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Next Generation Liquefaction Susceptibility Database and Modeling

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ABSTRACT

This paper presents a roadmap for the NGL liquefaction susceptibility project which aims to develop probabilistic liquefaction susceptibility models. The project has been divided into three tasks as: i) populating the NGL database with cyclic undrained laboratory test data that serve the needs of this project, ii) developing a predictive model of analyst assignments of material behavior characteristics (e.g., sand- and clay-like) using cyclic test metrics to assess the cyclic test results consistently and objectively, and iii) developing probabilistic liquefaction susceptibility models that predict probabilities of material behavior characteristics conditioned on readily measured soil properties such as index test results or CPT soil behavior type indices. The database assembled for this work consists of 406 cyclic direct simple shear and 153 cyclic triaxial test results. The analyst responses referenced in Task ii were expressed in the form of beta distributions defined by the mean and uncertainty of the material type characterization (on a 0 to 1.0 scale, with 0 and 1 representing clay-like and sand-like, respectively). The final task is ongoing and is planned to be completed by the time of the conference and will provide one or more probabilistic liquefaction susceptibility models. The model developed in the second task allows prediction of soil behavior type characteristics.

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Introduction

The Next Generation Liquefaction (NGL) susceptibility project aims to develop probabilistic liquefaction susceptibility models, which are needed as the first step in assessments of seismic ground failure. The research has been separated into three tasks: i) populating NGL database with cyclic undrained laboratory test data that serve the needs of liquefaction susceptibility assessment, ii) quantifying cyclic test metrics from cyclic test results and developing a predictive model of expert assignments of material behavior characteristics (e.g., sand- and clay-like) using these metrics, iii) developing probabilistic liquefaction susceptibility models that predict probabilities of material behavior characteristics conditional on readily measured soil properties such as index test results or CPT soil behavior type indices.

The first task involved populating the NGL database with undrained cyclic direct simple shear (CDSS) and triaxial (CTX) test results on intact samples with nearby cone penetration test (CPT) data. Cyclic test results on reconstituted samples were also collected, which cannot be related to CPT results but can provide insights into material-based trends and the effects of different cyclic stress paths. The aim was to collect high-quality cyclic laboratory test results with available field measurements so that susceptibility trends observed in laboratory tests could be mapped to both CPT metrics and index tests. Currently, the NGL database hosts cyclic undrained test results from 406 CDSS and 153 CTX specimens (details will be documented in a pending PEER report). The raw test results are accessible through the NGL web platform ([1], nextgenerationliquefaction.org), which is updated regularly with new data and provides a lab test viewer tool to enable visualization and downloads of the raw test data.

The second task focuses on analyzing hysteretic behavior observed during cyclic tests including the stress-strain response, pore pressure generation, rate of strain accumulation, and stress paths. In this project, soil behavior type is defined as a distribution ranging from 0 to 100% rather than the “susceptible”, “not-susceptible”, or “intermediate” classifications used previously ([2-3]). In order to have a consistent and objective assessment, quantitative cyclic test metrics are proposed to capture attributes of cyclic behavior. Separate models were developed between cyclic test metrics and expert analyst assignments for CDSS and CTX results.

The final task relates liquefaction susceptibility probabilities (i.e., probabilities of different soil behavior types) to commonly available soil properties such as plasticity index *PI* (obtained from laboratory tests) and soil behavior type indices derived from CPT soundings. By so doing, the susceptibility model will adhere to the NGL definition of susceptibility as being governed solely by inherent material characteristics, independent of soil state and loading conditions.

NGL Database

The NGL database is perhaps the most fundamental element of the NGL project. The database was created as a relational database structured with a series of interconnected tables. By using key connections between tables, data from interrelated entries can be queried using structured query language JOIN statements. The data is publicly available for any application and modeling efforts.

Prior to the present work, the database consisted of 45 CDSS and 38 CTX cyclic undrained test results [4-6]. Within the scope of this project, 361 CDSS and 115 CTX cyclic undrained test results [7-20] were added to the NGL database. Data was collected in three tranches: (1) tests conducted on intact specimens of transitional soils for research purposes, (2) tests conducted on intact specimens of transitional silts for engineering project applications, and (3) tests conducted on reconstituted sand and transitional silt specimens. Histograms presenting Atterberg limits and water contents of the test specimens are presented in Figure 1.

