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



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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. Work to date has focused on compiling high-value case histories, developing a database template, and planning for needed supporting studies. 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.

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1. 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 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 *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-ground failure could be identified. In the early stages of case history-based evaluation of liquefaction potential, the boundary between liquefaction cases and non-ground failure cases was drawn by hand in a generally conservative manner. More recently, Bayesian analysis procedures have been used to evaluate

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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. Research 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 general opacity of the model development process leads 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 activities thus far have 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 explain the NGL project vision, scope, organization, and status; describe data products, including illustration of what constitutes a case history; summarize data collection efforts that have been completed thus far; describe the role of supporting studies; and present anticipated products and next steps.

2. 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 2011 earthquakes 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. 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 [Section 1](#), 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 [\[1\]](#) 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 facilitate studies on key effects poorly constrained by the database, and to establish a collaborative framework for model development by distinct teams drawing upon common resources. Our vision is that the process of database development, supporting studies, 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 [\[2,3\]](#), which developed this research approach and enjoyed substantial global buy-in and broad application.

3. NGL data products

The NGL database will consist, at its core, of a GIS platform 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.

- *Depositional history.* This includes geology, age, depositional environment, occurrence of liquefaction from previous earthquakes, previous ground mitigation, and constriction records for man-made fill.
- *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. Information on shear wave velocity is also desirable.
- *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 literature review [4–6] and seven workshops held to date in California and Japan. The number of currently available case histories in recent liquefaction triggering models are 230 for borehole/standard penetration test-based site characterization [5], 268 for cone penetration test-based site characterization [7], and 422 for shear-wave velocity-based site characterization [8]. 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, 2008 Patras Greece, 2010 Maule Chile, 2010 El Mayor-Cucapah Mexico, 2010–2011 Canterbury New Zealand, 2011 Tohoku Japan, and 2012 Emilia Italy 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.

3.1. 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 Fig. 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.

3.1.1. 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 its geographic extent, a description of the lack of ground failure (as applicable), the date/time of the observation, and the precise location (with

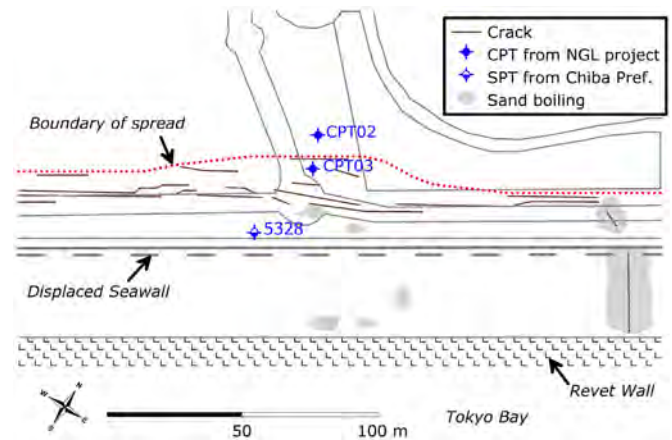


Fig. 1. Sea front in Urayasu city where lateral spread occurred by the 2011 Tohoku Earthquake.

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 depth that is not manifest at the ground surface.

In the case of the Urayasu site, the reconnaissance was performed by GEER [9] and includes information from all of the above-listed sources. Fig. 1 distills the essential observations for the purpose of identifying portions of the site with and without ground failure.

3.1.2. 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. Ideally, information on the horizontal distribution of these features is also provided; while this information may not always be available, notes on the likely geological heterogeneity made by the field engineer/geologist are useful.

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 index testing when samples are available. Information related to soil type that significantly increases 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 the potential for undrained strength normalization).

Penetration resistance testing from CPT is desirable due to the relative standardization of these procedures. In the case of

