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Next Generation Liquefaction Laboratory Database for Susceptibility and Cyclic Strength Assessment

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ABSTRACT

We present a database under development containing data from cyclic laboratory tests on soils containing appreciable fines fractions from published studies. The tested fine-grained soils have varying levels of plasticity and liquefaction susceptibility. We focus on field sites that have been the subject of detailed site characterization programs, typically consisting of cone penetration testing, borings with thin-walled tube/piston sampling, and cyclic laboratory testing. The data are organized into a publicly accessible database to facilitate future model development. Some of the data were included in the development of commonly used susceptibility models, which have differences in the range of plasticity characteristics for which a soil is considered susceptible. A point of agreement among existing models is that cyclic testing of fine-grained soils is the best approach to assess susceptibility and cyclic strength loss potential. Cyclic testing is not always feasible, and the community database presented here will have a key role in supporting the eventual development of probabilistic models for liquefaction susceptibility and cyclic strength relationships for cohesive soils. An important element of eventual model development is deciding upon indices from cyclic tests that are indicative of different types of soil behavior. To this end, we describe response parameters derived from stress-strain curves that hold promise for distinguishing “sand-like” (liquefaction) from “clay-like” (cyclic softening) soil behavior.

INTRODUCTION

Earthquake-induced ground failure analysis proceeds in three distinct phases, including evaluation of: i) susceptibility, ii) cyclic resistance expressed as a cyclic stress ratio, and iii) consequences. This paper focuses predominantly on susceptibility. The definition of susceptibility was discussed at a 2023 PEER Workshop (Stuedlein et al. 2023a). Areas of agreement during the workshop were (1) plasticity is fundamentally related to susceptibility, (2) susceptibility assessment guides selection of engineering evaluation procedures used to evaluate cyclic strength in step (ii), and (3) cyclic laboratory testing is the best way to assess susceptibility and define cyclic strength of fine-grained soils for which relatively undisturbed samples can be retrieved. An area that was not resolved was whether environmental conditions, loading conditions, and soil state should be considered in susceptibility criteria. For instance, in a low seismicity area, a clean, dense sand material has a very low probability of triggering and might be considered “not-

susceptible” since it is predicted to not trigger under design-level shaking. Furthermore, the ratio of water content to liquid limit, w_c/LL , has been used in some susceptibility criteria for fine-grained soils, where w_c/LL is a measure of the soil state. According to such criteria, a susceptible soil could become non-susceptible by consolidating it to a lower water content. The workshop also included discussion of whether different researchers may have used the term “susceptibility” in different ways. Boulanger and Idriss (2024) posited that susceptibility assessment does not influence cyclic strength when a logic tree approach is used and suggested the phrase “cyclic strength evaluation criteria” be used instead of “susceptibility criteria”.

In this paper, we refer to susceptibility as distinguishing sand-like from clay-like behavior based on mineral composition, regardless of soil state, loading conditions, or environmental conditions. High plasticity, clay-like soils are not susceptible to liquefaction, and should be analyzed using cyclic softening procedures (Boulanger and Idriss 2006). Low plasticity sand-like soils are susceptible to liquefaction, even if they are very dense and are predicted to not trigger. Furthermore, unsaturated sand-like soils are considered susceptible to liquefaction because we believe that degree of saturation is best accommodated by adjustments to the cyclic resistance ratio rather than the susceptibility criteria.

Cyclic laboratory testing cannot be performed for all projects due to budget and schedule constraints. Empirical relationships based on available cyclic laboratory testing are therefore important. Raw data in the form of stress and strain time-series have historically not been published alongside papers and reports describing the results of laboratory studies. Rather, the authors interpret the data in the manner they see fit and publish summaries of the data and analysis in figures and/or tables. Synthesizing the findings across a range of published studies is often challenging because authors often choose to prepare their figures in different ways, and processed data presented in some studies is not available in others. For these reasons, organizing the raw data into a publicly accessible database substantially advances the profession’s ability to evaluate existing models and develop new models from the available cyclic laboratory test data.

