PACIFIC EARTHQUAKE ENGINEERING RESEARCH CENTER

PEER Workshop on Liquefaction Susceptibility

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PEER Report No. 2023/02

Pacific Earthquake Engineering Research Center
Headquarters at the University of California, Berkeley
May 2023

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ABSTRACT

Seismic ground failure potential from liquefaction is generally undertaken in three steps. First, a susceptibility evaluation determines if the soil in a particular layer is in a condition where liquefaction triggering could potentially occur. This is followed by a triggering evaluation to estimate the likelihood of triggering given anticipated seismic demands, environmental conditions pertaining to the soil layer (e.g., its depth relative to the ground water table), and the soil state. For soils where triggering can be anticipated, the final step involves assessments of the potential for ground failure and its impact on infrastructure systems. This workshop was dedicated to the first of these steps, which often plays a critical role in delineating risk for soil deposits with high fines contents and clay-silt-sand mixtures of negligible to moderate plasticity. The workshop was hosted at Oregon State University on September 8-9, 2022 and was attended by 49 participants from the research, practice, and regulatory communities.

Through pre-workshop polls, extended abstracts, workshop presentations, and workshop breakout discussions, it was demonstrated that leaders in the liquefaction community do not share a common understanding of the term "susceptibility" as applied to liquefaction problems. The primary distinction between alternate views concerns whether environmental conditions and soil state provide relevant information for a susceptibility evaluation, or if susceptibility is a material characteristic. For example, a clean, dry, dense sand in a region of low seismicity is very unlikely to experience triggering of liquefaction and would be considered not susceptible by adherents of a definition that considers environmental conditions and state. The alternative, and recommended, definition focusing on material susceptibility would consider the material as susceptible and would defer consideration of saturation, state, and loading effects to a separate triggering analysis. This material susceptibility definition has the advantage of maintaining a high degree of independence between the parameters considered in the susceptibility and triggering phases of the ground failure analysis.

There exist differences between current methods for assessing material susceptibility – the databases include varying amount of test data, the materials considered are distinct (from different regions) and have been tested using different procedures, and the models can be interpreted as providing different outcomes in some cases. The workshop reached a clear consensus that new procedures are needed that are developed using a new research approach. The recommended approach involves assembling a database of information from sites for which in situ test data are available (borings with samples, CPTs), cyclic test data are available from high-quality specimens, and a range of index tests are available for important layers. It is not necessary that the sites have experienced earthquake shaking for which field performance is known, although such information is of interest where available. A considerable amount of data of this type are available from prior research studies and detailed geotechnical investigations for project sites by leading geotechnical consultants. Once assembled and made available, this data would allow for the development of models to predict the probability of material susceptibility given various independent variables (e.g., in-situ tests indices, laboratory index parameters) and the epistemic uncertainty of the predictions. Such studies should be conducted in an open, transparent manner utilizing a shared database, which is a hallmark of the Next Generation Liquefaction (NGL) project.

Keywords: liquefaction, susceptibility, ground failure, testing, NGL

ACKNOWLEDGMENTS AND DISCLAIMER

Execution of this Workshop was made possible by the sponsors (acknowledged below), the participants and, critically, the Oregon State University graduate student and post-doctoral assistants including Ms. Mahrooz Abed, Dr. Sandeep Chitta, Dr. Ali Dadashiserej, Dr. Amalesh Jana, Mr. Logan McGinn, Mr. Nicholas Peterson, Ms. Talenta Pitso, Ms. Jiayao Wang, and Mr. Eshan Yazdani. The writers also thank the Kearney Dean of Engineering, Scott A. Ashford, College of Engineering, Oregon State University for support of Workshop expenses.

This Workshop and report were funded by the Pacific Earthquake Engineering Research (PEER) Center, under Contract No. 1179-NCTRIN and the College of Engineering, Oregon State University. The opinions, findings, conclusions, and recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Pacific Earthquake Engineering Research (PEER) Center, the Regents of the University of California, Oregon State University, and the State of Oregon.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION, PURPOSE, AND SCOPE

1.1 INTRODUCTION

The typical progression of engineering analysis of soil liquefaction involves three steps: determination of liquefaction susceptibility, evaluation of liquefaction triggering for one or more earthquake scenarios, and assessment of the consequences of liquefaction triggering. Although each of these steps is associated with considerable epistemic uncertainties, the basic framework for engineering analyses of liquefaction triggering and the consequent deformations or instability has been established. However, these analyses hinge upon whether a particular stratum is deemed susceptible to liquefaction, with considerable risk or cost associated with incorrectly assessing susceptibility. The Next Generation Liquefaction (NGL) Project aims to advance the state of the art in liquefaction research in part through the provision of consensus-based, probabilistic methodology for assessment of liquefaction potential and risk, and includes components ranging from the development of case history and laboratory databases, supporting studies, and model development. This PEER Workshop, held on September8 - 9, 2022 on the Oregon State University campus in Corvallis, OR, was conducted as a supporting study under the umbrella of the NGL Project to seek consensus on liquefaction susceptibility.

