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1   Next Generation Liquefaction Database

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7   The Next Generation Liquefaction database is a resource for the geotechnical

8   hazard community. It is publicly available online under the following digital object

9   identifier (DOI): 10.21222/C2J040. The database organizes objective liquefaction

10   data into tables and fields (columns of information), with the relationships among

11   the tables and fields described by a schema. The data is organized into tables

12   pertaining to (i) sites, including geotechnical and geophysical site investigation

13   data, surface geology information, and laboratory test data, (ii) earthquake events,

14   including source and ground motion information, and (iii) observations of sites

15   following events. The schema was vetted through community outreach efforts

16   involving multiple workshops and meetings. Users can view the data, download

17   existing data, and upload new data though a geographic information system (GIS)-

18   based graphical user interface. Information uploaded to the database is reviewed by

19   a database working group to verify consistency between uploaded data and source

20   documents. The database is replicated in DesignSafe where users can interact with

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21   the data using Python scripts in Jupyter notebooks, view point cloud data using

22   Potree, and interact with geospatial data using QGIS.

INTRODUCTION

24   Semi-empirical procedures for evaluating liquefaction susceptibility, triggering, and effects

25   combine empirical observations with various aspects of theory. Measurements of penetration

26   resistance [e.g., Seed et al. (1983), Çetin et al. (2004) and (2018), Idriss and Boulanger (2012),

27   for standard penetration test, SPT; Robertson and Wride (1998), Moss et al. (2006), Boulanger

28   and Idriss (2016) for cone penetration test, CPT], or shear wave velocity, V_S [e.g., Andrus and

29   Stokoe (2000), Kayen et al. (2013)] are generally utilized to assess soil resistance to

30   liquefaction. Qualitative geology-based criteria can also be used to estimate relative levels of

31   liquefaction resistance (Youd and Hoose, 1977; Youd and Perkins, 1978; Obermeier et al.,

32   1990; Lewis et al., 1999). In a similar manner, liquefaction resistance at the regional scale can

33   be modeled using geospatial variables (Zhu et al., 2015 and 2017). Surface ground motion

34   parameters are combined with wave propagation theory to estimate stress demands at a

35   particular depth, and this demand is compared with resistance to obtain a factor of safety or the

36   probability of liquefaction given a certain event. For this reason, procedures for evaluating

37   liquefaction rely strongly on empirical data. An analogous data-driven model development

38   approach has been adopted by the various Next Generation Attenuation (NGA) projects (e.g.

39   NGA-West2, Bozorgnia et al. 2014 for shallow crustal earthquakes in active tectonic regions;

40   NGA-East, Goulet et al. 2018 for stable continental regions; and NGA-Subduction, Kishida et

41   al. 2017, for subduction events). A goal of the NGL project is to facilitate a similar process for

42   modeling liquefaction triggering and consequences.

43   Variations over time of the cumulative numbers of case histories in the SPT, CPT, and V_S

44   liquefaction databases are presented in Figure 1 along with the cumulative numbers of ground

45   motion records in the NGA-West2 and NGA-Subduction projects. The number of ground

46   motion records in the NGA projects has grown exponentially with time, as indicated by the

47   essentially linear slope in semi-log space in Figure 1. The liquefaction databases, by contrast,

48   show essentially exponential growth from about 1960 to 1995, but the growth has slowed

49   recently, with very few new case histories introduced into these databases since 1995. This

50   trend is not due to a lack of available data. For example, the Canterbury Earthquake Sequence

51   in 2010 and 2011 produced tens of thousands of cone penetration tests with observations of

52   ground performance during multiple earthquakes (e.g., van Ballegooy et al. 2014; Maurer et

al. 2014). Furthermore, post-1995 earthquakes that have produced potential liquefaction case history information include: 1999 Kocaeli, 1999 Chi-Chi, 1999 Duzce, 2001 Bhuj, 2001 Nisqually, 2001 Peru, 2002 Denali, 2004 Niigata Chuetsu-Oki, 2007 Niigata Ken Chuetsu-Oki, 2007 Pisco, 2008 Iwate, 2009 L'Aquila, 2010 Maule, 2010 El Mayor Cucapah, 2011 Tohoku-Oki, 2012 Emilia, 2015 Nepal, 2016 Kaikoura, 2017 Puebla, 2018 Hokkaido Eastern Iburi, 2018 Anchorage, and 2019 Ridgecrest.
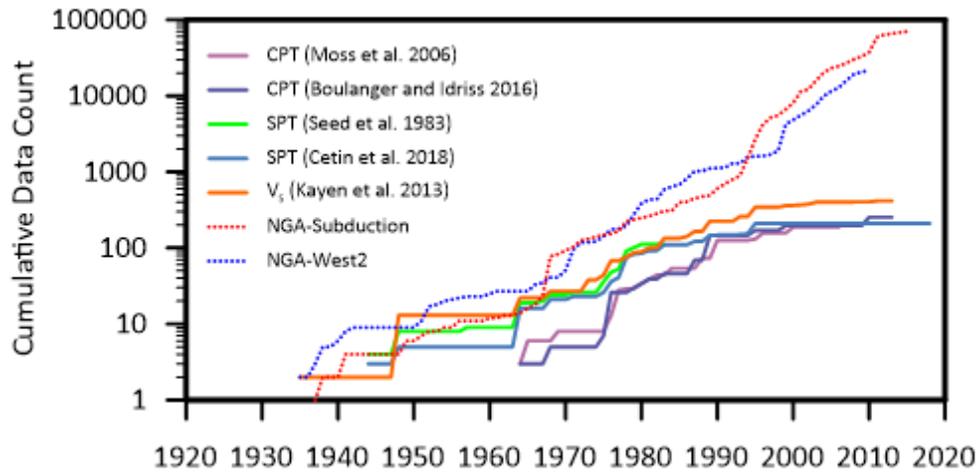
Figure 1. Cumulative number of liquefaction case histories utilized in various triggering models, and ground motion records in the NGA-West2 and NGA-Subduction projects.

We believe that liquefaction case history databases have lagged behind the exponential growth exhibited by the ground motion databases because the NGA projects involved a broad community effort surrounding database development, whereas development of liquefaction datasets has largely been undertaken by small research groups [i.e., Seed et al. (1983) and Çetin et al. (2004 and 2018) for standard penetration test (SPT) data, Moss et al. (2006) for cone penetration test (CPT) data, Kayen et al. (2013) for shear-wave velocity (V_S) data, and Zhu et al., (2015) for geospatial data] without a broader organizational framework. A larger community effort is needed to optimize the potential to learn from recent events and grow the liquefaction database both in size and quality. The need for a publicly available liquefaction database was the first recommendation of the committee commissioned by the National Academies of Sciences, Engineering, and Medicine to address the state of the art and practice in assessment of earthquake-induced liquefaction and its consequences (National Academies 2016):

76   "Recommendation 1. Establish curated, publicly accessible databases of relevant

77   liquefaction triggering and consequence case history data. Include case histories in

78   which soils interact with built structures. Document the case histories with relevant

79   field, laboratory, and physical model data. Develop the databases with strict

80   protocols and include indicators of data quality."

81   The Next-Generation Liquefaction (NGL) project was designed in part to address this clear

82 need. NGL is a multi-year community-based effort consisting of three components: (1) a

83 transparent, open-source liquefaction database, (2) supporting studies for effects that should be

84 captured in models but that cannot be constrained by case history data, and (3) model

85 development (Stewart et al. 2016).

86   This paper presents the structure of the NGL relational database, and the graphical user

87 interface (GUI) developed to upload, view, and download data. We also discuss the review

88 process implemented to ensure that uploaded data are consistent with source documents. The

89 GUI allows users to interact with the data in a limited manner, but model developers will need

90 to work with the data in ways that are not implemented in the GUI. For this reason, the database

91 is periodically replicated in DesignSafe, a cyberinfrastructure for the natural hazards

92 community (Rathje et al. 2017). This allows users to formulate their own queries, perform high

93 level data analysis, integrate geospatial datasets, and draw conclusions. We discuss several

94 publicly available tools in DesignSafe and provide example queries to extract desired data, and

95 show examples of geospatial data integration.