We present results of recent work to organize cyclic laboratory test data performed on fine-grained soils into the Next Generation Liquefaction (NGL) relational database (Ulmer et al. (2023) <https://doi.org/10.21222/C23P70>). Each study contains extensive field investigations, including cone penetration testing, drilling and sampling using thin-walled tubes (many using piston samplers), and laboratory testing including index tests and cyclic triaxial and/or direct simple shear tests. We first present an overview of the studies included in the NGL database. Finally, we present a number of different metrics that we consider promising for quantifying susceptibility based on measured stress-strain responses.

LABORATORY TEST DATASETS

Locations of the sites from which we have organized data into the NGL database are presented in Fig. 1 and to-date include six sites in the Pacific Northwest of the U.S. with testing performed at Oregon State University, seven sites in Adapazari, Türkiye, with testing performed at ZETAS laboratory in Istanbul and at the UC Berkeley advanced geotechnical laboratory, and seven sites in Christchurch, New Zealand with testing performed at the University of Canterbury. Table 1 summarizes the test types, number of cyclic tests, and Atterberg limit ranges for the tested soils. A total of 207 CDSS and 145 CTX tests have been added to the NGL database as part of this study, and data from each region from Fig. 1 are discussed below.

Table 1. Summary table of cyclic test results in NGL database

Site	Reference	Test Type	Number of Specimens	Liquid Limit, LL (%)	Plasticity Index, PI (%)
Gainsborough, New Zealand	BEA*	CTX	5	40 – 42 (41.0)	12 – 16 (14.0)
Barrington, New Zealand	BEA	CTX	4	30 – 31 (30.5)	NP – 7 (2.6)
Caulfield, New Zealand	BEA	CTX	3	22 – 28 (25.3)	2 – 8 (4.0)
Riccarton, New Zealand	BEA	CTX	7	24 – 33 (28.3)	NP – 9 (5.5)
Cashmere, New Zealand	BEA	CTX	11	23 – 41 (32.6)	NP – 15 (7.6)
EQC-3_Avondale, New Zealand	BEA	CTX	5	-	-
EQC-4_Avondale, New Zealand	BEA	CTX	6	-	-
Adapazari Site A, Türkiye	S03*	CTX, CDSS	23, 3	27 – 69 (41.2)	NP – 45 (15.8)
Adapazari Site C, Türkiye	S03	CTX, CDSS	20, 1	24 – 69 (40.2)	NP – 38 (14.6)
Adapazari Site D, Türkiye	S03	CTX, CDSS	7, 1	25 – 37 (30.3)	NP – 14 (8.4)
Adapazari Site F, Türkiye	S03	CTX	23	22 – 45 (30.6)	NP – 22 (6.7)
Adapazari Site G, Türkiye	S03	CTX, CDSS	8, 7	26 – 37 (31.5)	NP – 14 (8.0)
Adapazari Site I, Türkiye	S03	CTX	16	23 – 71 (38.0)	NP – 36 (11.8)
Adapazari Site J, Türkiye	S03	CTX, CDSS	7,1	23 – 52 (30.6)	NP – 25 (7.0)
OSU-PDX Airport Test Site (Site D), OR, USA	Jana & Stuedlein (2021, 2022)	CDSS	12	68 – 78 (70.4)	26 – 29 (27.4)
Van Buren Bridge Site (Site B), OR,USA	Dadashiserej et al. (2022a,b)	CDSS	30	39 – 50 (44.6)	11 – 16 (13.8)
Boone Bridge Site (Site F), OR,USA	SEA23	CDSS	30	0 – 50 (22.2)	NP – 20 (3.6)
PDX-TS4 Site (Site E), OR,USA	SEA23	CDSS	49	39 – 87 (60.0)	10 – 31 (20.4)
OSU-Longview Blast Test Site (Site A), OR,USA	SEA23	CDSS	56	40 – 51 (46.8)	11 – 19 (14.8)
Site G, OR,USA	Dadashiserej et al. (2024)	CDSS	17	0 – 45 (19.4)	NP – 10 (4.0)

