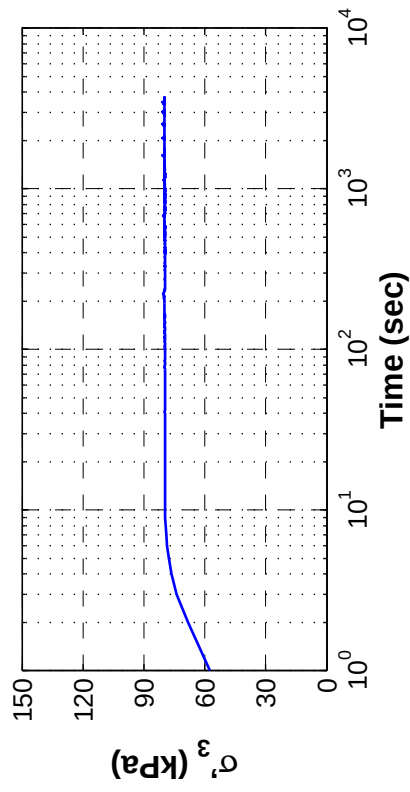


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-4	σ'_c (kPa):	77
Borehole:	DM-1B	Loading Freq (Hz):	0.1
Sample No.:	6U	B-Value:	0.982
Sampler Type:	D&M	CSR:	0.5
Spec. Depth (m):	6.17	N to $\epsilon_{Ax-S.A.}$:	3%
Date Tested:	10/28/14	N to $\epsilon_{Ax-D.A.}$:	5%
Date Sampled:	10/23/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	141.31	Gs:	---
Spec. Diam. (mm):	61.204	e_c :	0.75
Dry Mass (g):	636.13	PI (%):	NP
		FC (%):	1

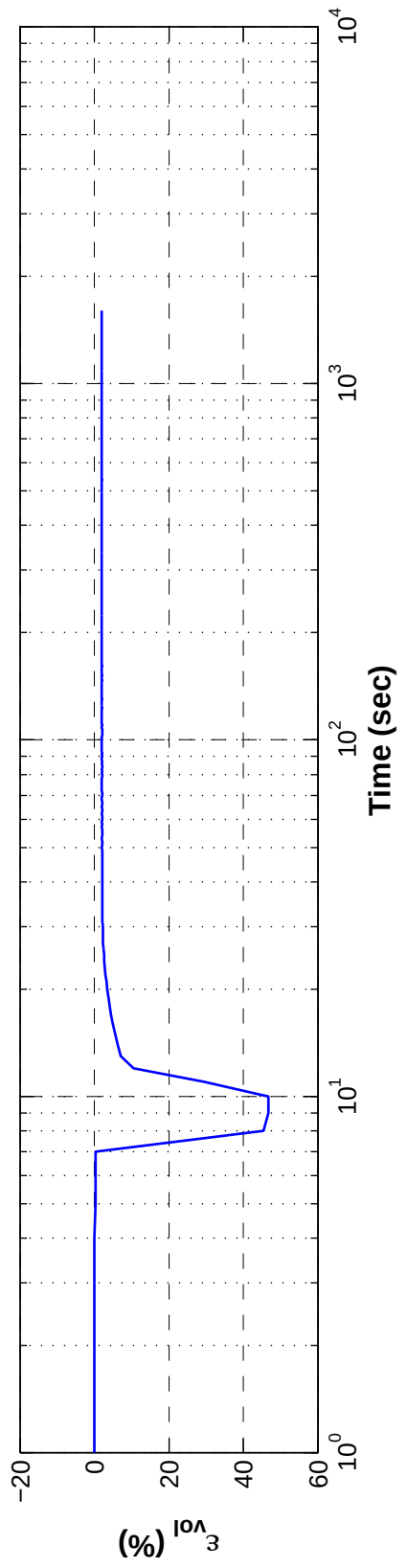
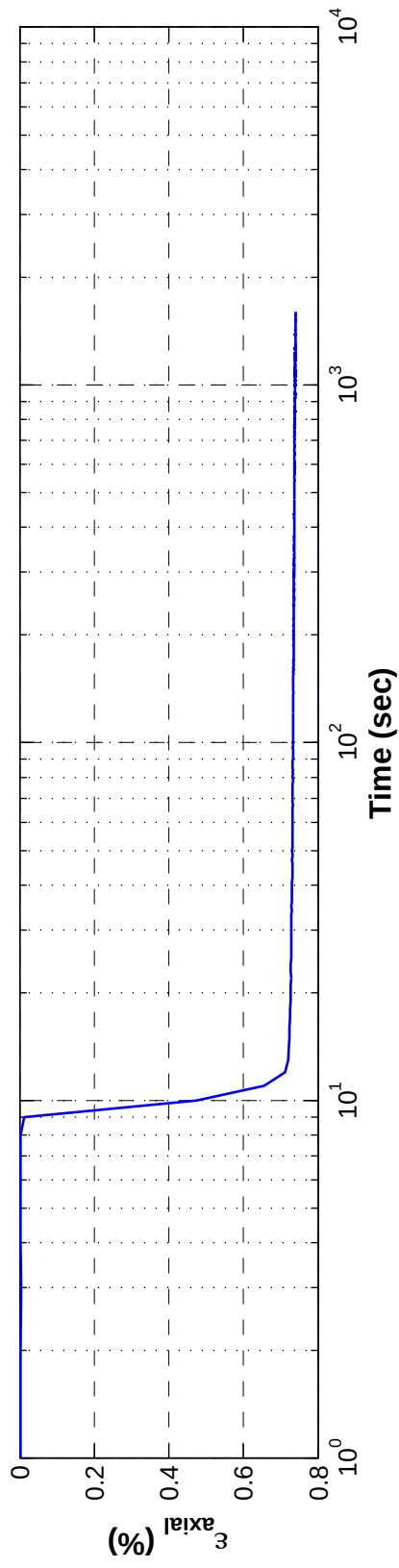
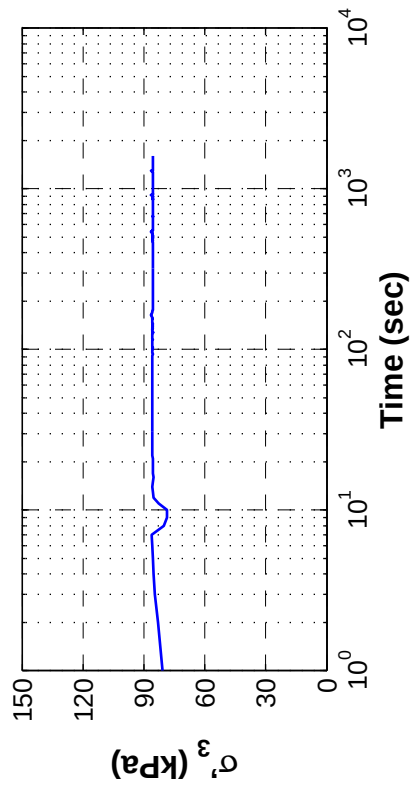
Specimen and Isotropic Consolidation Data

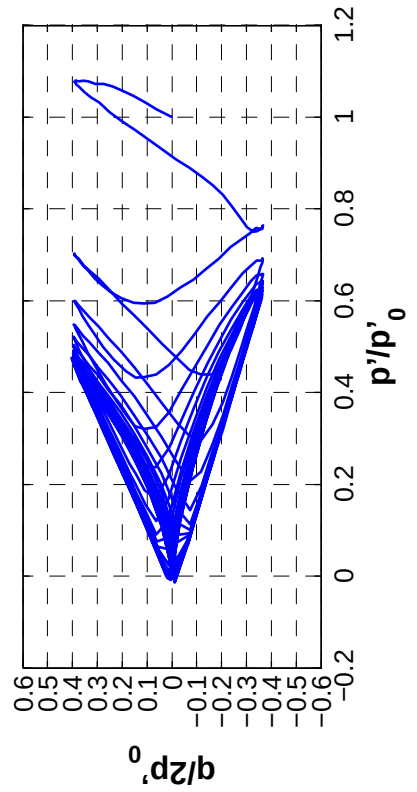
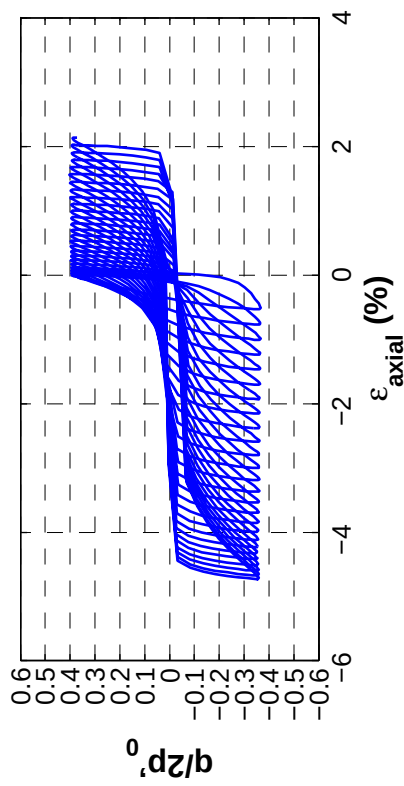
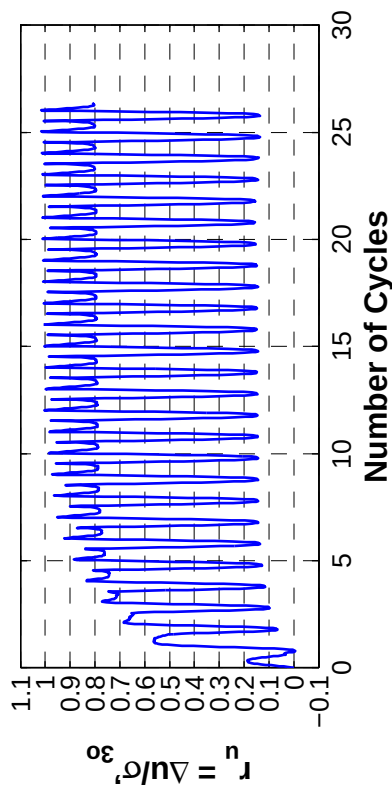
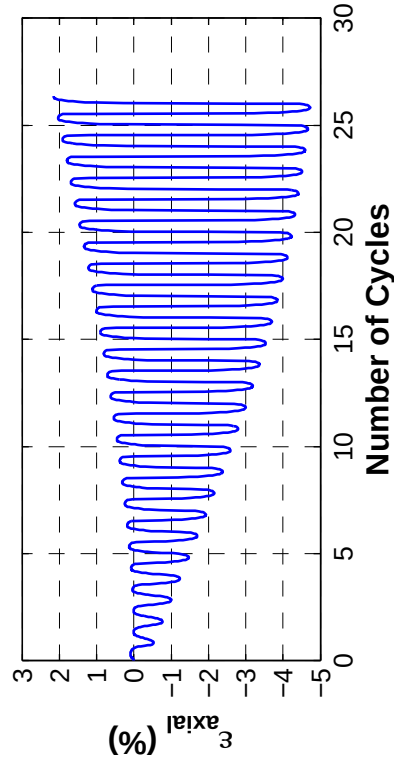
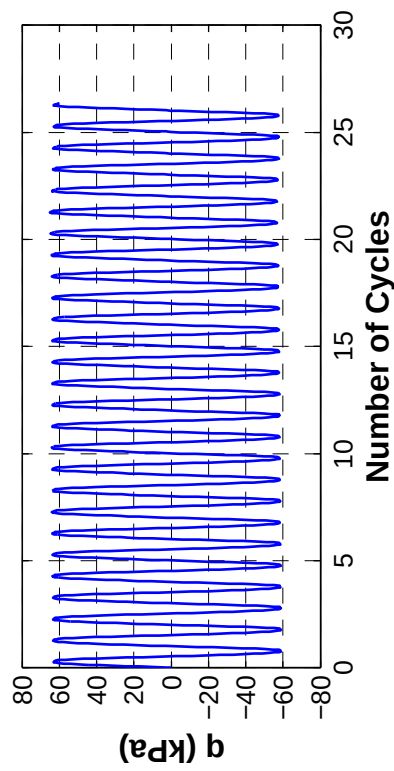
Site: EQC-4
Borehole: DM-1B
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.17
Date Tested: 10/28/14
Date Sampled: 10/23/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-4
Borehole: DM-1B
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.17
Date Tested: 10/28/14
Date Sampled: 10/23/14



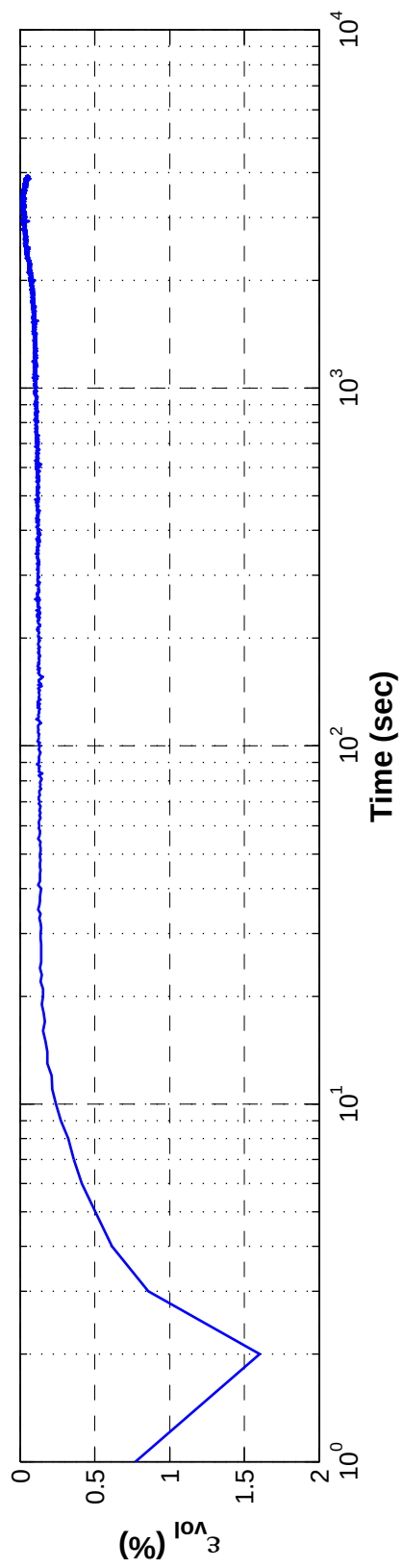
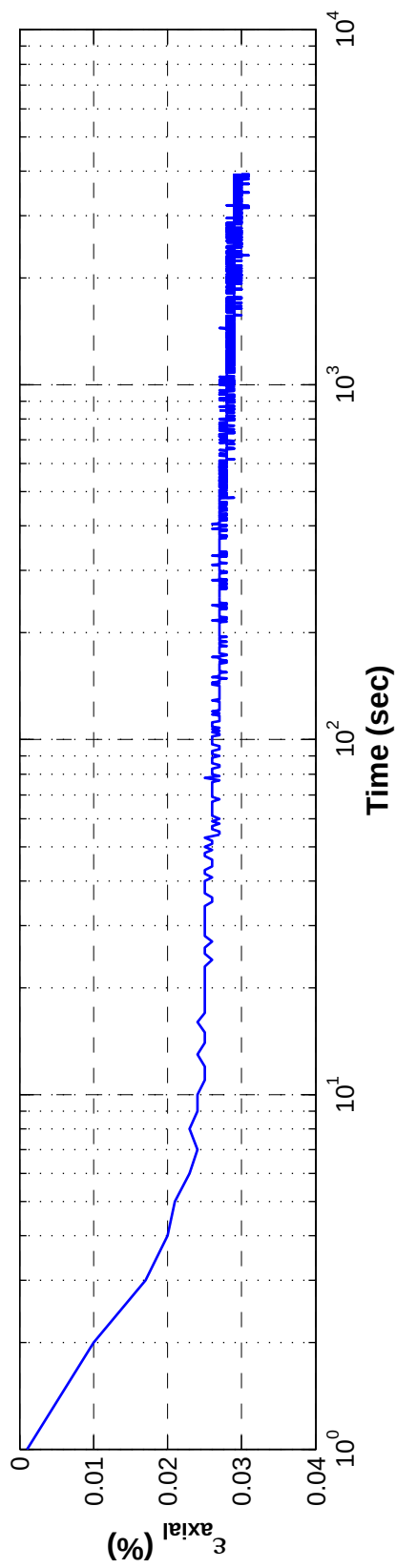
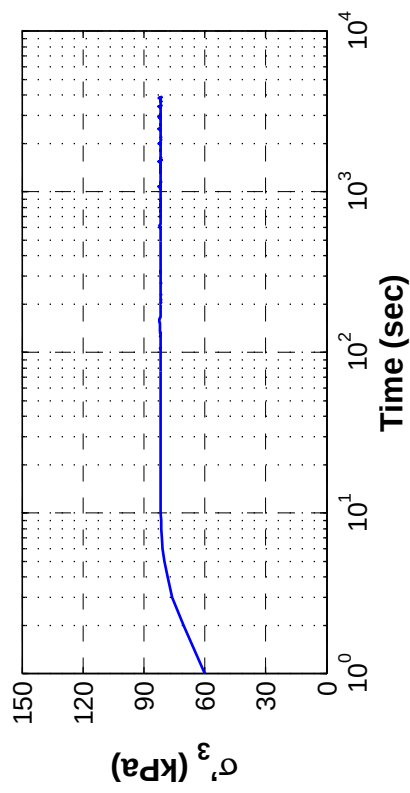


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-4	σ'_c (kPa):	81
Borehole:	DM-1B	Loading Freq (Hz):	0.1
Sample No.:	6U	B-Value:	0.982
Sampler Type:	D&M	CSR:	0.38
Spec. Depth (m):	6.325	N to $\epsilon_{Ax-S.A.}$ =3%:	13
Date Tested:	10/29/14	N to $\epsilon_{Ax-D.A.}$ =5%:	18
Date Sampled:	10/23/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	139.84	Gs:	2.68
Spec. Diam. (mm):	61.129	e_c :	0.73
Dry Mass (g):	635.14	PI (%):	NP
		FC (%):	1

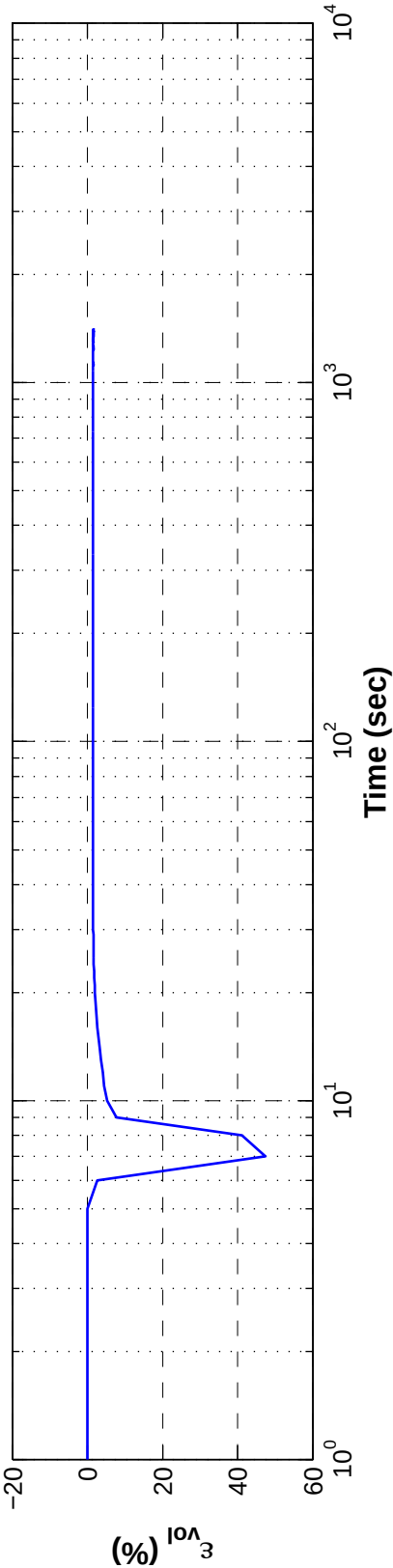
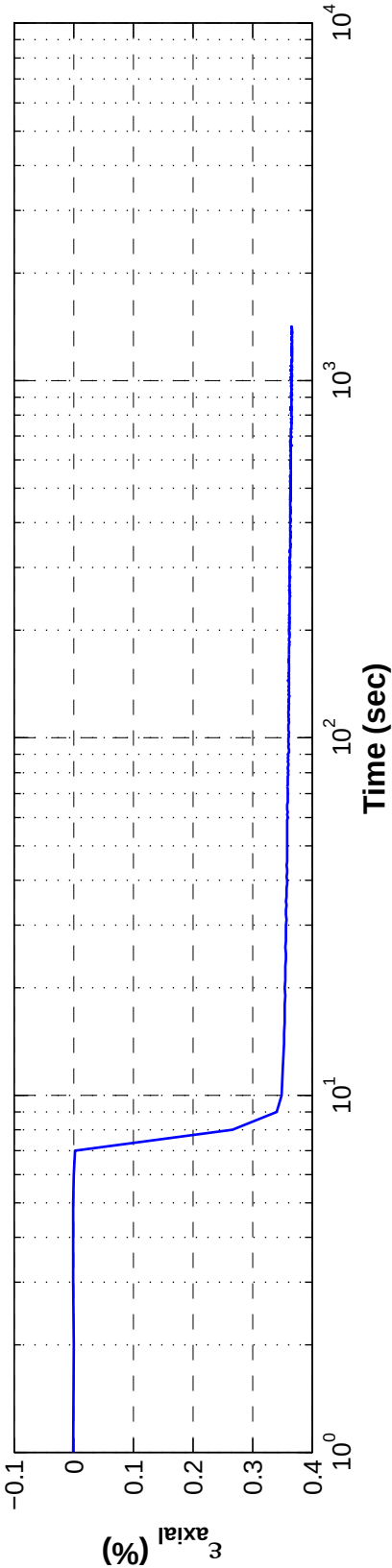
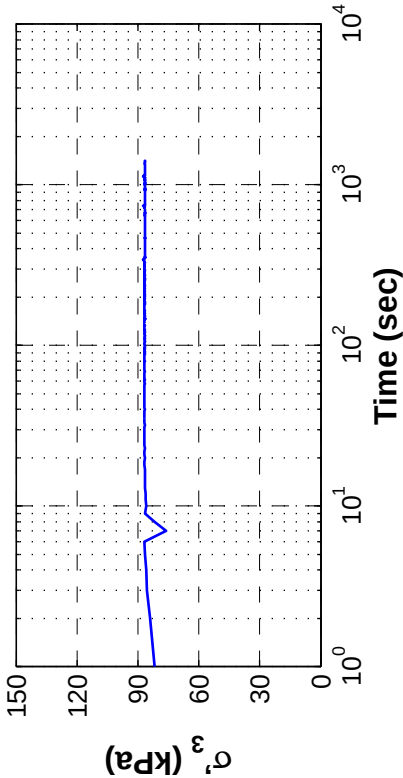
Specimen and Isotropic Consolidation Data