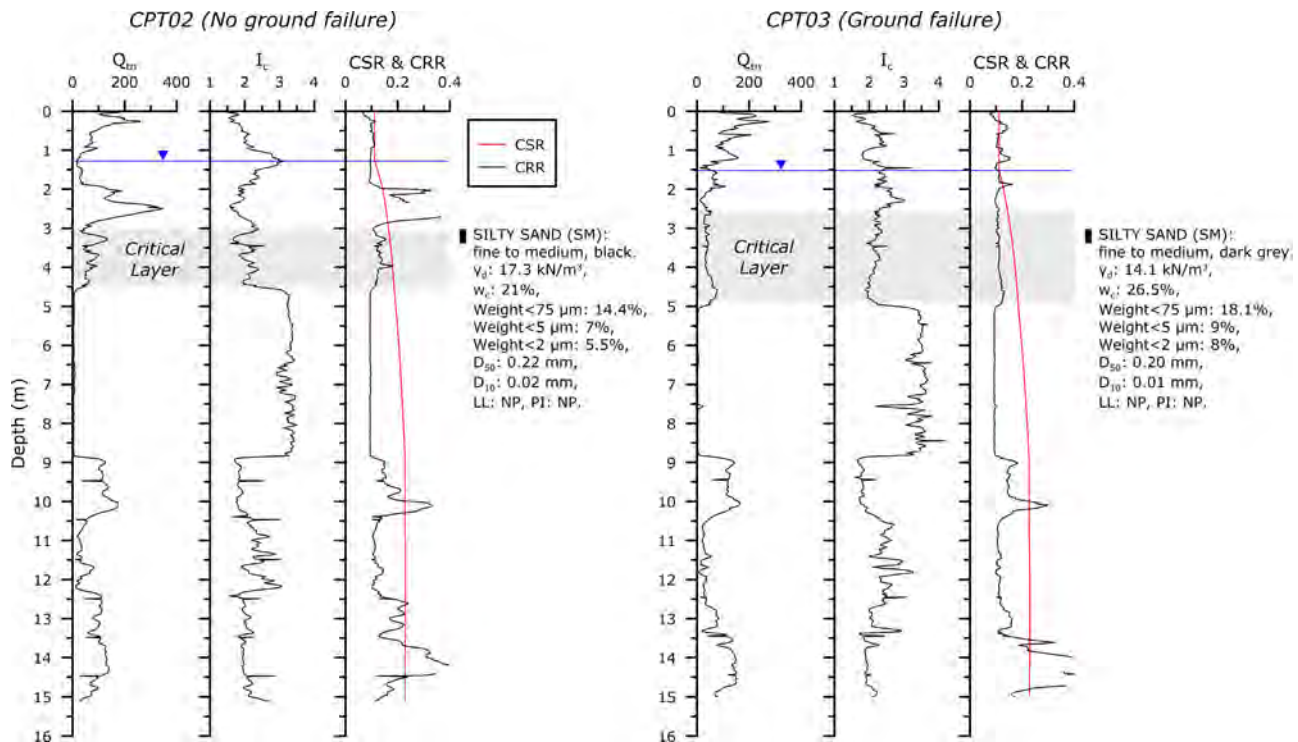


Fig. 2. Normalized CPT resistance (Q_m), soil behavior type index (I_c), cyclic stress ratio (CSR) and cyclic resistance ratio (CRR) profiles at the locations of no ground failure and ground failure at Urayasu Sea Front site. Laboratory index test results from the samples retrieved by a CPT sampler are indicated.

standard penetration testing, energy ratios associated with the hammer lift and drop mechanism should be reported. These energy ratios ideally are based on site- and equipment-specific energy measurements [10], but otherwise can be based on local experience or published values [11,12]. *In situ* seismic velocity testing will also be included with the geotechnical characterization where available.

At the example Urayasu site, Fig. 2 shows results of CPT soundings both in the ground failure/liquefaction zone and outside of the lateral spread. The ground water depth at this location is 1.3–1.5 m. The cone data in Fig. 2 has been processed and evaluated per recommendations provided in [13] as dimensionless and overburden-normalized penetration resistance (Q_m) and soil behavior type index (I_c). The site characterization in this case included CPT-based sampling in layers judged to be most critical for ground failure; results of index tests from these samples are shown in Fig. 2. The interpretation of this data for identification of the ‘critical layer’ is deferred to a subsequent section on the NGL flatfile.

3.1.3. Ground motion

For the NGL database, ground motion characterization generally pertains to the intensity of shaking at the ground surface and its uncertainty. 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 [14]) 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 [15]. 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 will be included in the database.