NGL DATABASE STRUCTURE

97   The NGL database is a relational database, meaning that it has a well-defined data structure

98 and can be queried using structured query language (SQL). The term "database" is often

99 informally applied to file repositories lacking a formal organizational structure. In contrast, a

100 relational database is organized into a schema that describes the tables, fields, and relationships

101 among tables. In this context, a *table* is a collection of information containing a series of *fields*

102 (or columns). Database fields are related using keys. Every entry in the database is assigned a

103 *primary key* that uniquely identifies the field. In some cases, a field from one table might appear

104 in another table to relate the two tables. In this case, the primary key from the host table appears

105 as a *foreign key* in the other table to map the relationship.

106   The NGL database schema was developed over a number of years by a database working
107   group, and vetted by an interested community of geotechnical earthquake engineers through a
108   series of public workshops. Draft versions of the database were presented during workshops at
109   the University of California, Berkeley, in July 2017, and at the University of California, Los
110   Angeles in September 2018. The database schema presented here is the product of that process.
111   While the database structure is essentially complete, population of the database is ongoing and
112   is anticipated to continue indefinitely as additional data become available.

113   The NGL database consists of 60 tables that can be broadly categorized as: general, site,
114   event, and observation (Tables 1-4, respectively). The general tables contain fields about the
115   users, reviewers, project team members, and miscellaneous tables related to permissions,
116   password reset requests, and version logs. The general table also contains fields for file uploads
117   and citations of published datasets or other publications. The site tables contain
118   geotechnical/geological information such as CPT data, SPT data, soil layer descriptions (as in
119   borehole logs), geophysical measurements, laboratory tests, and groundwater table depth.
120   Geospatial data, such as geology maps, digital elevation models, etc. may also be included with
121   or linked to a specific site. The event tables contain information about the earthquake source,
122   recording stations, and ground motion intensity measures from recordings (if available). The
123   observation tables contain results of post-earthquake reconnaissance at the site, which may
124   include photographs, maps, measured ground deformations, commentary on the presence of
125   liquefaction surface manifestation or lack thereof, and links to large datasets such as light
126   detection and ranging (LIDAR), structure from motion (SfM), or geospatial raster files.

127

128 **Table 1.** General tables.

Table Name	Table Description	Number of Fields
CRES	Site creator	2
CREO	Observation creator	2
CRET	Test creator	2
DICT	Dictionary (service table)	7
FILE	Table storing supplemental files (16 MB max)	6
FILE_EXT	Table storing information about large supplemental files (>16 MB)	4
OBSM	Observation member information	3
OBSR	Observation Reviewer	3
password_resets	Password Reset	4
PERM	Permissions	5
phinxlog	Version log	5
CITATION	Citation for a publication	3
SITM	Site member information	3
SITR	Site Reviewer	3
TESM	Test member information	3
TESR	Test Reviewer	3
USER	User Information	14

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132 **Table 2.** Site tables.

Table Name	Table Description	Number of Fields
BORH	General information for boreholes	11
DETL	Within-layer Description	4
GIND	Invasive Geophysical Investigation – Data	5
GINV	General information for geophysical investigation	7
GRAG	General information for particle size distribution test	4
GRAT	Particle Size Distribution – Data	4
GSWD	Surface Wave Geophysical Test – Dispersion Curve	5
GSWG	General information and configuration for surface wave geophysical test	7
INDX	Index Tests	9
ISPT	Standard Penetration Test Results	9
OTHF	Other Field Tests	7
OTHR	Other Laboratory Tests	6
PLAS	Atterberg Limits	6
RDEN	Relative Density	6
SAMF	Associated Files for Laboratory Tests	4
SAMP	General information for sample	11
SCPG	General information for Cone Penetration Test (CPT)	10
SCPT	Standard Penetration Test (SPT) – Data	6
SITC	Site Comments	5
SITE	Site general information	8
SITF	Junction table relating a file to a site	4
SITP	Junction table relating a publication citation to a site	4
SPEC	General information for specimens	7
STRA	Stratigraphic Layer Description	7
SWVD	Surface Wave Geophysical Test Data – V_S/V_P Profiles	7
SWVG	General Information for Surface Wave Geophysical Test	4
TEPT	Test Pit	8
TESC	Test Comments	5
TESF	Junction table relating a file to a test	4
TESP	Junction table relating a publication citation to a test	4
TEST	General information for in-situ tests	9
WATR	Ground water table information	5

133

134 **Table 3.** Event tables.

Table Name	Table Description	Number of Fields
EVNT	General information for earthquake events	20
GMIM	Ground Motion Intensity Measure recorded or estimated at a site	9
IM	Recorded Intensity Measure	125

SEGM	Fault Segments (finite fault models)	11
STAT	Recording stations	15

135

136 **Table 4.** Observation tables.

Table Name	Table Description	Number of Fields
FLDD	Displacement vectors	8
FLDF	Junction table relating a file to an observation	6
FLDP	Junction table relating a publication citation to an observation	4
FLDM	Liquefaction manifestation	11
FLDO	General information for field observation	6
OBSC	Observation Comment	5

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138   A total of 494 different fields are contained within the tables defined by Tables 1 through
139 4. A dictionary describing each individual field in these tables is provided in an interactive
140 webpage: http://nextgenerationliquefaction.org/schema/index.html. The current schema at that
141 web page is updated from an earlier version presented by Brandenberg et al. (2018), and any
142 future changes will also be reflected in the online schema. Here we describe several example
143 tables to illustrate key aspects of database functionality.

144   Figure 2 shows example site investigation tables and fields, with arrows indicating the
145 primary key / foreign key relationships between tables. A site consists of a primary key
146 (SITE_ID), site name (SITE_NAME), latitude (SITE_LAT), longitude (SITE_LON),
147 description of surface geology (SITE_GEOL), a remark about the site (SITE_REM), a boolean
148 field indicating whether the site has been submitted for review (SITE_STAT), and a boolean
149 field indicating whether the site has been reviewed (SITE_REVW). Minimum data
150 requirements for the SITE table are: SITE_NAME, SITE_LAT, and SITE_LON.

151   Because the NGL database scheme uses the word "site," an operational definition is
152 required. A site is a high level entity into which a team of NGL users organize their data. A
153 site generally represents a contiguous geographical area that has been investigated by the team
154 and for which observations of liquefaction effects have been made for an event or sequence of
155 events. Latitude and longitude fields are required for each site so that the site can be located on
156 the map within the GUI, but that does not mean that a site should be interpreted as a single
157 location in space. Geotechnical conditions and observations of liquefaction effects may vary
158 spatially within a site. Users must exercise judgment in assigning a specific geographical area

159   to a site, and are encouraged to provide a remark explaining their rationale for organizing the
160   information with a site.

161   Once a site has been established, a test or set of tests used to evaluate site conditions may
162   be defined for that site. Note that the TEST table has a SITE_ID field, which is a foreign key
163   that links the TEST table with a particular SITE. In the TEST table TEST_NAME,
164   TEST_TYPE, TEST_LAT, and TEST_LON are required fields. In this manner, multiple tests
165   may be specified for a specific site without the need for repeating information from the site
166   table. The types of tests illustrated in Figure 2 include CPT (SCPG), borehole (BORH), surface
167   wave geophysical test (GSWG), groundwater table measurement (WATR), and sample
168   (SAMP). As shown in Figure 2, an individual test has a location, which does not necessarily
169   align with that of the SITE. Although not shown in Figure 2, additional test types, including
170   stratigraphy (STRA), detailed soil description (DETL), test pit (TEPT), and invasive
171   geophysical tests (GINV), may also be provided. Furthermore, users may upload source
172   materials such as PDF files, photos, maps, etc. as Binary Large Object (BLOB) files. We limit
173   BLOB file size to 16 MB because large files could slow operation of the database and GUI.
174   When a user wishes to include a file larger than 16 MB in the site data, the large data files must
175   be published outside of the NGL database and assigned a digital object identifier (DOI). The
176   DOI for the published data may then be included with the NGL database site data using the
177   CITATION and FILE_EXT tables. We require that external files be published and assigned a
178   DOI to maintain integrity of the data, and ensure that the URL created by appending the DOI
179   to http://doi.org/ will always point to the correct data location. For example, the NGL website
180   can be found at http://doi.org/10.21222/C2J040, and will always be accessible through this
181   DOI even if the host location of the website changes.