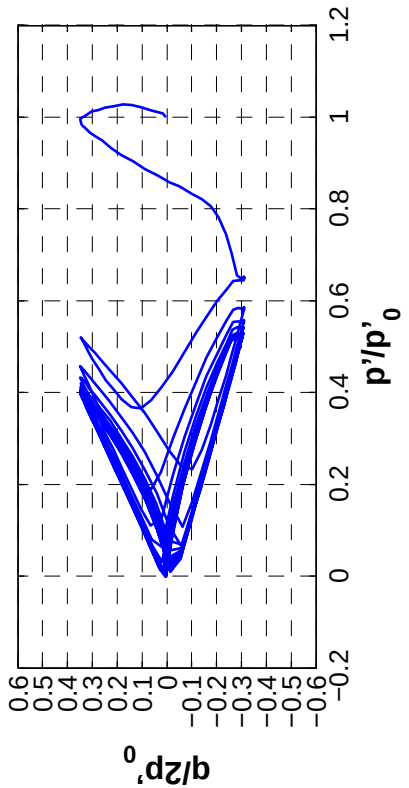
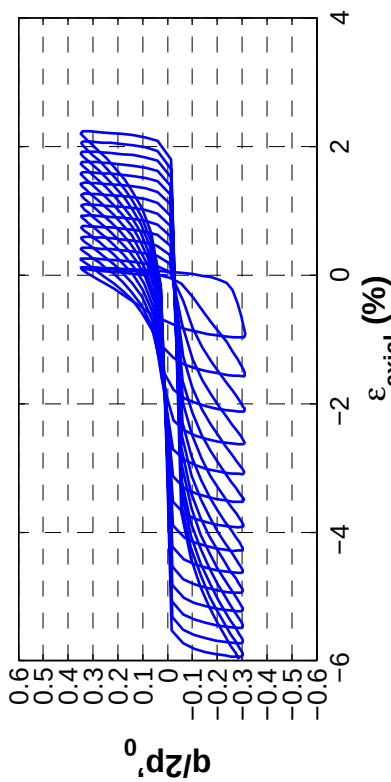
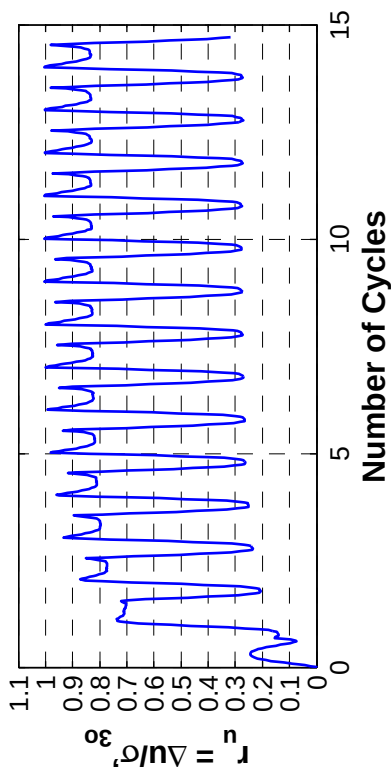
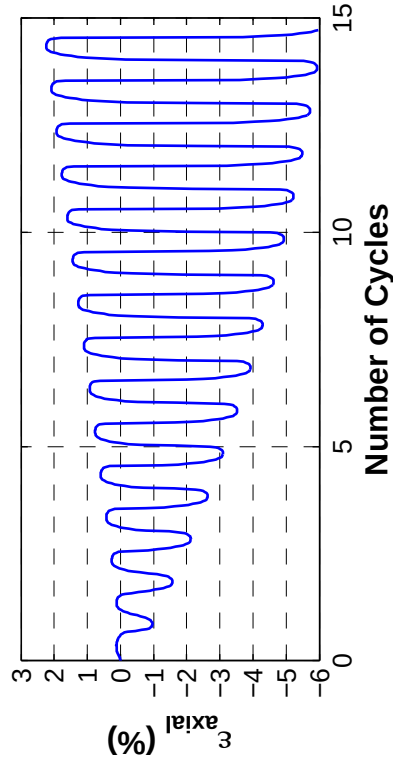
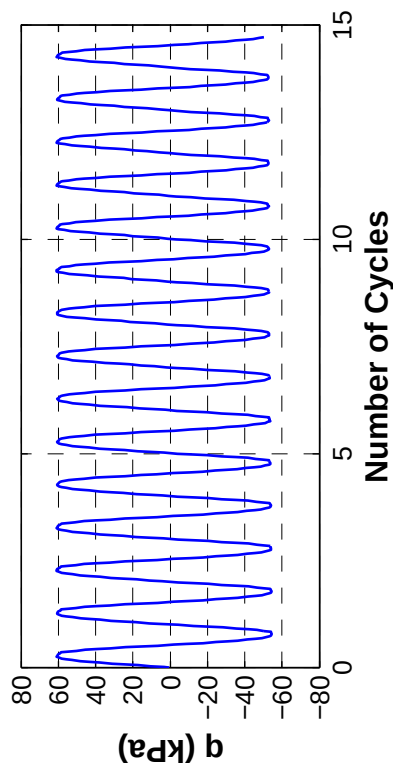
Site: EQC-4
Borehole: DM-1B
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.325
Date Tested: 10/29/14
Date Sampled: 10/23/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-4
Borehole: DM-1B
Sample No.: 6U
Sampler Type: D&M
Spec. Depth (m): 6.325
Date Tested: 10/29/14
Date Sampled: 10/23/14



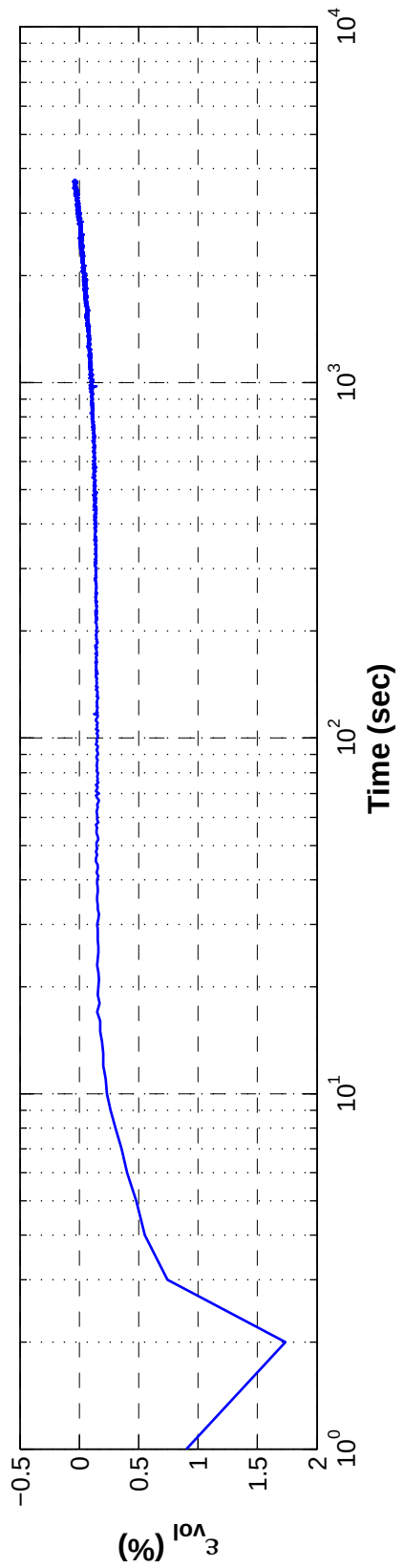
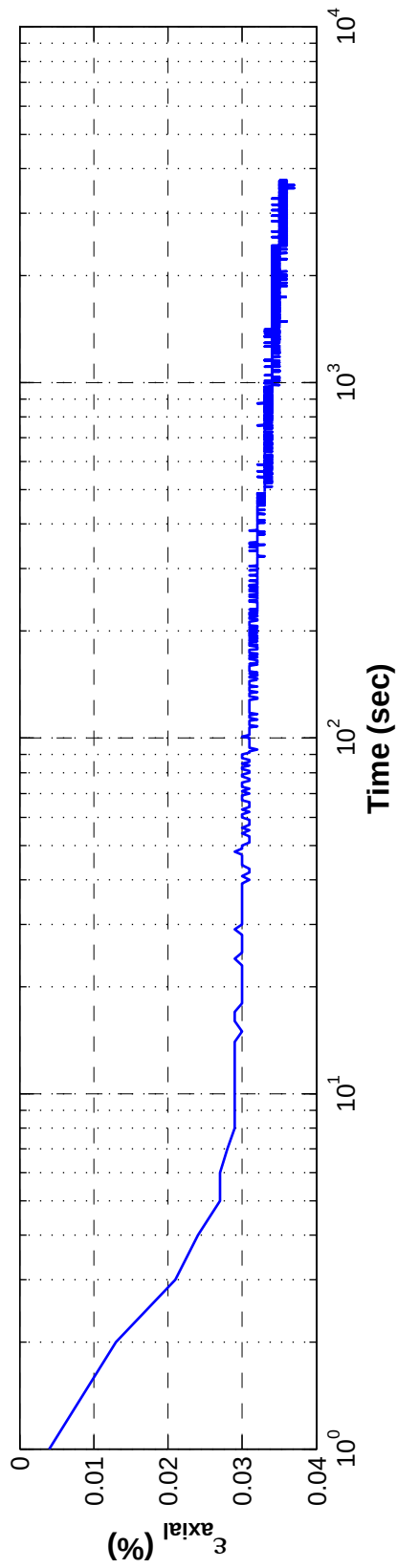
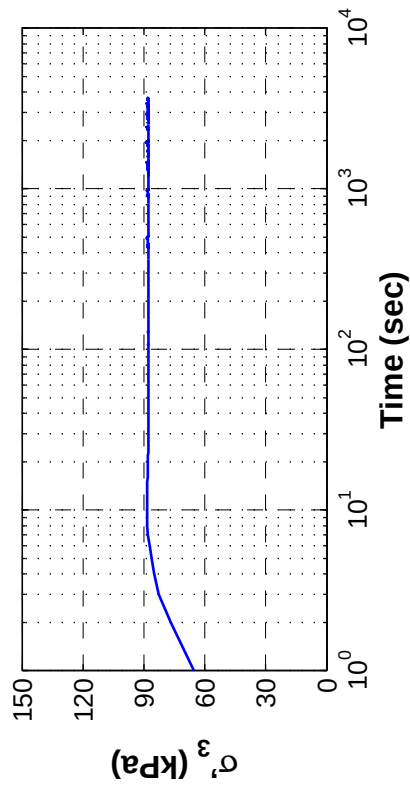


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-4	σ'_c (kPa):	87
Borehole:	DM-1B	Loading Freq (Hz):	0.1
Sample No.:	7U	B-Value:	0.978
Sampler Type:	D&M	CSR:	0.34
Spec. Depth (m):	6.87	N to $\epsilon_{Ax-S.A.}$ =3%:	5
Date Tested:	10/30/14	N to $\epsilon_{Ax-D.A.}$ =5%:	7.5
Date Sampled:	10/23/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	136.476	Gs:	---
Spec. Diam. (mm):	61.057	e_c :	0.79
Dry Mass (g):	600.20	PI (%):	NP
		FC (%):	9

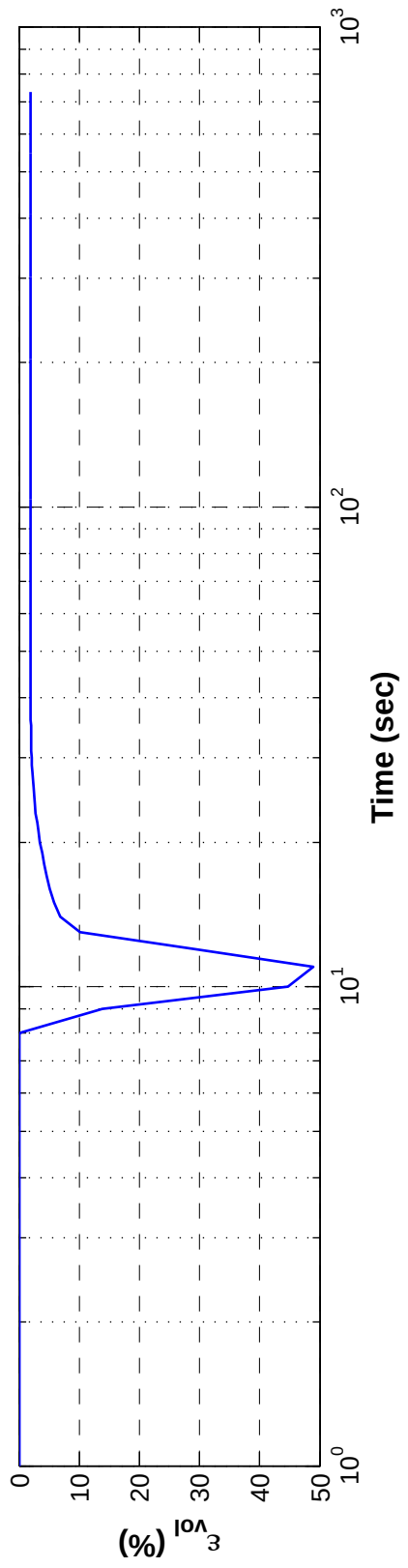
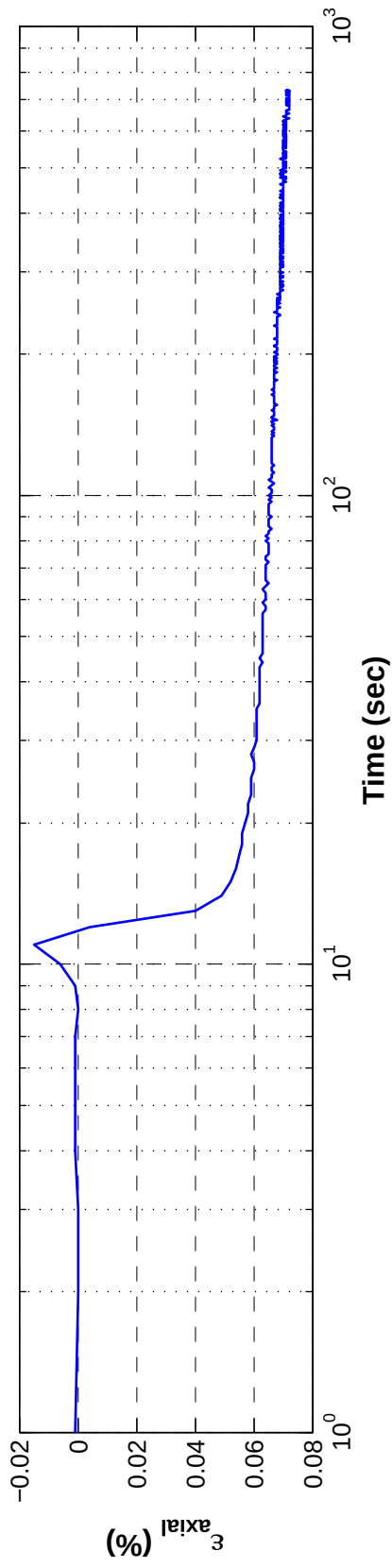
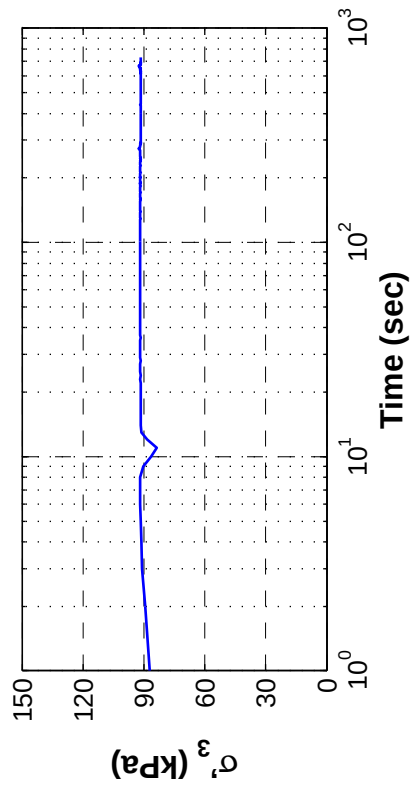
Specimen and Isotropic Consolidation Data

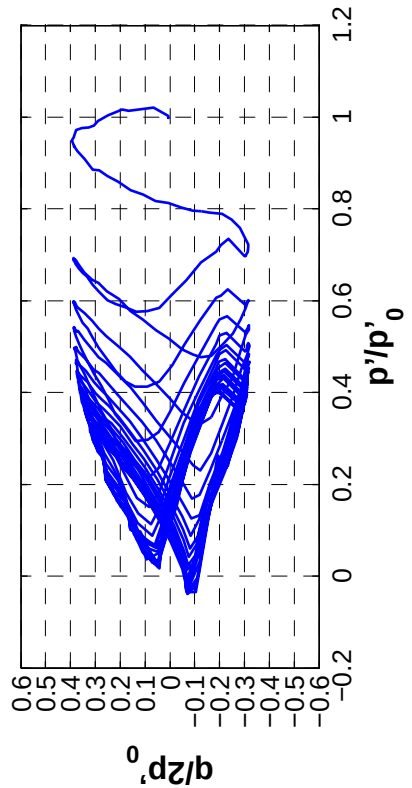
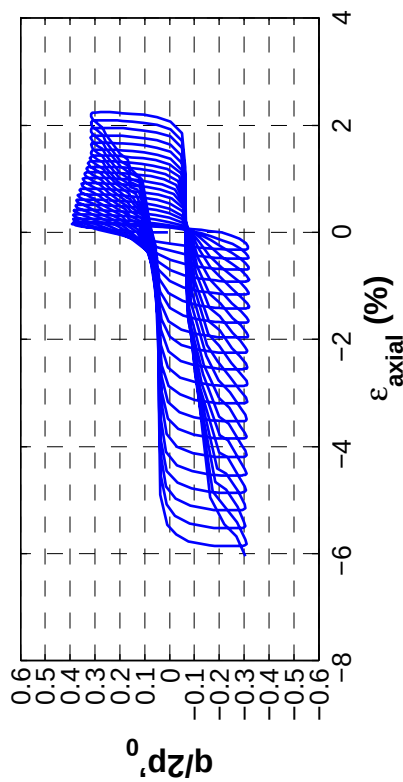
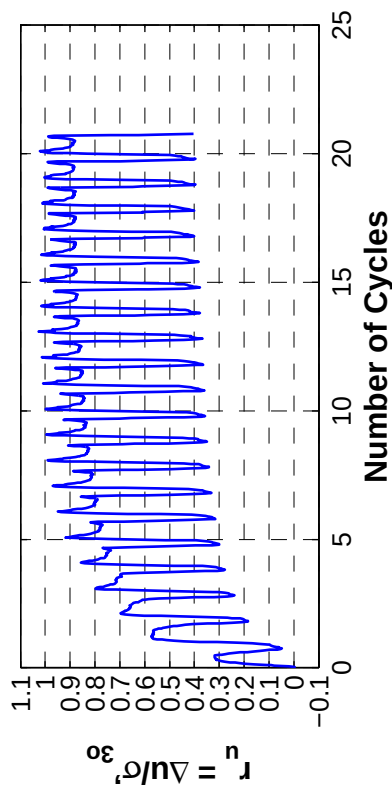
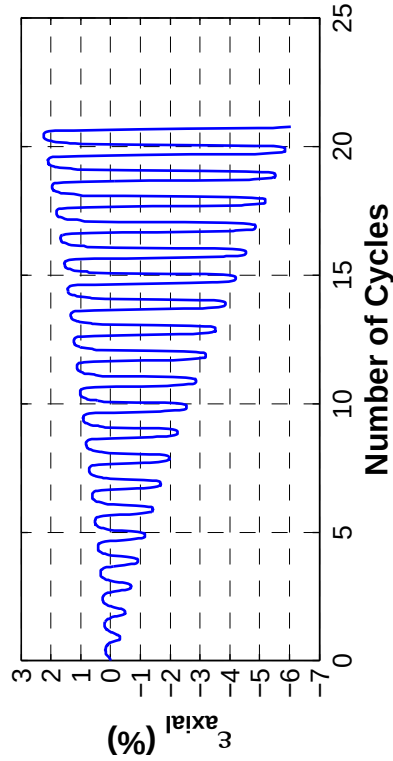
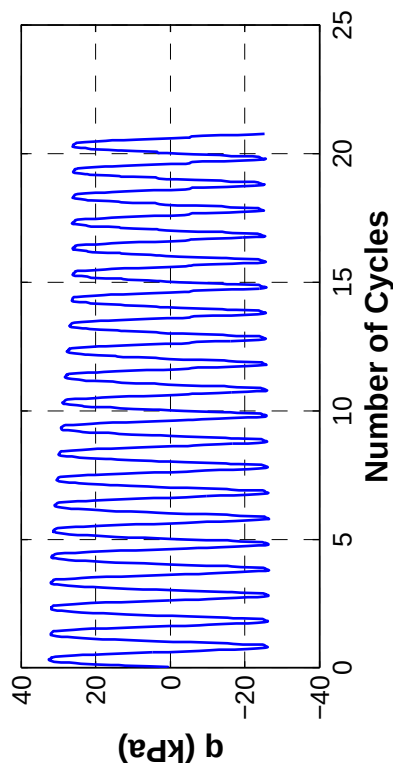
Site: EQC-4
Borehole: DM-1B
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 6.87
Date Tested: 10/30/14
Date Sampled: 10/23/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-4
Borehole: DM-1B
Sample No.: 7U
Sampler Type: D&M
Spec. Depth (m): 6.87
Date Tested: 10/30/14
Date Sampled: 10/23/14