We propose the following procedures for estimating median PGA and its associated uncertainty, in order of preference:

1. When a ground motion recording instrument (accelerograph or seismograph) is located at the site of interest or in reasonable proximity, intensity measures from the recording are used, possibly with some correction for the effects of liquefaction on the record, depending on the time at which liquefaction occurred (details in [16]). The uncertainty in this case would be derived solely from uncertainty in the liquefaction correction. An acceptable distance to the accelerograph is admittedly subjective, and should be evaluated in consideration of geological heterogeneity. While this issue remains unresolved, it is likely that at separation distances > 50 – 200 m, ground motions would be developed using approaches (2) or (3) below.
2. When the earthquake event that produced the case history is included in ground motion databases used to derive ground motion prediction equations (GMPE), the natural log mean intensity measure at the site should be taken as the sum of the GMPE mean (using appropriate site parameters including V_{S30} and basin depths, or alternatively site terms derived from site-specific analysis), the event term associated with that earthquake and the GMPE, and a mapped within-event residual to correct for spatial variations in path and source effects not captured by the GMPE (this residual is mapped using the simple Kriging method, [17]). This approach, which is explained further in [18], takes into consideration available recordings of the earthquake, while accounting for differences in site conditions among recording sites. The natural log standard deviation applicable to this estimate is associated with the within-event residual term, and varies spatially. For locations near ground motion recording sites, the standard deviation is small; for sites

far from instruments, it approaches the within-event standard deviation (generally denoted ϕ_{ln}) from the GMPE. This approach is similar to procedures given previously [19–22], but has distinct features as described by Kwak et al. [18].

3. When recordings are available for the earthquake in question, but the event was not included in the GMPE database, the procedure from (2) can be applied but with the event term set to zero. In this case the mapped residuals will likely have a non-zero mean.
4. When recordings for the event are either not available or are very sparse, GMPE log mean predictions should be used. These estimates carry a larger degree of uncertainty than those from (1), (2), or (3).

For all three approaches, the GMPE should be appropriate for the tectonic regime that produced the earthquake event [23]. Ground motion estimates from approach (2) will converge to the recorded PGA as the separation distance between an accelerometer and the site approaches zero. For this reason, approaches (1) and (2) provide the same result for sites very near a ground motion recording instrument, aside from the liquefaction correction. 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 $PGA \approx 0.17$ g (using procedure 3 above) with an uncertainty of $\phi_{ln} = 0.28$ (natural log units). The uncertainty estimate is based on semi-variograms by [24], 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. This important aspect of the NGL project is described further in [16].

3.2. NGL flatfile

The NGL flatfile is envisioned as a synthesis of parameters used for model development. Parameters used in three recent liquefaction triggering models [5,7,8] 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 $M = 7.5$, and a parameter representing soil penetration resistance or seismic velocity. Parameter CSR^* is computed as (adapted from [12], 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 σ_v and σ'_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_σ is an overburden factor to correct the seismic resistance for decreased soil dilatancy as effective

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

Parameters	Boulanger et al. [5] (SPT)	Boulanger and Idriss [7] (CPT)	Kayen et al. [8] (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, γ			
Static shear stress on horizontal plane, τ_{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, σ_v	•	•	•
Effective vertical stress, σ'_v	•	•	•
Shear stress reduction factor, r_d	•	•	•
Earthquake-induced cyclic stress ratio, CSR	•	•	•
Overburden correction factor, K_σ	•	•	
Shear stress correction factor, K_α		•	
Magnitude scaling factor, C_M	•	•	•
CSR for $M = 7.5$, $\sigma'_{v0} = 1$ atm, 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, $(N_1)_{60cs}$	•		
Normalized shear wave velocity, V_{s1}			•
Equivalent clean-sand tip resistance, q_{c1Ncs}		•	
Equivalent clean-sand corrected blow count, $(N_1)_{60cs}$	•		

stress increases, K_{α} 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_{σ} , K_{α} , 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 Eq. (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.

To illustrate this process, we apply to the Urayasu case history site the r_d , K_{σ} , K_{α} , and C_M estimates from [7]. Fig. 2 identifies the depth range for the “critical layer.” This process of identifying the critical layer is itself 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 (non-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).

Fig. 3 shows where the results for the critical layers plot relative to the Boulanger and Idriss [7] probabilistic liquefaction triggering criteria and their data. The uncertainty around the plotted data points 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.

4. NGL data collection to date

As mentioned in Section 1, work to date in the NGL project has been directed in part towards developing high-value case histories. In this section, we provide an overview of data collection to date. 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.