182
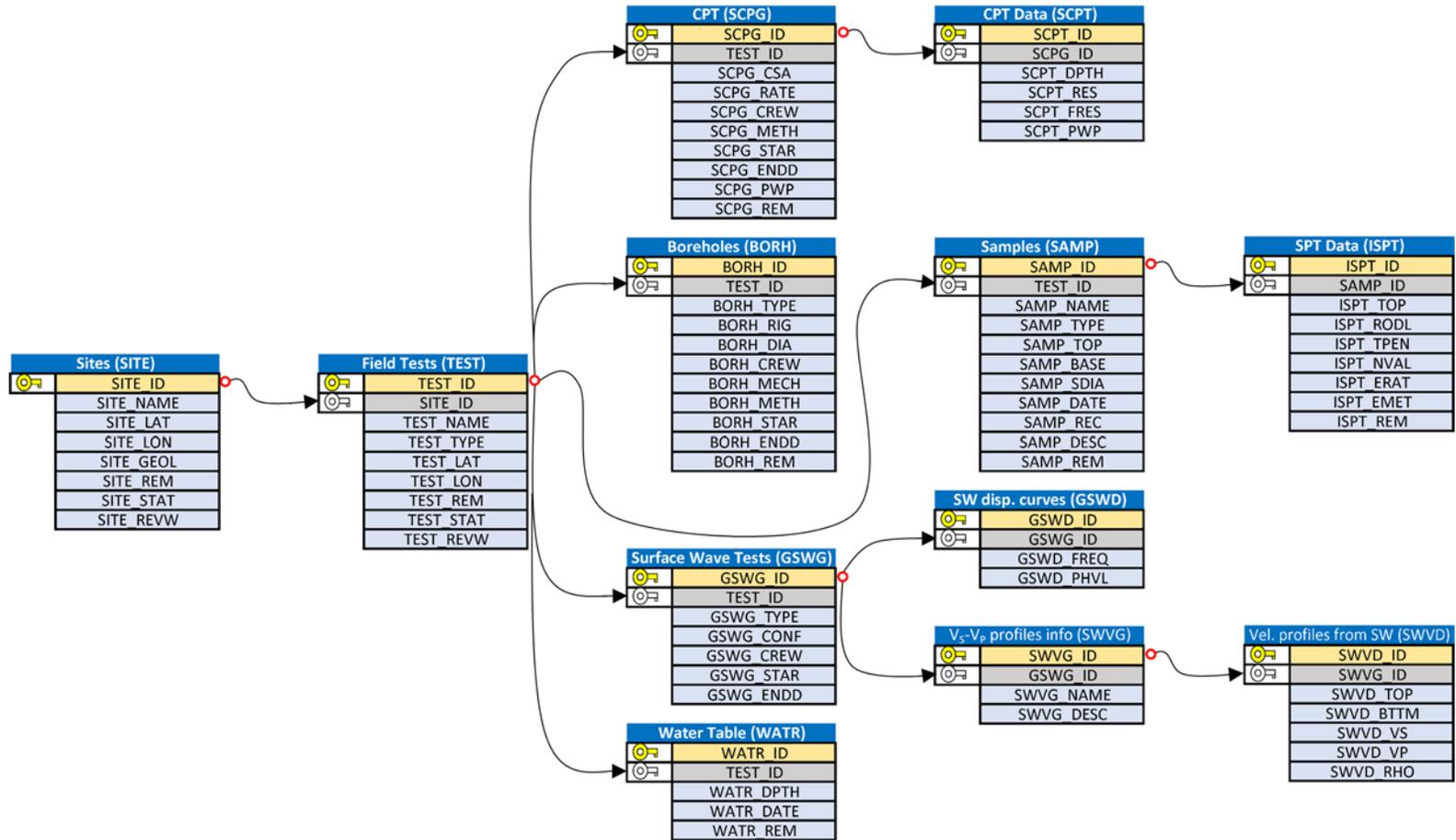
Figure 2. Subset of NGL relational database schema illustrating tables containing site investigation data.

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185   For CPT data, the SCPG table contains general information about the test, including the

186   cone area (SCPG_CSA), push rate (SCPG_RATE), crew (SCPG_CREW), method

187   (SCPG_METH) (e.g., ASTM D5778-12), time stamp at the start and end of the test

188   (SCPG_STAR and SCPG_ENDD, respectively), position of the pore pressure measurement

189   (SCPG_PWP), and remarks (SCPG_REM). The CPT data are contained in the SCPT table,

190   which has SCPG_ID as a foreign key. The fields include depth (SCPT_DPTH), tip resistance

191   (SCPT_RES), sleeve friction (SCPT_FRES), and pore pressure (SCPT_PWP). Minimum data

192   requirements for the SCPT table are: SCPT_DPTH and SCPT_RES.

193   For SPT data, users enter borehole information in the BORH table such as borehole type,

194   rig, diameter, crew, hammer drop mechanism, start and end dates. Users then also enter

195   information about the samples in the SAMP table, including the sampler type, diameter, and

196   depth of the top and bottom of the sample. SPT blow count data are entered in the ISPT table,

197   which contains SAMP_ID as a foreign key. Users can enter the distance that the sampler was

198   driven, the number of blows required to drive it that distance, hammer energy ratio, method

199   used to obtain hammer energy ratio (i.e., directly measured, calibrated rig, hammer type), and

200   rod length.

201   Figure 2 also shows the tables for surface wave measurements. In this case, users upload

202   general information about the surface wave measurements in the GSWG table, and the surface

203   wave dispersion curve data in the GSWD table. A velocity profile, or multiple velocity profiles,

204   obtained by inversion of the measured dispersion curve may also be uploaded in the SWVG

205   and SWVD tables. We consider a velocity profile from a surface wave measurement to be

206   subjective because the inversion procedure is highly non-unique and many different velocity

207   profiles may provide a good fit to a measured dispersion curve (e.g., Foti et al., 2018).

208   However, the measured dispersion curve is relatively objective, and therefore the dispersion

209   curve should be included in the database when possible.

210   Figure 3 illustrates tables associated with observations of liquefaction manifestation or lack

211   thereof. Observations are first organized into a junction table, FLDO, that contains the

212   observation primary key, and foreign keys for SITE_ID and EVNT_ID. These foreign keys

213   must be present because they connect the observation to the site and event for which the

214   observation was made. A general description of the observation at the site for the event should

215   be provided (FLDO_DESC). In some cases, an observation is made after a sequence of events

216   and it is not clear the extent to which each event contributed to the observation. In this case,

217 users must use judgment in selecting an event, and are encouraged to explain this in the

218 FLDO_DESC field. The ground motion intensity measure for traditional triggering procedures

219 has been peak horizontal acceleration (PGA), although other intensity measures, such as peak

220 ground velocity, peak ground displacement, 5%-damped pseudo-spectral acceleration for a

221 range of oscillator periods, significant duration, Arias intensity, and cumulative absolute

222 velocity above 5 cm/s^2 (CAV_5, Kramer and Mitchell 2006), can also be input. The method

223 used to estimate the intensity measure (GMIM_METHOD) is a required field, and can be

224 accompanied by a standard deviation (GMIM_STDDEV) representing uncertainty in the

225 estimate. Quantifying uncertainty is important because we envision three scenarios for ground

226 motion estimation, in order of increasing uncertainty:

227 (i)   A strong motion record is co-located with a liquefaction observation. Uncertainty
228   is minimized in this case. Currently 23 such sites are available in the NGL database,
229   which have produced 31 total observations. Procedures described by Kramer et al.
230   (2016) and Greenfield (2017) identify the timing of liquefaction triggering from
231   waveforms.

232 (ii)   The event is recorded by a network of strong motion stations, but a strong motion
233   record is not co-located with the liquefaction observation. In this case, spatial
234   interpolation techniques can be utilized, ideally with consideration of differences in
235   site conditions at the liquefaction observation site relative to the recording stations
236   [e.g., Stafford (2012); Kwak et al (2016)].

