## Title

PEER-NGL project: Open source global database and model development for the next-generation of liquefaction assessment procedures

**Authors**

Stewart, JP
Kramer, SL
Kwak, DY
et al.

**Publication Date**
2016-12-01

**DOI**
10.1016/j.soildyn.2016.07.009

Peer reviewed

6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch, New Zealand

# PEER-NGL Project: Open Source Global Database and Model Development for the Next-Generation of Liquefaction Assessment Procedures

J. P. Stewart[1], S. L. Kramer[2], D. Y. Kwak[3], M. W. Greenfield[4], R. E. Kayen[5], K. Tokimatsu[6], J. D. Bray[7], C. Z. Beyzaei[8], M. Cubrinovski[9], T. Sekiguchi[10], S. Nakai[11], and Y. Bozorgnia[12]

## ABSTRACT

The Next-Generation Liquefaction (NGL) project was launched to (1) substantially improve the quality, transparency, and accessibility of case history data related to ground failure; (2) provide a coordinated framework for supporting studies to augment case history data for conditions important for applications but poorly represented in empirical databases; and (3) provide an open, collaborative process for model development in which developer teams have access to common resources and share ideas and results during model development, so as to reduce the potential for mistakes and to mutually benefit from best practices. NGL at present is a concept developed from multiple international workshops; aside from concept development, work to date has focused on compiling high-value case histories. We describe the project motivation, explain and illustrate how data resources will be compiled and organized, summarize preliminary results from ongoing data collection, describe needed supporting studies, and review project status and next steps.

## Introduction

Early efforts toward the development of procedures for evaluation of liquefaction potential were based on laboratory testing. Since undisturbed sampling of the types of loose, clean, saturated sands known to have been involved in early documented cases of liquefaction is extremely difficult, tests were performed on reconstituted soil specimens. These tests provided valuable insights into the effects of factors such as soil density, effective confining pressure, and cyclic shear stress amplitude on liquefaction resistance, but it was eventually discovered that test specimens prepared to the same densities but by different procedures exhibited very different

---

[1] Prof., Civil & Env. Eng., University of California, Los Angeles, USA, jstewart@seas.ucla.edu
[2] Prof., Civil & Env. Eng., University of Washington, Seattle, USA, kramer@uw.edu
[3] Post-doc., Civil & Env. Eng., University of California, Los Angeles, USA, kwakdongyoup@gmail.com
[4] Ph.D. Researcher, Civil & Env. Eng., University of Washington, Seattle, USA, greenfie@uw.edu
[5] Senior Scientist, US Geological Survey, Menlo Park, USA, rkayen@usgs.gov
[6] Prof., Arch. & Bldg Eng., Tokyo Institute of Technology, Tokyo, Japan, kohji@o.cc.titech.ac.jp
[7] Prof., Civil & Env. Eng., University of California, Berkeley, USA, jonbray@berkeley.edu
[8] Ph.D. Researcher, Civil & Env. Eng., University of California, Berkeley, USA, zbeyzaei@berkeley.edu
[9] Prof., Civil & Natural Resources Eng., University of Canterbury, Christchurch, New Zealand, misko.cubrinovski@canterbury.ac.nz
[10] Assoc. Prof., Urban Env. Syst., Chiba University, Chiba, Japan, tsekiguc@faculty.chiba-u.jp
[11] Prof., Urban Env. Syst., Chiba University, Chiba, Japan, nakai@tu.chiba-u.ac.jp
[12] Executive Director, PEER, Berkeley, USA, yousef@berkeley.edu

liquefaction resistances when tested under identical stress and loading conditions. The differences were attributed to differences in soil fabric produced by the different specimen preparation procedures. Combined with potential age effects, the direct applicability of laboratory test results to field conditions was recognized as tenuous.

At that time, the standard of practice for evaluation of liquefaction potential shifted to a basis rooted in the interpretation of *in situ* behavior as interpreted from field case histories. Case histories of sites where potentially liquefiable soils were shaken during earthquakes were investigated with both site conditions and ground motions characterized. Sites where liquefaction occurred, as indicated by surficial evidence such as sand boils and ground cracking, were noted as were sites with no observed ground failure. The characteristics of the case histories were condensed into measures of loading, most commonly a magnitude-corrected cyclic shear stress ratio, and resistance, typically expressed in terms of penetration resistance. By plotting the case histories on axes of loading and resistance, combinations corresponding to liquefaction and non-liquefaction could be identified. In the early stages of case history-based evaluation of liquefaction potential, the boundary between liquefaction cases and non-liquefaction cases was drawn by hand in a generally conservative manner. More recently, Bayesian analysis procedures have been used to evaluate probabilities of liquefaction, taking into consideration uncertainties associated with individual data points and variabilities among the central values of distinct data points.

To date, research on liquefaction triggering and effects has occurred within the traditional framework of individual or small groups of researchers assembling and interpreting case history data to support the development of predictive models. Liquefaction case history databases have been developed based upon the initiative, effort, and personal connections and data inventories that individual researchers or research teams have been able to assemble over time. Typically only the team of researchers that assembled a particular database has had access to its source data. As a result, the databases have been of different size, breadth, and quality, and their vetting by only small groups of researchers has complicated the identification of potentially problematic data.

Under the traditional framework, the groups that assemble case history databases also develop empirical predictive models. The groups work independently to interpret individual case histories, a process that often requires judgment and subjective decisions. In this framework, the models developed by individual groups have often indicated different behavior due to differences in their databases, different interpretations of the data in their databases, potential errors in data interpretation, different approaches to constraining model behavior under data-poor conditions, and different philosophies of model development. Detailed discussions of subjective and philosophical decisions related to the interpretation of case history data, which can strongly affect model behavior, have rarely been published. In the end, the developed models make their way into practice to varying degrees depending largely on the reputation of the lead investigators and the venues used for dissemination of results.

It is not surprising that the models developed by individual teams of researchers operating in this framework can have significant differences. Varying levels of database size, breadth, and quality, the potential for mistakes in data interpretation, and the general opacity of the process lead to differences that cannot be clearly understood and judged by practitioners. This is clearly inefficient and undesirable. Unfortunately this is also the present state of liquefaction models in the US and elsewhere.

The Next Generation Liquefaction (NGL) project has been conceived by researchers at the Pacific Earthquake Engineering Research (PEER) center in California and partnering organizations globally as a new paradigm for ground failure research and engineering model development. As will be described in this paper, NGL is largely a concept at the present stage, being supported by seed funding that has targeted documentation of high-value case histories from recent earthquakes in Japan and New Zealand and supported many workshops that have contributed to the conceptual development of NGL. Over the long-term, the goals of NGL are to coordinate activities of international partners in support of a community database for liquefaction and related ground failure case histories. Moreover, we envision that distinct model teams will utilize this common database, in combination with results from supporting studies of key effects poorly constrained by available data, to develop next-generation models for liquefaction susceptibility, triggering, and effects in a much more transparent and collaborative manner than has been possible previously.

Subsequent sections of this manuscript elaborate upon the plans for and status of NGL, in particular:

1. Statement of NGL project vision, scope, organization, and status;
2. NGL data products, including illustration of what constitutes a case history;
3. Review of preliminary data collection efforts;
4. Role of supporting studies;
5. Anticipated products and next steps

## NGL Project Vision and Objectives

Procedures for engineering assessment of liquefaction hazards are based to a large extent on the interpretation of field performance data from sites that have or have not experienced ground failure attributable to liquefaction. In this context, *ground failure* refers to permanent displacements of the ground surface, which can be caused by liquefaction or other phenomena such as cyclic softening of clays or seismic compression of unsaturated soils. The number of case histories supporting liquefaction procedures is remarkably small. For example, while nearly 200-400 case histories support most modern liquefaction triggering procedures, typically only a few dozen of these most tangibly affect the position of the threshold curve. Empirical procedures for analysis of undrained residual strength of liquefied soils are also controlled by only a few dozen case histories. Given the small number of most relevant case histories, it is no surprise that existing databases are *incomplete*, meaning they cannot constrain important components of engineering predictive models.

This situation can now be improved by substantial increases in the size and quality of field performance data sets. The database expansion is to a large extent associated with the devastating earthquakes during 2011 in Japan and New Zealand, which caused a great deal of damage attributable to liquefaction and its effects. However, numerous other earthquakes have produced data that has not yet been considered in most of the current liquefaction triggering and effects models, including the 1999 events in Turkey and Taiwan, 2004 and 2007 events in western Japan, and the 2010 event in Chile. We describe some of the unique opportunities afforded by recent case histories subsequently in this paper.