Geotechnical engineers have historically divided soil behavior into “sand-like” and “clay-like” due to their significantly different responses during static loading. This precedent serves the profession well for sands and clays, but falls short for transitional (or, equivalently, intermediate) soils (clayey sands, nonplastic sandy silts and silts, and low-plasticity clayey silts) as well as for interlayered deposits, for which the assessment of liquefaction susceptibility is difficult. Many of the currently available susceptibility and triggering models are largely based on the interpretation of field performance data from sites that have or have not exhibited surficial evidence of liquefaction as typically characterized through observations of sand boils, ground cracks, or large permanent deformations. While the interpretation of case histories is useful, the NGL Project seeks to evaluate susceptibility through a separate process in which laboratory data is being carefully parsed to distinguish “sand-like” from “clay-like” behavior. Nonetheless, significant questions regarding the linkage between physical (e.g., consistency limits) and correlated (e.g., CPT-based soil behavior type index, I_c) quantities and threshold soil behavior (from “sand-like” to “intermediate”, and from “intermediate” to “clay-like”) exist.

1.2 PURPOSE AND SCOPE OF THIS WORKSHOP

The goals of the PEER Workshop on Liquefaction Susceptibility were to: (1) organize and conduct a one-and-a-half day long workshop fully-aligned with the ongoing efforts of the Next Generation Liquefaction (NGL) team that is focused on developing improved data resources and models related to liquefaction susceptibility and triggering; and (2) prepare a summary report describing the outcomes of the workshop and the specific consensus-based recommendations on the needed elements of next-generation liquefaction models and the steps needed to produce such models. Accordingly, the Workshop organizers sought to identify challenges and research opportunities for improved assessments of liquefaction susceptibility, centered on three broad themes:

1. The current state-of-the practice and its limitations;
2. The linkage between laboratory observations, and field characterization and response; and,
3. Options for future susceptibility models that could be used, for example, in conjunction with liquefaction triggering models or hazard mapping.

Vehicles for exploring these three themes included the solicitation of extended abstracts on the topic of liquefaction susceptibility in response to several prompts, a pre-Workshop poll of participants, and the Workshop itself, which included a mix of brief presentations, break-out sessions, and moderated discussion sessions. Key to advancing the objectives of the Workshop, the organizers sought to draw participants from a broadly diverse set of expert practitioners, governmental agency representatives, and academicians.

1.3 WORKSHOP ORGANIZING COMMITTEE

The Workshop organizing committee (OC) included faculty members and researchers drawn from the NGL Project and PEER member universities, and include (in alphabetical order):

Besrat Alemu, Workshop Secretary and graduate research assistant, School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331;

T. Matthew Evans, Professor, School of Civil and Construction Engineering, and Associate Dean for Faculty and Staff Advancement, College of Engineering, Oregon State University, Corvallis, OR 97331;

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Armin W. Stuedlein, Workshop Chair and Professor, School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97331;

Kristin J. Ulmer, Research Engineer, Geoscience and Engineering Department, Southwest Research Institute, San Antonio, TX 78238; and,

Katerina Ziotopoulou, Associate Professor, Department of Civil and Environmental Engineering, University of California, Davis, CA 95616.

The OC was initially formed by PEER Workshop grant PIs Armin W. Stuedlein, Jonathan P. Stewart, and T. Matthew Evans. Discussions by this subset identified the need to more strongly link the OC to current NGL efforts and diversify membership in the OC. Subsequently Steven Kramer (NGL), Kristin Ulmer (NGL), and Katerina Ziotopoulou (PEER member faculty) were invited to help organize the Workshop. Pre-workshop organizational activities were recorded and filed by Workshop Secretary Besrat Alemu.