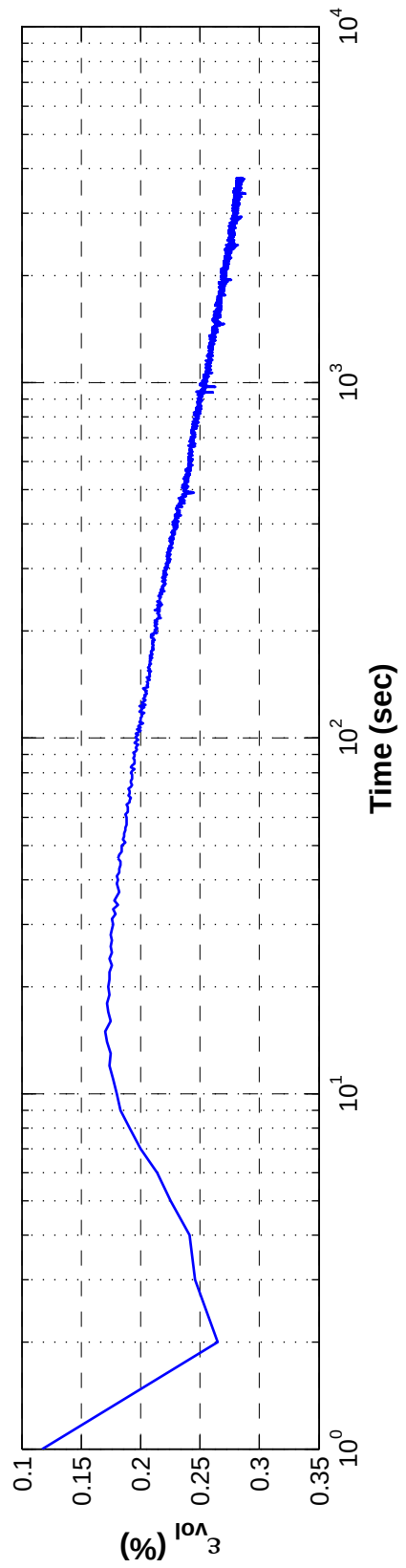
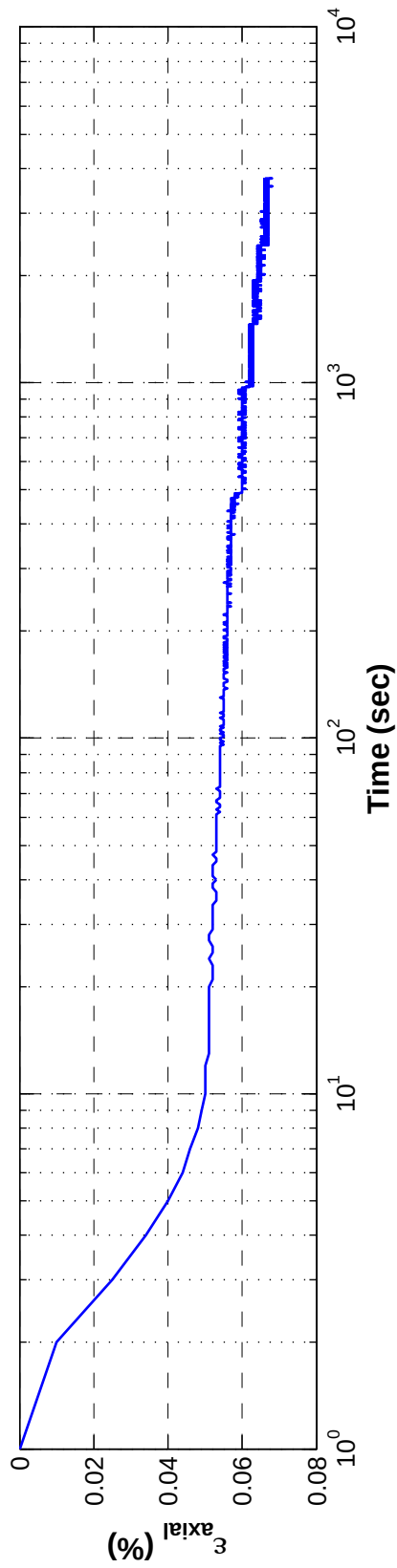
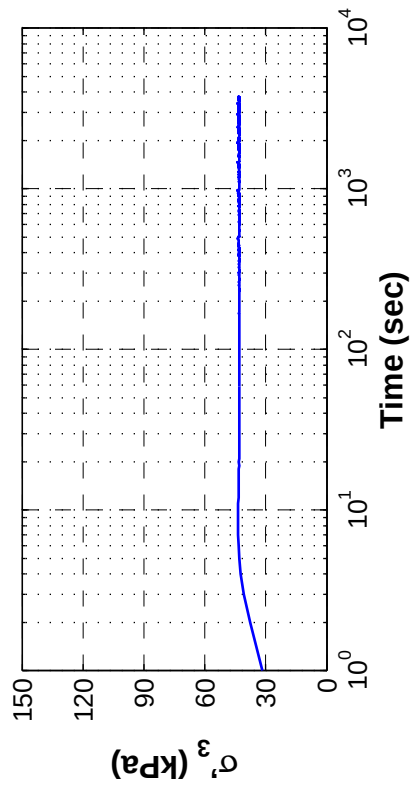


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-4	σ'_c (kPa):	41
Borehole:	DM-2	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.984
Sampler Type:	D&M	CSR:	0.35
Spec. Depth (m):	2.27	N to $\epsilon_{Ax-S.A.}$ =3%:	12
Date Tested:	11/2/14	N to $\epsilon_{Ax-D.A.}$ =5%:	14
Date Sampled:	10/24/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	128.34	Gs:	2.68
Spec. Diam. (mm):	61.14	e_c :	0.95
Dry Mass (g):	516.04	PI (%):	NP
		FC (%):	34

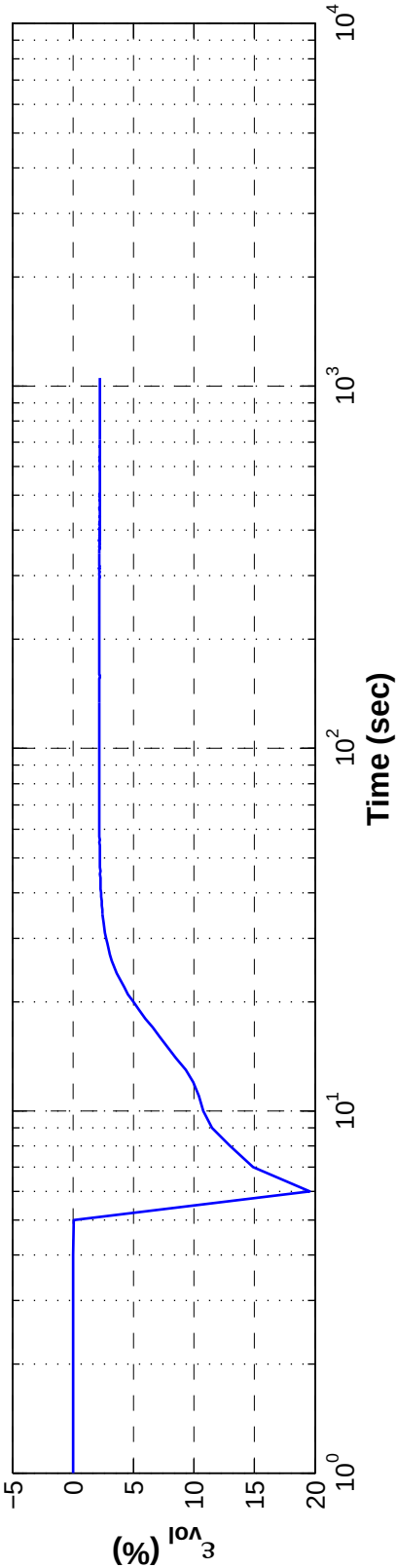
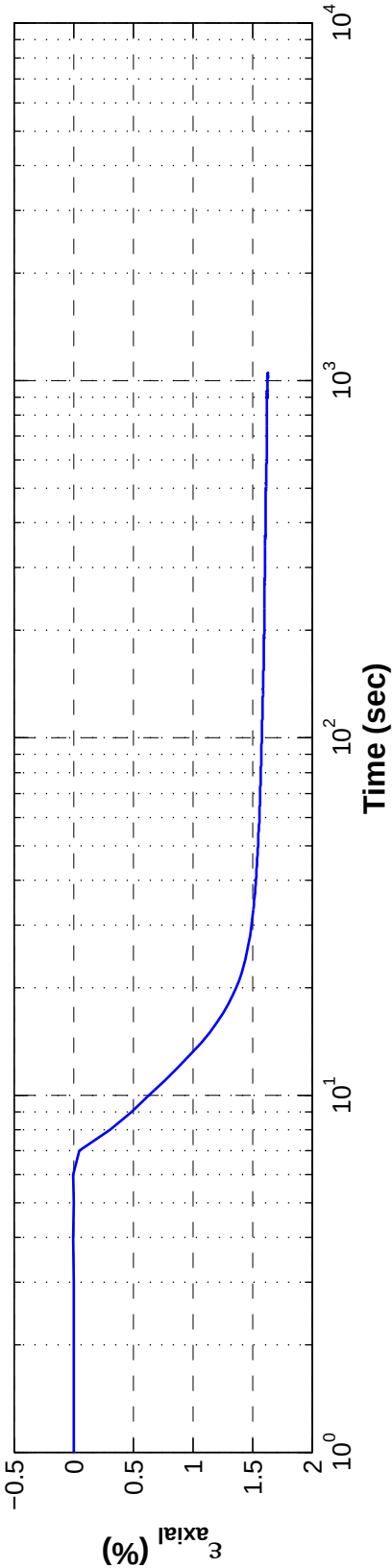
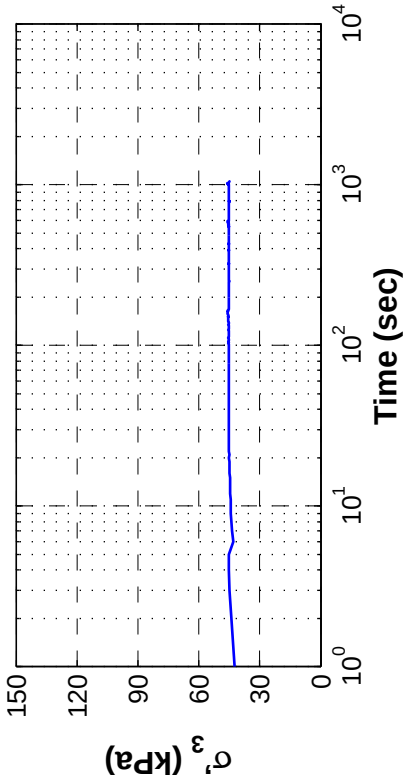
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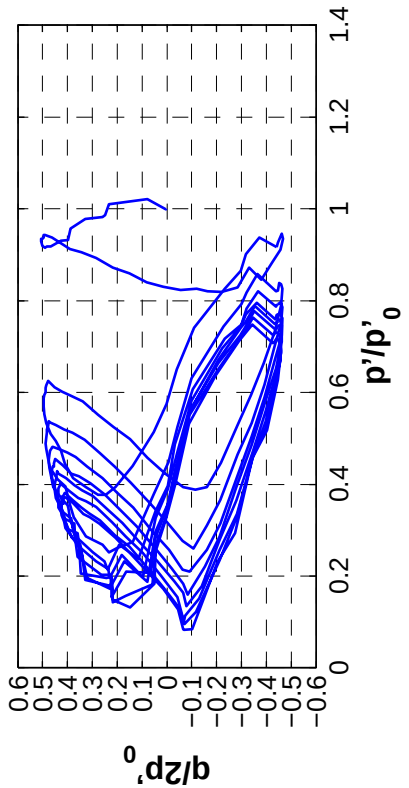
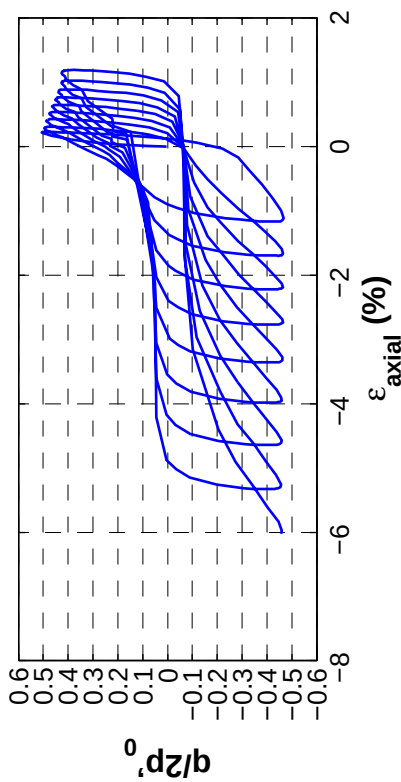
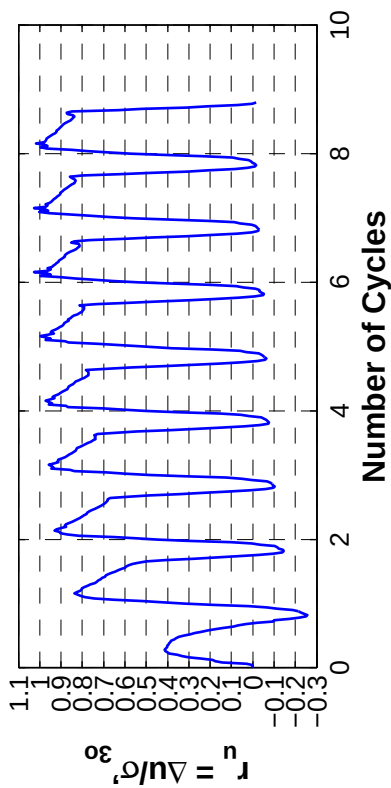
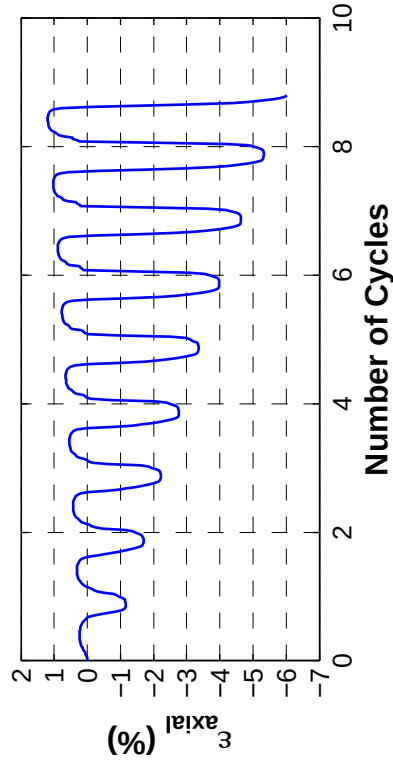
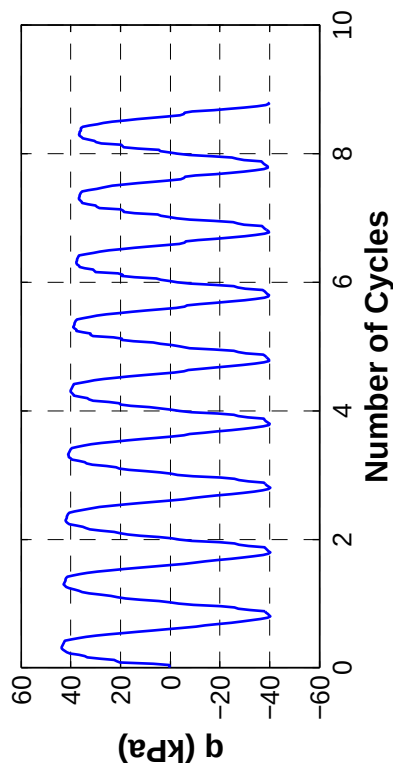
Site: EQC-4
Borehole: DM-2
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.27
Date Tested: 11/2/14
Date Sampled: 10/24/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-4
Borehole: DM-2
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.27
Date Tested: 11/2/14
Date Sampled: 10/24/14