*BEA = Beyzaei et al. (2015, 2018) and Beyzaei (2017), S03 = Sancio (2003) SEA23 = Stuedlein et al. (2023b)

After the 1999 Kocaeli earthquake (M7.5) in Türkiye, significant settlements and deformations of foundation systems were observed in Adapazari, primarily due to localized cyclic failures of fine-grained foundation soils. The region is characterized by interlayered low plasticity silty and clayey deposits. Numerous researchers visited Adapazari post-earthquake to document ground failures systematically along surveyed lines (Bray and Stewart, 2000). Sancio (2003) and Bray and Sancio (2006) describe subsequent site investigations, which included borings with

Standard Penetration Tests (SPT) and Cone Penetration Tests (CPT). Relatively undisturbed soil samples were collected from boreholes using thin-walled samplers (the resulting soil specimens are referred to subsequently as “intact”) and various laboratory tests were conducted, including cyclic triaxial tests, post-cyclic monotonic tests, and consolidation tests. Fig. 2 presents results of one of the cyclic triaxial tests on an intact specimen in a standard format applied for this project (data from Sancio 2003).

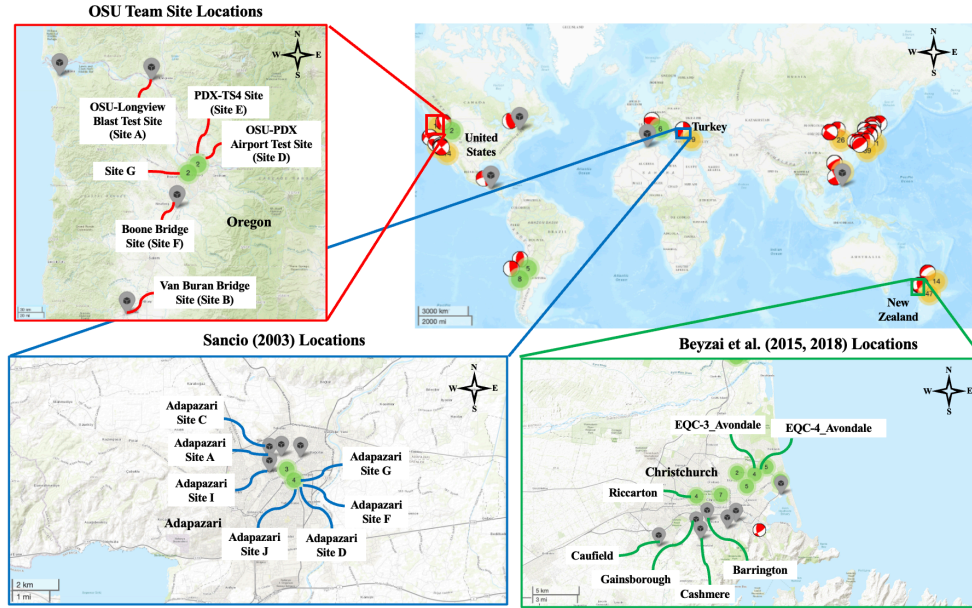


Figure 1. Map of sites corresponding to cyclic tests entered into the NGL database as part of this study.