1.4 ORGANIZATION OF THIS REPORT

This report is divided into several chapters which provide an overview and summary of the Workshop. The organization of the Workshop is presented in Chapter 2 and includes the considerations and planning activities, limitations encountered, and a brief summary of lessons learned which may be useful to those planning future similar workshops. Chapter 3 summarizes the Pre-Workshop poll of participant's views on issues associated with the assessment of liquefaction susceptibility and which helped guide the conduct of the Workshop. Chapter 4 presents comprehensive descriptions of each of the three Workshop sessions, including presentations to participants, breakout session questions and participant responses, and corresponding discussions which concluded each of the sessions.

Chapter 5 presents the organizing committee's interpretations of key issues raised during the Workshop discussions. Research needs that were identified by Workshop participants and the organizing committee are summarized in Chapter 6. Chapter 7 provides concluding remarks and is followed by a bibliography of references cited. Four appendices accompany this report, including the list of Workshop participants (Appendix A), extended abstracts addressing various issues related to liquefaction susceptibility contributed by Workshop participants (Appendix B), the full pre-Workshop poll and results (Appendix C), and concluding with the detailed Workshop Agenda (Appendix D). Appendices E, F, and G of this report points the reader to the invited Workshop presentation slides in the form of electronic supplements which are posted on the PEER Report webpage.

2 ORGANIZATION OF THE WORKSHOP

2.1 APPROACH

The workshop was organized to facilitate information gathering and data-informed collaborative discussions among participants, with the goal of answering three fundamental questions:

- What is the current state-of-practice and what are its limitations?
- Where should the professional practice be in 5 to 10 years, specifically considering model development and resource needs?
- What opportunities exist for synthesizing laboratory- and field-based observations?

These fundamental questions guided the work of the OC, including the invitation of participants, attendee pre-Workshop activities, development of the Workshop agenda, and design of breakout group activities. Each of these aspects is discussed briefly below.

Invitation of Participants. From the outset, the OC worked to ensure balanced participation by identifying individuals from academia and the public and private sectors who are actively working in the area of liquefaction susceptibility and potential, specifically related to transitional soils. Balance in individual expertise was also considered when developing the invitation list, including laboratory and in-situ testing, numerical simulations, statistical modeling, and regional-scale assessments. In addition to invitees identified by the OC, an announcement of the Workshop and solicitation of participants was issued to US academics through the USUCGER email list service. Applications submitted by interested participants were to include their name, position, and affiliation, a statement describing their primary interest in participating, a title and summary of the extended abstract which would be submitted if selected, and a list of three research products that represent the theme of the Workshop. Four participants were selected by the OC following submission of applications. Due to travel restrictions associated with the COVID-19 pandemic or other factors, several participants joined virtually or were unable to participate. The final list of participants included 33 academics, 10 practitioners, and six state or federal government employees from 10 U.S. states and five countries outside of the U.S. The final list of participants is included in Appendix A.

Pre-Workshop Activities. To inform, and better guide discussions during the Workshop, attendees were asked to complete two main pre-workshop activities: (i) develop an extended abstract for review by the OC (see Appendix B); and (ii) complete a short anonymous pre-Workshop poll (see Chapter 3 and Appendix C). After reviewing the extended abstracts, the OC identified 19 of 31 submissions whose authors would be invited to present their work at the Workshop. The results from the pre-Workshop poll were synthesized and used in the development of the Workshop Agenda and the breakout session activities.

Extended Abstracts. Solicitation of extended abstracts by the OC served several purposes, including: (1) a means for participants to communicate their current perceptions and/or research inquiries on liquefaction susceptibility to other participants prior to the Workshop (through pre-Workshop distribution of the abstracts), and (2) identification of potential gaps in the Workshop Agenda during the planning stage.

The instructions for submitting extended abstracts included the request to address three broad Workshop themes (Section 1.2) by responding to one or more prompts regarding liquefaction susceptibility and modeling identified by the OC, summarized by:

1. What is the state-of-the-art?
2. What are the consequences of incorrectly assessing liquefaction susceptibility, and under what conditions are these consequences most acute?
3. What are the relevant geological, material characteristics, in-situ tests, or modeling processes which drive the challenges associated with the methods currently in use?
4. What data resources would help improve understanding?
5. How should the next generation of liquefaction susceptibility models be formulated to advance the state-of-the-art?
6. Have you experienced a case where the determination of susceptibility proved to be pivotal, and what were the considerations associated with the application of typical (i.e., state-of-the-practice) susceptibility procedures?
7. Can you describe a case where liquefaction susceptibility was assessed using methods beyond those typically applied, given the importance of the project and consequences of liquefaction?