4.1. Japan sites

The 2011 M 9.0 Tohoku earthquake produced a wealth of field observations of liquefaction and non-ground failure, including sites with measured ground deformations and measured foundation performance [9]. 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:

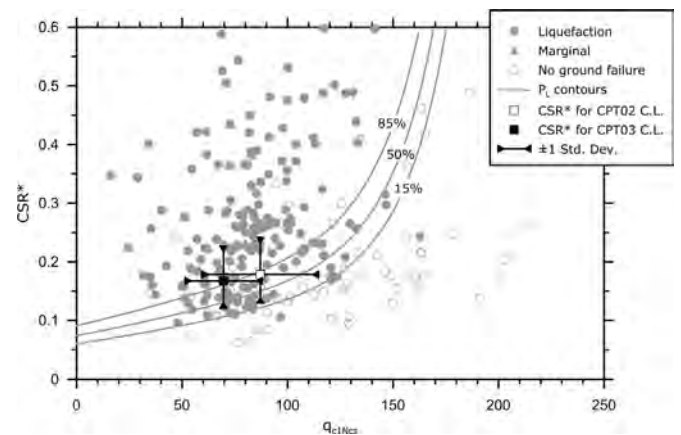


Fig. 3. Liquefaction triggering database showing CSR^* vs. q_{c1Ncs} and $CRR_{M7.5, \sigma' = 1atm}$ for 15, 50, and 85% probabilities of liquefaction [7]. Data points for critical layers and ± 1 standard deviations of CSR^* and q_{c1Ncs} are shown for no ground failure (CPT02) and ground failure (CPT03) locations at example site in Urayasu, Japan.

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. Liquefaction sites with ground motion recordings provide the opportunity to estimate conditions at the liquefaction triggering threshold, as described further in [16].
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.
5. Non-ground failure sites poorly explained by current methods for liquefaction susceptibility and triggering assessment.

Based on the above criteria, seven sites were investigated in the first phase of data collection (completed in April–July 2014) and four sites were investigated in the second phase (completed in September–October 2015) as shown in Fig. 4. One site was selected per the first criterion (lateral ground deformation), nine were selected per the second, fourth, and/or fifth criteria (all near accelerographs, including two vertical arrays), and one was selected per the third criterion (Mihama-ward). Table 3 lists the sites and attributes that led to their selection. Testing at the sites included CPT (including sampling), borings with sampling include SPTs with energy measurements, tube sampling for advanced laboratory tests (i.e., consolidation and undrained monotonic triaxial tests), and shear wave velocity measurements using surface wave methods.

4.1.1. Lateral spread at Urayasu City

The ground failure and non-ground failure example described in Section 3.1 (Figs. 1–3) is from the Urayasu lateral spread site.

Table 2

Parameters for liquefaction triggering analysis for non-ground failure (CPT02) and ground failure (CPT03) locations at example site. Derived parameters from [7].

	M	PGA (g)	Critical Interval (m)	Avg. Depth (m)	GWT Depth (m)	σ_v (kPa)	σ_v' (kPa)	r_d	CSR	K_{σ}	K_{α}	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_c (MPa)	f_r (%)	Q	n	F	I_c	C_N	q_{c1N}	Δq_{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



Fig. 4. Locations of ground failure or non-ground failure sites investigated in first phase of NGL characterization work in Japan (base map from Google Earth™).

Fig. 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 hydraulic fill on an average slope of about 3%. Although a free-face is located below the spread feature, it did not participate in the spread because a pile-supported quay wall stabilized the free-face.

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 Fig. 5. We performed four CPTs, one boring with SPT, and four SASWs 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 [25].

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.

4.1.2. Strong ground motion stations

Observations of liquefaction and non-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 are estimated. For this reason, GEER reconnaissance activities emphasized locations near accelerographs [9]. Resulting observations and preliminary analyses of these conditions are provided by [26] for 22 liquefaction sites and 16 non-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 [27] 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 [28], except that borehole depths are variable. Boring logs and *V_s* profiles are available for KiK-net vertical array sites that extend to considerably larger depths. As described by [26], there are several complications in the use of geotechnical data from these arrays, including lack of quantitative soil type information (from laboratory tests), unknown SPT energy levels, which are particularly variable at K-NET

Table 3
List of sites in Japan characterized to date from NGL project.

