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Abstract. Soil liquefaction and resulting ground failure due to earthquakes presents a significant hazard to distributed infrastructure systems and structures around the world. Currently there is no consensus in liquefaction susceptibility or triggering models. The disagreements between models is a result of incomplete datasets and parameter spaces for model development. The Next Generation Liquefaction (NGL) Project was created to provide a database for advancing liquefaction research and to develop models for the prediction of liquefaction and its effects, derived in part from that database in a transparent and peer-reviewed manner, that provide end users with a consensus approach to assess liquefaction potential within a probabilistic framework. An online relational database was created for organizing and storing case histories which is available at http://nextgenerationliquefaction.org/ (https://www.doi.org/10.21222/C2J040, [1]). The NGL field case history database was recently expanded to include the results of laboratory testing programs because such results can inform aspects of liquefaction models that are poorly constrained by case histories alone. Data are organized by a schema describing tables, fields, and relationships among the tables. The types of information available in the database are test-specific and include processed-data quantities such as stress and strain rather than raw data such as load and displacement. The database is replicated in DesignSafe-CI [2] where users can write queries in Python scripts within Jupyter notebooks to interact with the data.

Keywords: Liquefaction, Database, Laboratory.

1 Introduction

Quantifying liquefaction susceptibility, triggering, and effects requires datasets that span a wide parameter space, and a modeling framework that is founded in first principles known to control soil response to undrained shear. The combination of a physically meaningful modeling framework and a significantly large data set is required to develop robust semi-empirical models regressed from the data. To date, the emphasis of the Next Generation Liquefaction (NGL) project has been on field case histories of liquefaction and its effects, as well as no-ground failure cases ([1]; [3]). A major goal of NGL is to support this model building process by providing objective data to modeling teams, along with results of additional supporting studies to constrain effects that cannot be established solely from data.

While the NGL database will support model development over a certain parameter space, it is not currently adequate to constrain models over the parameter space required for application. As one example, liquefaction models need to be applicable over a wide range of vertical effective stresses (also known as K_σ affects), ranging from effectively zero up to perhaps 6 atm. The available case histories involve relatively shallow soils, and hence do not include high-overburden pressure cases. Extending models across broad parameters spaces requires additional information, which can often be provided by laboratory studies of soil behavior. As a result, the NGL database schema of Brandenberg et al. [3] was expanded to allow for this information; this manuscript describes this work.

2 Laboratory Database Schema

2.1 Database Structure

A thorough description of the field case history portion of the NGL database structure can be found in Brandenberg et al. [1]. The laboratory component is built into the NGL relational database framework and is a structured database that can be queried using structured query language (SQL). A relational database comprises tables linked to one another by means of identifiers called keys. Each table has a primary key that uniquely identifies table entries. If two tables are linked, the primary key of a table is used as a foreign key in another table. Primary-foreign key relationships produce the organized hierarchical structure of a database. Such organizational structure is called schema. The NGL laboratory component was developed in consultation with the NGL database working group (S.J. Brandenberg, K.O. Cetin, R.E.S. Moss, K.W. Franke, K. Ulmer, and P. Zimmaro). The schema presented here is mostly complete, but population of the database is ongoing and should continue indefinitely as more testing is performed and researchers share data. The schema may have fields and/or tables added in the future if there is sufficient interest in additional types of datasets.

Twenty-four tables were added to the NGL database for the laboratory component with a laboratory table (LAB) at the top of the hierarchy. The field case history component is joined to the sample table via the sample-test table allowing samples to be associated with a test (under the field case history schema) or not (under the laboratory component schema). The hierarchy of the laboratory component schema is shown in Fig. 1. Table 1 contains descriptions for each database table. There are 140 fields contained within the tables defined in Table 1 and shown in Fig. 1.

The table names in Table 1 below also correspond to the primary keys of those tables (for example, table SPEC has a primary key SPEC_ID). SPEC_ID is used as a foreign key in the following tables: TXG, DSSG, PLAS, RDEN, OTHR, INDX, GRAG, and CONG. The TXG table primary key, TXG_ID is used as a foreign key in the TXS table, which has a primary key TXS_ID that is used as a foreign key in the TXD table. Similarly, the DSSG table primary key, DSSG_ID, is used as the foreign key in DSSS which has a primary key DSSS_ID that is used as a foreign key in DSSD1D and DSSD2D. The FILE table with a primary key FILE_ID is used as a foreign key in the OTHR table, which therefore has two foreign keys, SPEC_ID and FILE_ID. GRAG_ID is used as a foreign key in the GRAT table. CONG_ID is used as a foreign key in the CON_STGE table which has its primary key (CON_STGE_ID) used in the COND table.