237 (iii) Strong motion records are sparse or non-existent for a particular event, and shaking
238   intensity is estimated using a ground motion model. This approach involves
239   significant uncertainty and judgment, but is frequently required for case histories
240   used in previous susceptibility, triggering, and/or consequences models.
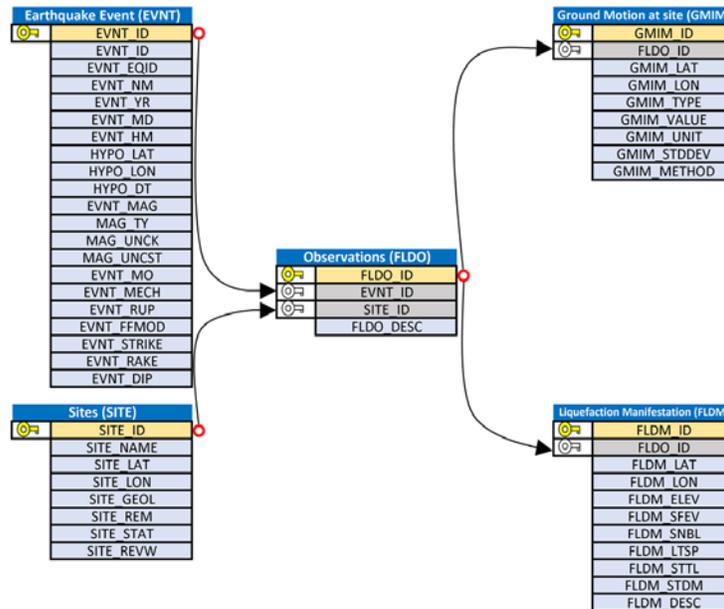
Figure 3. Subset of NGL relational database schema illustrating tables containing event data.

Users may describe detailed observation(s) of site performance using the FLDM table. The location of the observation is indicated by the FLDM_LAT, FLDM_LON, and FLDM_ELEV fields. The FLDM_SFEV field indicates whether there is surface evidence of liquefaction (0 = no, 1 = yes). It is important to note that FLDM_SFEV = 0 indicates that an observation was made, and surface evidence was confirmed to have not occurred. A lack of surface evidence does not necessarily indicate a lack of liquefaction at some depth within the soil profile. Additional fields include evidence of sand boils (FLDM_SNBL), lateral spreading (FLDM_LTSP), settlement (FLDM_STTL), and structural or foundation damage (FLDM_STDM). Additional data entry options include descriptions of observations, ground displacement vectors uploaded using the FLDD table, and files such as photographs and maps of observations of damage uploaded using the FILE and FLDF tables. Minimum data requirements for the FLDM table are: FLDM_LAT, FLDM_LON, FLDM_SFEV, FLDM_SNBL, FLDM_LTSP, FLDM_STTL, and FLDM_STDM.

GRAPHICAL USER INTERFACE

The web GUI was developed using PHP: Hypertext Preprocessor, Hypertext Markup Language 5, Javascript, and Cascading Style Sheets within the CakePHP web framework. The GUI also utilizes two Application Program Interfaces (API's) to organize the data geospatially: the Environmental Systems Research Institute Arc Geographic Information System API and

262 the Leaflet Javascript API. The GUI can be used to visualize, upload, and download
263 liquefaction case history data. The homepage of the database provides an overview of the
264 geographic distribution of events, sites, and observations (Figure 4). The NGL database GUI
265 also allows users to interact with the data by means of a list view (Figure 4b), which is
266 convenient for seeing all of the data fields for a particular site, event, or observation in tabular
267 form.

268 In map view, users can utilize the left panel to filter the data based on earthquake name,
269 magnitude range, or by selecting specific events from the event list. Although not shown in
270 Figure 4, the left panel also enables filtering data based on field performance by including or
271 excluding sites that exhibited surface evidence, sand boils, lateral spreading, settlement, and/or
272 structural damage. Case histories can also be filtered based on available field investigation
273 information, including boreholes, CPTs, test pits, geophysical tests, and other tests. The right
274 panel provides viewing options, including the ability to show or hide various database objects,
275 and to change the map view to topographic (default), imagery, or terrain.
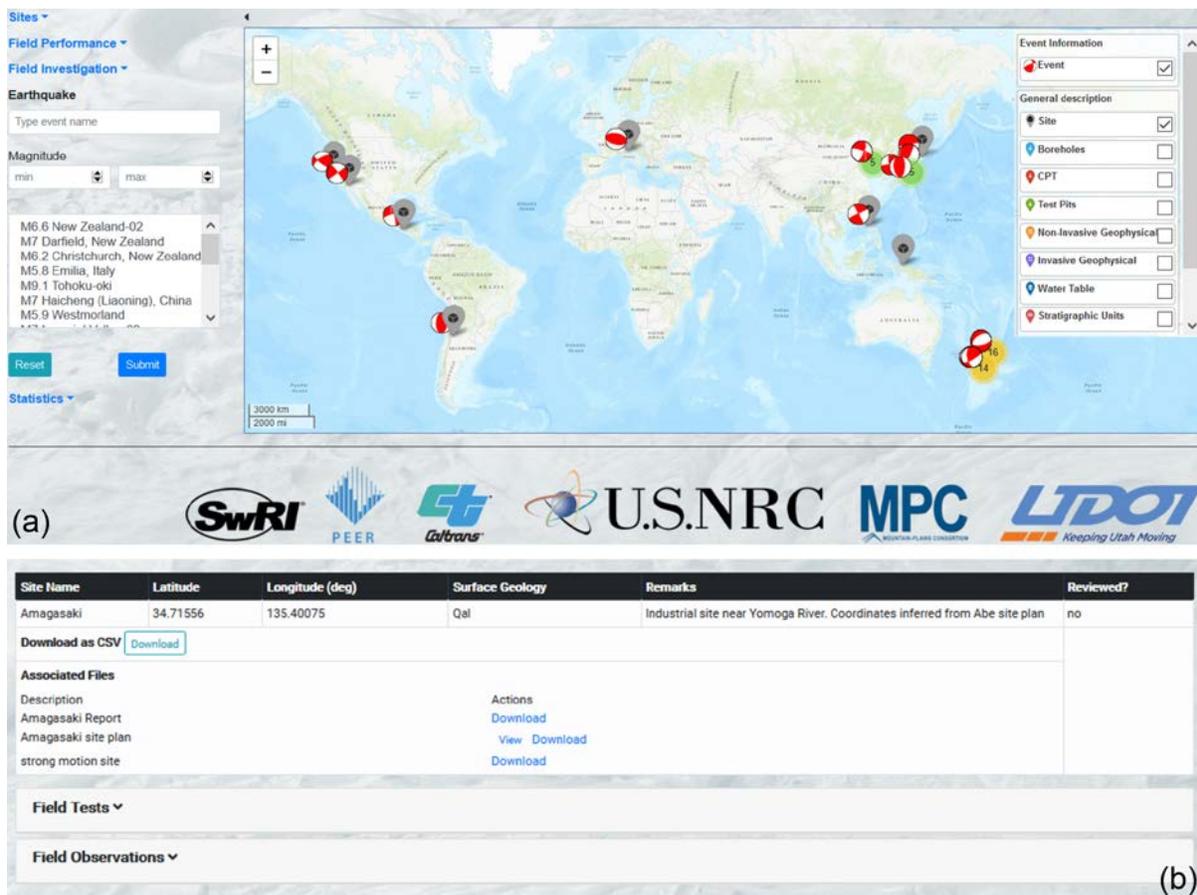
276
277 **Figure 4**. (a) Homepage of the NGL database GUI (map view); and (b) organized list of case histories
278 in the database (list view).