Location	Tests	Latitude	Longitude	Nearest Station	PGA (g) at N. S.	Site-to-exploration distance (km)	Ground failure observation
Urayasu, Chiba	CPT/SASW	35.63692	139.93215	HND/Keiyo Gas	0.174	0.61	Lateral spread
	SPT/CPT/SASW	35.63802	139.93352	HND/Keiyo Gas	0.174	0.54	
	CPT/SASW	35.63793	139.93356	HND/Keiyo Gas	0.174	0.54	
	CPT/SASW	35.64029	139.93828	HND/Keiyo Gas	0.174	0.73	
Choshi, Chiba	SPT/CPT/SASW	35.73536	140.82732	CHB005/K-NET	0.179	0.02	No ground failure
	SPT/CPT/SASW	35.60048	140.10209	Chiba-g/PARI	0.128	0.16	
Chuo, Chiba	SPT/CPT/SASW	35.60048	140.10209	Chiba-g/PARI	0.128	0.16	No ground failure
Inage, Chiba	CPT/SASW	35.63469	140.07777	CHB024/K-NET	0.237	0.07	Severe liquefaction
Sunamachi, Tokyo	CPT/SASW	35.66226	139.83430	TKY013/K-NET	0.144	0.06	No ground failure
Tatsumi, Tokyo	CPT/SASW	35.64967	139.80849	TKY017/K-NET	0.223	0.27	Moderate liquefaction
Shinariake, Tokyo	CPT/SASW	35.62293	139.79100	Shinariake/TMG	0.122	0.12	No ground failure
Tsuchiura, Ibaraki	SPT/CPT	36.07283	140.19481	IBR014/K-NET	0.506	0.01	Minor liquefaction
Sendai, Miyagi	SPT/CPT	38.26597	140.92858	MYG013/K-NET	1.547	0.01	Moderate liquefaction
Ishinomaki, Miyagi	CPT			MYG010/K-NET		0.01	Moderate liquefaction
Mihama-ward, Chiba	Adv. lab tests/SASW	35.63096	140.05287	CHB024/K-NET	0.237	2.283	No ground failure to severe liquefaction



Fig. 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.

and PARI sites [29], and limited spatial resolution of velocity data. Our site characterization was motivated in large part by a need to fill these data gaps. As shown in Table 3, we investigated seven K-NET sites, one PARI site, and one site maintained by the Tokyo Metropolitan Government site (Shinariake).

Among the eight 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 [16]. Site TKY017 had moderate liquefaction and was investigated for similar reasons. Site IBR014 had minor liquefaction, apparently involving a deep liquefiable layer (~20 m). Two sites investigated in the Sendai area experienced high-amplitude shaking; MYG013 experienced PGA > 1.0 g and had moderate liquefaction involving a medium dense sandy and silty gravel layer, while MYG010 experienced PGA > 0.4 g and had moderate liquefaction on a medium to dense sand layer.

We performed CPTs for each investigated site, and SPTs for CHB005, Chiba-g, IBR014, and MYG013. 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 [10]; comparison of these results to those for adjacent K-NET and PARI logs suggest SPT efficiencies from that prior work that are both larger and smaller than the U. S. standard of 60%. This suggests a lack of uniformity in field testing procedures and/or equipment. 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 [30]. 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 indicated in Table 3 as site-to-exploration distance, there are cases in which borings and CPTs were not co-located with accelerographs. This resulted from inabilities to secure necessary site access for field work in some cases.

4.1.3. 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 [31]. As shown in Fig. 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

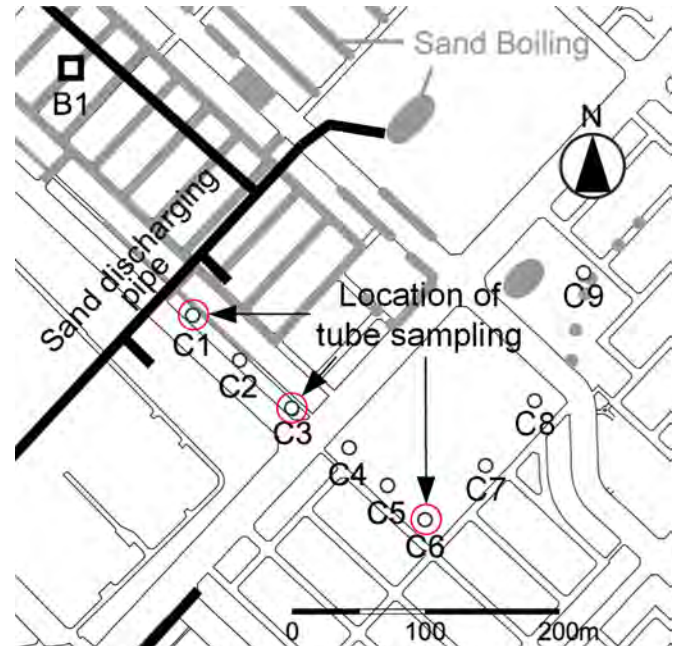


Fig. 6. Mihama-ward site showing CPT locations, sand discharging pipe, and sand boiling traces [31].

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 [31], 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.”