To illustrate database functionality, consider the following example data entry for a triaxial cyclic shear test:

- First, the laboratory where the testing was performed needs to be created as an entry in the LAB table where information such as the lab name, location in latitude and longitude coordinates, and any description of the laboratory are entered. The specific testing program that the triaxial test was performed within also needs to have an entry created in the LAB_PROGRAM table and associated with the LAB entry using the LAB_ID foreign key in the LAB_PROGRAM table. Any personnel who worked on the testing program and are to be associated with the testing program can be linked to it through the LAB_PROGRAM_USER junction table.
- The sample used in the testing is assigned an identifier (SAMP_ID) and its name (SAMP_NAME), sample type (SAMP_TYPE), depth to the top and base of the sample within a boring if associated with a boring (SAMP_TOP, SAMP_BASE) these would be left blank if the material was a synthetic mixture created in the lab), the diameter of the sample (SAMP_SDIA), the date the sample was obtained (SAMP_DATE), the recovery rate for the sample (SAMP_REC), description of the sample (SAMP_DESC), and any remarks (SAMP_REM) are entered. This sample entry can be associated with the testing program via the LAB_PROGRAM_SAMP table and associated with a field test if it was not synthesized in the lab via the SAMP_TEST table.
- A specimen obtained from the sample (associated via the SAMP_ID foreign key) is assigned an ID (SPEC_ID), name (SPEC_NAME), and other metadata such as (1) the depth to the top and bottom of the specimen (SPEC_TOP, SPEC_BASE) if the specimen is from a boring (these would be left blank if the material was a synthetic mixture created in the lab), (2) name of the person or organization who did the testing (SPEC_CREW), and (3) other remarks about the specimen (SPEC_REM).
- Results of index testing, relative density measurements, grain size distribution analysis, or other testing are provided in tables INDX, RDEN, GRAG/GRAT, PLAS, and OTHR, respectively. That data is connected via the SPEC_ID foreign key to the SPEC table. If consolidation tests were performed separate from triaxial or direct shear tests, then metadata from each stage of the consolidation tests such as final effective vertical stress and final height of the specimen (CONG_STGE_SIGV and CONG_HI, respectively) is entered into the CONG and CON_STGE tables and the consolidation data – time and displacement – are entered into the COND table. The

COND table is linked via CON_STGE_ID as the foreign key which is linked to the CONG table using the CONG_ID foreign key.

- Triaxial data is entered by first entering the general metadata for the triaxial test (TXG table) such as initial void ratio, water content, specimen diameter, initial height, and any descriptive information (TXG_E0, TXG_W0, TXG_DIAM, TXG_H0, and TXG_DESC, respectively). The triaxial test stage table (TXS) contains a foreign key to the TXG table and also contains fields for the stage number, type of stage (i.e. consolidation, monotonic loading, or cyclic loading), drainage (i.e. drained, undrained, or neither), and a description of the stage (TXS_ST, TXS_TY, TXS_DR, and TXS_DESC, respectively). The triaxial test data (TXD) table has a foreign key connecting it to the TXS table (TXS_ID) and has fields for time, deviator stress, cell pressure, pore pressure, axial strain, radial strain, and volumetric strain vectors (TXD_TIME, TXD_SD, TXD_CP, TXD_PP, TXD_EA, TXD_ER, TXD_EV, respectively).

Direct simple shear tests are entered similarly to triaxial tests, however there is an option for entering data for 1- or 2-directional loading.