279

280   Users may view site, event, and observation data through the GUI, as illustrated in Figure
281 5, which shows results from a cone penetration test (CPT_21506) performed in Christchurch,
282 New Zealand after the Canterbury earthquake sequence. The plot shows measured cone tip
283 resistance, sleeve friction, and pore pressure. The figure is not stored in the database as an
284 image, but rather is generated from the data when a user clicks the "Plot" button. This prevents
285 potential inconsistencies between the data stored in the database and the figure. In a similar
286 manner, users can plot borehole data, including stratigraphic details and SPT blow counts,
287 shear wave velocity profiles (and dispersion curves for surface wave measurements), and
288 observations of earthquake damage including photographs, maps, and damage descriptions.
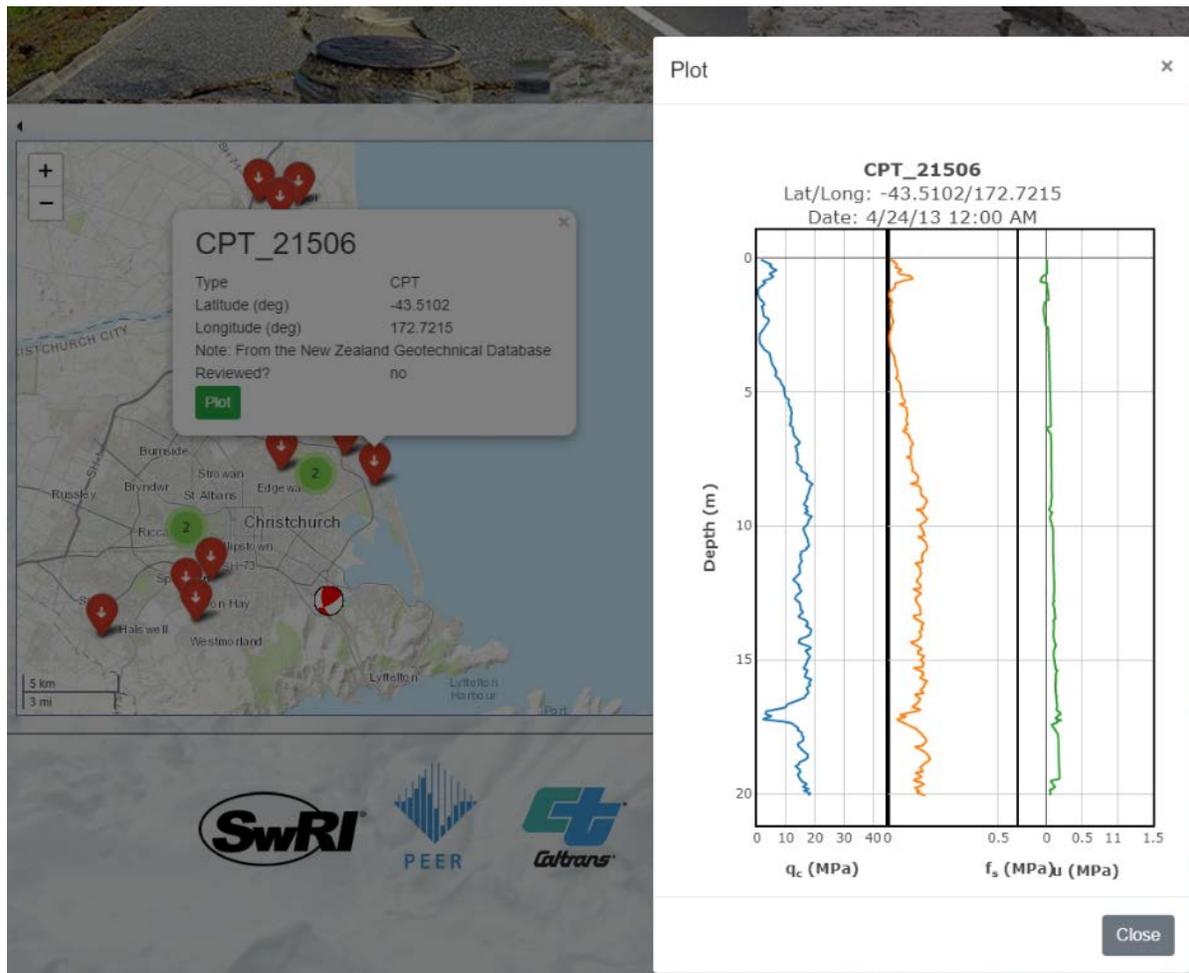
290 **Figure 5**. Screenshot of NGL GUI showing CPT data for CPT_21506 in Christchurch, New Zealand.
291

DATA REVIEW PROCESS AND QUALITY CONTROL

All data uploaded to the NGL database is reviewed using tools incorporated within the GUI. The NGL Database Working Group provides oversight to the review process. The goals of the review are to (i) ensure consistency between uploaded information and source documents, (ii) verify that all required fields are provided, (iii) identify ambiguities, or items that require clarification, and (iv) check for reasonableness of data to identify errors in data entry such as incorrect unit conversions, inappropriate negative values, etc. The review is intended to be objective; subjective opinions are not part of the review process. For example, a reviewer is justified in requesting clarification when data uploaded to the database does not agree with the same data plotted in a publication. On the other hand, a reviewer may believe that SPT data without hammer energy ratio measurements are not valuable and should not be included in development of a liquefaction model. However, the reviewer cannot decline the data based on this subjective opinion. The NGL project has been structured in such a way that subjective judgments of this type are not made during database development, instead being reserved for the model development phase. Two independent reviewers must formally review each individual piece of information uploaded to the database.

Database population is usually performed in two-steps. During the first step, users and research teams upload data, which is flagged as un-submitted and un-reviewed, and is only available to project team members in the NGL GUI. Once the user or team believes the data is ready, they submit it to the review team, at which point the data is flagged as submitted, but un-reviewed and is made available to all NGL users through the NGL GUI. After all components of a case history have been reviewed and accepted, the case history is flagged as reviewed. At this stage, users may request a DOI for their dataset. A case history is complete only if includes at least the minimum required data components, and the original source of each individual piece of information is provided. Source documents are often journal or conference publications, technical reports, theses or dissertations. It is also possible for users to upload original (not previously published) data for which the source documents can be given as field and/or laboratory minutes or notes. In such cases, the assignment of a DOI is recommended to associate the data with the user.

Within the NGL GUI, review functions are only accessible to users having appropriate permissions. As a result, regular users are not able to access the review section of the GUI. Case history components are reviewed using three separate panels in the NGL GUI. Figure 6a

324   shows a list of post-earthquake observations under review, while Figure 6b shows the review
325   form for a specific observation entry in the NGL database. Similar forms are available for site
326   information and field investigation data. The review process for an example case history and
327   additional information on the quality control process implemented in the NGL project are
328   provided by Zimmaro et al. (2019b).
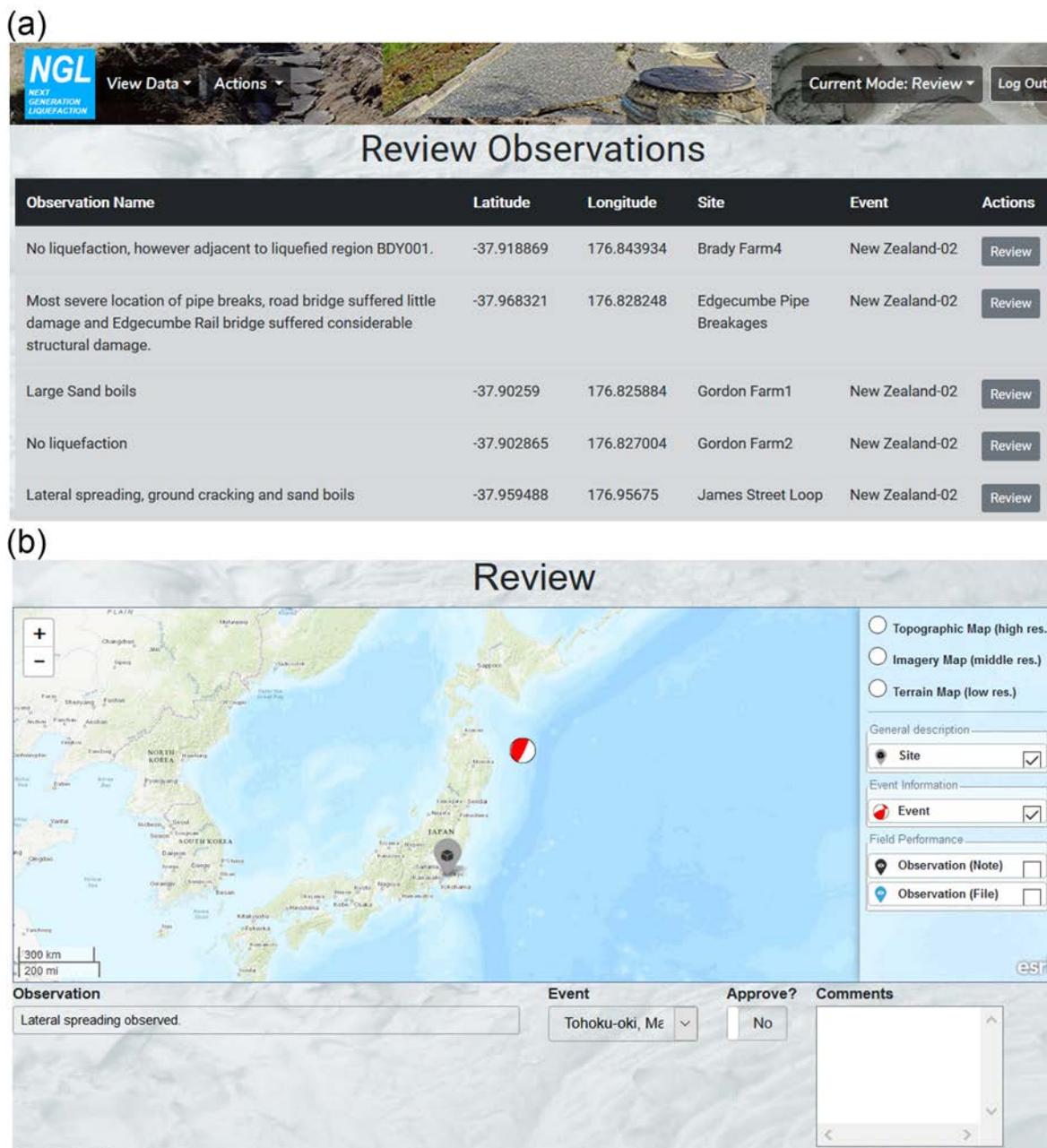
329
330 **Figure 6.** (a) Review observation panel showing post-earthquake observations under review; (b) review
331 form for post-earthquake observations.