To fully realize the benefits of new and existing data resources, fundamental changes are needed in the manner by which data are collected and analyzed. As described in the Introduction, the traditional research approach is somewhat opaque regarding database development and case history interpretation. This complicates the task of practitioners to select the best of the available models for a particular application. Difficulties occur when the research community is unable to put forth clear standards on best practices, which is the current state of affairs for most important problems in liquefaction hazard assessment, including susceptibility, triggering, residual strength, and the analysis of displacements. The ongoing National Research Council (NRC) study was undertaken to respond to this lack of clarity, although the recommendation of specific models was not part of the committee's scope.

NGL was established to support the development of a community database for liquefaction case histories, to help identify the need for and to help facilitate studies on key effects poorly constrained by the database, and to establish a collaborative framework within which models can be developed by distinct groups of model developers drawing upon these resources. Our vision is that the entire process of database development and model development would be undertaken with regular communication among investigators via project coordination meetings and with public workshops to enable community engagement and input. A major benefit of this approach is that the resulting model predictions would reflect genuine, 'apples-to-apples', epistemic variability associated with alternate methods of interpreting a common data set, which is not the case today.

This approach is motivated in part by the success of the Next-Generation of Attenuation (NGA) projects for ground motion prediction (e.g., Power et al., 2008; Bozorgnia et al., 2014), which developed this research approach and enjoyed substantial global buy-in and broad application.

## NGL Data Products

The NGL database will consist, at its core, of a GIS platform (Google Earth, ArcGIS, or similar) documenting as completely as practical individual case histories of liquefaction, ground failure or non-ground failure (where 'ground failure' indicates permanent ground displacement). Attribution of data sources will be provided, but data will be presented in a common format. A usable case history of field performance generally requires the following attributes:

- *Observations of field performance from post-event reconnaissance.* This can vary from notes and photographs to relatively detailed mapping efforts producing ground failure displacement measurements.
- *Geotechnical data.* Required information on geotechnical conditions at a site of interest includes the soil stratigraphy, ground water depth, details pertaining to soil type (typically from gradation and index tests), and penetration resistance.

- *Ground motions.* The characterization of ground motion most often involves intensity measures such as peak acceleration, pseudo-spectral acceleration, or cumulative absolute velocity, but increasingly also may include full waveforms that are used to judge the presence and timing of liquefaction triggering.

The present availability of this information has been assessed through review of prior data compilations (e.g., Cetin et al. 2000, Boulanger et al., 2012, Moss et al., 2003) as well as presentations and discussions at the aforementioned international workshops. The number of currently available case histories in recent liquefaction triggering models are 230 for borehole/standard penetration test-based site characterization (Boulanger et al., 2012), 268 for cone penetration test-based site characterization (Boulanger and Idriss, 2014), and 422 for shear-wave velocity-based site characterization (Kayen et al., 2013). As part of the NGL project, we seek to significantly expand the size and breadth of the data set using observations from relevant events that are either missing from or not adequately represented in the existing inventories. Those events include the 1999 Kocaeli Turkey, 1999 Chi Chi Taiwan, 2004 and 2007 events near Niigata Japan, 2010 Maule Chile, 2011 Christchurch New Zealand, and 2011 Tohoku Japan earthquakes.

We argue that the NGL database as archived in a GIS platform is for practical purposes *objective*, in that it reports factual information on field performance, geotechnical conditions, and seismic demands. NGL will also populate a *Flatfile*, which will contain a synthesis of parameters used for model development. The process of distilling the information from the database to the format required for a flatfile is subjective. We illustrate through example the contents of the database and flatfile in the subsections below, including discussion of the subjective decisions required to produce a flatfile data point.

### *NGL GIS Database*

The GIS database is intended to document as completely as practical (and in a common format), case histories of liquefaction, related ground failures, and non-ground failures. Aspects of the required documentation include the field performance, geotechnical conditions, and ground motions. We illustrate these aspects of a typical case history using an example site having both ground failure (liquefaction-induced lateral spreading) and non-ground failure in adjacent areas. As shown in Figure 1, the site is located in Urayasu (Lat: 35.6380°; Long: 139.9335°), and the case history is related to performance from the 2011 Tohoku earthquake mainshock.

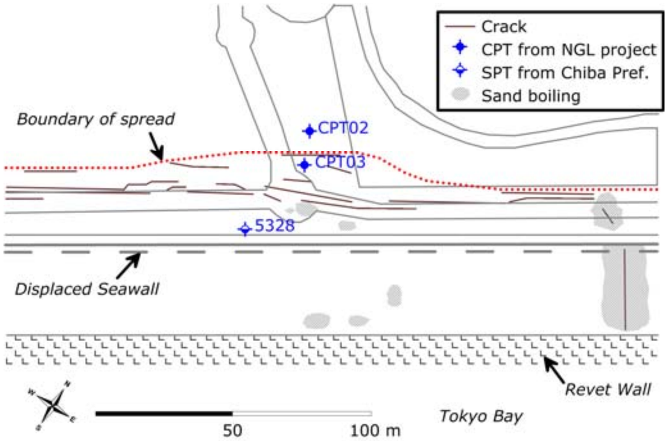

**Figure 1.** Sea front in Urayasu city where lateral spread occurred by the 2011 Tohoku Earthquake.

*Field performance*

Reliable evaluation of field performance requires post-event reconnaissance from a trusted source such as the Geotechnical Extreme Events Reconnaissance (GEER) association, the Earthquake Engineering Research Institute (EERI), local professional or governmental groups, and/or local university professors and students. The minimal required documentation is a written description of ground failure that occurred at the site and in the vicinity, a description of the lack of ground failure (as applicable), the date/time of the observation, and the precise location (with geodetic coordinates) of the observations. Additional useful information includes ground-based photographs, maps of surface features, relatively advanced imaging of surficial features through Light Detection And Ranging (LiDAR) scanning, or post-event images of the site from air photos or satellites. Evidence of ground failure from these data sources may include sediment boils, ground cracks, and deformations of above- or below-ground structures. Liquefaction can be identified as the cause of ground failure when sediment boils are observed. A lack of ground failure is an important observation, but it should be understood that such an observation does not preclude the occurrence of liquefaction or strength loss at the site.

In the case of the Urayasu site, the reconnaissance was performed by GEER (GEER, 2011) and includes information from all of the above-listed sources. Figure 1 distills the essential observations for the purpose of identifying portions of the site with and without ground failure.

*Geotechnical conditions*

A case history of ground failure is only useful for model development if some quantitative evaluation of site conditions is available. All sites listed in the NGL database will have such information. At this time, we anticipate that the minimum required information will include the soil stratigraphy, ground water depth, details pertaining to soil type, and penetration resistance. Information on soil type is critical and is an element of site data that is often missing or incomplete. The minimum required information on soil type is tip and sleeve resistance from cone penetration test (CPT) soundings or soil classification based on visual inspection or testing when samples are available. Additional information related to soil type that can significantly increase the value of a case study includes:

- Gradation testing and plasticity tests
- Water content
- Assessments of mechanical behavior of soil through cyclic testing or undrained monotonic testing in combination with consolidation tests (to evaluate potential undrained strength normalization).

Penetration resistance testing from CPT is desirable due to the standardization of these procedures. In the case of standard penetration testing, energy ratios associated with measurements should be reported. These energy ratios ideally are based on site- and equipment-specific energy measurements (Abou-Matar and Goble, 1997), but otherwise can be based on local experience or published values (e.g., Youd et al., 2001; Cetin et al., 2004). *In situ* seismic velocity testing will also be included with the geotechnical characterization where available.

At the example Urayasu site, Figure 2 shows results of CPT soundings both in the ground failure/liquefaction zone and the non-ground failure zone. The ground water depth at this location is 1.3 to 1.5 m. The cone data in Figure 2 has been processed and evaluated per the recommendations of Robertson (2012) as a dimensionless and overburden-normalized penetration resistance ($Q_{tn}$) and soil behavior type index ($I_c$). The site characterization in this case included CPT-based soil sampling in layers judged to be most critical for ground failure during field work; results of index tests from these samples are shown in Figure 2. The interpretation of this data for identification of the 'critical layer' is deferred to a subsequent section on the NGL flatfile.