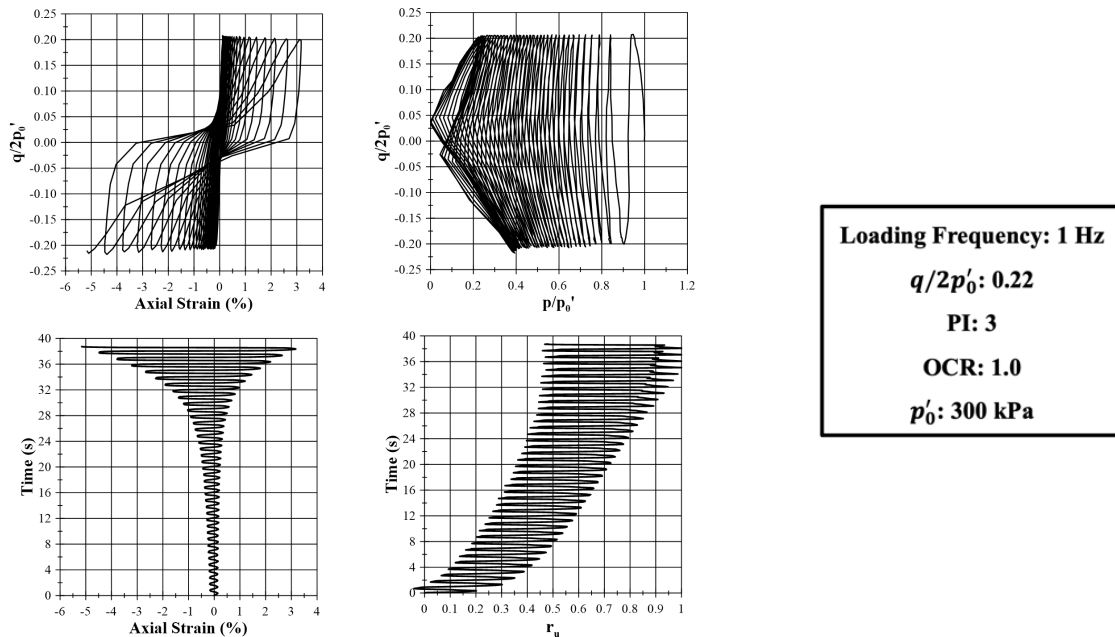


Figure 2. Cyclic triaxial test results for a sample from on Adapazari Site A, specimen A6-P1A. Data source is Sancio (2003).

The 2010-2011 Canterbury earthquake sequence (and notably the 2011 M6.2 Christchurch earthquake) in New Zealand led to extensive liquefaction-induced ground failures, resulting in significant damage to buildings, infrastructure networks, and critical lifeline systems throughout Christchurch and the surrounding region. The soil conditions in Christchurch include interlayered sands and low- to medium-plasticity silts. Following the earthquake, detailed site investigations were conducted, which included CPTs and borings to obtain both intact and disturbed soil samples. As described by Beyzaei et al. (2015, 2018), cyclic triaxial tests, post-cyclic reconsolidation tests, and index tests on these samples were performed at the University of Canterbury to assess the soil behavior under cyclic loading conditions, as part of a broader effort to better understand field performance at sites of interest. Fig. 3 illustrates a representative result of a cyclic triaxial test, in the same format used for Fig. 2, using data from Beyzaei et al. (2015, 2018).