The received extended abstracts addressed these seven prompts from a broad range of perspectives and experiences. The breadth and the depth of current views of, and research thrusts by, participants in the area of liquefaction susceptibility are evident in the rich collection of abstracts found in Appendix B. These abstracts were reviewed by the OC and selected contributors were invited to present their abstracts during the Workshop.

Workshop Agenda. Each day of the Workshop was organized into a combination of formal presentations, breakout group activities, and larger group discussions, with a half-day session dedicated to each of the three fundamental questions listed above. Each session began with a group of presentations followed by breakout groups and concluding with moderated discussions amongst all participants. Pacing was deliberate and activities varied to ensure that participants remained engaged and ample time was provided for "sidebar conversations", which were often observed to carry over into the broader group discussions. Appendix D provides the Workshop Agenda, which is briefly summarized as:

Day 1, Welcome and Opening Remarks
Welcome, Agenda, and Workshop Objectives
Overview and Summary of Pre-Workshop Poll

Day 1, Session 1: State-of-Practice and Limitations
Parts A & B: Presentations
Breakout Session
Report
Discussion/Debriefing

Day 1, Session 2: Where Do We Want to Be in 5 – 10 Years? Model Development, Resource Needs/Gaps
Parts A & B: Presentations
Breakout Session
Report
Discussion/Debriefing

Day 2, Session 3: Opportunities for Synthesizing Laboratory- and Field-based Observations, Consensus Recommendations
Parts A & B: Presentations
Breakout Session
Report
Discussion/Debriefing

Day 2, Closing Remarks
Observations on Workshop Discussions
Closing Remarks

Breakout Session Activities. The OC used the extended abstracts selected for presentation and the results from the anonymous pre-Workshop poll to design the breakout session activities. Workshop attendees were provided with selected poll results for each session and asked to reflect on those responses in various ways. In this way, breakout session activities were focused and had prescribed "deliverables" to facilitate discussions amongst the attendees at the end of each session. Importantly, all breakout activities were conducted outdoors. This served to change the tone of the conversations from those conducted in the main venue and provide variety in the flow of the day, effectively disrupting the relative comfort zones of the attendees and forcing engagement in the breakout activities. The 37 in-person attendees were randomly divided into six groups for the first and third breakout sessions. This was a deliberate decision intended to make each group unique, rather than prescriptive. For example, some groups were academic-heavy while others contained a higher proportion of practitioners, and some groups were geographically diverse and others more homogenous. This resulted in diversity of thought and opinion when group discussions were reported back to the entire audience, further encouraging discussion amongst all attendees. The second breakout session occurred late in the afternoon, and the OC anticipated relative lower participant energy levels. Accordingly, this session was programmed to be interactive in nature. Specific questions were developed using results from the pre-Workshop poll in an effort to probe attendees' opinions about liquefaction susceptibility. The questions were printed on poster boards and attendees were asked to throw rocks into cups or complete evolutionary histograms to indicate their responses to the questions.

Virtual Participants. Given that several countries as well as individuals are still experiencing the impacts of the pandemic, in addition to individual circumstances, the workshop aimed to provide hybrid participation. Out of the 49 total participants, 12 were virtual. Virtual participants were able to view slides projected in the Workshop room, as well as engage in the in-person moderated discussions, facilitated through a suite of four fixed cameras and microphones. The virtual participants were formed into an additional seventh group for the breakout activities and were placed into a virtual breakout room to hold their discussions during the first and third breakout sessions. For the second breakout session, virtual participants received the questions via an online poll and provided their replies there.

2.2 LIMITATIONS

The workshop managed to provide a venue for participants to share their opinions and experiences and to elicit the participants' thoughts on the questions posed. Participant turnout was good, although not everyone invited was able to participate in-person or in limited instances, at all. An increasing amount of anecdotal and scientific evidence has emphasized the limitations of virtual meetings compared to face-to-face interactions, meetings, and learning experiences. The workshop was not an exception to this, although the virtual group managed to have vibrant conversations and efficiently report back to the audience during breakout sessions as well as pose questions after presentations. While the virtual participation was as carefully as possible considered and facilitated, the virtual attendees missed out on the in-person technical and networking interactions and most likely were not as vocal as they would likely have been in person. The presence of some of the virtual attendees was also understandably not continuous, given either time zone differences or the fact that virtual events have been found to be challenging to keep up with.