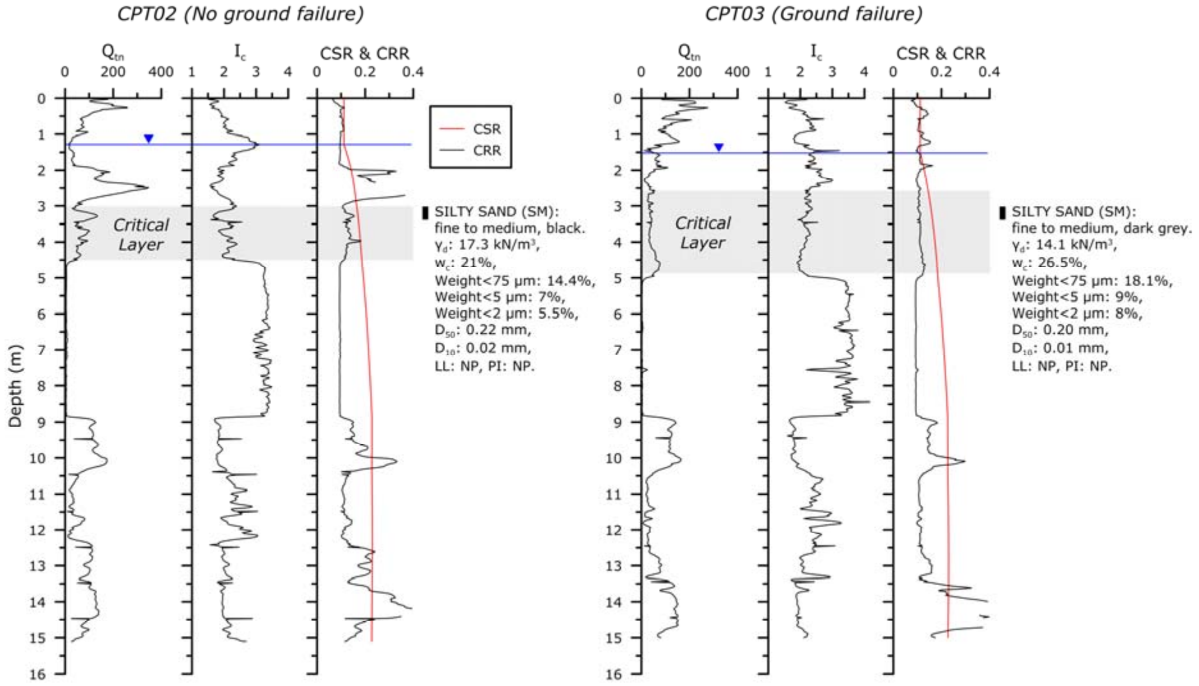

**Figure 2**. Normalized CPT resistance ($Q_{tn}$), soil behavior type index ($I_c$), cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) profiles on the location of no ground failure and ground failure. Laboratory index test results from the samples retrieved by a CPT sampler are indicated.

### *Ground Motion*

For the NGL database, ground motion characterization generally pertains to the intensity of shaking at the ground surface. The only exception to this is vertical arrays, where ground motions are recorded at depth (a rare circumstance at ground failure case history sites). The evaluation of cyclic stresses at depth given the shaking intensity at the surface is a modeling issue that enters the documentation at the flatfile stage, as described in the next section.

The ground motion intensity measure used for liquefaction analysis is generally the horizontal, median-component (denoted RotD50, Boore, 2010) peak ground acceleration (*PGA*). This parameter is widely used because the product of *PGA* and total vertical stress at the depth of interest is generally taken as proportional to the peak shear stress imposed by the earthquake at that depth (Seed and Idriss, 1971). Additional intensity measures used in some cases are cumulative absolute velocity beyond a 5 cm/s threshold ($CAV_5$), Arias intensity ($I_A$), and pseudo-spectral accelerations at various oscillator periods. Our remarks here are focused on *PGA*, but additional intensity measures are likely to be included in the database.

We propose the following procedures for estimating *PGA*, in order of preference:

1. When the earthquake event that produced the case history is included in ground motion databases used to derive ground motion prediction equations (GMPE), ground motions at the site should be taken as the sum (in natural log units) of the GMPE median (using appropriate site parameters including $V_{S30}$ and basin depths), the event term associated with that earthquake and the GMPE, and a mapped within-event residual to correct for spatial correlations in path and source. This approach, which is explained further in Kwak et al. (2015a), takes into consideration recordings in the vicinity of the case history site, while accounting for differences in site conditions. This approach is similar to procedures given previously by Wald et al. (2005), Yamazaki et al. (2000), Sawada et al. (2008), and Bradley (2014), but has distinct features as described by Kwak et al. (2015a).
2. When recordings are available for the earthquake in question, but the event was not included in the GMPE database, the procedure from (1) can be applied but with the event term set to zero. In this case the mapped residuals will likely have a non-zero mean.
3. When recordings for the event are either not available or are very sparse, GMPE log mean predictions should be used. These estimates are likely to carry a larger degree of uncertainty than those from (1) or (2).

For all three approaches, the GMPE should be appropriate for the tectonic regime that produced the earthquake event (Stewart et al., 2015). Ground motion estimates from approach (1) will converge to the recorded *PGA* as the separation distance between an accelerograph and the site approaches zero. For this reason, the procedures listed above apply both to sites with and without on-site or adjacent ground motion recordings. For sites with a strong motion station within some nominal distance (likely about 100 m), the recorded ground motion would likely be directly used. In addition to recent case histories, we expect to re-process ground motions for previous case histories in this manner so that demands for all NGL sites are estimated consistently.

For the example Urayasu site, recordings near the site produce a median estimate of *PGA* ≈ 0.174 g (using procedure 2 above) with an uncertainty of 0.28 (natural log units). The uncertainty estimate is based on semi-variograms by Jarayam and Baker (2009), and takes into consideration the separation distance between the site and the nearest ground motion station, which is 0.5 km.

A subset of sites that is being developed in NGL has observations of liquefaction manifest at the surface and ground motion recordings that exhibit evidence of liquefaction effects. Special procedures have been developed to interpret ground motions for these sites, with the goal of identifying conditions at the liquefaction triggering threshold. Kramer et al. (2015) describe in more detail this important aspect of the NGL project.

### *NGL Flatfile*

The NGL flatfile is envisioned as a synthesis of parameters used for model development. Parameters used in three recent liquefaction triggering models (Boulanger et al., 2012; Boulanger and Idriss, 2014; Kayen et al., 2013) are shown in Table 1. The NGL flatfile for triggering model development would include these parameters and likely others identified over the course of the project.

The key parameters produced from the flatfile that are used for the development of triggering models are a “reference” cyclic stress ratio (denoted *CSR**) that corresponds to reference conditions of $\sigma'_{v0} = 1$ atm, $\tau_{static} = 0$, and $\mathbf{M} = 7.5$, and a parameter representing soil penetration resistance or seismic velocity. Parameter *CSR** is computed as (adapted from Cetin et al., 2004, and others):

$$CSR^* = 0.65 \frac{\sigma_v}{\sigma_v'} \frac{PGA}{g} r_d \times \frac{1}{K_\sigma K_\alpha C_M} \tag{1}$$

where $\sigma_v$ and $\sigma_v'$ are total and effective stresses at the depth of interest (usually the center of the critical layer), $r_d$ is a stress reduction factor to account for the flexibility of the soil column above the depth of interest, $K_\sigma$ is an overburden factor to correct the seismic resistance for decreased soil dilatancy as effective stress increases, $K_\alpha$ is a shear stress correction factor to account for changes in dilatancy when static, horizontal-plane shear stresses are non-zero, and $C_M$ is a magnitude scaling factor to account for the increasing severity of seismic demands as **M** increases.

A number of parameters, such as $r_d$, $K_\sigma$, $K_\alpha$, and $C_M$ are not source data, but are intermediate parameters that characterize particular components of most liquefaction triggering models. As such, these parameters are somewhat subjective and will vary between modelers. Naturally, *CSR** as derived from Equation (1) is then also subjective. This subjectivity may require multiple flatfiles for multiple modeling teams, or at least separate families of parameters within a single flatfile for those teams. The fundamental differentiation of objective data in the NGL database and subjective data in the flatfile is an important element of NGL.