CLOUD-BASED DATABASE INTERACTION VIA DESIGNSAFE

333   The NGL database GUI allows users to upload, visualize, and download data from the NGL

334 database, but users cannot use the GUI to perform calculations on the data. If, for example, a

335 user wished to compute a liquefaction index such as LPI_{ISH} (Maurer et al. 2015) for a specific

336 CPT sounding, or perform geospatial liquefaction analysis (e.g. Zhu et al. 2015, 2017) they

337 could not do so through the GUI. One option for such analyses is to download CPT data and

338 perform calculations on local computers. However, we anticipate that the size of the database

339 will eventually render this approach infeasible.

340   To permit users to interact with the NGL database in the cloud, and integrate the NGL data

341 into their custom workflows, we periodically replicate the NGL database in DesignSafe. The

342 significance of this replication is that users can interact with the DesignSafe version of the

343 database via applications available through the DesignSafe Discovery Workspace, such as

344 Jupyter notebooks, QGIS, and the Potree point cloud viewer. A Jupyter notebook is a server-

345 client application that allows editing and running notebook documents via a web browser. It

346 combines rich text elements (equations, figures, HTML, LaTeX) and computer code executed

347 by a Python kernel (Perez and Grainger 2007). These Jupyter notebooks utilize Python libraries

348 for performing SQL queries to extract data from the database, where the extracted data may

349 then be processed using custom computer code. Five example Jupyter notebooks that perform

350 basic tasks that we anticipate users might perform during model development have been

351 published in DesignSafe. One notebook provides example queries that extract various data into

352 tables (Brandenberg and Zimmaro, 2019a, DOI: 10.17603/ds2-xvp9-ag60.). Notebooks are

353 also available for viewing CPT (Brandenberg and Zimmaro, 2019b, DOI: 10.17603/ds2-99kp-

354 rw11), boring logs and SPT (Lee et al., 2019, DOI: 10.17603/ds2-sj7t-av93), and invasive and

355 non-invasive geophysical tests (Zimmaro and Brandenberg, 2019, DOI: 10.17603/ds2-tq39-

356 kp49 and Brandenberg and Zimmaro, 2019c, DOI: 10.17603/ds2-cmn0-h864).

357 **Example SQL Queries**

358   Figure 7 shows an example SQL query that extracts CPT data at the Wildlife Array site.

359 The query is actually a single text string, but is broken into five lines here for clarity. The query

360 begins on Line (6) of the Jupyter notebook, where the SELECT command queries TEST_ID,

361 TEST_NAME, SCPT_DPTH, SCPT_RES, and SCPT_FRES. Note that data is queried from

362 two different tables (TEST and SCPT), and the table name is prepended to the field name with

363 a "." separator. Line (7) utilizes an INNER JOIN command, which synthesizes two tables into

364 a single table based on a common shared key. In this case, the SCPT and SCPG tables are
365 combined based on a common value of SCPG_ID, which is the primary key for SCPG and a
366 foreign key for SCPT. In line (8) another INNER JOIN adds the TEST table based on the
367 TEST_ID key, and in line (9) the final INNER JOIN adds the SITE table based on the SITE_ID
368 key. In line (10), the WHERE statement indicates that the requested data should be included in
369 the query result for sites where SITE_NAME = 'Wildlife Array'. The output from the query
370 shown in Figure 7 is a small excerpt of the overall resulting data table. Note that different CPT
371 soundings are indicated by different TEST_ID values.

```
In [8]:    1  import pymysql
           2  import pandas as pd
           3
           4  %run ./Connection.ipynb
           5  cursor = cnx.cursor()
           6  command = 'SELECT TEST.TEST_ID, TEST.TEST_NAME, SCPT. SCPT_DPTH, SCPT.SCPT_RES, SCPT.SCPT_FRES FROM SCPT '
           7  command += 'INNER JOIN SCPG ON SCPT.SCPG_ID = SCPG.SCPG_ID '
           8  command += 'INNER JOIN TEST ON TEST.TEST_ID = SCPG.TEST_ID '
           9  command += 'INNER JOIN SITE ON SITE.SITE_ID = TEST.SITE_ID '
          10  command += 'WHERE SITE.SITE_NAME = "Wildlife Array"'
          11  cursor.execute(command)
          12  result = cursor.fetchall()
          13  df = pd.read_sql_query(command, cnx)
          14  pd.set_option('display.max_rows', 10)
          15  df
```

Out[8]:

	TEST_ID	TEST_NAME	SCPT_DPTH	SCPT_RES	SCPT_FRES
0	977	3Cg_pre	0.0	0.0000	0.000000
1	977	3Cg_pre	0.1	0.0000	0.000000
2	977	3Cg_pre	0.2	0.0000	0.000000
3	977	3Cg_pre	0.3	0.0000	0.000000
4	977	3Cg_pre	0.4	0.5886	0.021950
...	...	...	...	...	...
2267	1006	10Cg	12.6	25.9278	0.282613
2268	1006	10Cg	12.7	26.8009	0.292130
2269	1006	10Cg	12.8	27.8898	0.303999
2270	1006	10Cg	12.9	27.1148	0.295552
2271	1006	10Cg	13.0	26.8696	0.000000

372 2272 rows × 5 columns

373 **Figure 7.** Example SQL query to extract CPT data from Wildlife Array site, and output table showing
374 truncated result.

375

376 Figure 8 shows an example query of Event and Observation data for the Wildlife Array
377 site. In this case, the query extracts earthquake magnitude (EVNT_MAG), name
378 (EVNT_NAME), and year (EVNT_YEAR), along with observation latitude (FLDM_LAT),
379 longitude (FLDM_LON), whether surface evidence of liquefaction was observed
380 (FLDM_SFEV), and a description of the observation (FLDM_DESC). Observations are
381 available at the Wildlife Array site for four different events, two of which produced surface
382 evidence of liquefaction (1981 **M**5.9 Westmorland and 1987 **M**6.54 Superstition Hills-02) and

383   two of which produce no surface evidence (1987 **M**6.2 Superstition Hills-01 and 2010 **M**7.2