2.3 LESSONS LEARNED

On Attendance and Participation. The workshop succeeded in bringing key researchers and practitioners together who shared their experiences and voiced their opinions on the three main questions that the Workshop aimed to resolve. Virtual participants were reasonably vocal and encountered no accessibility issues (i.e., screen sharing, view of the room, acoustics). One OC member participated virtually, and a relevant lesson learned in this regard was that this likely helped with keeping virtual participants more accountable and engaged.

On In-Person Activities. Graduate students from the host institution joined the workshop and actively assisted with the in-person activities, and execution of the breakout sessions in particular. The graduate student assistance represented a critical component in ensuring that all participants and breakout groups knew what was going on at any given moment.

On Debriefing Sessions. Breakout Sessions 1 and 3 asked attendees to hold conversations and provide answers to specific questions (see Sections 4.1 and 4.3). The answers of each group were shared with the rest of the audience by a selected group representative. In retrospect, one opportunity for improvement would have been to request the notes of each group.

On the Pre-Workshop Poll. The pre-Workshop poll (Appendix C) was helpful in two respects: (1) it helped the OC prepare the breakout sessions and guide fruitful conversations on controversial topics, and (2) it helped attendees to think deeper about certain issues and to be prepared beyond collecting their thoughts for their extended abstracts (Appendix B). The poll's anonymity also helped the attendees provide their honest opinions and remain open to revisiting them later during the workshop. Anecdotal evidence indicates that at least one participant claimed that their opinion on liquefaction susceptibility changed following participation in the Workshop. A lesson learnt was that the poll could have been redistributed after the end of the workshop to probe whether attendees changed their minds regarding any of the questions.

3 PRE-WORKSHOP POLL

3.1 OVERVIEW

Prior to the Workshop, a poll (Appendix C) was developed to gain information about the attendees' professional backgrounds and experience, and their interpretations of a number of issues relating to the assessment of liquefaction susceptibility. Responses to the poll were useful both in a general sense and for guiding design of the Workshop Agenda (Appendix D). A brief presentation synthesizing the responses was provided at the beginning of the Workshop.

The poll consisted of 20 questions relating to current practice, problematic soil conditions, limitations of current procedures, use of additional (e.g., geologic) information to guide liquefaction susceptibility assessments, and thoughts on how liquefaction susceptibility assessment procedures could be improved. Some of the questions lent themselves to statistical or numerical interpretation and others involved open-ended written responses. This chapter presents a brief summary of the questions and interpreted general categories, when possible, of the responses. Not all attendees responded to the poll and not all respondents responded to each individual question. A complete listing of the responses can be found in Appendix D.

3.2 SUMMARY OF RESPONSES

The first two questions were oriented toward the backgrounds of the attendees. The OC sought input from the research and practitioner communities and invited participants from both (Figure 3.1). The average level of experience of all respondents was approximately 19 years (Figure 3.2).

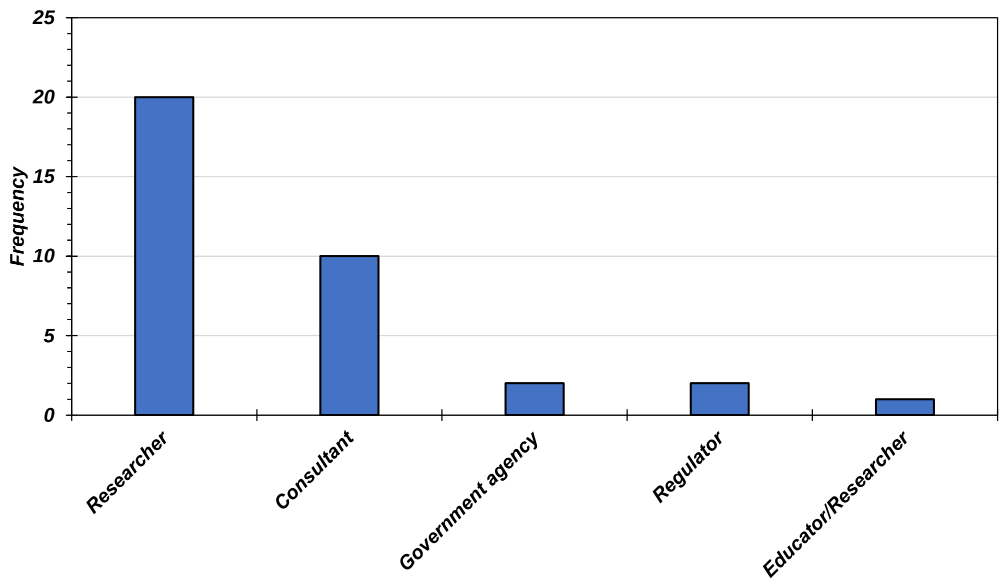

Figure 3.1 Employment roles of Workshop attendees (Poll Question #1).