**Table 1.** List of parameters used in three recent liquefaction triggering models.

| Parameters | Boulanger et al., 2012 (SPT) | Boul. & Idriss, 2014 (CPT) | Kayen et al., 2013 ($V_s$) |
|---|---|---|---|
| **Fundamental Parameters** | | | |
| Moment magnitude, **M** | ● | ● | ● |
| Peak ground acceleration, *PGA* | ● | ● | ● |
| Liquefaction manifestation | ● | ● | ● |
| Average depth to critical layer | ● | ● | ● |
| Depth to ground water table | ● | ● | ● |
| Unit weight, $\gamma$ | | | |
| Static shear stress on horizontal plane, $\tau_{hv}$ | | | |
| Fines content, *FC* | ● | ● | |
| CPT tip resistance, $q_c$ | | ● | |
| CPT sleeve friction, $f_s$ | | ● | |
| SPT blow count, *N* | ● | | |
| SPT energy ratio (if measured) | ● | | |
| Shear wave velocity, $V_s$ | | | ● |
| **Intermediate or Derived Parameters** | | | |
| Total vertical stress, $\sigma_v$ | ● | ● | ● |
| Effective vertical stress, $\sigma_v'$ | ● | ● | ● |
| Shear stress reduction factor, $r_d$ | ● | ● | ● |
| Earthquake-induced cyclic stress ratio, *CSR* | ● | ● | ● |
| Overburden correction factor, $K_\sigma$ | ● | ● | |
| Shear stress correction factor, $K_\alpha$ | | | |
| Magnitude scaling factor, $C_M$ | ● | ● | ● |
| *CSR* for **M**=7.5, $\sigma_v'$=1atm, and $\alpha$=0, *CSR** | ● | ● | ● |
| Exponent for overburden normalization, *n* | | ● | |
| Soil behavior type index, $I_c$ | | ● | |
| Overburden correction factor, $C_N$ | ● | ● | ● |
| Overburden-normalized tip resistance, $Q_{tn}$ and $q_{c1N}$ | | ● | |
| Overburden-normalized sleeve friction, *F* | | ● | |
| Friction ratio, $F_r$ | | ● | |
| SPT energy ratio (if inferred) | ● | | |
| Energy- and overburden stress-corrected blow count, $(N_1)_{60}$ | ● | | |
| Normalized shear wave velocity, $V_{s1}$ | | | ● |
| Equivalent clean-sand tip resistance, $q_{c1Ncs}$ | | ● | |
| Equivalent clean-sand corrected blow count, $(N_1)_{60cs}$ | ● | | |

To illustrate this process, we apply to the Urayasu case history site the $r_d$, $K_\sigma$, $K_\alpha$, and $C_M$ estimates from Boulanger and Idriss (2014). Figure 2 identifies the depth range for the "critical layer.” This process of identifying the critical layer is itself highly subjective. In the present case our judgment is that the base of the critical layer is bound by a non-susceptible (clay) layer. The shallow limit of the critical layer is bound by a dense near-surface layer (no-ground failure location) and by relatively plastic (high $I_c$) material within the ground failure zone. Table 2 shows the parameters required for flatfile development for these sites both in the ground failure and non-ground failure regions (using CPT-based soil penetration resistance).

**Table 2.** Parameters for liquefaction triggering analysis for no-ground failure (CPT02) and ground failure (CPT03) locations at example site. Derived parameters from Boulanger and Idriss (2014).

| | **M** | $PGA$ (g) | Critical Interval (m) | Avg. Depth (m) | GWT Depth (m) | $\sigma_v$ (kPa) | $\sigma_v'$ (kPa) | $r_d$ | CSR | $K_\sigma$ | $K_\alpha$ | $C_M$ | $CSR*$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CPT02 | 9 | 0.174 | 3.0-4.5 | 3.75 | 1.27 | 67.5 | 43.2 | 1.0 | 0.177 | 1.08 | 1 | 0.916 | 0.178 |
| CPT03 | 9 | 0.174 | 2.5-5.0 | 3.75 | 1.51 | 67.5 | 45.5 | 1.0 | 0.168 | 1.07 | 1 | 0.939 | 0.167 |
| | FC (%) | $q_c$ (MPa) | $f_s$ (MPa) | $f_r$ (%) | Q | n | F | $I_c$ | $C_N$ | $q_{c1N}$ | $\Delta q_{c1N}$ | $q_{c1Ncs}$ | CRR ($P_L$=15%) |
| CPT02 | 14.4 | 4.41 | 0.046 | 1.04 | 65.7 | 0.5 | 1.06 | 2.07 | 1.57 | 68.3 | 18.7 | 87.1 | 0.123 |
| CPT03 | 18.1 | 2.82 | 0.022 | 0.77 | 40.6 | 0.5 | 0.78 | 2.17 | 1.58 | 44.1 | 25.5 | 69.7 | 0.107 |

Figure 3 shows where the results for the critical layers plot relative to the Boulanger and Idriss (2014) probabilistic liquefaction triggering criteria and their data. The uncertainty around the plotted data points in the horizontal and vertical directions are related to dispersion of $PGA$ (vertical direction) and penetration resistance within the critical layer (horizontal direction). The example sites plot near the liquefaction triggering threshold.

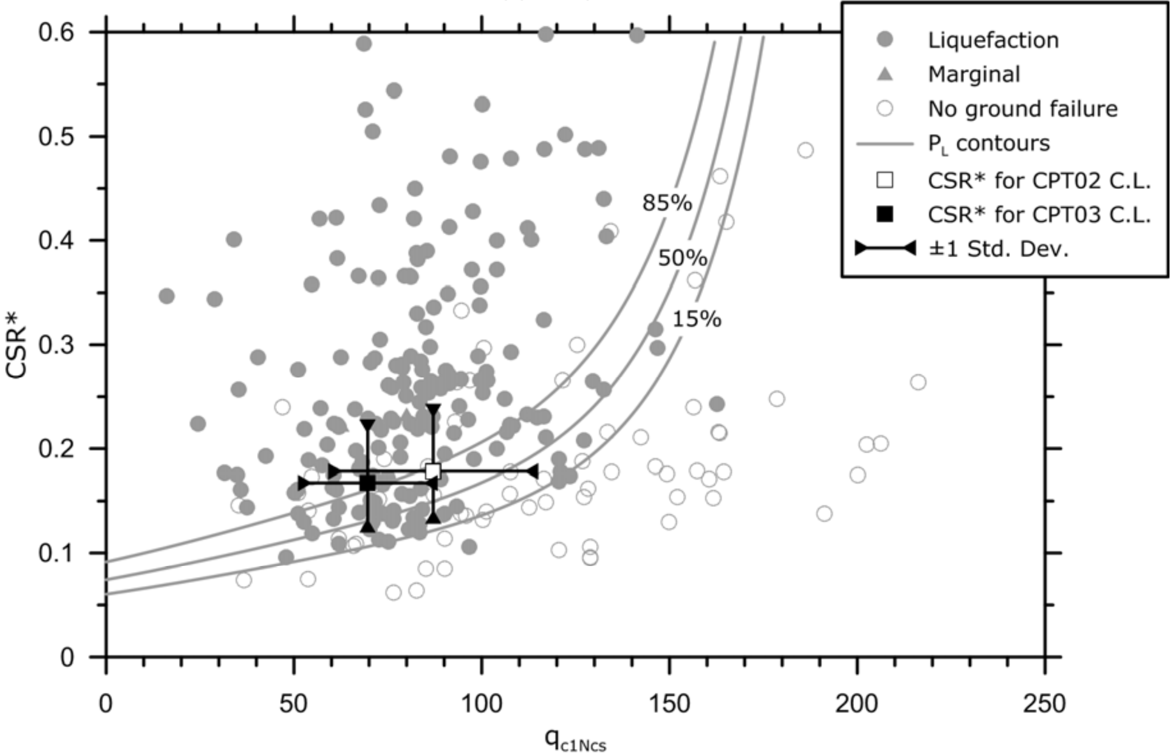

**Figure 3.** Liquefaction triggering database showing $CSR*$ vs. $q_{c1Ncs}$ and $CRR_{M7.5,\sigma'=1atm}$ for 15, 50, and 85% probabilities of liquefaction (after Boulanger and Idriss, 2014). Data points for critical layers and ±1 standard deviations of $CSR*$ and $q_{c1Ncs}$ are shown for no ground failure (CPT02) and ground failure (CPT03) locations at example site in Urayasu, Japan.

## Preliminary Data Collection

As mentioned in the Introduction, work to date in the NGL project has been directed towards developing high-value case histories and formulating the project vision, organization, and scope. In this section, we provide an overview of data collection to date and additional efforts planned in the near-future relative to the time of this writing (June 2015). We describe how sites were selected for geotechnical characterization and the types of tests that were performed. In all cases, the sites selected for characterization activities had prior geotechnical data that was supplemented to fill data gaps in the present work.