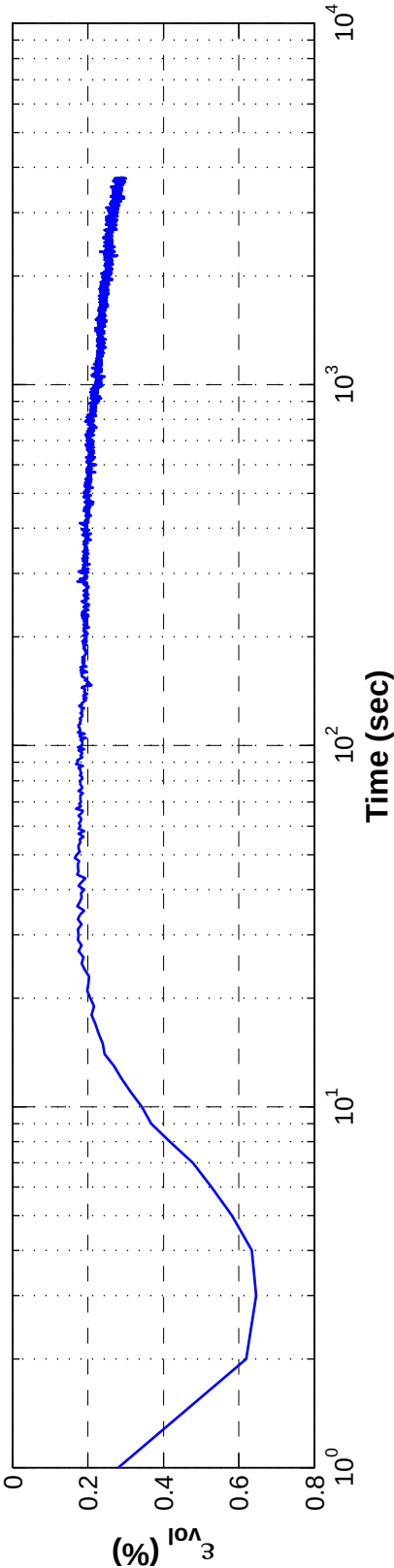
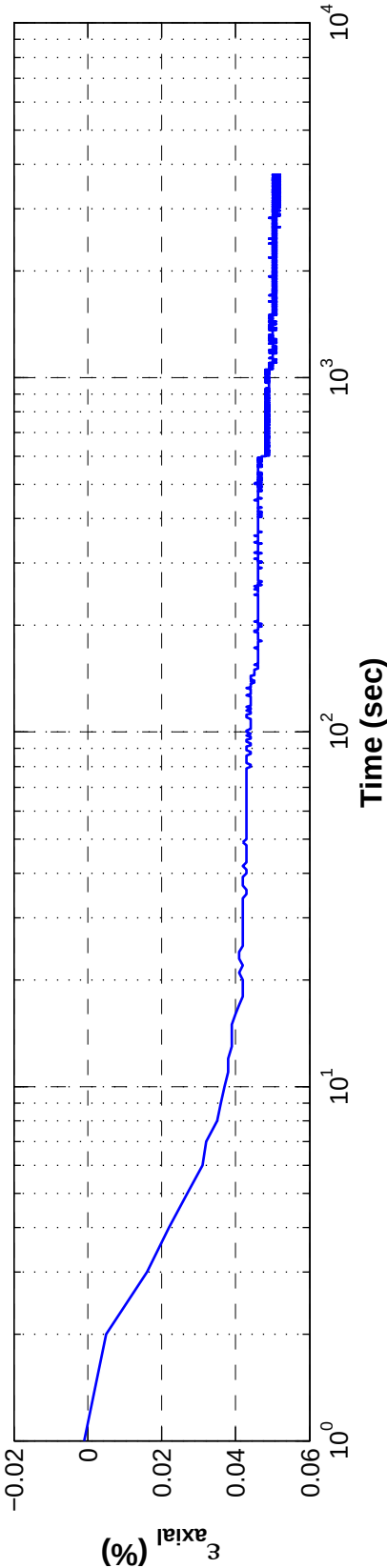
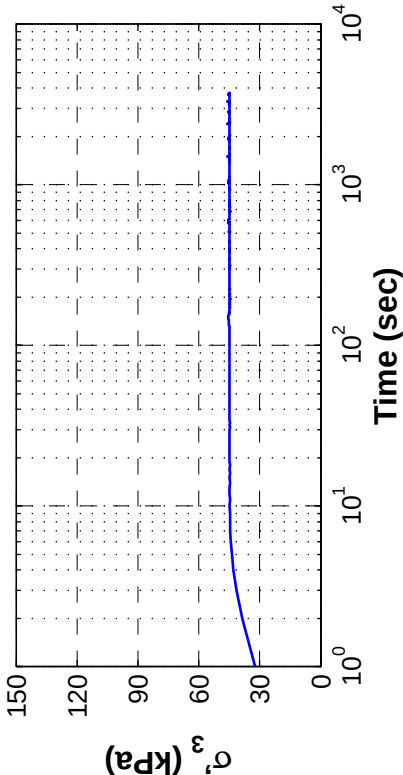


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-4	σ'_c (kPa):	43
Borehole:	DM-2	Loading Freq (Hz):	1
Sample No.:	3U	B-Value:	0.964
Sampler Type:	D&M	CSR:	0.48
Spec. Depth (m):	2.425	N to $\epsilon_{Ax-S.A.}$ =3%:	5
Date Tested:	11/3/14	N to $\epsilon_{Ax-D.A.}$ =5%:	7
Date Sampled:	10/24/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	135.12	Gs:	---
Spec. Diam. (mm):	61.16	e_c :	0.88
Dry Mass (g):	564.70	PI (%):	NP
		FC (%):	36

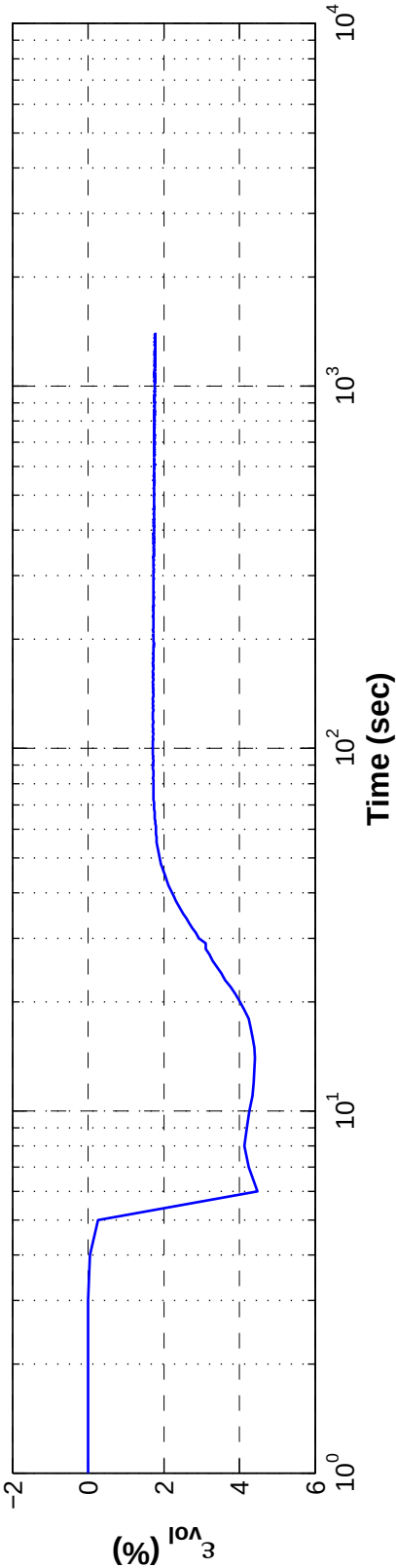
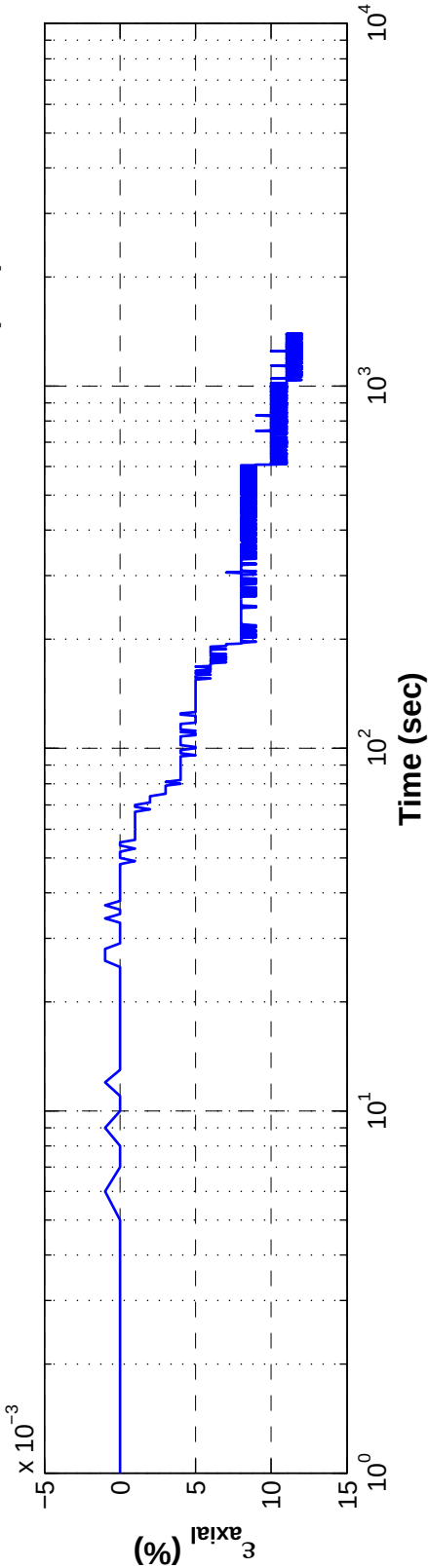
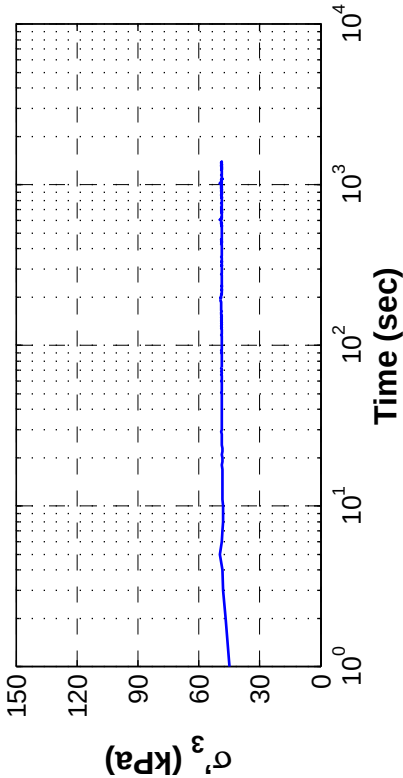
Specimen and Isotropic Consolidation Data

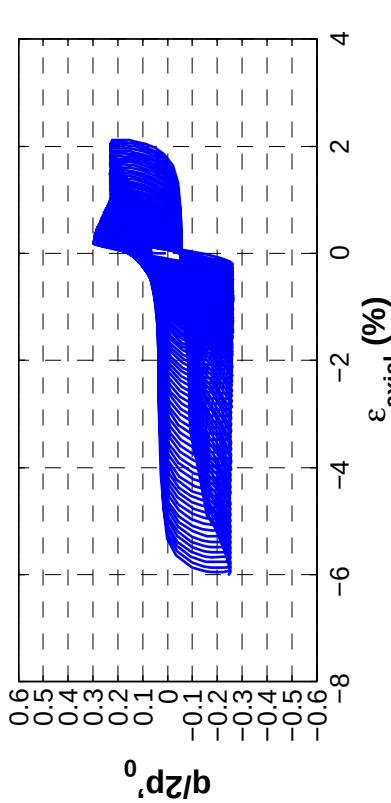
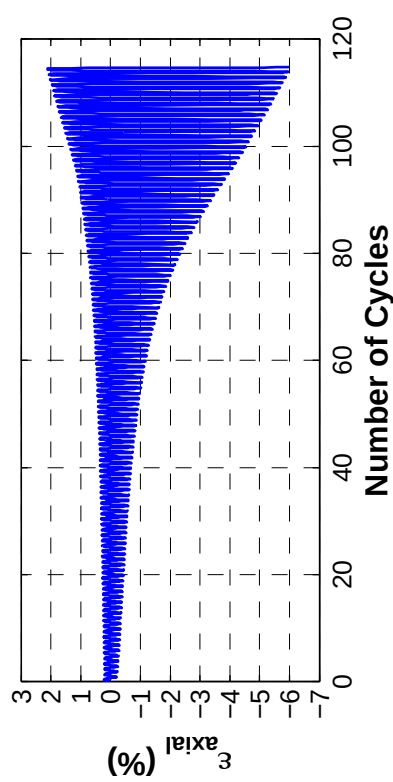
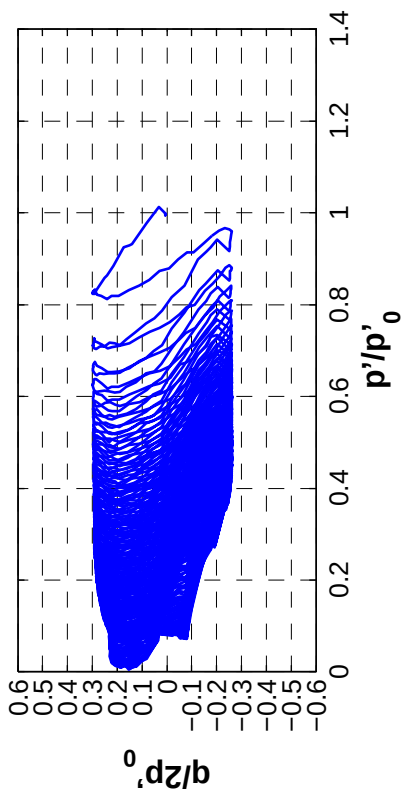
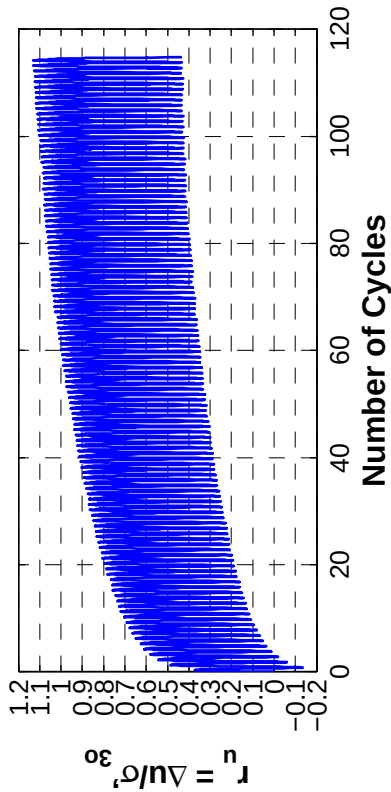
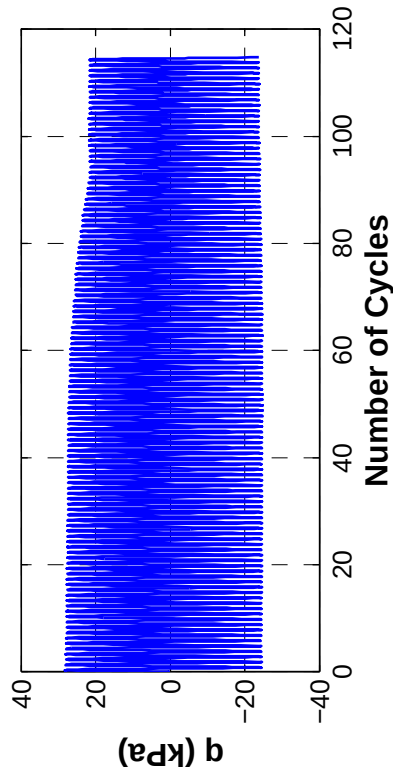
Site: EQC-4
Borehole: DM-2
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.425
Date Tested: 11/3/14
Date Sampled: 10/24/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-4
Borehole: DM-2
Sample No.: 3U
Sampler Type: D&M
Spec. Depth (m): 2.425
Date Tested: 11/3/14
Date Sampled: 10/24/14



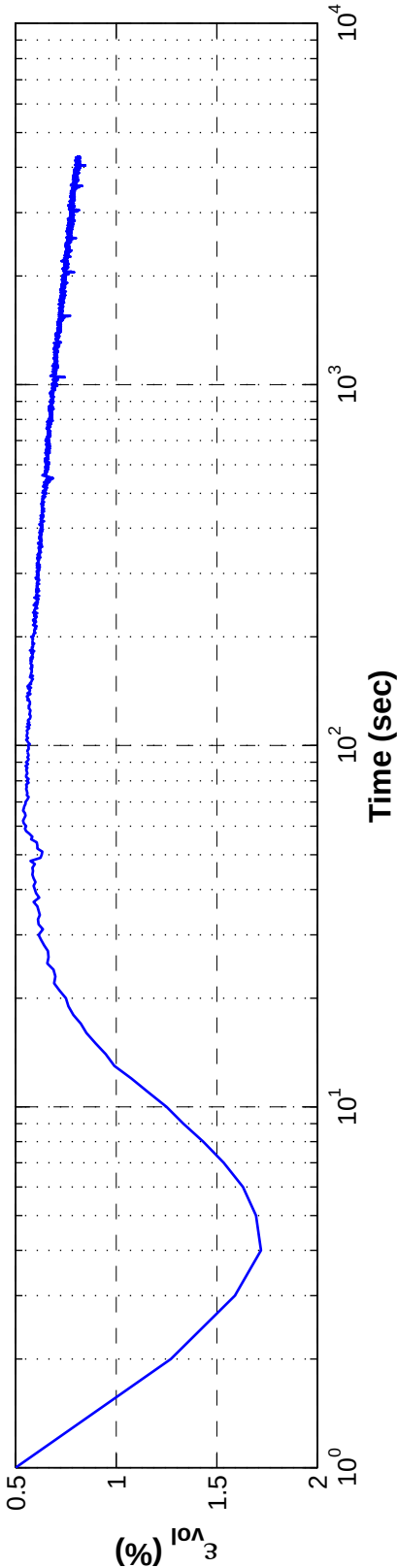
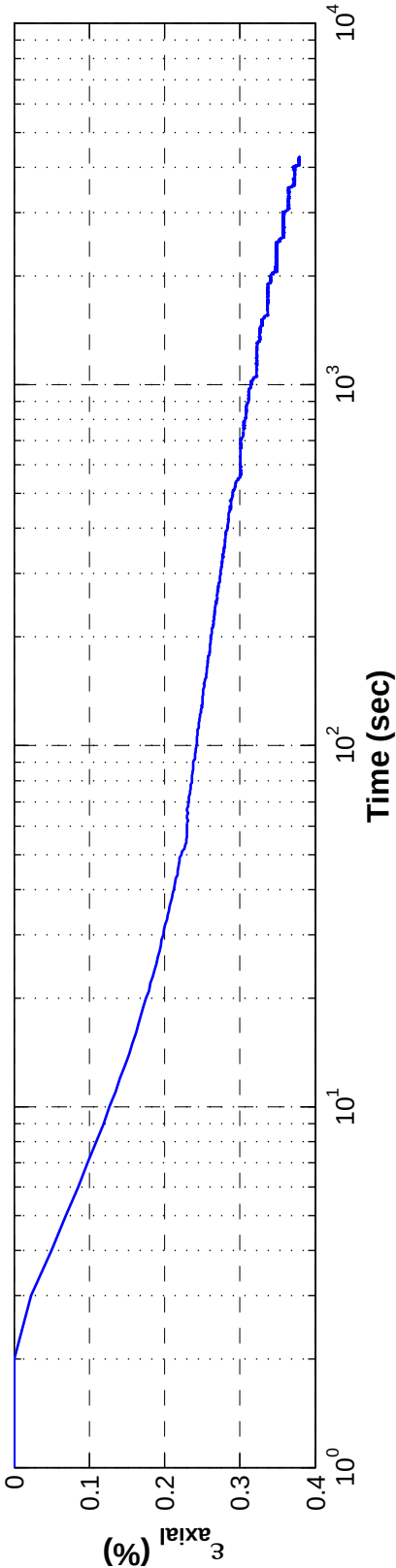
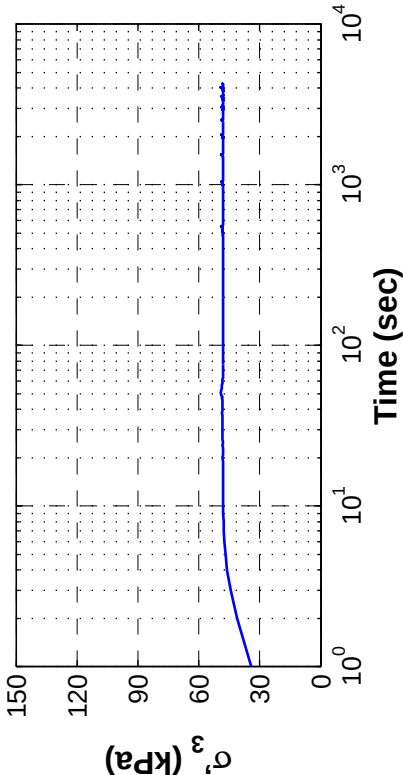


Specimen and Isotropic Cyclic Triaxial Test Data

Site:	EQC-4	σ'_c (kPa):	47
Borehole:	DM-2	Loading Freq (Hz):	1
Sample No.:	4U	B-Value:	0.99
Sampler Type:	D&M	CSR:	0.28
Spec. Depth (m):	2.72	N to $\epsilon_{Ax-S.A.}$ =3%:	87
Date Tested:	11/4/14	N to $\epsilon_{Ax-D.A.}$ =5%:	95
Date Sampled:	10/24/14	Post-Cyclic Test:	Reconsol
Spec. Ht. (mm):	139.66	Gs:	---
Spec. Diam. (mm):	60.85	e_c :	1.26
Dry Mass (g):	470.38	PI (%):	NP
		FC (%):	22