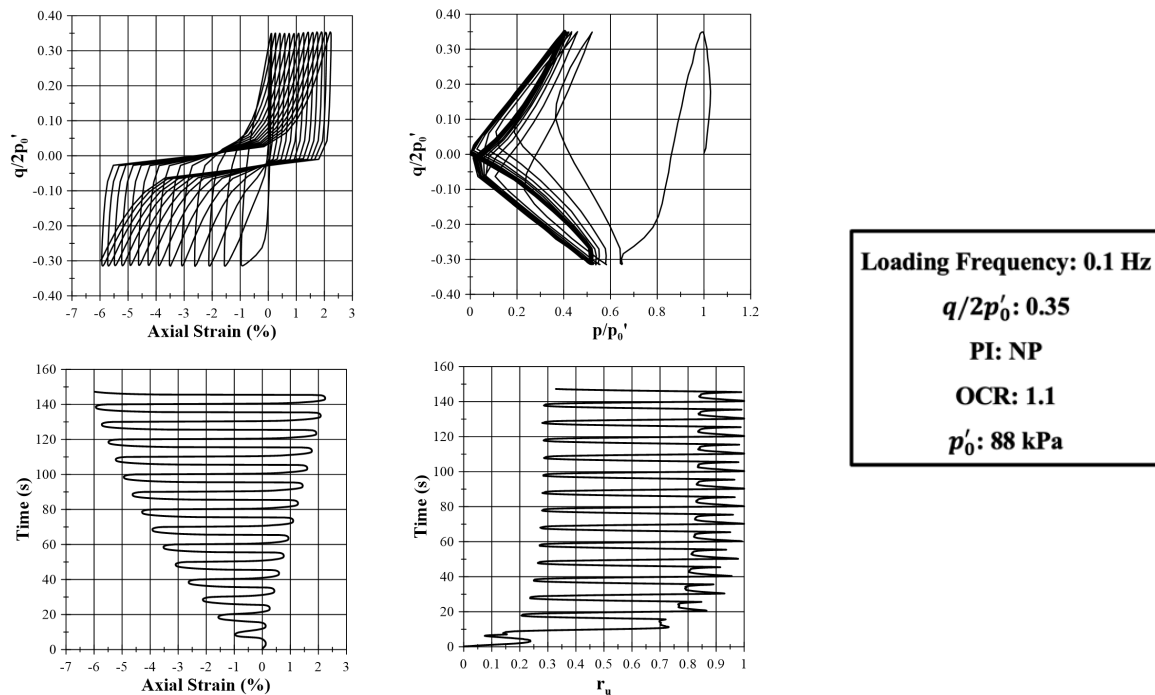


Figure 3. Cyclic triaxial test results for a sample from EQC-4_Avondale site, specimen EQC4-DM1B-7U-A. Data source is Beyzaei et al. (2015, 2018).

Test data like that in Figs. 2-3 can be used to evaluate soil response leading to an assessment of sand-like or clay-like soil behavior, which is useful for the development of susceptibility models. Another useful application is to use the data to evaluate the cyclic strength of soil, which is important for various geotechnical projects. Cyclic tests have been performed for several projects in the Pacific Northwest to measure the cyclic strength of low- to medium-plasticity fine-grained soils at various sites. Researchers at Oregon State University have conducted cyclic direct simple shear tests to evaluate the cyclic strength of these soils, as described by Jana and Stuedlein (2021, 2022), Dadashiserej et al. (2022a,b), Stuedlein et al. (2023b) and Dadashiserej et al. (2024). The results from these tests have been incorporated into the NGL database. Fig. 4 illustrates one of the results from a cyclic direct simple shear test, highlighting the cyclic response and strength characteristics of the silty soils in Oregon.