### *Field work in Japan*

The 2011 **M** 9.0 Tohoku earthquake produced a wealth of field observations of liquefaction and non-liquefaction, including sites with measured ground deformations and measured foundation performance (GEER, 2011). Following extensive discussions at several international workshops among many of the authors of this paper and others with expertise and experience in this area, priorities for site characterization were identified as follows:

1. Sites having well documented lateral ground deformation from traditional mapping and LiDAR imaging.
2. Sites having ground motion instrumentation and well-documented field performance with respect to liquefaction or lack of ground failure.
3. A series of sites on reclaimed land areas in Mihama ward, Chiba Prefecture. The fill materials in these areas were placed hydraulically.
4. Vertical ground motion array sites, many operated by the Port and Airport Research Institute, where varying levels of ground failure were observed.

Based on the above criteria, seven sites at the locations in Figure 4 were investigated in the first phase of data collection (completed in April-July 2014). One site was selected per the first criterion (lateral ground deformation) while six were selected per the second criterion (near strong ground motion stations). Table 3 lists the sites and attributes that led to their selection. Testing at the sites included CPT (including sampling) and borings with sampling include SPTs with energy measurements. Work currently in the planning stages will occur at sites selected per criteria 2-4.

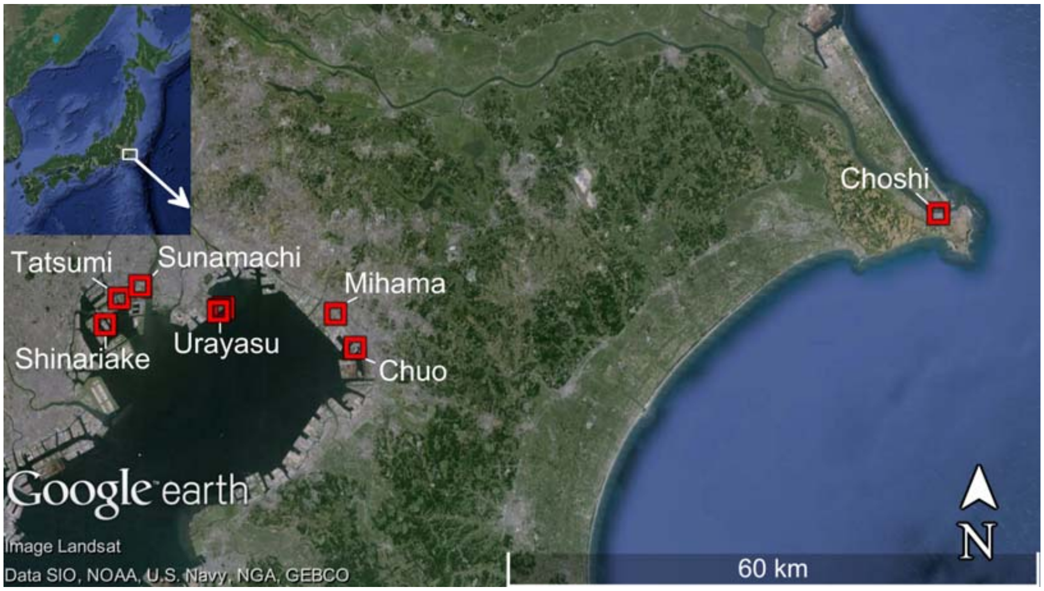

**Figure 4.** Locations of ground failure or no-ground failure sites investigated in first phase of NGL characterization work in Japan (base map from Google Earth$^{TM}$).

**Table 3.** List of first-phase characterized sites in Japan from NGL project.

| **Location** | **Tests** | **Latitude** | **Longitude** | **Nearest Station** | **PGA (g) at N.S.** | **Site-to-station distance (km)** | **Ground failure observation** |
|---|---|---|---|---|---|---|---|
| Urayasu, Chiba | CPT | 35.63692 | 139.93215 | HND /Keiyo Gas | 0.174 | 0.61 | Lateral spread |
| | SPT / CPT | 35.63802 | 139.93352 | HND /Keiyo Gas | 0.174 | 0.54 | |
| | CPT | 35.63793 | 139.93356 | HND /Keiyo Gas | 0.174 | 0.54 | |
| | CPT | 35.64029 | 139.93828 | HND /Keiyo Gas | 0.174 | 0.73 | |
| Choshi, Chiba | SPT / CPT | 35.73536 | 140.82732 | CHB005 /K-NET | 0.179 | 0.02 | No ground failure |
| Chuo, Chiba | SPT / CPT | 35.60048 | 140.10209 | Chiba-g /PARI | 0.128 | 0.16 | No ground failure |
| Mihama, Chiba | CPT | 35.63469 | 140.07777 | CHB024 /K-NET | 0.237 | 0.07 | Severe liquefaction |
| Sunamachi, Tokyo | CPT | 35.66226 | 139.83430 | TKY013 /K-NET | 0.144 | 0.06 | No ground failure |
| Tatsumi, Tokyo | CPT | 35.64967 | 139.80849 | TKY017 /K-NET | 0.223 | 0.27 | Moderate liquefaction |
| Shinariake, Tokyo | CPT | 35.62293 | 139.79100 | Shinariake /TMG | 0.122 | 0.12 | No ground failure |

### *Lateral Spread at Urayasu City*

The ground failure and non-ground failure example described in the previous section (Figures 1-3) is from the Urayasu lateral spread site. Figure 5 is a plan view of the spread feature, showing displacement vectors of up to 2.8 m horizontally towards the sea (1.0 m of subsidence also occurred). The width of the spread feature is about 600 m. The spreading occurred in artificial fill towards a free-face height estimated as 6 m based on the fill thickness and surface elevations of pre-fill borings from Chiba Prefecture Geology and Environment Information Bank (CP, 2015). A supporting estimate of the free-face height is computed using the lateral dimension of a revetment slope below the sea wall and its approximate slope of 2H:1V.

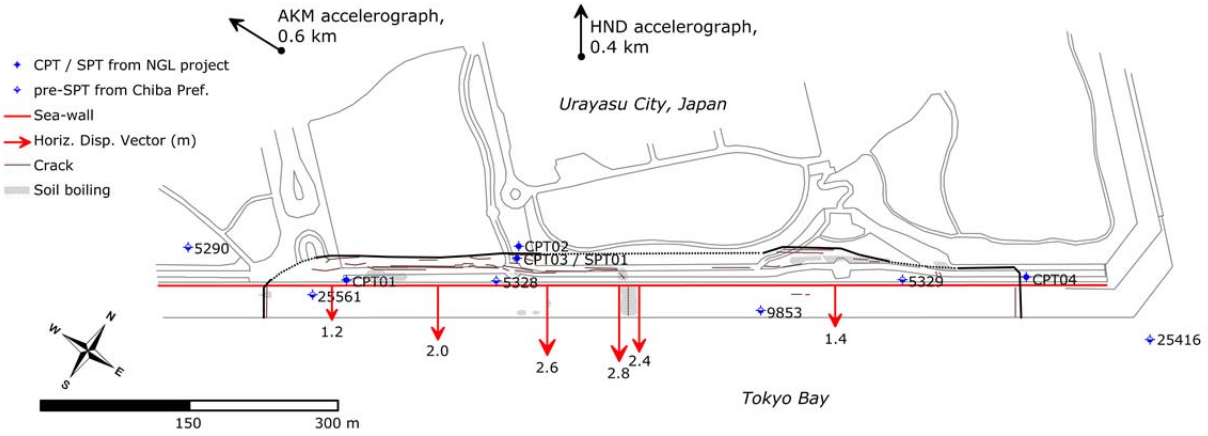

**Figure 5.** Plan view of Urayasu sea front where lateral spread occurred during 2011 **M** 9.0 Tohoku earthquake mainshock. All surface features based on field mapping, ground and air photos, and LiDAR imaging.

Site performance was first documented by the GEER reconnaissance team using field mapping and photography. A subsequent phase of work in the GEER reconnaissance imaged ground morphology using terrestrial LiDAR. Both the field mapping and LiDAR imaging were used to evaluate displacement vectors and to support the development of the site plan in Figure 5. We performed four CPTs and one boring with SPT to evaluate subsurface conditions inside and outside of the deformation zone. There are also four pre-existing boring logs performed in the 1970s to 1990s, which are available from Chiba Prefecture (CP, 2015).

Four other lateral spread sites have similar levels of mapping but lack geotechnical data. This data may be compiled in future work. The inventory of data from these sites is useful both for triggering and semi-empirical lateral spread models.