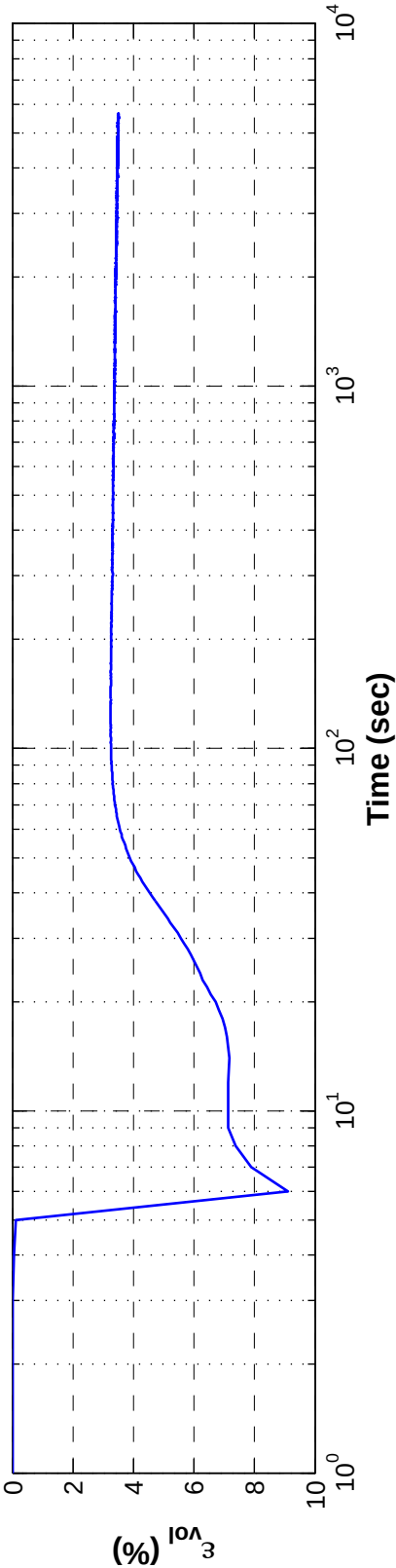
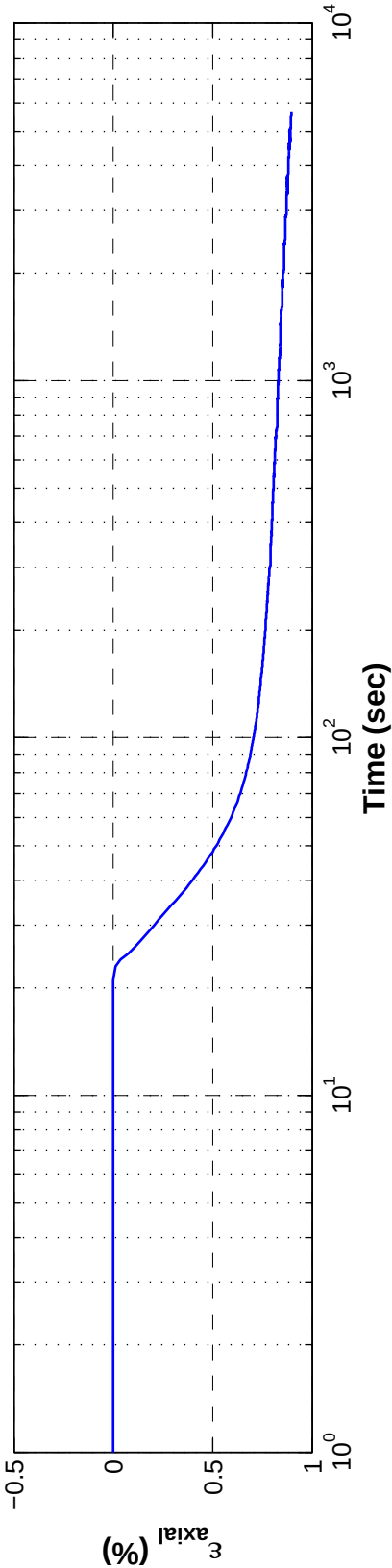
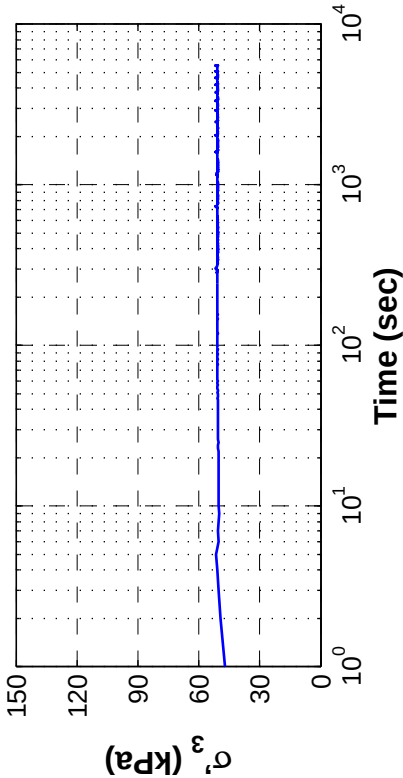
Specimen and Isotropic Consolidation Data

Site: EQC-4
Borehole: DM-2
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 2.72
Date Tested: 11/4/14
Date Sampled: 10/24/14



Specimen and Post-CTX Reconsolidation Data

Site: EQC-4
Borehole: DM-2
Sample No.: 4U
Sampler Type: D&M
Spec. Depth (m): 2.72
Date Tested: 11/4/14
Date Sampled: 10/24/14



Appendix C.6

Raw Cyclic Triaxial Test Data

Data files for cyclic triaxial testing are provided as an electronic appendix attached to this dissertation.

Appendix D

Steady State Testing of Reconstituted Specimens

APPENDIX D: STEADY STATE TESTING OF RECONSTITUTED SPECIMENS

Steady state testing (SST) was conducted on reconstituted specimens prepared using soil mixtures that combined similar cyclic triaxial (CTX) test specimens from a given soil layer. Particle size distributions, index properties, and CPT data were considered in selecting which CTX specimens to combine. Appendix C provides the CTX specimen properties.

- “Site 2 Soil Mix” combines S2-DM1-7U-A and S2-DM1-7U-B
- “Site 14 Soil Mix” combines S14-DM2-5U-A and S14-DM2-5U-B
- “Site 33 Soil Mix” combines S33-DM1-4U-A and S33-DM1-5U-A

Index testing of CTX specimens was conducted at the University of Canterbury Geomechanics Laboratory. Minimum ($e_{\min}$) and maximum ($e_{\max}$) void ratio tests were conducted in accordance with the Japanese Standard JIS A 1224:2000 Test Method for Minimum and Maximum Densities of Sands as outlined in Taylor (2015) with translation to English by Dr. Yasuyo Hosono. The tests are applicable for soils with at least 95% sand (particle diameter = 75 μm – 2 mm). The ASTM Standards for maximum density (ASTM D4253-16) and minimum density (ASTM D4254-00R06) specify that the ASTM test methods are applicable for soils with up to 15% soil particles passing a No. 200 (75 μm) sieve. The silty soils used for steady state testing had $FC \geq 10\%$, near or above the approximate limit of applicability for $e_{\min}$ and $e_{\max}$ testing as defined by the Japanese and ASTM standards.

Steady state testing often refers to laboratory-prepared specimens according to their relative density (D_r). However, using D_r for soils with significant fines is an issue because of the segregation of fines and coarse particles and differing fine/coarse particle interaction and void space distribution for wet vs. dry soil conditions (i.e., $e_{\min}$ and $e_{\max}$ testing conducted on dry soils whereas specimens prepared via moist tamping). Additionally, the layered subsurface conditions characteristic of the alluvial Christchurch environment lead to in-situ variations in density and fines sequencing that are not replicated with uniform laboratory-prepared specimens, making it difficult to relate laboratory testing of such soils to a field equivalent. Therefore relative density and void ratio are used as indexes for comparison among tests from each soil mixture, rather than between the soil mixtures from different sites or to in-situ conditions.

Several $e_{\min}$ and $e_{\max}$ tests were conducted on the selected CTX specimens at UC Berkeley following the Japanese Standard, prior to mixing soils. After combining the CTX specimens, index testing was done on the resulting soil mixtures. Void ratio test data is summarized in the following tables.

Minimum and Maximum Void Ratios from Testing at UC Berkeley

Site 33 Soil Mix

	S33-DM1-4U-A (FC = 11%)		S33-DM1-5U-A (FC = 10%)		Site 33 Soil Mix	
Test No.	$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$
1	---	---	1.25	0.69	1.25	0.63
2	---	---	1.25	0.69	1.26	0.63
3	---	---	1.26	0.68	1.26	0.63
4	---	---	1.26	---	1.25	---
5	---	---	1.26	---	1.27	---
6	---	---	1.25	---	1.26	---
7	---	---	1.24	---	1.27	---
8	---	---	1.24	---	1.26	---
9	---	---	1.26	---	---	---
Average	---	---	1.25	0.69	1.26	0.63
<i>U. of Canterbury</i>	1.298	0.596	1.321	0.684	---	---

Site 14 Soil Mix

	S14-DM2-5U-A (FC = 47%)		S14-DM2-5U-B (FC = 36%)		Site 14 Soil Mix	
Test No.	$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$
1	1.36	0.60	1.34	0.62	1.34	0.60
2	1.37	0.60	1.32	0.62	1.34	0.60
3	1.37	0.60	1.33	0.62	1.34	0.60
4	1.36	---	1.34	---	1.34	---
5	1.37	---	1.32	---	1.34	---
Average	1.37	0.60	1.33	0.62	1.34	0.60
<i>U. of Canterbury</i>	1.395	0.634	---	---	---	---

Site 2 Soil Mix

	S2-DM1-7U-A (FC = 30%)		S2-DM1-7U-B (FC = 43%)		Site 2 Soil Mix	
Test No.	$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$
1	1.30	0.61	1.34	0.59	1.30	0.59
2	1.30	0.61	1.34	0.60	1.31	0.59
3	1.30	0.60	1.35	0.60	1.31	0.59
4	1.30	---	1.34	---	1.31	---
5	1.29	---	1.34	---	1.31	---
Average	1.30	0.61	1.34	0.60	1.31	0.59
<i>U. of Canterbury</i>	---	---	1.371	0.667	---	---

Summary

	$e_{\max}$	$e_{\min}$	G_s
Site 33 Soil Mix	1.26	0.63	2.69
Site 14 Soil Mix	1.34	0.60	2.69
Site 2 Soil Mix	1.31	0.59	2.69

Fines Content

Fines content (FC) for CTX specimens was determined primarily through laser analysis; for some specimens, sieve/hydrometer analysis was also conducted. The following tables summarize FC data for the CTX specimens combined for the soil mixtures tested in this study and provide FC for each soil mixture obtained from a #200 sieve wash done after the soils were mixed.

Site 2

	FC (%), from laser	FC (%), from sieve	FC (%), sieve, soil mixture
S2-DM1-7U-A	30	41	39
S2-DM1-7U-B	43	54	

Site 14

	FC (%), from laser	FC (%), from sieve	FC (%), sieve, soil mixture
S14-DM1-5U-A	47%	---	44
S14-DM1-5U-B	36%	---	

Site 33

	FC (%), from laser	FC (%), from sieve	FC (%), sieve, soil mixture
S33-DM1-4U-A	11	---	24, 30
S33-DM1-5U-A	10	---	

Differences in FC from laser vs. sieve analysis were noted for several CTX specimens (Appendix C), with the sieve typically providing higher estimates of FC but no clearly quantifiable trend. Variations in FC from laser vs. sieve analysis ranged from negligible to 20%.

In performing the #200 sieve wash for each soil mixture, individual grains were observed to continue washing through the sieve, when the water coming through the sieve was otherwise clear. The water in the wash bowl was not cloudy and these individual grains settled almost instantly. The Christchurch silty soils are characterized by angular particles with relatively uniform particle size distributions. Considering the angular nature of these soils (as demonstrated with SEM photos in Chapter 4), it seems likely that very fine sands were continuing to wash through the #200 sieve.

Regardless of which FC estimate is considered, the Site 2 and Site 14 soil mixtures contain sufficient fines such that they control behavior of the soil matrix (FC > approximately 35%). The Site 33 soil mixture is in the transitional zone where fines begin controlling response. Selecting a single fines content estimate as representative of each soil mixture neglects consideration of these important details for intermediate silty soils. Additionally, as discussed in the main body of this dissertation, thoroughly mixed fines are not representative of layered in-situ silty soil conditions.

Specimen Preparation

Reconstituted specimens were prepared using the moist tamping method. Lubricated end caps were used for all specimens. Membranes were applied to the lucite end caps with a thin layer of vacuum grease between the membrane and face of the end cap. The end caps contained brass-sintered

coarse porous stones. For some tests, wetted filter paper was placed over the porous stones to prevent fines loss during specimen preparation, saturation, and consolidation.

Saturation

Saturation was a major issue for the Site 2 and Site 14 soil mixtures. Typically, reconstituted specimens of sand are flushed at the same stress at which back-pressure saturation will be conducted (e.g., 100 kPa), maintaining a differential vacuum of approximately 20-25 kPa. However, the Site 2 and Site 14 soil mixtures with significant fines resulted in reconstituted specimens that could not be flushed through typical procedures. To remedy this, flushing was conducted at a low stress (e.g., 30-40 kPa), prior to increasing effective stress to the level for back-pressure saturation. Attempting to flush at higher vacuums resulted in water not flowing through the specimen.

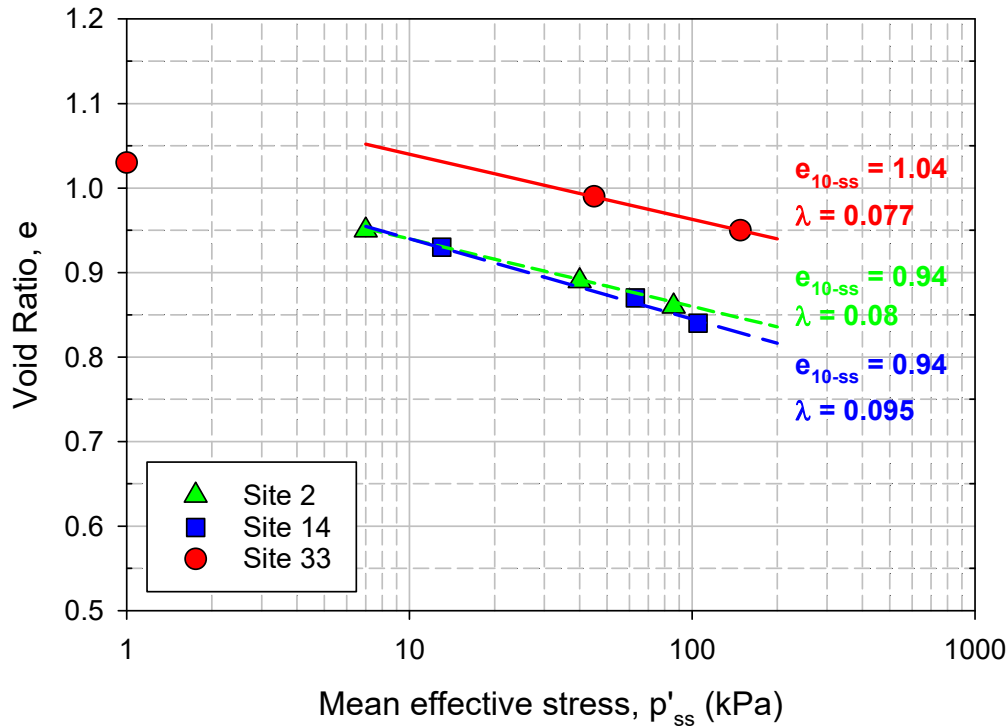
System compliance issues may have limited the maximum B-value that could be achieved during testing. B-values were observed to reach maximum values of $B \sim 0.94-0.95$, possibly due to chamber pressure leaking through the piston seal and the length of drain line tubing from the volume change device to the top/bottom drain line ports on the triaxial testing cell. B-values are indicated on the individual specimen test sheets. One test reached a maximum B-value of only ~ 0.76 before reaching maximum chamber and back pressures, however it is possible that specimen saturation was higher than the B-value indicated, due to issues with system compliance and considering that typical house pressure fluctuations were not observed in the effective stresses during undrained loading. Additionally, Tsukamoto (2017) presents laboratory data with results that were relatively insensitive to B-values from $\sim 0.7-1.0$. Based on these considerations, the test is included in this appendix.

Data Processing

Data were corrected for area and membrane effects. The area correction was applied assuming that the specimen deforms as a right cylinder during shearing. Membrane corrections were applied following Duncan & Seed (1967) to correct axial stress for membrane strength. For a load applied in compression, the membrane takes some of the applied load, resulting in a lower stress on the specimen. All tests were run undrained.

Findings

The testing presented in this appendix provides an initial look at the undrained response of laboratory-prepared specimens using soil mixtures from the silty soil case history sites. The steady state testing of Christchurch sandy soils presented by Rees (2010), Taylor (2015), and Markham (2015) provides context for the data presented in this appendix. The sandy soils tested in those studies are for fines contents typically ranging from $FC = 0-30\%$, as compared with the higher FC soils tested in this study. The following figure summarizes the results of the steady state testing on Site 2, Site 14, and Site 33 soils in semi-log $e-p'$ space. The Cubrinovski and Ishihara (2000) form of the steady state line was used to define the fitting parameters e_{10-ss} (steady state void ratio at $p'_{ss} = 10$ kPa) and λ (slope of the fitted line in semi-log space), where $e_{ss} = e_{10-ss} + \lambda (1 - \log_{10} p'_{ss})$.



The following table summarizes the results of this steady state testing and provides data from Markham (2015) for comparison:

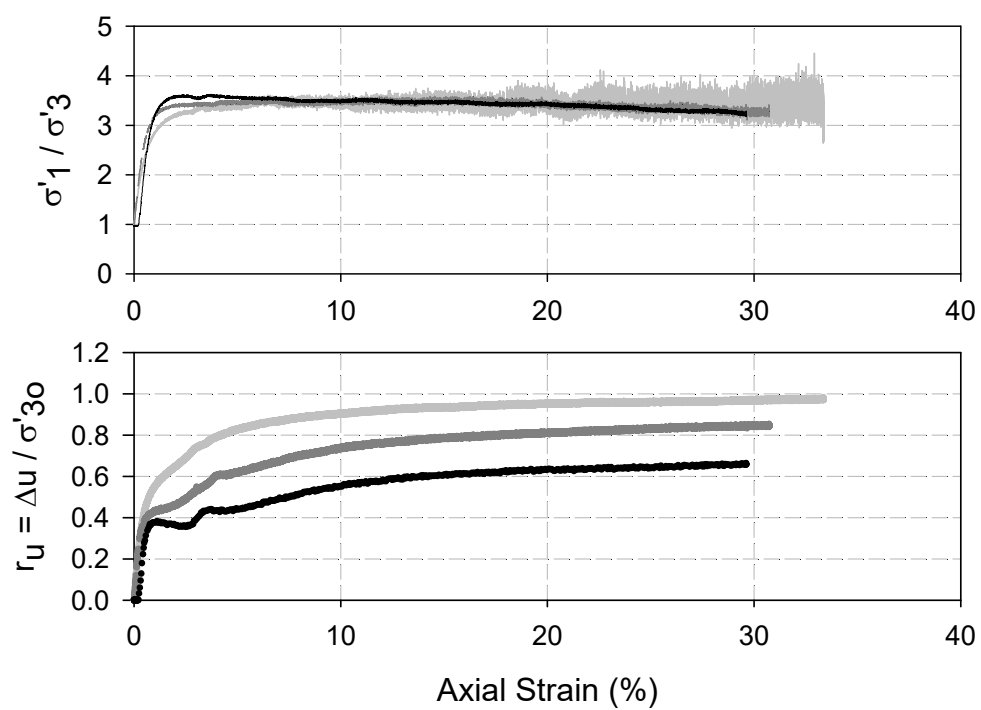
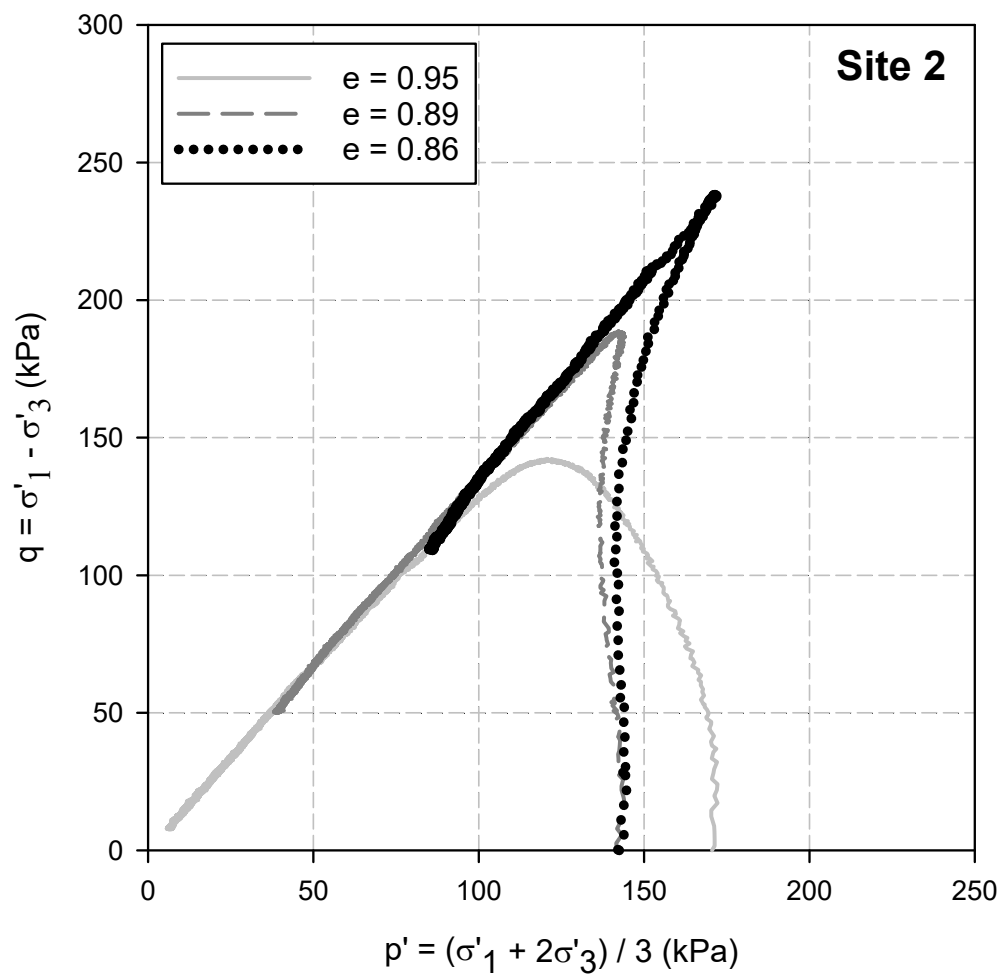
	FC (%)	e_{10-ss}	λ
Site 2	39	0.94	0.08
Site 14	44	0.94	0.095
Site 33	24	1.04	0.077
<i>Markham (2015):</i>			
<i>FTG-7 (Upper Sand)</i>	6	0.97	0.08
<i>CTH (Upper Sand)</i>	7	1.17	0.17
<i>CTH (Lower Sand)</i>	6	1.11	0.15
<i>CTUC (Upper Sand)</i>	7	1.14	0.20
<i>PWC (Lower Sand)</i>	5	1.21	0.21
<i>FTG-7 (Upper SM)</i>	38	0.97	0.19
<i>CTH (Upper ML)</i>	74	0.89	0.10