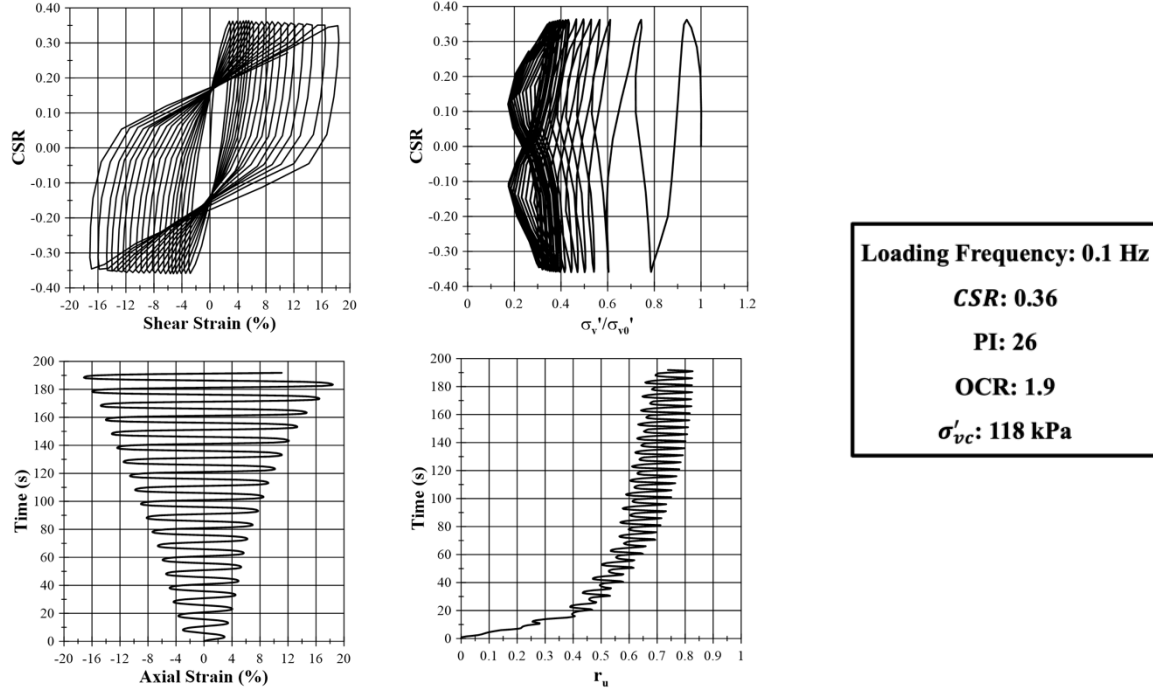


Figure 4. Cyclic triaxial test results for a sample from the OSU-PDX Airport Test Site (Site D), specimen B-6-S-1-CDSS19. Data source is Stuedlein et al. (2023).

QUANTITATIVE SUSCEPTIBILITY METRICS

Stress-strain hysteresis loops are different for susceptible and non-susceptible soils, with non-susceptible soils generally having “fatter” loops with more hysteretic damping, larger shear stress at the center of the loop, and less-pronounced dilatancy-induced strain hardening. While these characteristics may be obvious upon visual inspection, there is value in expressing these features in a quantitative manner so that numerical ranges for different types of soil behavior can be defined. Such metrics would facilitate uniform interpretation of cyclic test data across the database for model development. As shown in Fig. 5, Stuedlein et al. (2023) proposed a series of parameters to meet this need, which included: i) difference in cyclic shear stress amplitude at zero strain, ii) minimum tangent modulus of the cycle (minimum tangent shear modulus for CDSS and minimum tangent Young’s modulus for CTX), and iii) angle between stress reversals, within a given cycle. We modify these metrics by (1) rendering stress and strain quantities in dimensionless form by using decimal strain values instead of percent and by normalizing stress by the maximum absolute shear/deviatoric stress and (2) defining stress amplitude at the center of each hysteresis loop rather than at zero strain. The second modification was our observation that direct simple shear tests with a non-zero static shear stress tend to accumulate strain in the direction of the static shear stress and that triaxial tests tend to accumulate larger strains in the extension direction. Centering the hysteresis loop is therefore useful and is achieved by computing the stress amplitude at the mid-loop strain value for the cycle. Moreover, it should be noted that other factors such as maximum pore pressure generation ($r_{u,max}$) have been discussed and are likely to be implemented in the future.

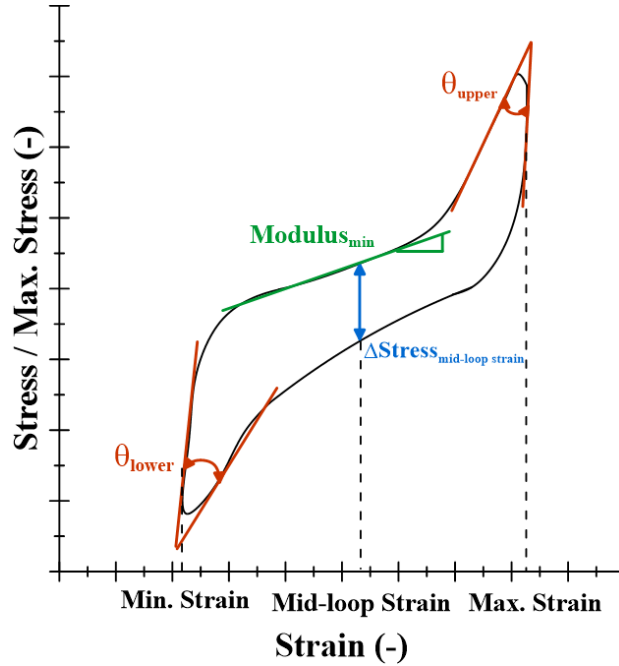


Figure 5. Schematic rendering of stress-strain loop from cyclic test illustrating definition of interpreted parameters that can be used to assess soil behavior types.