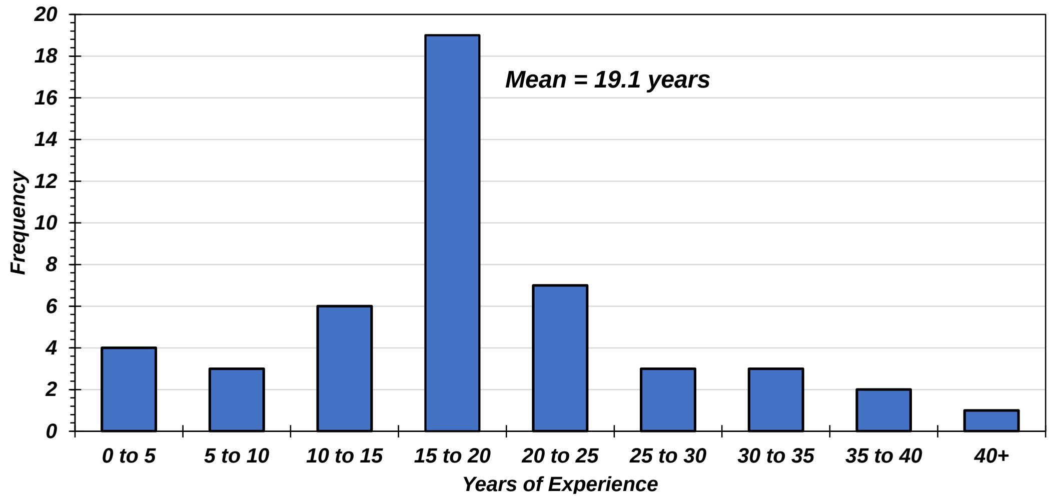

Figure 3.2 Experience levels of Workshop attendees (in years; Poll Question #2).

The organizers sought to evaluate the extent to which participants considered liquefaction susceptibility to be a separate issue from triggering versus a reflection of the likelihood of triggering. The third poll question probed the relative extents to which material characteristics (which would not reflect triggering issues) and state/environment characteristics (which would influence triggering) were considered to be significant with respect to susceptibility. Attendees were given 100 points to distribute among 17 parameters that could be taken to influence susceptibility, recognizing that the list was not exhaustive and that a number of the parameters were correlated with each other. The ranges, means, and coefficients of variations (COV) of the responses are summarized in Table 3.1. The top 10 vote-getters, in terms of their means, were plasticity index, *PI* (by a large margin), degree of saturation, soil behavior type index, relative density, mineralogy, fines content, depositional environment, age, and (in a three-way tie that brings the total number of parameters to 11) CPT tip resistance, clay content, and the water content-to-liquid limit, w_c/LL, ratio.

Table 3.1 Tabulated distribution of 100 points for influence of various parameters on liquefaction susceptibility (Poll Question #3).

Parameter	Minimum	Maximum	Mean	COV
Plasticity index	0	80	18.7	1.03
Degree of saturation	0	30	9.5	0.84
Soil behavior type index, Ic	0	40	9.4	1.11
Relative density	0	60	9.4	1.27
Mineralogy	0	100	7.6	2.29
Fines content	0	20	6.4	1.01
Depositional environment	0	20	5.7	0.96
Age	0	20	5	1.04
CPT tip resistance	0	20	4.8	1.35
Clay content	0	20	4.8	1.23
w_c/LL	0	40	4.8	1.63
Shear wave velocity	0	20	4.6	1.27
SPT resistance	0	20	3.3	1.56
Undrained strength ratio	0	35	2.6	2.49
CPT friction ratio	0	10	2	1.59
Undrained strength	0	8	0.8	2.24
Compression index	0	10	0.6	3.11