*Strong Ground Motion Stations in Tokyo and Chiba*

Observations of liquefaction and no-ground failure in the vicinity of accelerograph stations are especially valuable for model building, because the seismic demands at these sites have significantly less uncertainty than those for sites where ground motions must be estimated. For this reason, GEER reconnaissance activities emphasized locations near accelerographs (GEER, 2011). Resulting observations and preliminary analysis of these conditions are provided by Cox et al. (2013) for 22 liquefaction sites and 16 no-ground failure sites that are mostly located in the greater Tokyo Bay region of Japan.

Many of the accelerograph sites for which field performance and ground motion information are available also have some geotechnical data. For example, accelerographs within the K-NET network (Kinoshita, 1998) have boring logs, SPT *N*-values, and $V_S$ profiles that typically extend to 10-20 m depth. A similar format is used for accelerographs in the PARI network (PARI, 2015), except that borehole depths are variable. Boring logs and $V_S$ profiles are available for KiK-net vertical array sites, although these profiles extend considerably deeper. However, as described by Cox et al. (2013), there are several complications in the use of this data, including lack of quantitative soil type information (from laboratory index tests) and unknown SPT energy levels, which are particularly variable at K-NET and PARI sites (Kwak et al., 2015b). Our site characterization was motivated in large part by a need to fill these data gaps. As shown in Table 3, we investigated four K-NET sites, one PARI site, and one site maintained by the Tokyo Metropolitan Government site (Shinariake).

Among the five K-NET and PARI sites, three (CHB005, Chiba-g, TKY013) had no observable ground failure, despite low penetration resistance, shallow ground water, and the presence of silty soils. An important issue in these cases is whether those fine-grained materials are liquefaction-susceptible. Site CHB024 had severe liquefaction, and was investigated to support NGL-related activities to identify $CSR^*$–penetration resistance conditions at the liquefaction triggering threshold (as described by Kramer et al., 2015). Site TKY017 had moderate liquefaction and was investigated for similar reasons.

We performed CPTs for each investigated site, and SPTs for CHB005 and Chiba-g. An objective of the SPTs at K-NET and PARI stations was to investigate energy ratios for SPT *N*-values reported in the logs. Hammer energy ratios were recorded using equipment and analysis procedures given by Abou-Matar and Goble (1997). Laboratory index tests for specimens from SPT samplers and CPT samplers were also performed.

Three sites in Tokyo (Sunamachi, Tatsumi, and Shinariake) are located in the vicinity of ground motion stations (K-NET and Tokyo Metropolitan Government, TMG) and have instrumentation to record ground settlement and ground water table fluctuation measurements (TMG, 2011). We performed exploration at the Shinariake site, which has a downhole array with four seismographs at 2, 16, 36, and 75 m depth in addition to the ground water elevation and settlement instruments. This site experienced settlement but had no other surface manifestation of liquefaction.

As noted in Table 3, there are cases in which borings and CPTs were not co-located with accelerographs. This resulted from inabilities to secure necessary permission in some cases.

### *Mihama-Ward (reclaimed land by hydraulic fill)*

Mihama-ward in Chiba, Japan is constructed on reclaimed land that was developed using hydraulic fill procedures in the mid-1970s (Sekiguchi and Nakai, 2012). As shown in Figure 6, locations of discharge pipes are well known, which is useful because during hydraulic filling relatively fast flow velocities are expected near discharge locations (producing relatively coarse sediments) whereas slower velocities in intermediate areas would be expected to produce relatively fine-grained sediments. The variable composition of these materials is of considerable interest from a liquefaction susceptibility perspective.

After the Tohoku event, extensive reconnaissance of reclaimed land areas in Mihama-ward was conducted by Chiba University as well as several government agencies. The Chiba University reconnaissance, documented by Sekiguchi and Nakai (2012), mapped the surface manifestation of liquefaction according to three levels: 1) Heavy liquefaction: "The overflow area of the sand boiling found in the spot is more than about 1 m"; 2) Minor liquefaction: "The overflow area is less than about 1 m"; 3) no liquefaction: "No sand boiling was found."

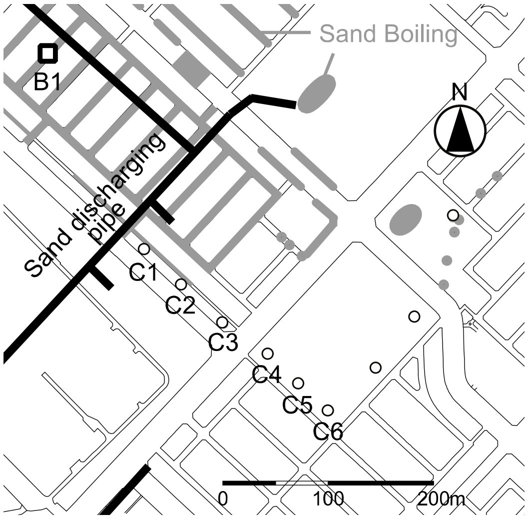

**Figure 6.** Mihama-ward site showing CPT locations, sand discharging pipe, and sand boiling traces (Sekiguchi and Nakai, 2012).

There is a general correlation between field performance and discharge pipe locations – with liquefaction being most concentrated near discharge pipes and intermediate areas having no-ground failure. Our work in this region has the objective of identifying soil compositional factors that contribute to varying levels of liquefaction severity. Many borings and a small number of CPTs have already been performed in the area (including the six CPTs shown in Figure 6), but laboratory test data is scarce and is not sufficient to study liquefaction susceptibility issues. Our future work will fill this data gap.

### *New Zealand*

Following the 2010-2011 Canterbury Earthquake Sequence (CES), several engineers and researchers conducted field studies in Christchurch, New Zealand to characterize subsurface conditions at sites that either had surface manifestation of liquefaction or no observed ground failure. Over 18,000 CPT soundings and over 3,000 soil exploratory borings have been performed since the CES making this dataset incredibly valuable, especially considering that each site was shaken multiple times by major earthquake events (four of which had **M** > 5.9).

Post-earthquake reconnaissance efforts were conducted by several organizations, including government agencies, private consultancies, academic research institutions, and volunteer engineers and geologists. The Earthquake Commission, Tonkin & Taylor, and the University of Canterbury facilitated many of these efforts. Among the four events, the best reconnaissance documentation is for the 4 September 2010 Darfield (**M** 7.1) and 22 February 2011 Christchurch (**M** 6.2) earthquakes. This documentation includes reports by the National Science Foundation (NSF)-sponsored Geotechnical Extreme Events Reconnaissance (GEER) Association. The observations contained in these reports have been incorporated in the Canterbury Geotechnical

Database maps, showing available post-earthquake observations throughout the Canterbury region for each of the four major earthquake events.

The NGL New Zealand dataset focused on pulling together a select number of the most insightful case histories from four well-documented geotechnical projects, the earliest beginning in 2011 and the most recent continuing today. Combining the resources of international, governmental, and private organizations, along with researchers from a diverse range of backgrounds, these projects represent a significant contribution to the global dataset in development of the next generation liquefaction assessment procedures. While the projects are individually detailed in separate publications, their case history data are being standardized and compiled for incorporation in the NGL database.

Canterbury, New Zealand subsurface geotechnical data were gathered from four projects summarized in Table 4, which collectively investigated the site locations shown in Figure 7. All sites within the dataset contain CPT data, with sonic boring, laboratory testing data, and shear wave velocity profiles available for many of the sites. Case histories at these sites are based on ground failure observations from the 2010-2011 Canterbury Earthquake Sequence and cover a broad spectrum of liquefaction effects, ranging from no observation to severe damage.

**Table 4.** New Zealand sites for NGL database

| Reference | No. of Sites | CPT | Sonic Boring | Undisturbed Sampling |
|---|---|---|---|---|
| Beyzaei et al. (2015), Stringer et al. (2015), UC Berkeley & Univ. of Canterbury (2015) | 8 | ● | ● | ● |
| Markham et al. (2015) | 8 | ● | | ● |
| Tonkin & Taylor (2013) | 12 | ● | ● | |
| Green et al. (2014) | 25 | ● | | |

**Figure 7.** Geographic distribution of NGL New Zealand sites in the Canterbury Region

The sites to be included in the NGL database are summarized as follows:

- *Project 1: NSF-PEER-MBIE-EQC Liquefaction Triggering & Consequence for Low-Plasticity Silty Soils (8 'SM' Sites)*

  Each site in the silty soils project has a CPT sounding, sonic boring with disturbed samples, and mud rotary cased boring with undisturbed sampling. Sites were selected based on the presence of silty soils in the upper few meters and comparisons of observed vs. predicted liquefaction for the September 2010 Darfield earthquake and the February 2011 Christchurch earthquake, with an emphasis on sites in which prevalent liquefaction triggering and ground settlement procedures over-predicted the observed performance.