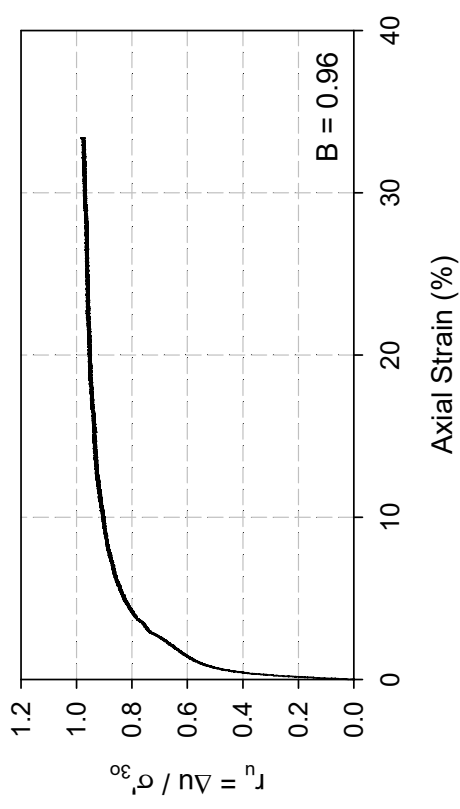
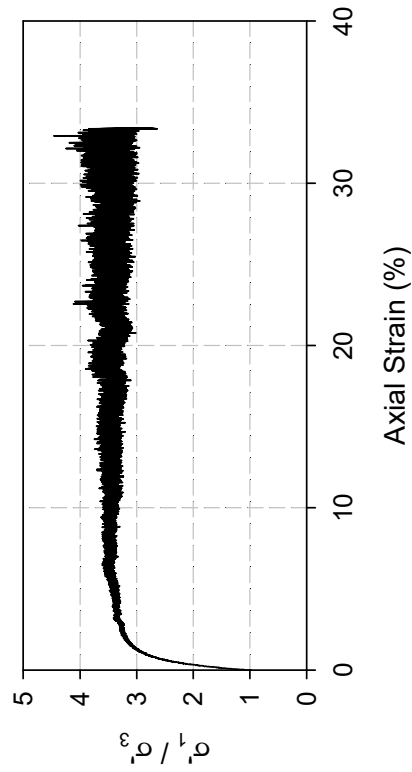
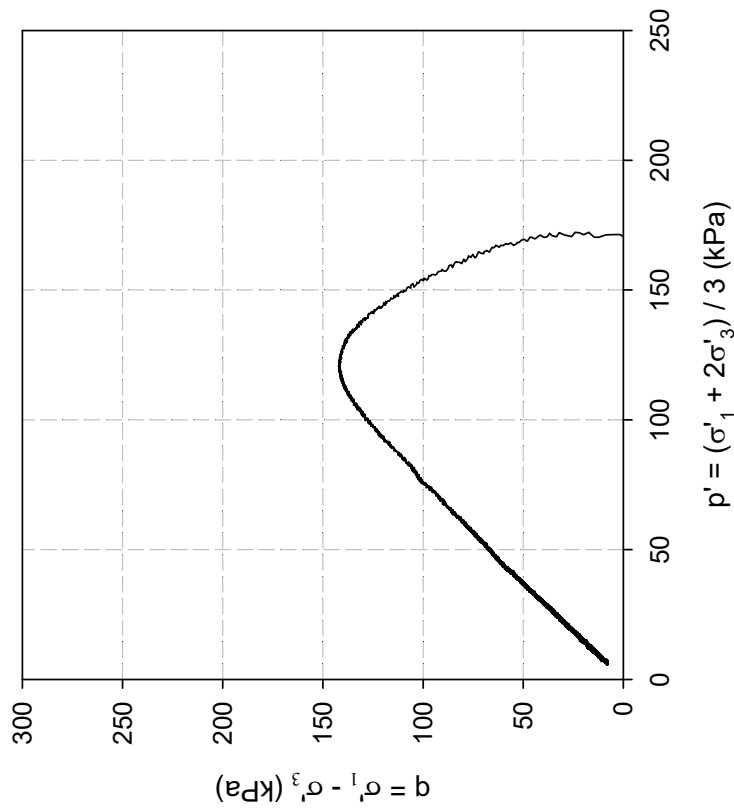
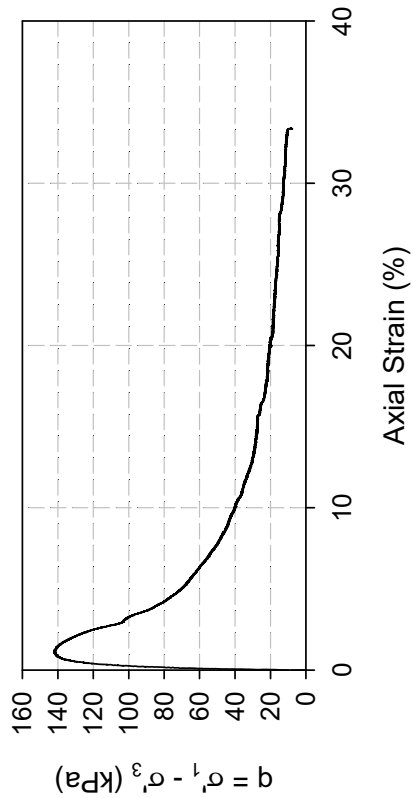
Key insights from this testing are summarized as follows:

- Steady state effective stress ratios (σ'_1/σ'_3) range from 3.2-3.3, corresponding to a friction angle of 32 degrees.
- With increasing FC, the vertical position of the SSL decreases as noted in the studies by Rees (2010), Taylor (2015), and Markham (2015). The slope also increases slightly, as noted in the literature and Taylor (2015). The decrease in vertical position with increasing fines content is more apparent than the change in slope.

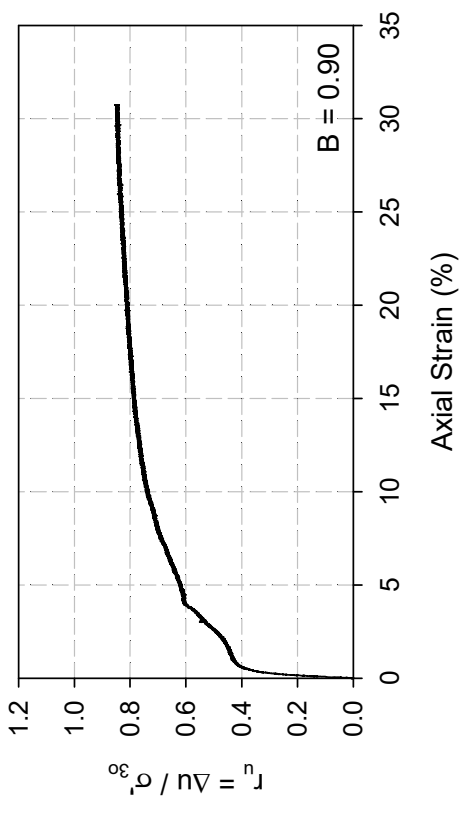
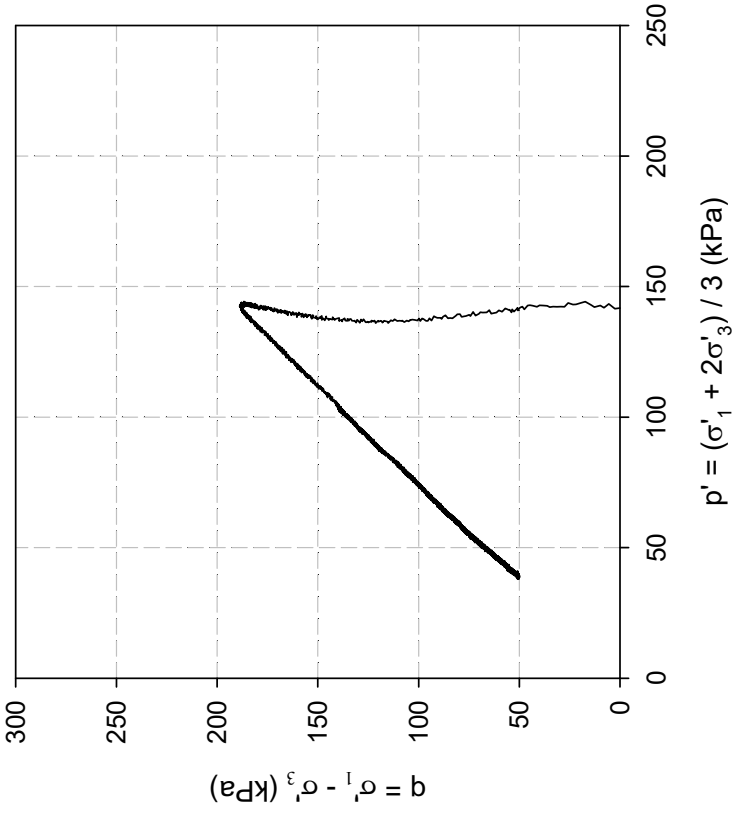
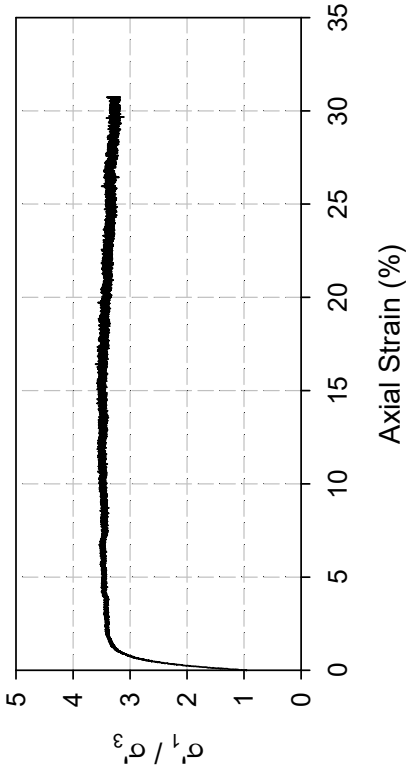
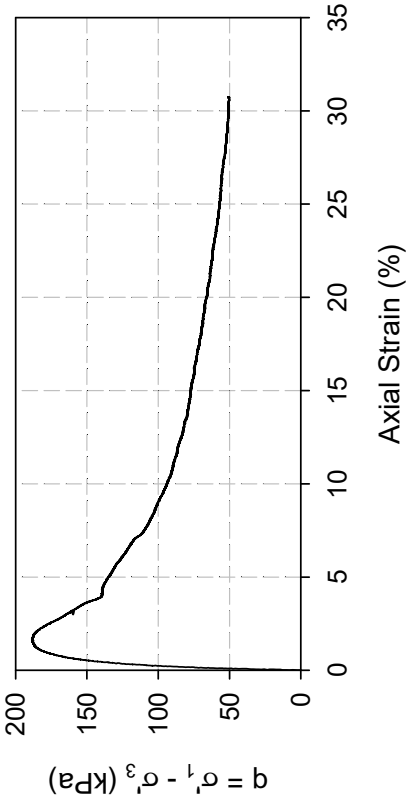
- The Site 33 data point at $p'_{ss} = 1$ kPa ($D_r \sim 37\%$) is estimated to be approximately at the UR-line (Cubrinovski and Ishihara 1998).
- Taylor (2015) and Markham (2015) note the potential effects of soil fabric and structure on laboratory-prepared specimens as compared with “undisturbed” specimens. Taylor (2015) observes that for soils with high FC ($> 30\%$), the projected end points for “undisturbed” specimens were typically positioned above the SSL established for homogeneous (reconstituted) specimens. This is in agreement with general understanding of natural vs. laboratory-prepared soils, and confirms the observations from this testing program wherein denser laboratory-prepared specimens than anticipated were required.
- As presented in the main body of this dissertation, consideration of fines sequencing and in-situ layering of Christchurch silty soils is critical for developing an understanding of the soil deposits at a site. With regard to steady state testing and laboratory-prepared specimens, high-quality (“undisturbed”) specimens maintain layering of fine-grained soils as soils within each layer move toward their own critical state. Mixed, homogeneous specimens will move to one critical state as it is one soil now. These minor variations in soil layering affect the response of the fine-grained soils in a way that is not observed in cleaner sands and reconstituted specimens.

Considering the above findings, additional testing for these soils could evaluate the effects of different methods of specimen preparation (e.g., moist tamping vs. pluviation). It would also be beneficial to perform similar steady state testing on high-quality (“undisturbed”) specimens obtained from the same layers at these silty soil sites, to evaluate the differences in observed response for natural vs. reconstituted silty soil specimens.

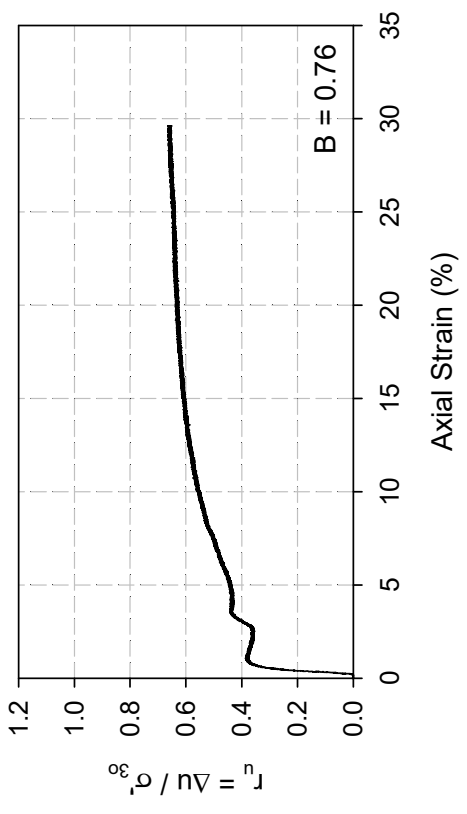
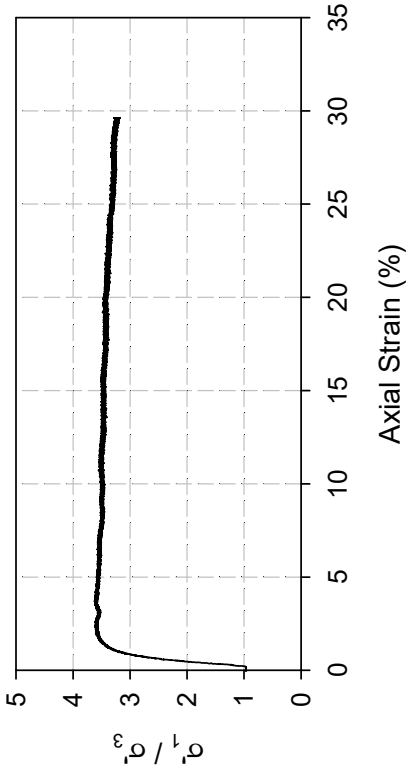
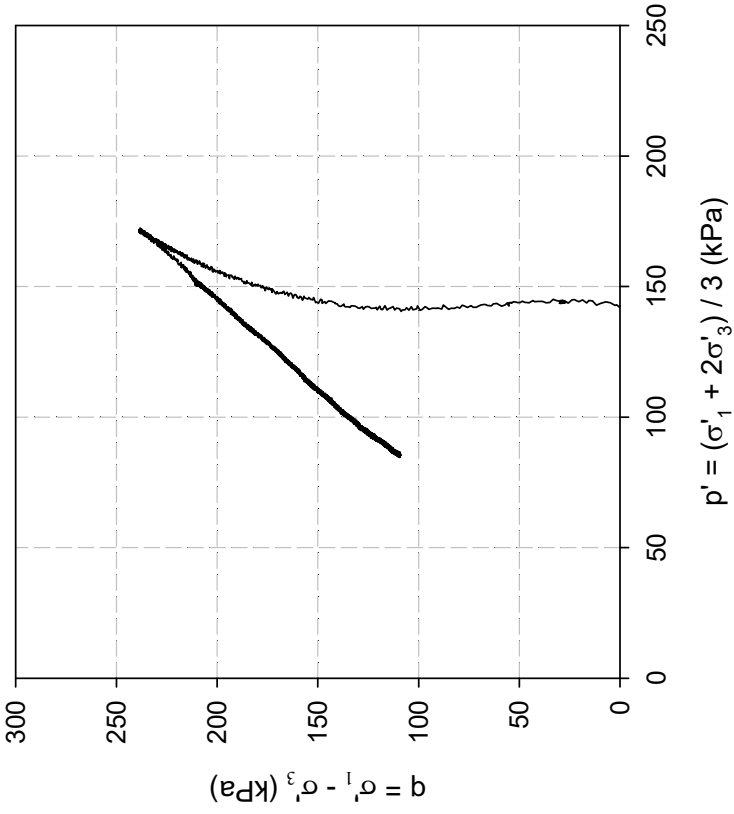
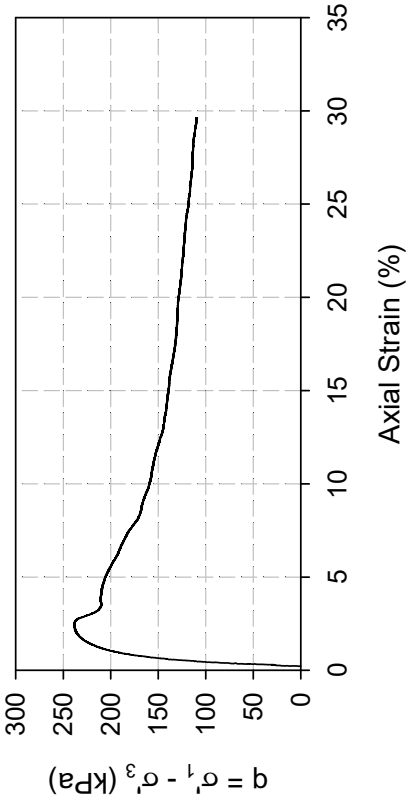