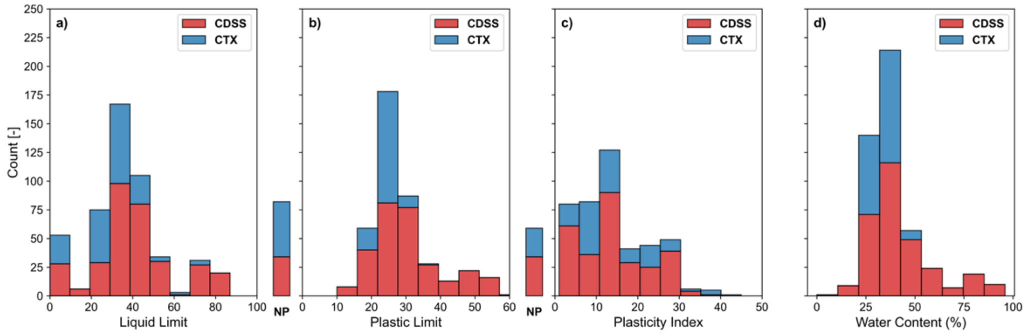

Figure 1. Histogram of a) liquid limit, b) plastic limit, c) plasticity index, and d) water content for all the cyclic test specimens in NGL database

Analyst Assignments

To interpret the cyclic behavior type from laboratory test results, an online form (Figure 2) was created to facilitate analyst test interpretations of a representative subset of 64 CDSS tests. The form uses a slider to record the cyclic behavior type (*CBT)* ranging from 0 to 1 based on their assessment of soil behavior type (e.g., shear stress vs. shear strain hysteresis loops, pore pressure ratio, r_u vs. number of loading cycles, indications of phase transformation in shear stress vs. vertical effective stress loops). *CBTs* near 1 suggest sand-like behavior, whereas *CBT*s near 0 suggest clay-like behavior. In addition to assigning a best-estimate *CBT* rating to each specimen, the analysts indicated their confidence in each rating by assigning a standard deviation to each assigned rating value. The corresponding mean (μ) and standard deviation (σ) is used to represent *CBT* as a beta distribution. The assignments were provided from nine analysts, who are the authors of this manuscript.

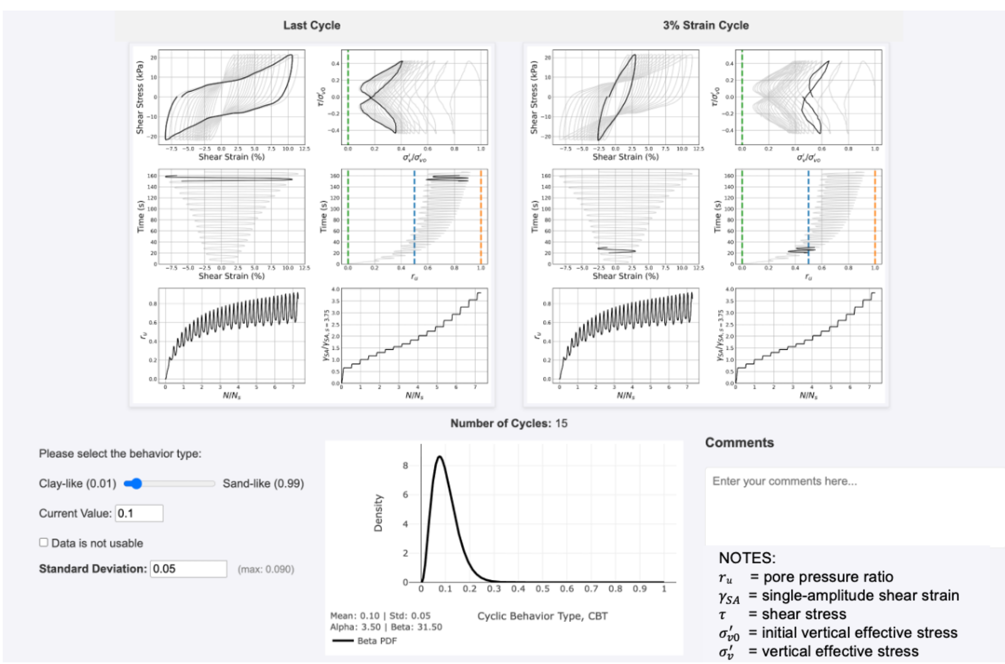

Figure 2. Example of the web-based form used to assess cyclic behavior rating. Data source: OSU-PDX Airport Blast Site (Site D).