  Beyzaei et al. (2015) and Stringer et al. (2015) provide detailed information on the laboratory testing program for two of the sites investigated as part of the silty soils project. Cyclic triaxial laboratory testing data, Atterberg limits, and particle size analysis are presented in addition to the field work and pre-existing data summaries.

  As the most recent of the four NGL New Zealand projects, the silty soils project includes direct support from NGL funding towards the field work and laboratory testing program. The three additional projects listed below were independently funded, but are being standardized and incorporated in the NGL database through the support of NGL funding.

- *Project 2: NSF CBD Project (8 'CBD' sites)*

  Each site in the Central Business District (CBD) of Christchurch project has at least one CPT sounding and at least one mud rotary cased boring with undisturbed sampling. Sites were selected based on observed building damage, covering varying degrees of damage due to global settlement and differential settlement. Significant amounts of silty sand are present in the upper few meters at some sites.

- *Project 3: Tonkin & Taylor Liquefaction Vulnerability Study (12 'T&T' sites)*

  Each site in the Liquefaction Vulnerability Study has one CPT sounding and one nearby soil boring with sampling. Sites were selected by Tonkin & Taylor to evaluate differences between CPT-based and SPT-based liquefaction triggering procedures.

- *Project 4: Virginia Tech & Univ. of Canterbury & Others Liquefaction Triggering Study (25 'VT-UC' sites)*

  The VT-UC sites are described in Green et al. (2014). The authors state that they:

  *... selected 25 sites to analyze in detail, many of which had minor surficial liquefaction manifestations resulting from the Darfield or Christchurch earthquake. The sites were evaluated during both these events, resulting in 50 high-quality case histories. The sites selected for detailed evaluation were located relatively close to strong ground motion stations and were characterized by both CPT soundings and surface wave testing.*

## Role of Supporting Studies

We envision the NGL liquefaction triggering and effects models as being ‘semi-empirical’, meaning that both empirical data analysis and results of supporting studies will be considered (to varying degrees) in model development. Supporting studies are needed to examine specific technical issues that are essential for model development but which cannot be resolved solely on the basis of empirical data, even after the database is expanded in the manner described above.

Some of the topics to be considered by such teams are envisioned to include liquefaction at large depth, pore pressure generation and strength loss in soils having high fines content and intermediate levels of plasticity, liquefaction of gravels, age effects on liquefaction resistance, potentially increased liquefaction resistance of thin soil layers near drainage boundaries (or the upper portion of relatively thick layers near the boundary), and volume change/shear deformations of soils having variable levels of density, fines content, and overburden stress. Some of these issues can be addressed by high-quality laboratory tests; centrifuge or large shake table model testing may also be used to resolve others. Still others may be addressed with numerical modeling of problems that employ well-calibrated constitutive models. Table 5 lists several topics that have been identified in international workshops, provides a brief explanation of the technical issues, and cites examples of prior work in the subject area.

For each of these technical issues, our approach will be to evaluate work to date on the subject, identify further research needs to further develop understanding of the issue so that it can be modelled, support projects to develop this understanding, and ultimately incorporate appropriate representations of the effect in NGL models.

Table 5 only pertains to liquefaction triggering models. Supporting studies will also likely be needed for a range of issues related to liquefaction effects, including ground settlement, structure settlement, post-liquefaction shear strength, and lateral spreading.

**Table 5.** Example topics where supporting studies are needed for NGL liquefaction triggering model development

| Topic | Issues | Example references |
|---|---|---|
| Liquefaction at depth | • Empirical data constrains models for depths, $z < \sim 12$ m<br>• Large epistemic uncertainty in $r_d$ models for $z > \sim 3$ m. Effects of profile, ground motion, and soil nonlinearity poorly understood.<br>• Large epistemic uncertainty in $K_\sigma$ models<br>• Modest epistemic uncertainty in factors for penetration resistance normalization, $C_N$ | $r_d$: Youd et al. (2001); Cetin et al. (2004), Idriss (1999), Kishida et al. (2009)<br>$K_\sigma$: Cetin et al. (2004); Boulanger (2003a)<br>$C_N$: Youd et al. (2001); Boulanger (2003a); Robertson (2012); Montgomery et al. (2014) |
| Effects of fines | • Compared to clean sands, soils with fines have reduced penetration resistance and different liquefaction 'strength' or resistance for a given state (or relative density, in case of non-plastic fines)<br>• Current modeling approaches are empirical, which combines the two effects. Preferred approach is to understand each effect and its sensitivity to fines content and fines plasticity | Effects on penetration resistance: Carraro et al. (2003)<br>Effects on liquefaction strength: Polito and Martin (2001)<br>*Approximate combined effects*: all recent triggering models |
| Ageing effects | • Empirical data is mostly from artificial fills and young (Holocene) sediments<br>• For a constant relative density, older materials have higher penetration resistance and higher liquefaction resistance<br>• The increase of liquefaction resistance is greater than predicted by the increased penetration resistance, so additional corrections needed. | Leon et al. (2006); Hayati and Andrus (2009); Andrus et al. (2009); Maurer et al. (2014) |
| Effects of static shear stress | • Effects of normalized static shear stress, $\alpha$, not included in most current models.<br>• One published model for effect of $\alpha$ on liquefaction resistance, but lack of community consensus | Boulanger (2003b) |

## Anticipated Products and Next Steps

As with prior NGA projects for ground motions, the NGL project deliverables are anticipated to consist of data resources and engineering predictive models. The data resources will include the NGL database and flatfile, as described previously. The liquefaction models will consist of probabilistic models for liquefaction susceptibility, triggering, and effects. The liquefaction triggering models will consist of equations for the limit state function representing the boundary between liquefaction and non-liquefaction. The liquefaction effects models will enable computations of free-field settlements, foundation settlements, free-field displacements from lateral spreading, and post-liquefaction liquefied shear strength.

Because liquefaction and ground failure analyses are routine in engineering practice and are of great practical importance, we anticipate the development of guidelines documents for application, likely tailored to needs of various agencies (e.g., Nuclear Regulatory Commission, State Departments of Transportation, U.S. Army Corps of Engineers).

As mentioned in the introduction, as of this writing, NGL is at present a concept that enjoys broad community support, but which is not yet fully launched due to pending funding commitments. Work to date has largely consisted of compilation of high-value data as described in this paper and the holding of workshops to develop the project vision. We expect the project to expand in scope and activity in 2016.

## Acknowledgments

Seed funding for NGL was provided by the Pacific Earthquake Engineering Research Center. This support is gratefully acknowledged. Many individuals in Japan, New Zealand, and the U.S. (too many to list) contributed to workshops in which the NGL framework was developed – they have our sincere gratitude.

## References

Abou-Matar H, Goble G. SPT dynamic analysis and measurements. *J. Geotech. & Geoenv. Eng.* 1997; **123**(10): 921-928.

Andrus R, Hayati H, Mohanan N. Correcting liquefaction resistance for aged sands using measured to estimated velocity ratio. *J. Geotech. & Geoenv. Eng.* 2009; **135**(6): 735–744.

Beyzaei CZ, Bray JD, Cubrinovski M, Riemer M, Stringer ME, Jacka M, Wentz FJ. Liquefaction resistance of silty soils at the Riccarton road site, Christchurch, New Zealand. *Proc. 6th Int. Conf. Earthquake Geotech. Eng.*, November 1-4, 2015, Christchurch, New Zealand.

Boore DM. Orientation-independent, nongeometric-mean measures of seismic intensity from two horizontal components of motion. *Bulletin of the Seismological Society of America* 2010; **100**(4): 1830-1835.

Boulanger RW. Relating $K_\alpha$ to relative state parameter index. *J. Geotech. & Geoenv. Eng.* 2003a; **129**(8): 770-773.

Boulanger RW. High overburden stress effects in liquefaction analyses. *J. Geotech. & Geoenv. Eng.* 2003b; **129**(12): 1071–082.

Boulanger RW, Idriss IM. CPT and SPT based liquefaction triggering procedures. *Center for geotechnical modeling Rep. No. UCD/CGM-14/01*, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, Calif, 2014.

Boulanger RW, Wilson DW, Idriss IM. Examination and reevalaution of SPT-based liquefaction triggering case histories. *J. Geotech. & Geoenv. Eng.* 2012; **138**(8): 898-909.