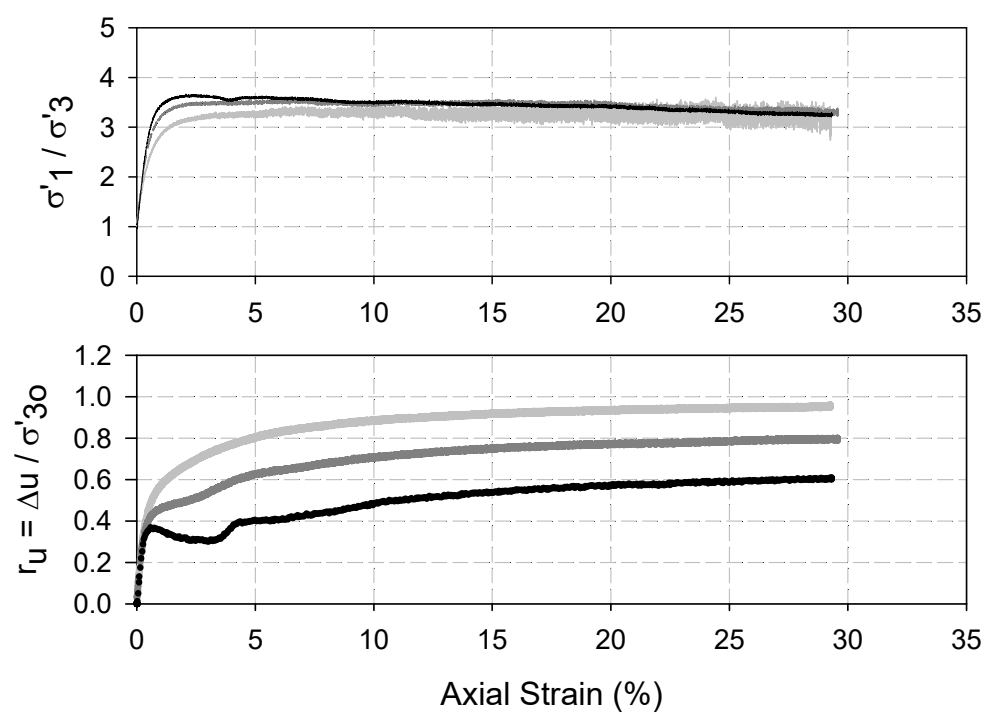
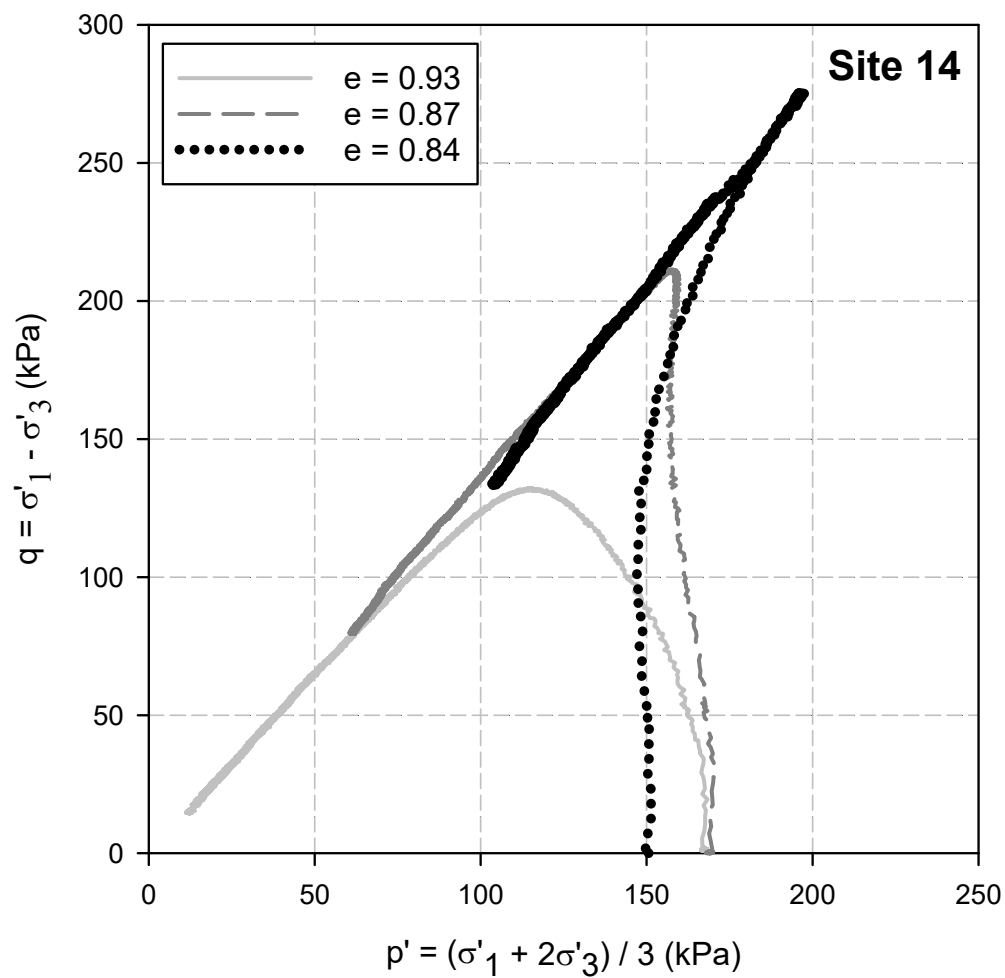
Site :	Site 2 - Gainsborough
Specimens Mixed :	S2-DM1-7U-A S2-DM1-7U-B
σ'_{30} (kPa) :	170
e :	0.95
Dr (%) :	---

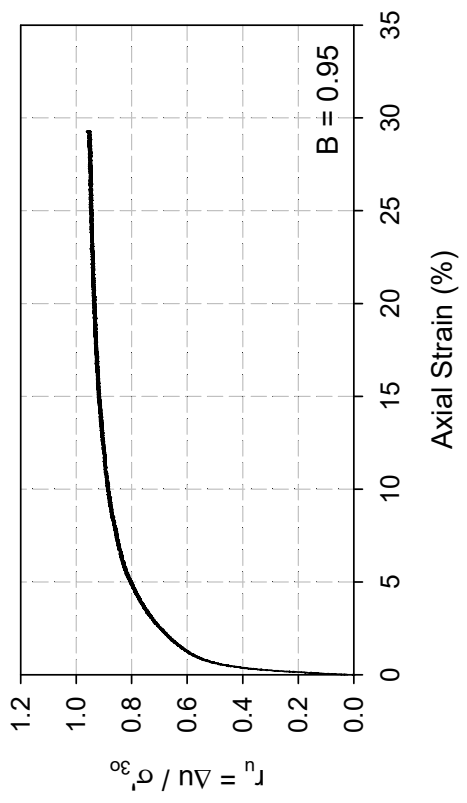
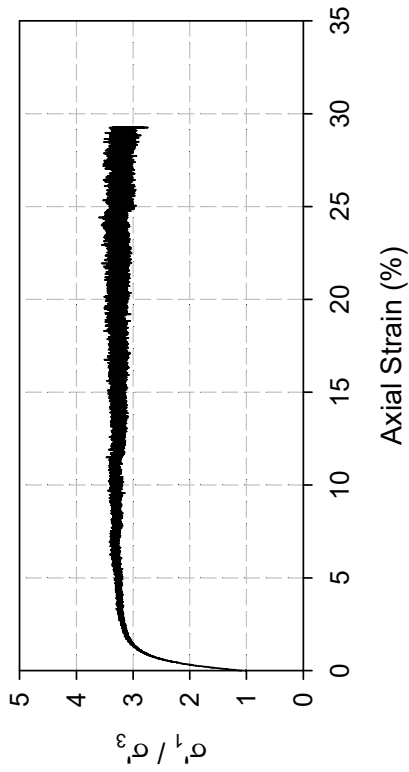
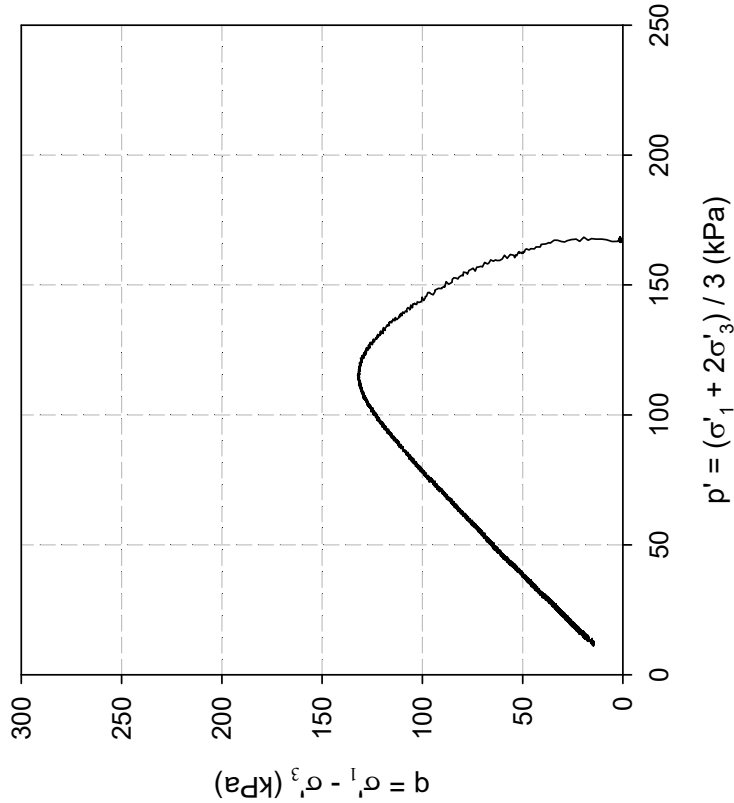
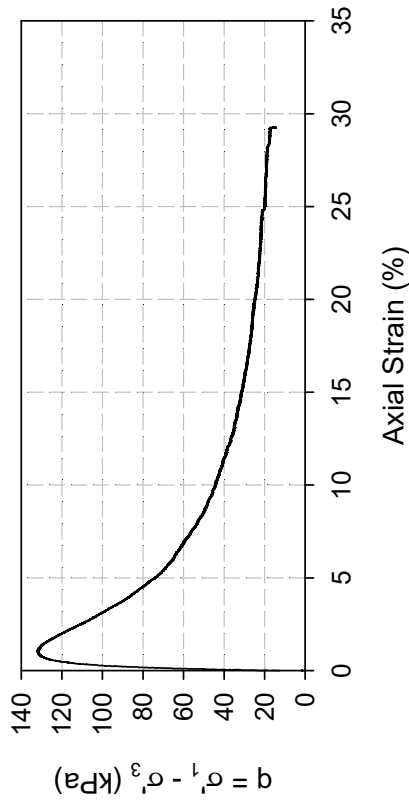


Site :	Site 2 - Gainsborough
Specimens Mixed :	S2-DM1-7U-A S2-DM1-7U-B
σ'_{30} (kPa) :	142
e :	0.89
Dr (%) :	---

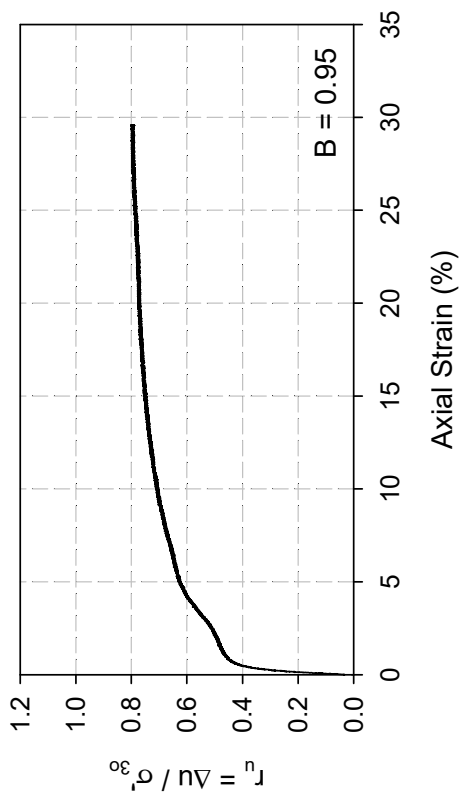
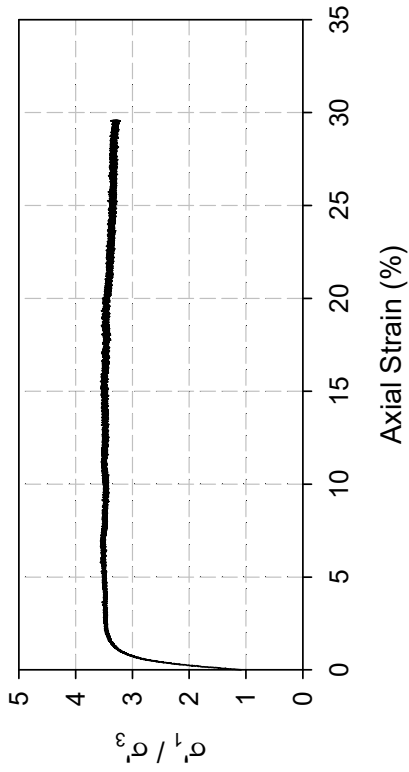
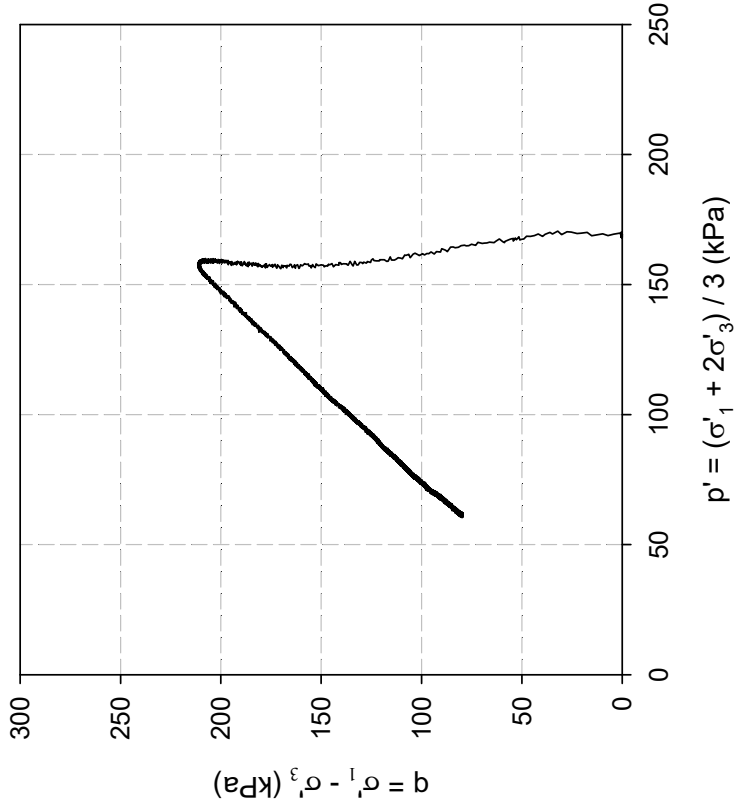
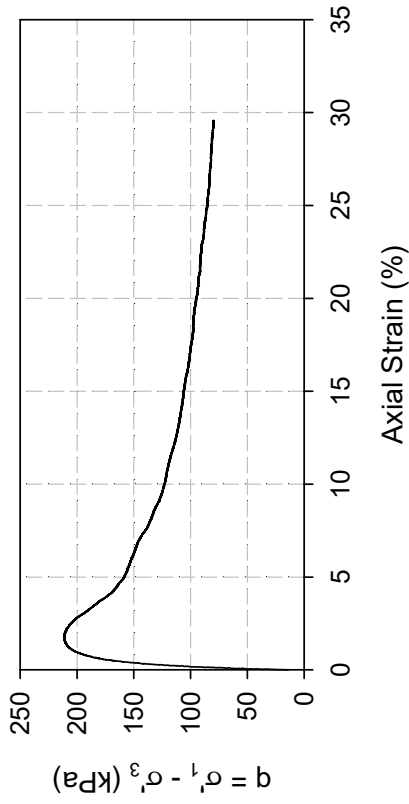


Site :	Site 2 - Gainsborough
Specimens Mixed :	S2-DM1-7U-A S2-DM1-7U-B
σ'_{30} (kPa) :	143
e :	0.86
Dr (%) :	---

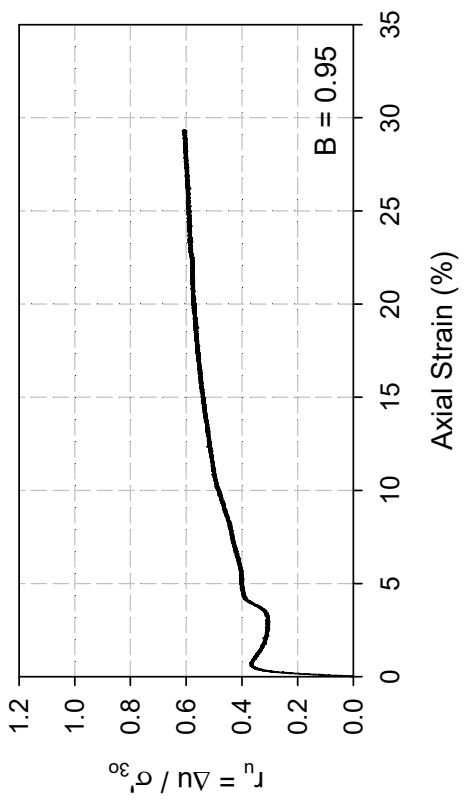
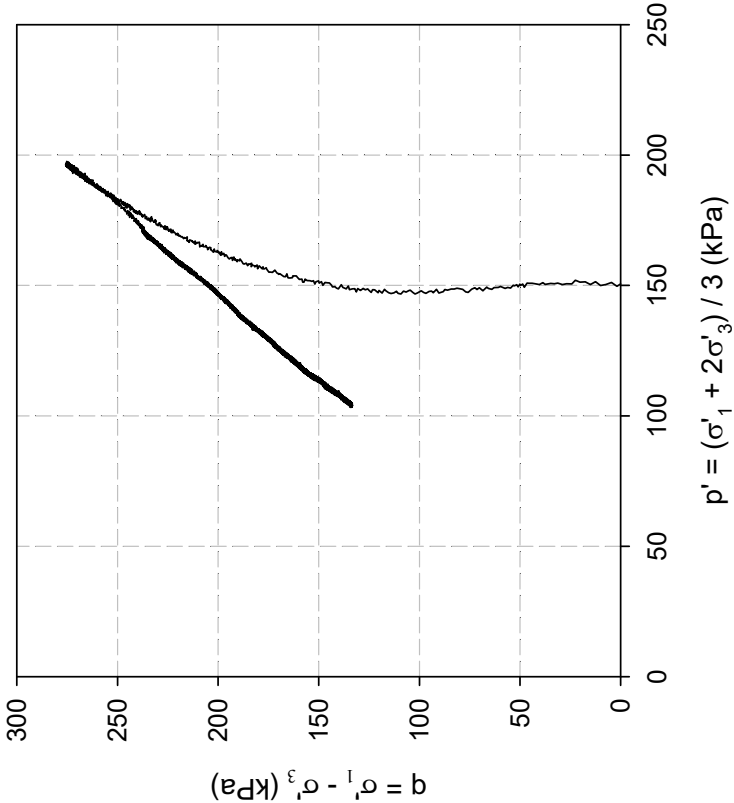
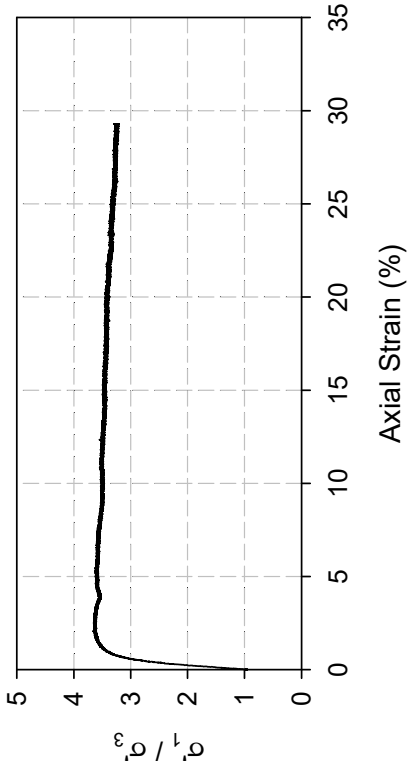
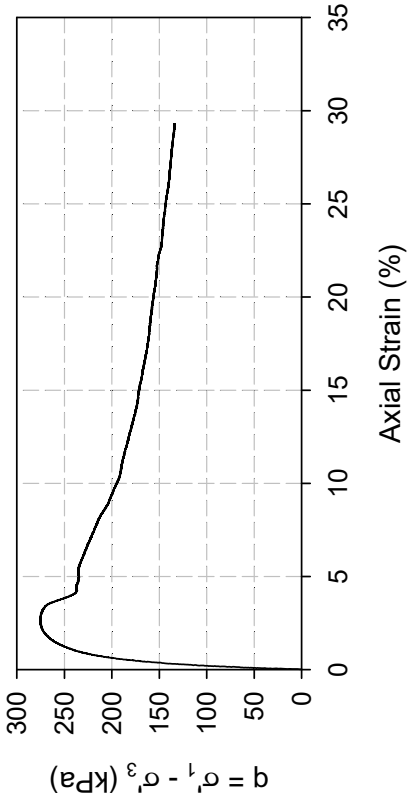