The parameters illustrated in Fig. 5 were computed for the tests listed in Table 1, with the results summarized in Table 2. Values in parentheses represent median and standard deviation values of each parameter, respectively. The normalized values of minimum modulus and delta stress presented in Table 2 use the absolute maximum stress for each respective loop as the normalizing stress. One notable trend is that θ_{upper} and θ_{lower} tend to be similar for CDSS tests, but θ_{lower} is significantly larger than θ_{upper} for CTX tests. We believe this is related to differences in the extension/compression regimes of a cyclic triaxial test, whereas direct simple shear tests without static shear stress are more symmetrical.

Table 2. Summary of interpreted stress-strain loop parameters for test data in the NGL database

Reference	Type of Test	Number of Tests	“Defining” Parameters			
			Normalized Modulus _{min}	Normalized Δ Stress (γ_{ML})**	θ_{lower} (°)	θ_{upper} (°)
S03*	CTX	110	0.45 – 214.28 (4.30 – 27.63)	0.18 – 0.81 (0.35, 0.12)	0.11 – 13.15 (1.55, 1.80)	0.02 – 4.28 (0.81, 0.63)
S03	CDSS	13	0.72 – 245.67 (6.01, 75.61)	0.30 – 0.61 (0.44, 0.10)	0.13 – 6.40 (2.25, 2.08)	0.83 – 7.94 (2.71, 2.25)
BEA	CTX	51	0.00 – 718.37 (1.12, 108.04)	0.04 – 0.68 (0.28, 0.12)	0.04 – 4.13 (1.60, 0.85)	0.03 – 2.62 (1.04, 0.56)
OSU Team	CDSS	194	0.00 – 201.24 (4.43, 28.38)	0.24 – 1.08 (0.54, 0.15)	0.01 – 16.25 (2.82, 2.80)	0.05 – 16.37 (2.74, 3.04)

*BEA = Beyzaei et al. (2015, 2018) and Beyzaei (2017), S03 = Sancio (2003) OSU Team = Stuedlein et al. (2023b), Jana & Stuedlein (2021, 2022), Dadashiserej et al. (2022a,b; 2024)

** Δ Stress (γ_{ML}): Delta stress at the mid-loop strain value for the cycle

Fig. 6 illustrates the parameters computed from the hysteresis loops. In the figure, red lines indicate the lines selected for calculating the angle of stress reversal at the upper and lower portions of the cycle. The blue line represents the difference in stress at the location of the mid-loop strain within the cycle. The green line indicates the minimum modulus in the middle portion of the loop.