Bozorgnia Y et al. NGA-West2 research project. *Earthquake Spectra* 2014; **30**(3): 973-987.

Bradley BA. Site-specific and spatially-distributed ground-motion intensity estimation in the 2010-2011 Canterbury earthquakes. *Soil Dynamics and Earthquake Engineering* 2014; **61**: 83-91.

Carraro JAH, Bandini P, Salgado R. Liquefaction resistance of clean and nonplastic silty sands based on cone penetration resistance. *J. Geotech. & Geoenv. Eng.* 2003; **129**(11): 965-976.

Cetin KO, Seed RB, Der Kiureghian A, Tokimatsu K, Harder LF Jr, Kayen RE, Moss RES. Standard penetration test-based probabilistic and deterministic assessment of seismic soil liquefaction potential. *J. Geotech. & Geoenv. Eng.* 2004; **130**(12): 1314-1340.

Cetin KO, Seed RB, Moss RES, Der Kiureghian A, Tokimatsu K, Harder LF Jr, Kayen RE, Idriss IM. Field performance case histories for SPT-based evaluation of soil liquefaction triggering hazard. *Geotechnical Research Rep. No. UCB/GT-2000/09*, Dept. of Civil and Environmental Engineering, Univ. of California, Berkeley, Calif, 2000.

Chiba Prefecture (CP). Chiba Prefecture Geology and Environment Information Bank (CGEIB). https://www.pref.chiba.lg.jp/suiho/chishitsu.html, last accessed at June 2015. (in Japanese)

Cox BR et al. Liquefaction at strong motion stations and in Urayasu City during the 2011 Tohoku-Oki Earthquake. *Earthquake Spectra* 2013; **29**(S1), S55-S80.

Geotechnical Extreme Events Reconnaissance (GEER). Geotechnical quick report on the Kanto plain region during the March 11, 2011, Off Pacific Coast of Tohoku Earthquake, Japan 2011. *Quick Report 1: GEER Association Report No. GEER-025a*, 2011.

Green RA, Cubrinovski M, Cox B, Wood C, Wotherspoon L, Bradley B, Maurer B. Select liquefaction case histories from the 2010–2011 Canterbury earthquake sequence. *Earthquake Spectra* 2014; **30**(1): 131-153.

Hayati H, Andrus R. Updated liquefaction resistance correction factors for aged sands. *J. Geotech. & Geoenv. Eng.* 2009; **135**(11): 1683-1692.

Idriss IM. An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential. *Proceedings of TRB Workshop on New Approaches to Liquefaction*, Publication No. FHWA- RD-99-165, Federal Highway Administration, January, 1999.

Kayen R, Moss RES, Thompson EM, Seed RB, Cetin KO, Der Kiureghian A, Tanaka Y, Tokimatsu K. Shear-wave velocity–based probabilistic and deterministic assessment of seismic soil liquefaction potential. *J. Geotech. & Geoenv. Eng.* 2013; **139**(3): 407-419.

Kinoshita S. Kyoshin Net (K-NET). *Seismological Research Letters* 1998; **69**: 309-332.

Kishida T, Boulanger RW, Abrahamson NA, Driller MW, Wehling TM. Seismic response of levees in Sacramento-San Joaquin Delta. *Earthquake Spectra* 2009; **25**(3): 557-582.

Kramer SL, Sideras SS, Greenfield MW. The timing of liquefaction and its utility in liquefaction hazard evaluation. *Proceedings of 6th International Conference on Earthquake Geotechnical Engineering*, October 1-4, 2015, Christchurch, New Zealand.

Kwak DY, Brandenberg SJ, Mikami A, Stewart JP. Prediction equations for estimating shear-wave velocity from combined geotechnical and geomorphic indexes based on Japanese data set. *Bulletin of the Seismological Society of America* 2015b. doi:10.1785/0120140326

Kwak DY, Stewart JP, Brandenberg SJ, Mikami A. Characterization of seismic levee fragility using field performance data. *Earthquake Spectra* 2015a. doi:10.1193/030414EQS035M

Leon E, Gassman SL,, and Talwani P. Accounting for soil aging when assessing liquefaction potential, *J. Geotech. & Geoenv. Eng.* 2006; **132**(3): 363-377.

Markham CS, Bray JD, Riemer MF, Cubrinovski M. Characterization of shallow soils in the Central Business District of Christchurch, New Zealand. *ASTM Geotechnical Testing Journal* 2015 (under review).

Maurer, B.W., Green, R.A., Cubrinovski, M., and Bradley, B.A. Assessment of aging correction factors for liquefaction resistance at sites of recurrent liquefaction, *Proceedings of the 10th U.S. National Conference on Earthquake Engineering*, 2014, Earthquake Engineering Research Institute, Anchorage, AK, 12 pp.

Montgomery J, Boulanger RW, and Harder, LF, Jr. Examination of the $K_\sigma$ overburden correction factor on liquefaction resistance. *J. Geotech. & Geoenv. Eng.* 2014; **140**(12), 04014066.

Moss RES, Seed RB, Kayen RE, Stewart JP, Youd TL, Tokimatsu K. Field case histories for CPT-based in situ liquefaction potential evaluation. *Geoengineering Research Rep. No. UCB/GE-2003/04*, Dept. of Civil and Environmental Engineering, Univ. of California, Berkeley, Calif, 2003.

Port and Airport Research Institute (PARI). Seismic network for ports. http://www.eq.pari.go.jp/kyosin/, last accessed at June 2015. (in Japanese)

Polito CP. Martin II, JR. Effects of nonplastic fines on the liquefaction resistance of sands. *J. Geotech. & Geoenv. Eng.* 2001; **127**(5): 408-415.

Power M, Chiou BSJ, Abrahamson NA, Bozorgnia Y, Shantz T, Roblee C. An overview of the NGA project. *Earthquake Spectra* 2008; **24**(1): 3-21.

Robertson PK. Interpretation of in-situ tests – some insights. *J.K. Mitchell lecture*, ISC'4, Brazil, 2012.

Sawada S, Suetomi I, Fukushima Y, Goto H. Characteristics and distribution of strong ground motion during the 2004 Niigata-ken Chuetsu and 2007 Niigata-ken Chuetsu-oki Earthquake in Japan. *Proceedings of the 14th World Conference on Earthquake Engineering*, 2008.

Seed HB, Idriss IM. Simplified procedure for evaluating soil liquefaction potential. *Journal of the Soil Mechanics and Foundations Division* 1971; **97**(SM9): 1249-1273.

Sekiguchi T, Nakai S. Effects of local site conditions on liquefaction damage in Mihama Ward of Chiba City. *Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake*, March 1-4, 2012, Tokyo, Japan

Stewart JP, Douglas J, Javanbarg M, Bozorgnia Y, Abrahamson NA, Boore DM, Campbell KW, Delavaud E, Erdik M, Stafford PJ. Selection of ground motion prediction equations for the Global Earthquake Model. *Earthquake Spectra* 2015; **31**(1): 19-45.

Stringer ME, Beyzaei CZ, Cubrinovski M, Bray JD, Riemer M, Jacka M, and Wentz FJ. Dynamic properties of Christchurch silty soils: Gainsborough Reserve. *Proc. 6th Int. Conf. Earthquake Geotech. Eng.*, November 1-4, 2015, Christchurch, New Zealand.

Tokyo Metropolitan Government (TMG). 2011 observation results for ground settlement and ground water table at Tokyo port. Internal report for Tokyo Metropolitan Government, 2011.

Tonkin and Taylor. Liquefaction Vulnerability Study, *T&T Report: 52020.0200/v1.0*, prepared for the Earthquake Commission (EQC), 52p, 2013.

University of California, Berkeley and University of Canterbury. *Liquefaction triggering & consequence for low-plasticity silty soils: Conventional wisdom vs. the Canterbury experience*. Data reports prepared for the NZ Ministry of Business, Innovation & Employment, submitted to Tonkin and Taylor, 2015 (to be published).

Wald DJ, Worden BC, Quitoriano V, Pankow KL. *ShakeMap manual: technical manual, user's guide, and software guide*. U.S. Geological Survey, 132 p, 2005.

Yamazaki F, Motomura H, Hamada T. Damage assessment of expressway networks in Japan based on seismic monitoring. *Proceedings of 12th World Conference on Earthquake Engineering*, 2000.

Youd TL et al. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. *J. Geotech. & Geoenv. Eng.* 2001; **127**(10): 817-833.