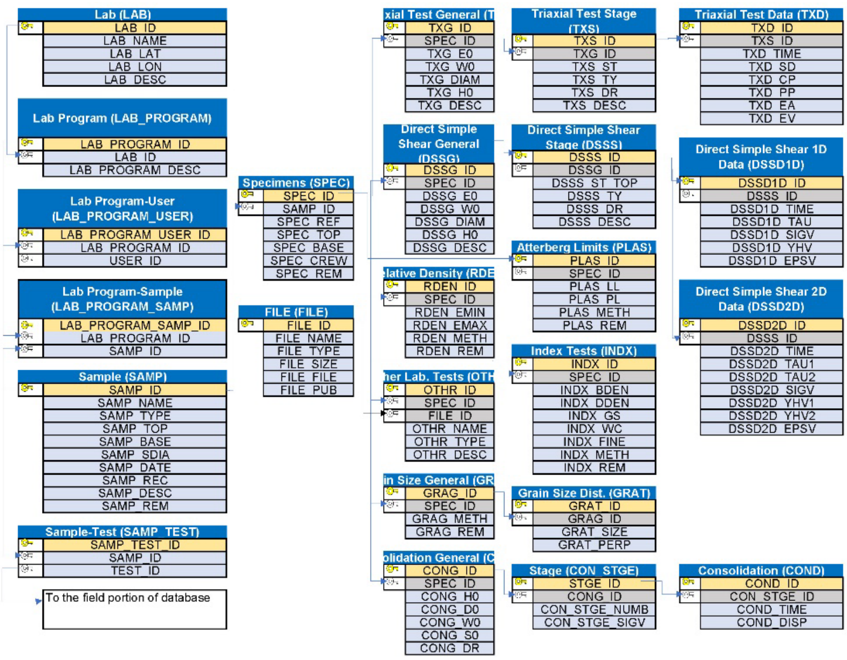

Fig. 1. Laboratory Component Relational Database Schema Showing Relationships Between Tables Using Keys.

Table 1. List of tables in the laboratory component of the NGL database.

Table Name	Table Description	Number of Fields
LAB	Laboratory information	5
LAB_PROGRAM	Testing Program information	3
LAB_PROGRAM_USER	Junction table between testing program and users	3
LAB_PROGRAM_SAMP	Junction table between testing program and sample	3
SAMP	General information for laboratory or field samples	10
SAMP_TEST	Junction table between sample and specimen	3
SPEC	General information for laboratory specimens taken from samples	7
INDX	Index tests include: dry and bulk density (ASTM D7263-09), water (moisture) content (ASTM D2216-10), and fines content (ASTM D21140-17). Standards recommended for each test are in parentheses.	9
RDEN	Relative density measurement	6
PLAS	Plasticity test (i.e., Liquid limit and plasticity limit) information (ASTM D4318-10e1)	6
GRAG	General information for particle size distribution analysis	4
GRAT	Test results (percent passing for a specific sieve) from particle size distribution analysis	4
OTHR	Other tests not specified above. Any format of test results can be uploaded.	6
FILE	Table storing supplemental files	5
DSSG	Direct simple shear test general information	7
DSSS	Information about each direct simple shear test stage	6
DSSD1D	One-dimensional direct simple shear test data	7
DSSD2D	Two-dimensional direct simple shear test data	9
TXG	Triaxial test general information	7
TXS	General information for triaxial test stages	6
TXD	Triaxial test data	8
CONG	Consolidation test general information	7
CON_STGE	Consolidation test stage information	5
COND	Consolidation test data	4

2.2 Data Querying and Visualization

Currently the laboratory component of the NGL database cannot be accessed in the same manner as the field case history component via the interactive website (https://nextgenerationliquefaction.org; https://www.doi.org/10.21222/C2J040) because there has not been adequate time or budget to add that capability. However, the database is replicated daily to DesignSafe [2], where it can be queried by any user using Python scripts in Jupyter notebooks. A Jupyter notebook is a server-client application that allows editing and running notebook documents in a web browser and combines rich text elements and computer code executed by a Python kernel [4]. Jupyter notebooks are published and available on DesignSafe in the NGL project partner data apps (Brandenberg et al. [2] and references therein).

Users can create their own custom Jupyter notebooks to query and visualize data from the NGL database for use in model development. The published notebooks are a good starting place to base new custom notebooks on and to learn how to write SQL queries in Python.

Fig. 2 illustrates the use of a Jupyter notebook for visualizing direct simple shear test data. The user can select a laboratory from the first dropdown menu and the tool populates the Program dropdown menu with all the testing programs at that particular lab. Based on the selection from the Program dropdown, the Sample dropdown is populated with all samples within that testing program. The user can then select a specimen from the Specimen dropdown menu and the tool populates the DSSG_ID dropdown menu with the direct simple shear general table IDs that are performed on that specimen (from the DSSG table). Based on the selection from that dropdown, the tool populates the DSSS_ID dropdown with the stages for that particular test. The tool plots the data from the selected stage in nine separate plots to help visualize it. Fig. 2 shows some subplots from the tool for a cyclic simple shear test performed at Oregon State University (OSU).