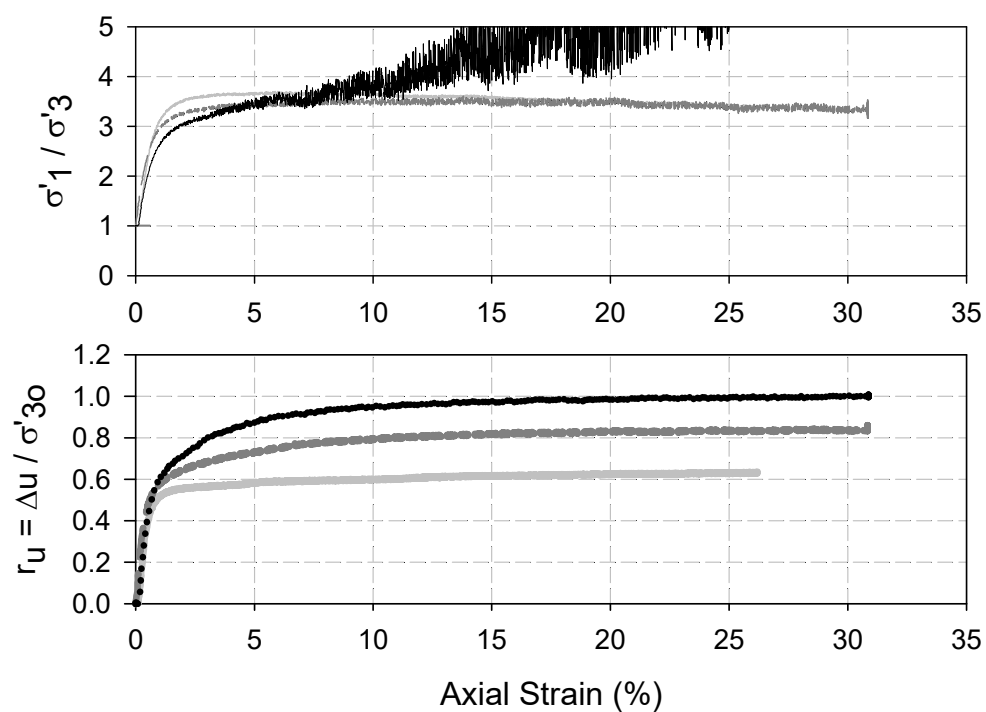
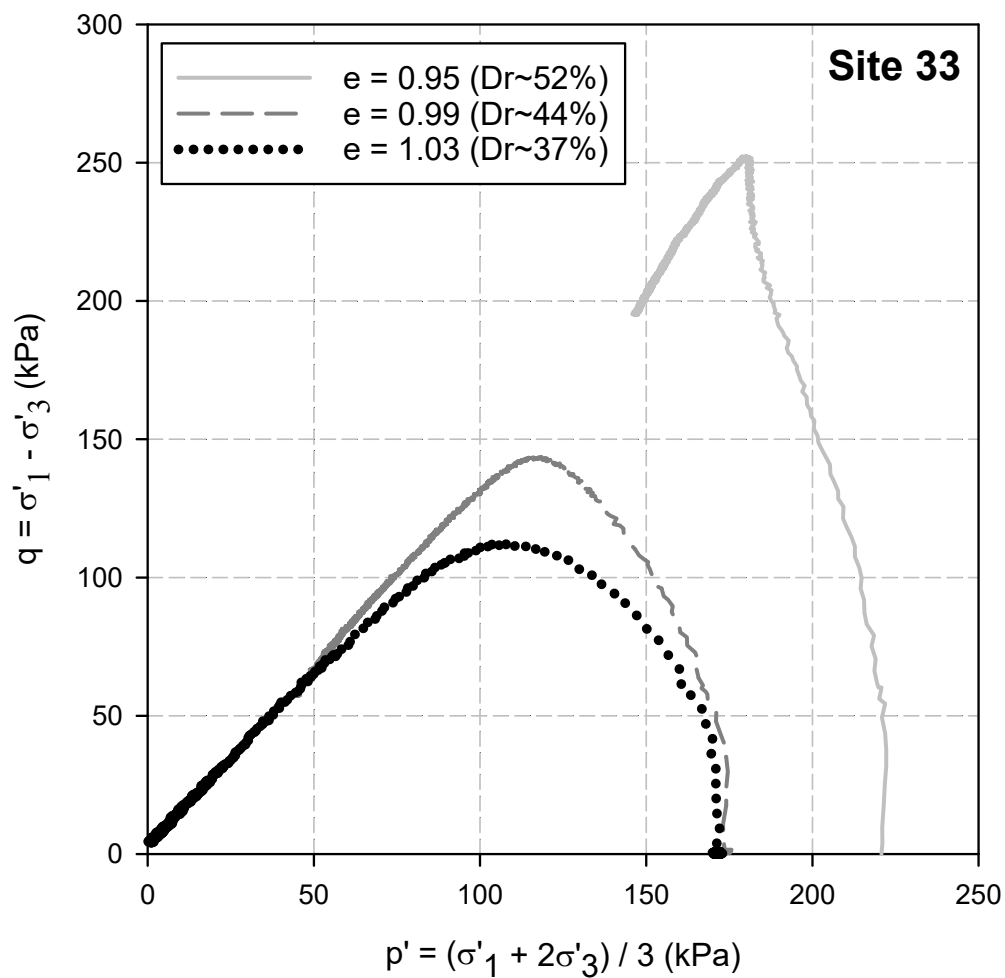
Site :	Site 14 - Barrington
Specimens Mixed :	S14-DM2-5U-A S14-DM2-5U-B
σ'_{30} (kPa) :	167
e :	0.93
Dr (%) :	---

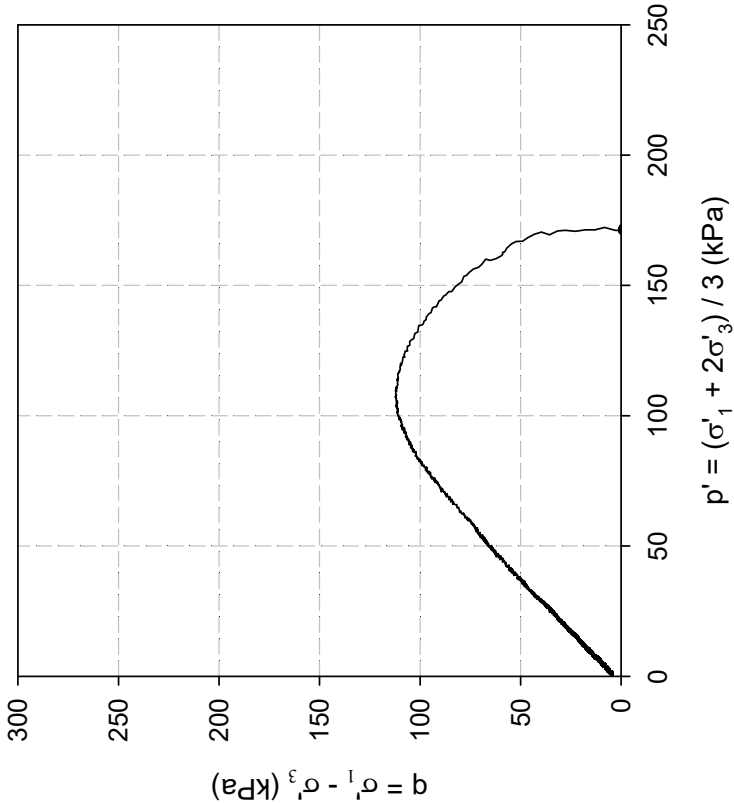


Site :	Site 14- Barrington
Specimens Mixed :	S14-DM2-5U-A S14-DM2-5U-B
σ'_{3o} (kPa) :	169
e :	0.87
Dr (%) :	---

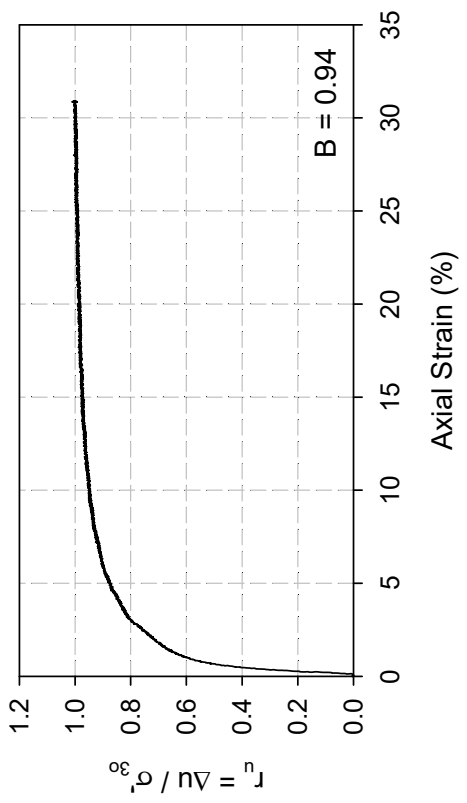


Site :	Site 14 - Barrington
Specimens Mixed :	S14-DM2-5U-A S14-DM2-5U-B
σ'_{30} (kPa) :	150
e :	0.84
Dr (%) :	---

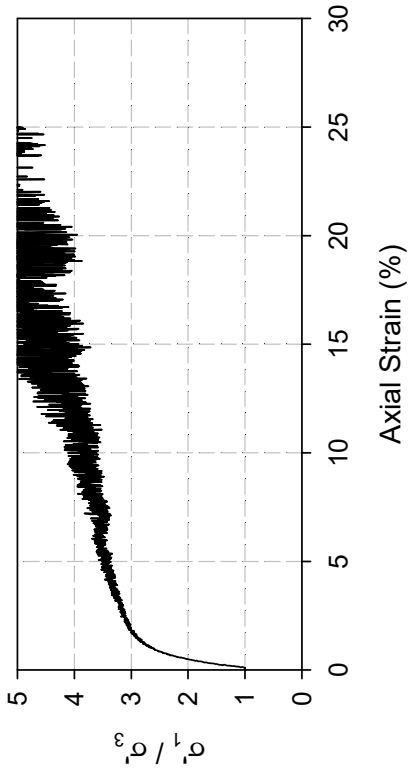
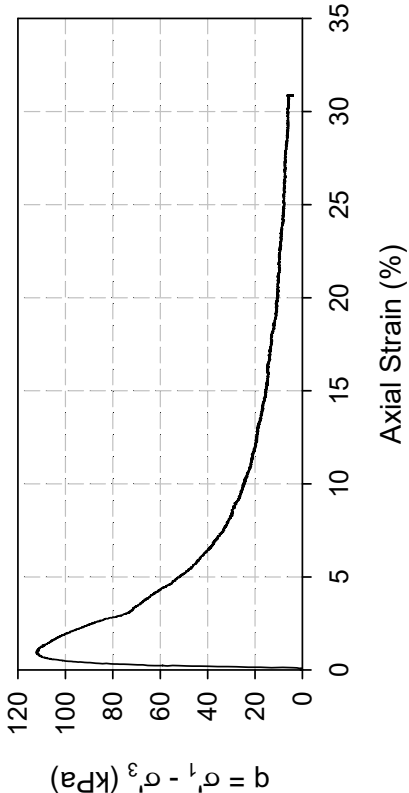




$$p' = (\sigma'_1 + 2\sigma'_3) / 3 \text{ (kPa)}$$



$$B = 0.94$$



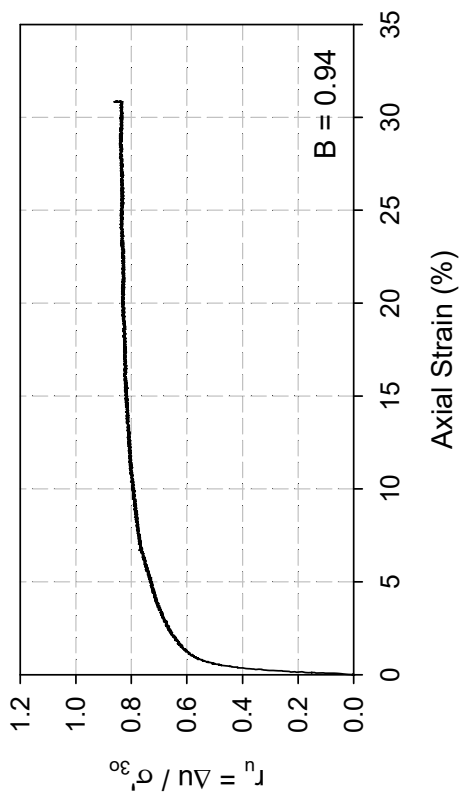
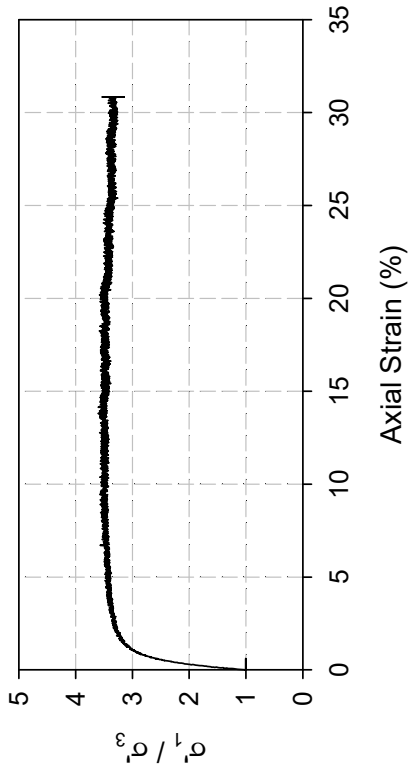
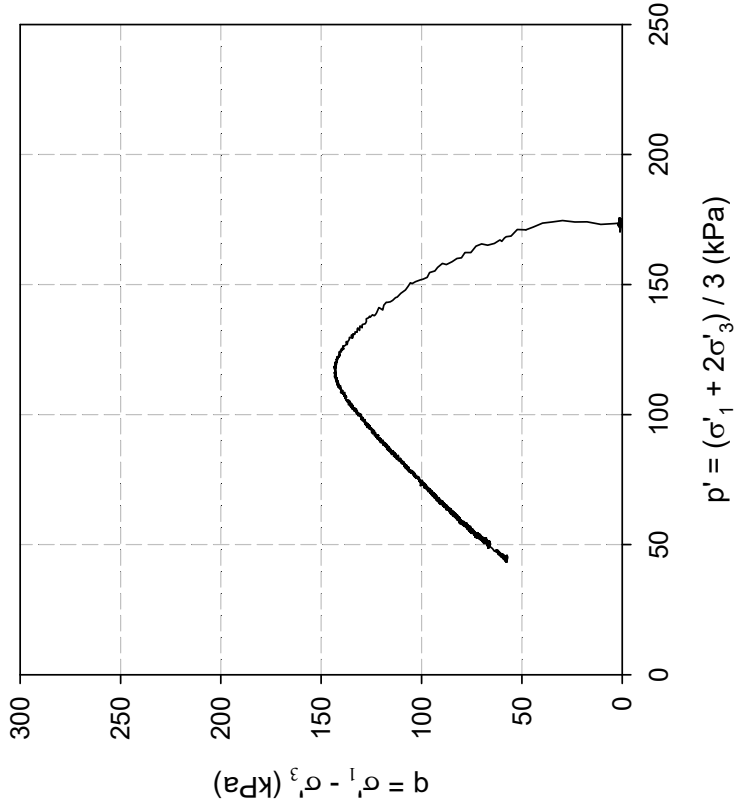
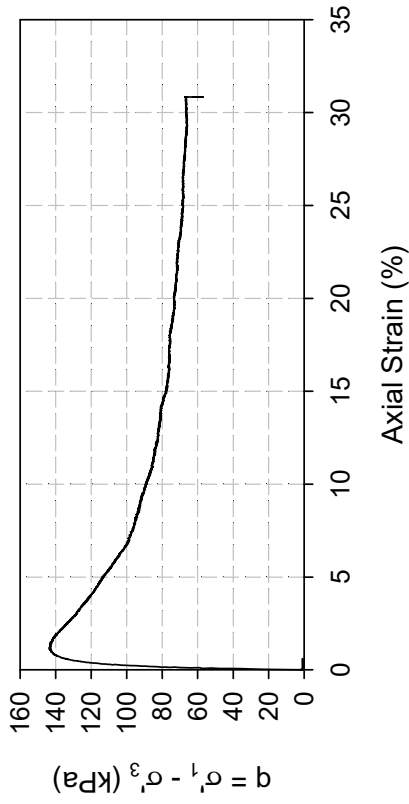
Site : Site 33 - Cashmere

Specimens Mixed : S33-DM1-4U-A
S33-DM1-5U-A

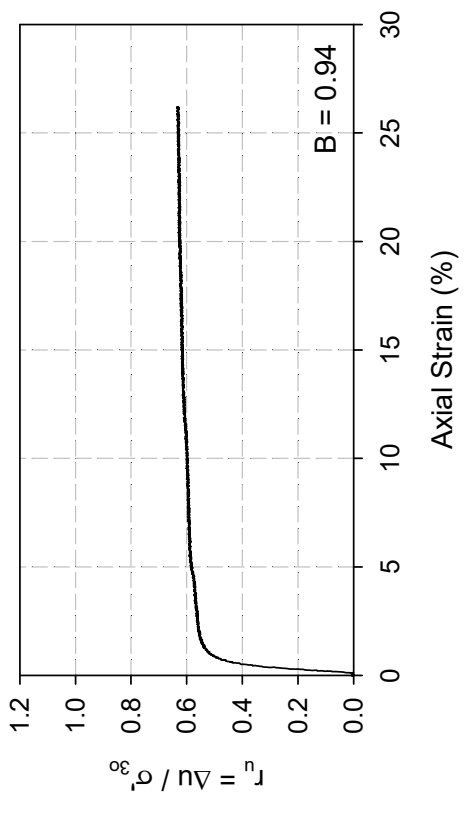
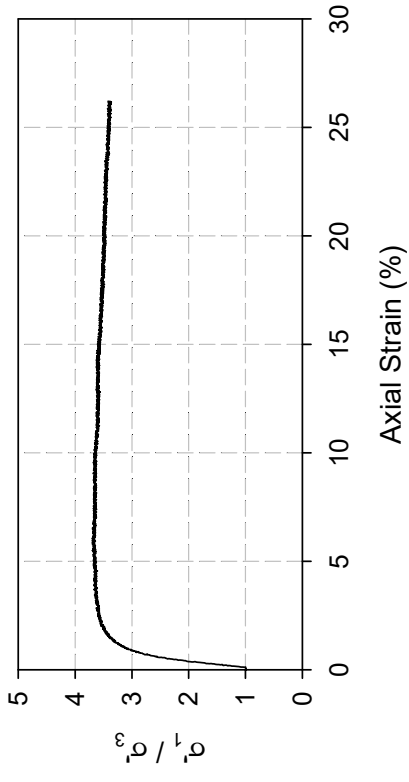
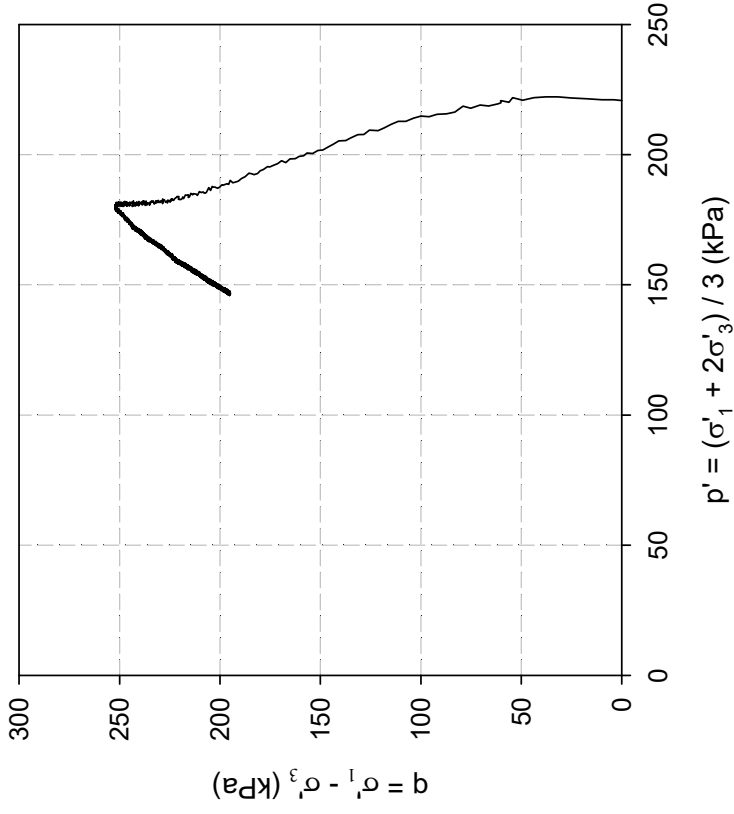
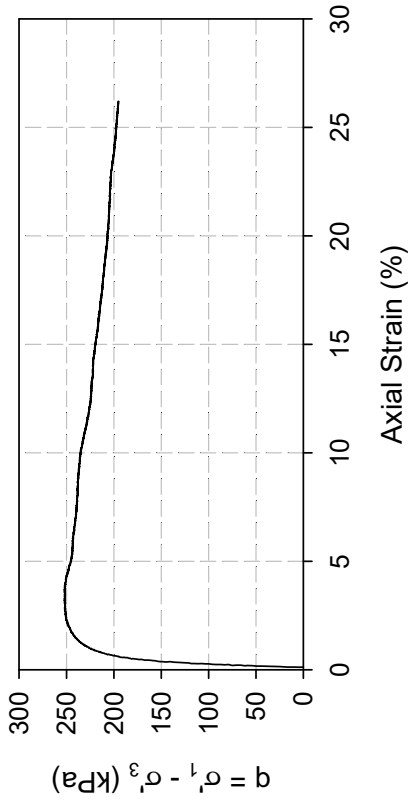
σ'_{30} (kPa) : 171

e : 1.03

Dr (%) : 37%



Site : Site 33 - Cashmere
Specimens Mixed : S33-DM1-4U-A
 S33-DM1-5U-A
 σ'_{30} (kPa) : 173
 e : 0.99
 Dr (%) : 44%



Site : Site 33 - Cashmere
Specimens Mixed : S33-DM1-4U-A
 S33-DM1-5U-A
 σ'_{30} (kPa) : 220
 e : 0.95
 Dr (%) : 52%