384   El Mayor-Cucapah).

385

386   **Figure 8.** Example SQL query to extract Event and Observation data from Wildlife Array site, and
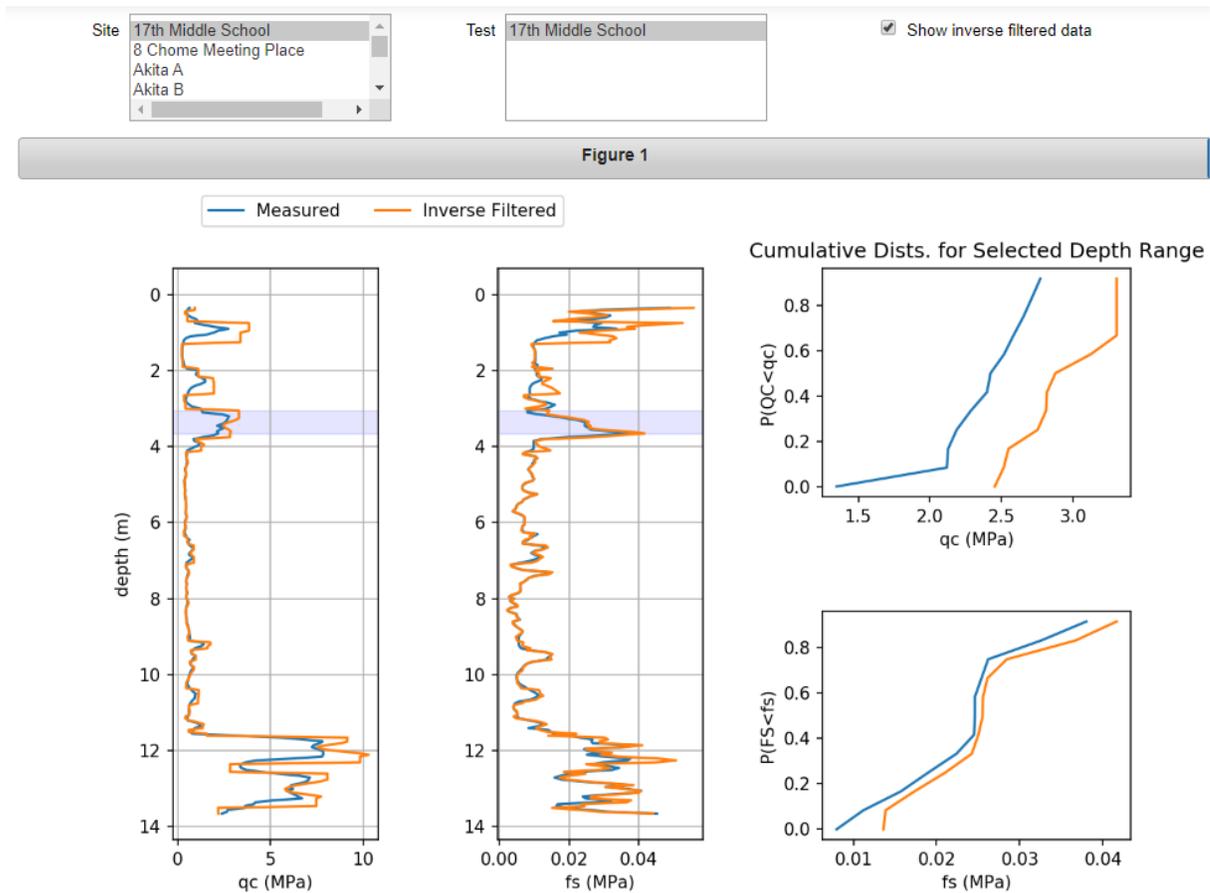387   output table showing truncated result.

388

389   **Visualization Tools for Geotechnical Site Investigation Data**

390   Figure 9 shows a Jupyter notebook for visualizing CPT data. Users select a site from a

391   dropdown menu, and the tool populates the *Test* box with CPT profiles for that site. The script

392   used to create this tool combines SITE and SCPT table entries using the INNER JOIN

393   command. It facilitates visualization of cone tip resistance (q_c) and sleeve friction (f_s) for CPT

394   profiles, along with cumulative distribution functions (CDFs) for user-specified depth ranges

395   (full-profile or narrower depth intervals). On the right side of the visualization panel, a box

396   labelled 'Show inverse filtered data' provides a filtered q_c profile based on the Boulanger and

397   DeJong (2018) procedure. This feature is useful for analyzing profiles with thinly-interbedded

398   soils.

399   Figure 10 shows a tool developed to visualize boring logs and SPT data. This tool allows

400   users to select a site from a dropdown menu only populated with sites having boring logs and/or

401   SPT data. This tool combines SITE, STRA, and ISPT tables data entries using the INNER

402   JOIN command. After selecting a site, the tool automatically populates the *Remarks* field

403   (which shows available remarks for that site) and the *TEST* box with all available boring logs

404   and SPT profiles for the site. After selecting a test, the tool plots SPT profiles (N-value versus

405   depth) and boring logs side-to-side on the same vertical scale. The tool also plots the CDF for
406   SPT data over user-specified depth ranges. Two additional visualization tools are available on
407   DesignSafe: (1) a tool showing dispersion curves and inverted V_S profiles (if available) for
408   non-invasive geophysical tests (i.e. surface wave methods), and (2) a tool showing shear wave
409   velocity profiles and CDFs from invasive geophysical tests (e.g., cross hole, down hole, and
410   suspension logging). The visualization tool for non-invasive geophysical tests combines SITE,
411   GSWG, GSWD, SWVG, and SWVD table entries, while the visualization tool for invasive
412   geophysical tests combines SITE and GIND table entries. In both cases table entries are
413   combined using the INNER JOIN command.

414

415

416

Figure 9. Output from the NGL CPT viewer available on DesignSafe.

418
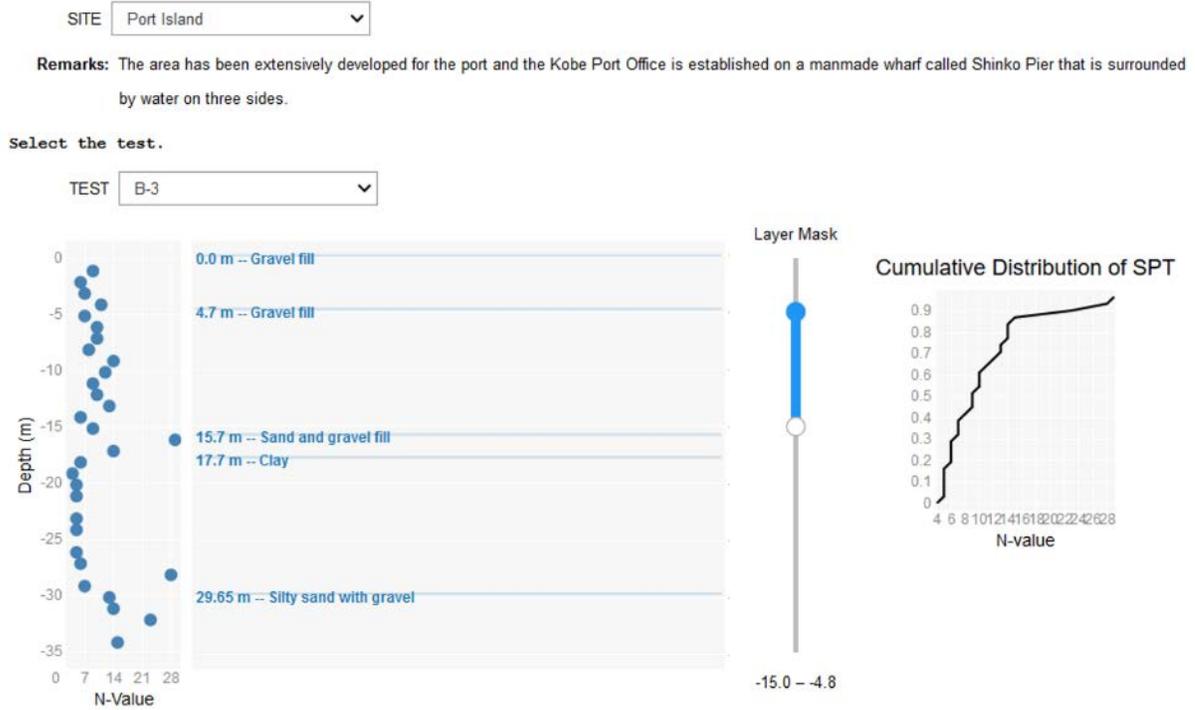
Figure 10. Output from the NGL SPT viewer available on DesignSafe.