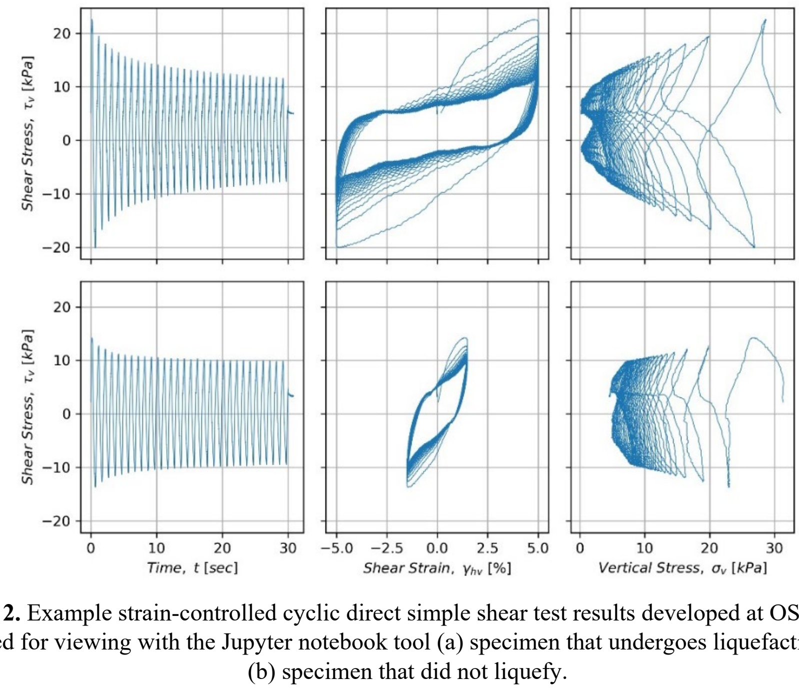

Fig. 2. Example strain-controlled cyclic direct simple shear test results developed at OSU and plotted for viewing with the Jupyter notebook tool (a) specimen that undergoes liquefaction and (b) specimen that did not liquefy.

3 Status of Database

As of this writing, the NGL database has 347 sites, 147 of which have been fully reviewed (meaning independently reviewed by two database working group members) and 135 have been partially review (reviewed once). The database includes 843 cone penetration tests (CPTs), 696 borehole tests with 7559 standard penetration test (SPT) measurements, 125 invasive shear wave velocity measurements (such as downhole), and 30 surface wave method tests (such as spectral analysis of surface waves (SASW)). Table 2 shows the labs testing programs currently in the database. The counts for laboratory tests are shown in Table 3. There are 6 laboratories and 8 laboratory testing programs. Tests other than direct simple shear, triaxial, and consolidation may be entered into the field database without specifying a laboratory, which is why the number of laboratories and test programs is low relative to the number of tests.

4 Application of NGL Laboratory Database

There are many potential problem-solving capacities within NGL such as the issues with adjustment factors (drainage effects (K_d), partial saturation, path correction (K_P), 2-dimensional loading (K_{2D}), initial effective stress (K_σ), initial static shear stress (K_α)), and the difficulty with liquefaction susceptibility criteria. The NGL database is also uniquely suited to addressing the issues with fine-grained soil susceptibility.

Table 1. Lab testing programs currently in the NGL database.

ID	Lab Program Description
1	Testing of samples from sites associated with the Canterbury Earthquake Sequence [5]
2	Cyclic and monotonic direct simple shear on Orange Co. Silica Sand [6]
3	Testing on samples from Mihama Ward associated with 2011 Tohoku earthquake [7]
4	Lab testing associated with [8] and [9] "https://doi.org/10.1016/j.soildyn.2018.09.012" & "http://dx.doi.org/10.1016/j.dib.2018.08.043"
5	Lab testing associated with Graded area east of New River at SW edge of Brawley
6	Lab testing associated with 1979-1981 with CPT retesting in 2003 [10]
7	Cyclic testing on clay-silt blends [6]
8	Testing of remolded samples from Mihama Ward

Table 2. Counts of laboratory tests within the NGL database.