Distinctive Cyclic Test Metrics

During the assignment process, each analyst considered multiple specific cyclic behavior characteristics. The cyclic test metrics used herein, as proposed by [9] and discussed in [21] with updates and improvements, are intended to quantitatively describe cyclic behavior (e.g., clay-like vs sand-like). To avoid using metrics with strong correlations with other metrics, a reduced set of five metrics are used including: *i*) maximum pore pressure ratio, $r_{u,max}$; *ii*) dilative modulus, $G_{dilative}$, which is the shear modulus just prior to stress reversal, normalized by double amplitude cyclic shear stress (τ_{DA}); *iii*) the tangent shear modulus corresponding to the average strain in a given hysteresis loop normalized by the dilative shear modulus, $\frac{G_{tan,mid-loop\ strain}}{G_{dilative}}$; *iv*) the difference in cyclic shear stress ($\Delta\tau_{cyc}$) corresponding to the average strain normalized by double amplitude cyclic shear stress; and *v*) curvature in the shear strain accumulation with number of normalized loading cycles, determined using three-point curvature assessments [22]. The metrics are dimensionless. Figure 3 illustrates cyclic test metrics other than $r_{u,max}$.

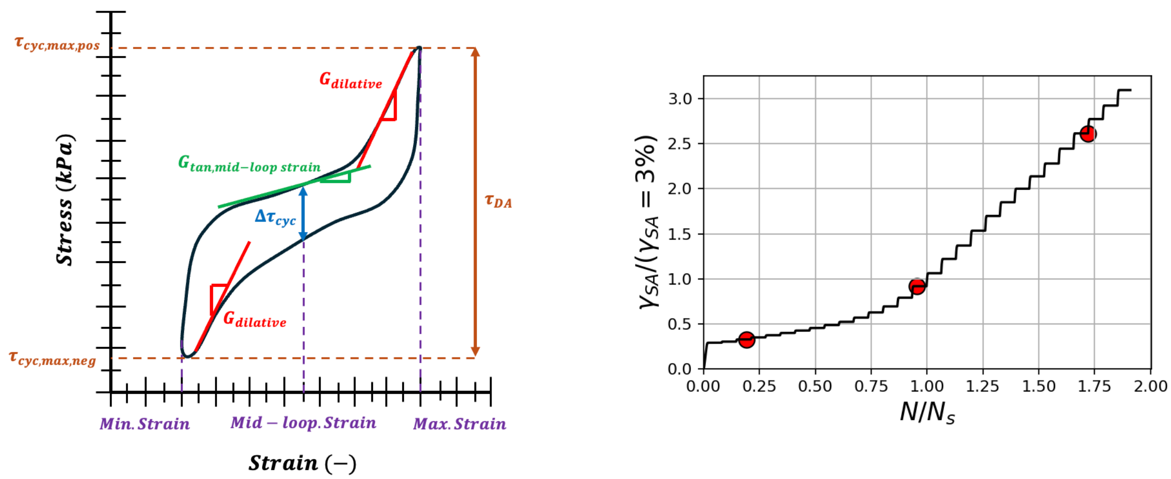

Figure 3. Schematic of the hysteresis metrics on a) strain vs. stress plot, b) number of cycles vs. strain

Conclusions

The first step in assessments of seismic ground failure is to determine the susceptibility of the soil under cyclic loading. A three-task roadmap is presented within this manuscript including: i) populating the NGL database with cyclic undrained laboratory test data that serve the needs of this project, ii) development of a model between expert assignments of material behavior characteristics and cyclic test metrics and iii) developing liquefaction susceptibility models that predict probabilities of material behavior characteristics conditional on readily measured soil properties such as index test results or CPT soil behavior type indices. At the time of the submission of this manuscript, the first two tasks have been completed and efforts for the final task are ongoing which is planned to be completed by the time of the conference. The eventual proposed model will be probabilistic, in contrast to previous models that were deterministic but with intermediate ranges where predictions are ambiguous (e.g., [2-3]). The probabilistic model will incorporate uncertainty in liquefaction susceptibility related to the spread in the data, between-sample variability for a given analyst, and epistemic uncertainty between analysts. Because the probabilistic model directly reflects data variability and epistemic uncertainty, it will be different from prior probabilistic models (e.g., [23-24]) that were derived to capture the range of outcomes from deterministic models.

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