There is a general correlation between field performance and discharge pipe locations – with liquefaction being most concentrated near discharge pipes and intermediate areas having non-ground failure. Our work in this region had 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 nine CPTs shown in Fig. 6). NGL has contributed to this effort by targeted sampling of soils from presumed critical layers in liquefaction, marginal, and non-ground failure areas. Results of this testing are being compared to traditional susceptibility criteria [32,33] and inferences of soil behavior derived from more advanced

testing (consolidation, triaxial undrained monotonic and cyclic shear).

4.2. New Zealand sites

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 22,000 CPT soundings and over 4500 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 focuses 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 Fig. 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 CES and cover a broad spectrum of liquefaction effects, ranging from no observation to severe damage.

The New Zealand sites to be included in the NGL database are summarized in the following sections. Each project was led by researchers and engineers who participated in the post-earthquake reconnaissance, bringing first-hand observations and expert knowledge to the case history analysis. The case histories included in these projects were selected for being comprehensive, vetted investigations with high-quality detailed data out of the quantity available in the Canterbury Geotechnical Database.

Table 4
New Zealand sites for NGL database.

Project name	No. of sites	CPT	Sonic boring	Undisturbed sampling
SM [34,35,41]	8	•	•	•
CBD [36–38,42]	8	•		•
T&T [39]	12	•	•	
VT-UC [40]	25	•		

4.2.1. NSF-PEER-MBIE-EQC liquefaction triggering and consequence for low-plasticity silty soils

The silty soils project will contribute eight sites to the NGL database. Each site has a minimum of one CPT sounding, a sonic boring with disturbed bulk samples, a mud rotary cased boring with undisturbed sampling, and crosshole seismic testing. 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. [34] and Stringer et al. [35] 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 with NGL support.

4.2.2. NSF-EQC CBD project

The Central Business District (CBD) of Christchurch project will contribute eight sites to the NGL database. Each site has at least one CPT sounding and at least one mud rotary cased boring with undisturbed sampling. Cyclic triaxial laboratory testing data, Atterberg limits, and particle size analysis are available in addition to the field work. 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. An additional three sites from the CBD project are also being considered for incorporation in the NGL database, to cover instances of non-liquefaction within the CBD. Several studies [36–38] developed the data for this work.

4.2.3. Tonkin+Taylor liquefaction vulnerability study

The T&T study will contribute twelve sites to the NGL database. Each site has one CPT sounding and one nearby soil boring with sampling. Fines content data are available for the soil borings. Sites were selected by Tonkin & Taylor to evaluate differences between CPT-based and SPT-based liquefaction triggering procedures, quantifying vulnerability to liquefaction-related damage beyond typical settlement estimates [39].

4.2.4. Virginia Tech and Univ. of Canterbury and others liquefaction triggering study

The VT-UC study will contribute twenty-five sites to the NGL database. Each site has one CPT sounding and SASW/MASW testing, as described in [40]. With the goal of investigating sites that exhibited differing liquefaction behavior during the Darfield and Christchurch earthquakes, 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.



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

5. Role of supporting studies

We envision the NGL liquefaction susceptibility, 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, effects of fines content and plasticity on penetration resistance, 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 modeled, 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,

Table 5

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

Topic	Issues	Example references
Liquefaction at depth	<ul style="list-style-type: none"> Empirical data constrains models for depths, $z < \sim 12$ m Large epistemic uncertainty in r_d models for $z > \sim 3$ m. Effects of profile, ground motion, and soil nonlinearity poorly understood. Large epistemic uncertainty in K_σ models Modest epistemic uncertainty in factors for penetration resistance normalization, C_N 	r_d : [11,12,43,44] K_σ : [12,45] C_N : [11,13,45,46]
Effects of fines	<ul style="list-style-type: none"> 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) 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: [47] Effects on liquefaction strength: [48] <i>Approximate combined effects</i> : all recent triggering models
Ageing effects	<ul style="list-style-type: none"> Empirical data is mostly from artificial fills and young (Holocene) sediments For a constant relative density, older materials have higher penetration resistance and higher liquefaction resistance The increase of liquefaction resistance is greater than predicted by the increased penetration resistance, so additional corrections needed. 	[49–52]
Effects of static shear stress	<ul style="list-style-type: none"> Effects of normalized static shear stress, α, not included in most current models. One published model for effect of α on liquefaction resistance, but lack of community consensus 	[53]

structure settlement, post-liquefaction shear strength, and lateral spreading.

6. 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 flatfiles, 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-ground failure. 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).

NGL at present is 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 and plan. We anticipate future growth in the project scope and activity.

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