Tests	Total
Index (specific gravity, water content, and/or percent passing number 200 sieve)	3847
Relative Density	77
Plasticity (Atterberg limits)	1385
Gradation	4495
Direct Simple Shear	53
Triaxial	63
Consolidation	4

4.1 Contributions Addressing Transitional Silt Soils

Ongoing research on the seismic response and liquefaction susceptibility of transitional silts conducted at OSU has led to the development of a significant laboratory dataset currently being added to the NGL database. Targeted sites have been investigated using mud-rotary drilling with thin-walled tube sampling, downhole shear wave velocity tests, and cone penetration tests. Laboratory investigation consists of soil characterization (e.g., Atterberg limits, gradation), quantification of stress history, and evaluation of monotonic and cyclic strength of natural, intact specimens. At present, six distinct study sites have been developed. The dataset consists of tens of constant-rate-of-strain consolidation and constant-volume, mono-tonic direct simple shear (DSS) tests on soils from each site, with the goal of establishing SHANSEP parameters suitable for the low and moderate plasticity silts. The dataset also includes over 150 stress-controlled and tens of strain-controlled, constant-volume cyclic DSS tests most of which are accompanied with post-cyclic reconsolidation of monotonic shearing phases. Representative oedometric compression specimens were used to judge sample quality using compressions ratios (e.g.,[11]) and provided the basis for selecting recompression consolidation techniques for DSS test specimens in view of the generally high quality of the samples. With fines contents and plasticity indices ranging from 25 to 100% and 0 to 38, this dataset will serve to refine thresholds in the transition between sand-like and intermediate, and intermediate and clay-like behavior. Portions of the OSU dataset have been and are continuing to be uploaded as sponsored projects progress towards closure.

4.2 Stress effects (K_σ and K_α) work

In cyclic stress-based liquefaction triggering evaluations (e.g. [12]), the overburden stress correction factor (K_σ) is used to modify the cyclic resistance ratio of the soil (*CRR*) for confining stresses (σ'_c) other than one atmosphere (atm), and the initial shear stress correction factor (K_α) is used to modify the *CRR* for when the initial static shear stress (τ_s) is not equal to zero. One approach to account for these effects de-pends on laboratory test data from tests such as cyclic triaxial, cyclic direct simple shear, or cyclic torsional shear. Tests are performed to develop relationships between cyclic stress ratio

(*CSR*) and the number of cycles to liquefaction (*N*) for a given soil and similar relative density (D_r), σ'_c, and τ_s. Typically, this is done first using a base-line condition, such as σ'_c = 1 atm and τ_s = 0. *CRR* can then be computed from the *CSR*-*N* curve assuming a value of *N* associated with a given magnitude event. To compute K_σ or K_α, the same soil is tested using the same set of conditions but changing either σ'_c or τ_s. The ratio of the *CRR* of the second test to the *CRR* of the baseline test is the K_σ or K_α correction factor. Results from laboratory tests have shown that an increase in σ'_c leads to a reduced *CRR*, and the presence of a non-zero τ_s can either increase or decrease the *CRR* depending on the state of the soil.

As part of the NGL project, an ongoing study is investigating the effects of σ'_c and τ_s on liquefaction triggering [13]. The study requires *CSR* vs *N* relationships from many laboratory tests to develop K_σ and K_α models that apply to a variety of soils under a wide range of stress conditions. The laboratory component of the NGL database provides a centralized, open-source location to store the data from these published laboratory tests to facilitate the development of these K_σ and K_α models. There is a significant advantage to storing stress and strain relationships throughout the duration of the cyclic tests rather than providing only the summary statistics that the original authors reported (e.g., *CRR*, K_σ, K_α). For example, the computation of *CRR* requires the selection of a liquefaction triggering criterion. Some studies choose strain-based criteria, while others choose pore pressure-based criteria. The computation of *CRR* also requires the selection of an *N* that corresponds to the magnitude or duration of interest (e.g., **M**7.5). The value of *N* has typically been between 10 and 20 in published studies. Directly providing the stress and strain relationships through-out the duration of the cyclic tests, as the laboratory component of the NGL database does, circumvents these issues and allows model developers to consider a single, consistent interpretation and/or alternative frameworks and triggering criteria.

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