420

Visualization Tools for Geospatial Data

Observations of liquefaction manifestation are increasingly utilizing techniques such as LIDAR (e.g. Olsen et al., 2012; Imakiire and Koarai, 2012; Konagai et al., 2013; and Rathje et al., 2017), SfM applied to digital photos collected using unmanned aerial vehicles (UAV's) (e.g. Franke et al., 2017; Stewart et al., 2019; and Winters et al. 2019), and correlation analysis of satellite images (Rathje et al., 2017). Furthermore, geospatial products such as maps of surface geology, bodies of water, and digital elevation models provide useful information for liquefaction triggering evaluation, and have been used to supplement geotechnical data in regional liquefaction assessment procedures (e.g., Zhu et al. 2015, 2017). These geospatial data objects are important to include in the NGL database..

An example application of linking geospatial data with NGL data is provided for observations in Trona and Argus after the 2019 Ridgecrest earthquake sequence. A Geotechnical Extreme Events Reconnaissance Association (GEER) reconnaissance team visited these sites after the earthquakes (Stewart et al. 2019) to perform ground-based observations using GPS trackers, digital cameras, and hand-held measuring devices, and subsequently a team visited these sites to fly UAV's and gather image data. Data from these reconnaissance missions was published in DesignSafe (Brandenberg et al. 2019 and Winters et al. 2019), and assigned DOI's that are included as citations in the CITATION table and linked to the observation through the FLDP table. Orthomosaic images obtained from the UAV survey (Winters et al. 2019) are superposed on a surface geology map (Smith 2009) using QGIS in DesignSafe in Figure 11. Three different orthomosaics are shown, and a zoomed-in view of one orthomosaic shows a railroad that required repair due to liquefaction effects near the intersection of three different geologic units [sdg (gravel and sand), oal (older alluvium), and sd (sand and silt)].

442
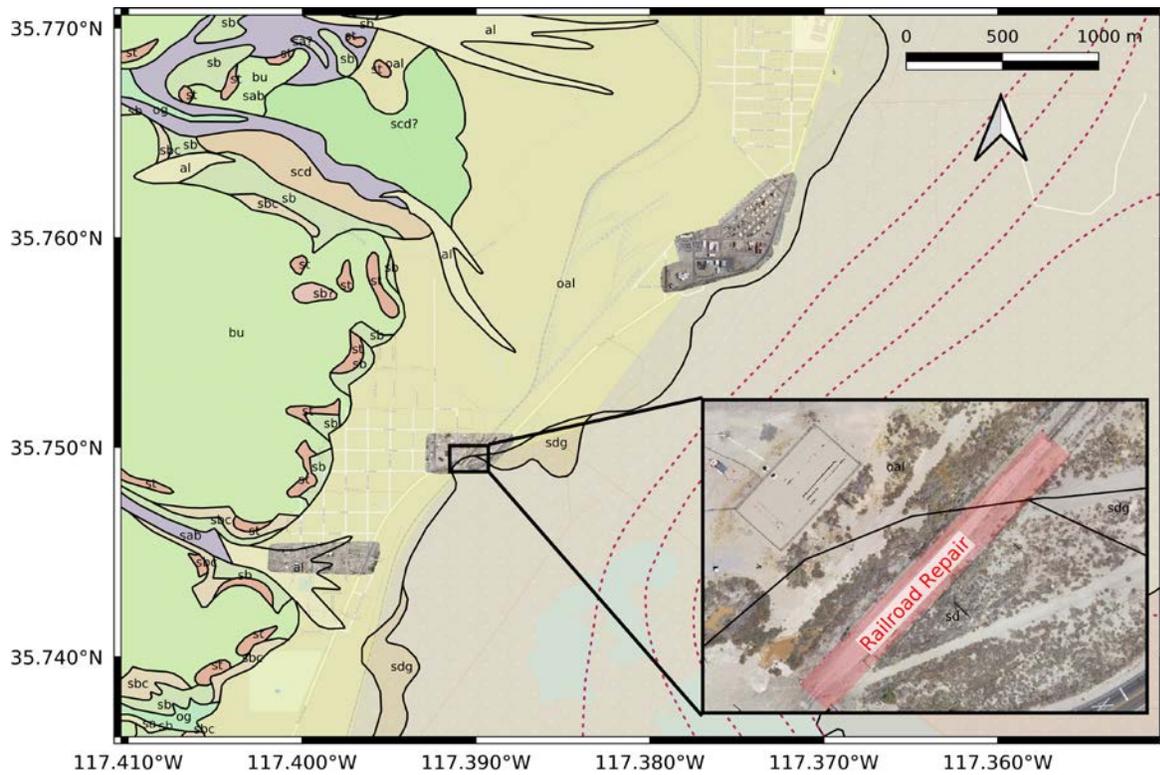
Figure 11. Map of Trona and Argus where liquefaction effects were observed after the Ridgecrest earthquake sequence. The map includes orthomosaic images obtained from UAV SfM surveys (Winters et al. 2019), and a surface geology map by Smith (2009).

A point cloud generated by SfM processing of the UAV images shows surface evidence of liquefaction at the site of the Family Dollar store in Trona, CA in Figure 12. The image is a screenshot from the Potree point cloud viewer available in DesignSafe. Sand ejecta originating from a utility pole near the left side of the image flowed over the gravel and parking lot toward the sign on the right of the image.
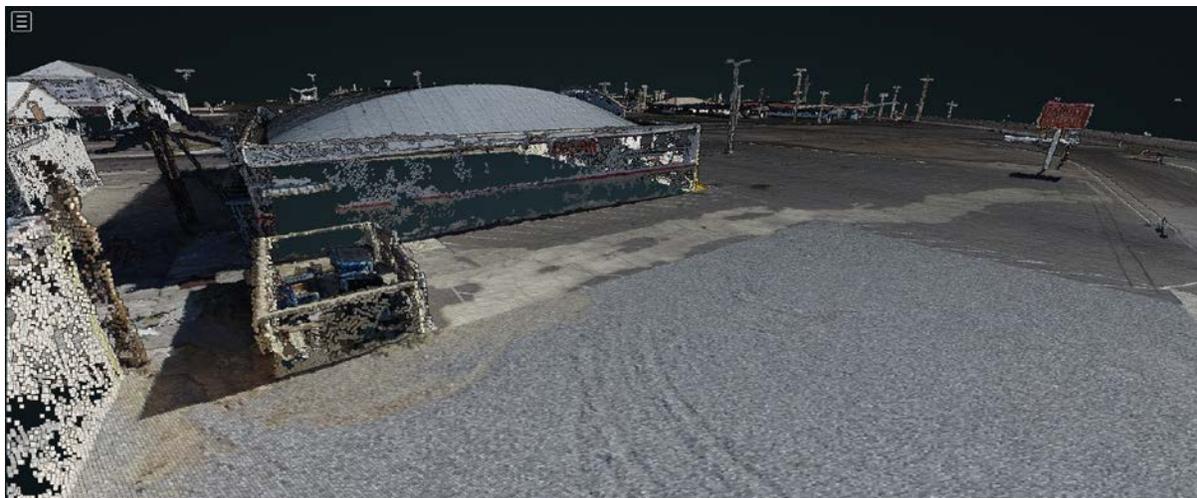
451

452 **Figure 12**. Point cloud from SfM processing of UAV images at the Family Dollar building in Trona,
453 CA (Winters et al. 2019).

454 **CONCLUSION**

455   In this paper we present the Next Generation Liquefaction (NGL) database (Zimmaro et al.
456 2019a, DOI: 10.21222/C2J040). The NGL database is an open-source tool that results from a
457 multi-year, ongoing community effort. We describe the NGL database organizational structure
458 (i.e. the schema describing relationships among tables) and provide information about selected
459 tables in the database, including minimum data requirements. The NGL database contains
460 objective information about liquefaction, or lack thereof, during past earthquake events. Each
461 individual site and observation component is reviewed through a formal vetting process
462 coordinated by the NGL Database Working Group.

463   The NGL database is accessible through a GUI that allows users to upload, visualize, and
464 download data. The database is also replicated onto DesignSafe where users can write queries
465 and utilize Jupyter notebooks to interact with the data in the cloud, and integrate geospatial
466 data into their workflow. We envision these cloud-based tools to be particularly useful for data
467 analysis in support of development of future liquefaction susceptibility, triggering, and
468 consequences models.

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