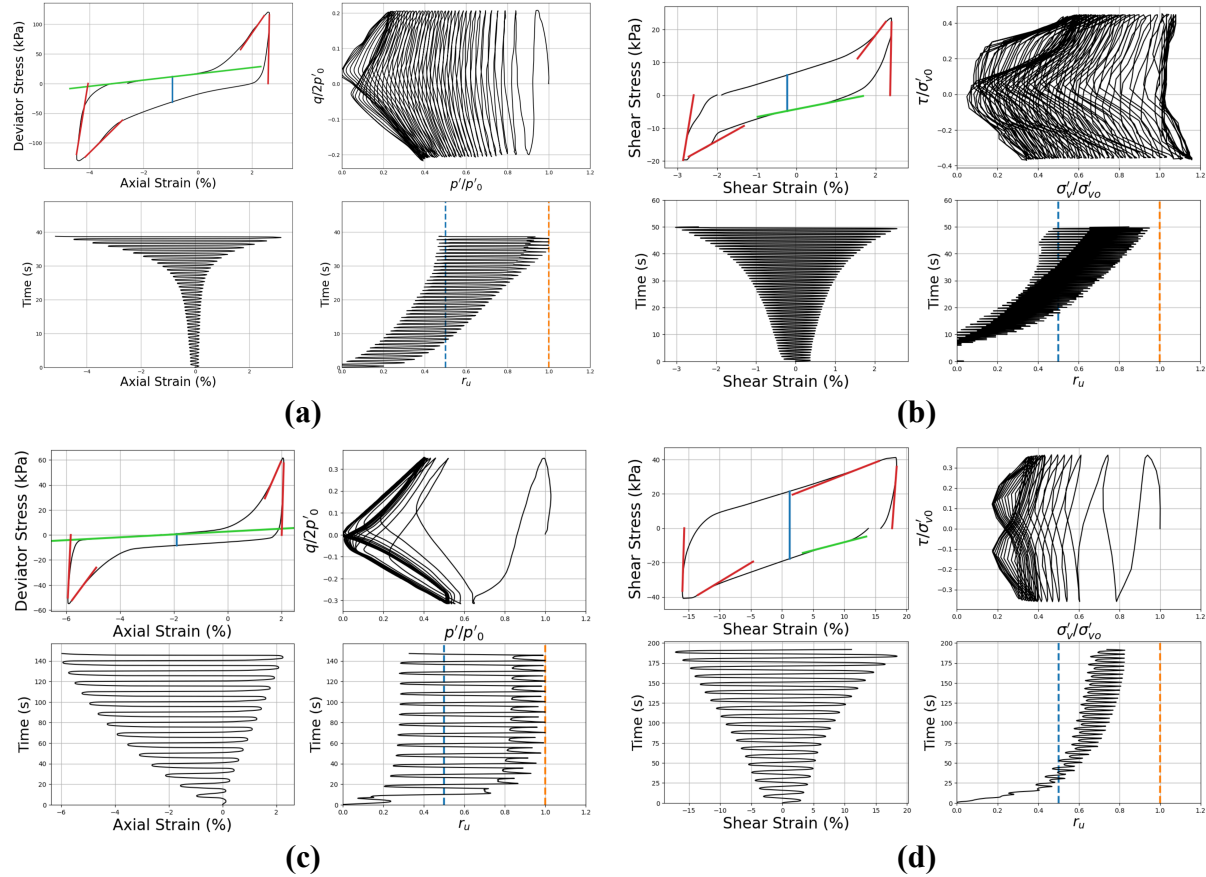


Figure 6. Interpreted cyclic test results in NGL database for a) Sancio (2003) – CTX – A6-P1A, b) Sancio (2003) – CDDS – G4-P3-3, c) Beyzaei et al. (2018) – CTX – EQC4-DM1B-7U-A, d) OSU Team – CDSS – B-6-S-1-CDSS19

DISCUSSION AND RESULTS

Liquefaction risk assessments encompass three critical phases: susceptibility, triggering, and effects. Research teams have been developing models for liquefaction triggering and effects using the Next Generation Liquefaction (NGL) project database (e.g., Hudson et al. 2024). Aside from improving and expanding the NGL database, the long-term aim of the present initiative is to improve understanding of soil properties that correlate with liquefaction susceptibility, and ultimately to develop probabilistic models that reflect that improved understanding.

The practical importance of liquefaction susceptibility analysis is that different methods are used to evaluate strength loss and effects for susceptible and non-susceptible materials. For susceptible or "sand-like" soils, semi-empirical correlations are used to evaluate triggering potential and associated cyclic strengths, both in NGL and legacy models (e.g., Boulanger and Idriss 2016; Cetin et al. 2018). For non-susceptible or "clay-like" soils, the potential for cyclic softening and associated cyclic strengths are evaluated based on laboratory test results (Boulanger

and Idriss 2006). Due to distinct procedures for susceptible and non-susceptible materials, the evaluation of susceptibility is often a critical element in the analysis of ground failure potential for fine-grained soils.

In this paper, we have described a number of interpreted parameters from undrained cyclic testing that can be used to identify soil type as sand- or clay-like. Additional metrics are likely to be added in future work. The selected interpreted parameters include the: i) minimum normalized modulus within the cycle, ii) normalized stress difference at the mid-loop strain between maximum and minimum values corresponding to a specific cycle, iii) angle between stress reversals. These parameters have been evaluated for 145 CTX and 207 CDSS tests, with the result in Table 2.

Future research will identify the ranges of these interpreted parameters that correspond to sand- and clay-like soil behavior and will investigate correlations between these interpreted parameters and more readily obtained material properties such as LL , PI , I_c , and others.

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