Of the parameters in the Top 10 list, five (plasticity index, soil behavior type index, mineralogy, fines content, and clay content) can be interpreted as inherent material characteristics, five (degree of saturation, relative density, age, CPT tip resistance, and w_c/LL ratio) can be interpreted as state/environmental characteristics, and one (depositional environment) can be interpreted either way. The sum of the means of the "inherent material characteristics" category was 43.7 and the corresponding sum of the "state/environmental" category was 29.8, revealing a general sense that liquefaction susceptibility was more strongly influenced by material characteristics than state/environmental characteristics. The increasing use of cone penetration testing for characterization of liquefaction resistance motivated a question regarding the reliability of CPT-based assessment of liquefaction susceptibility. The responses, shown graphically in Figure 3.3, indicate that respondents considered CPT-based assessments of liquefaction susceptibility to be generally reliable but improved with complementary measurements of fines content and with cyclic laboratory test data. No respondents rated CPT-based assessments as highly reliable, two as not generally reliable, and one as poor.

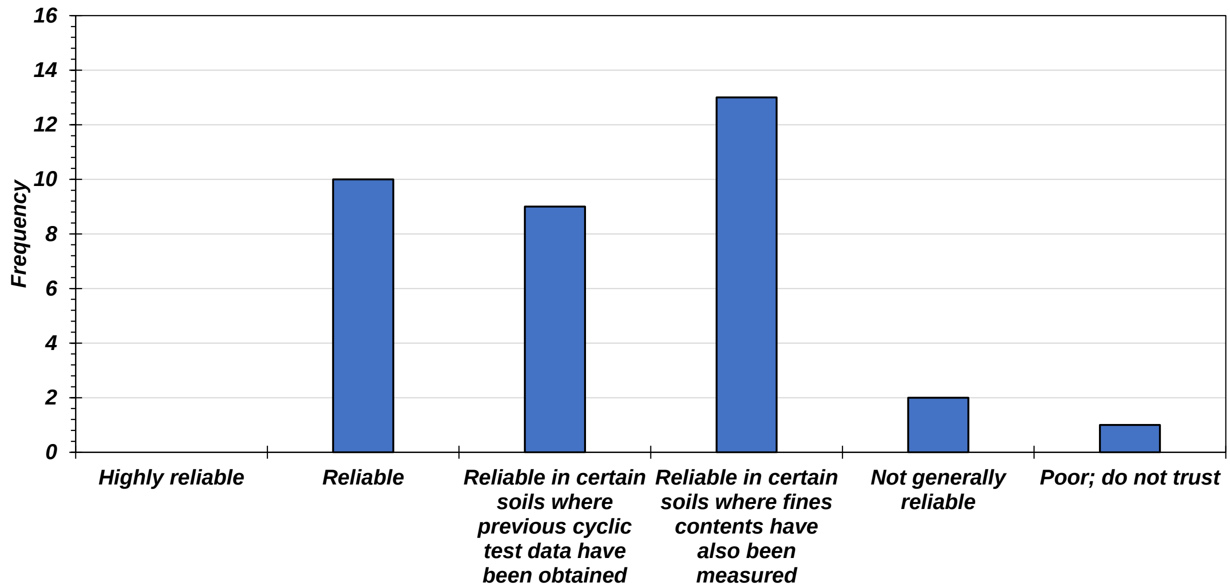

Figure 3.3 Reliability of CPT-based assessment of liquefaction susceptibility (Poll Question #4).

Susceptibility issues are often centered on the effects of fine-grained soils, either alone or, more commonly, mixed with coarse-grained soils. In mixed soils with small fractions of fine-grained particles, the fines are contained within the voids of a skeleton of coarse-grained particles that resist applied stresses through interparticle forces at their contacts. With large fractions of fine-grained particles, however, the coarse-grained particles are not in contact with each other and essentially "float" in a matrix of fine-grained particles that provide the resistance to applied stresses. Workshop attendees were asked to state their understanding of the fraction of fine-grained particles at which the transition occurs from coarse-grained control of behavior to fine-grained control. As shown in Figure 3.4, the majority of the responses indicated that the fine-grained fraction would control behavior at fines contents above 25 to 35%. Interestingly, none of the respondents selected 50%, which is the fines content used in the Unified Soil Classification System to distinguish coarse-grained from fine-grained soils. The respondents' thresholds are generally consistent with recent literature on this topic (Cubrinovski and Ishihara 2002; Thevanayagam et al. 2002; Simpson and Evans 2016; Park and Santamarina 2017).

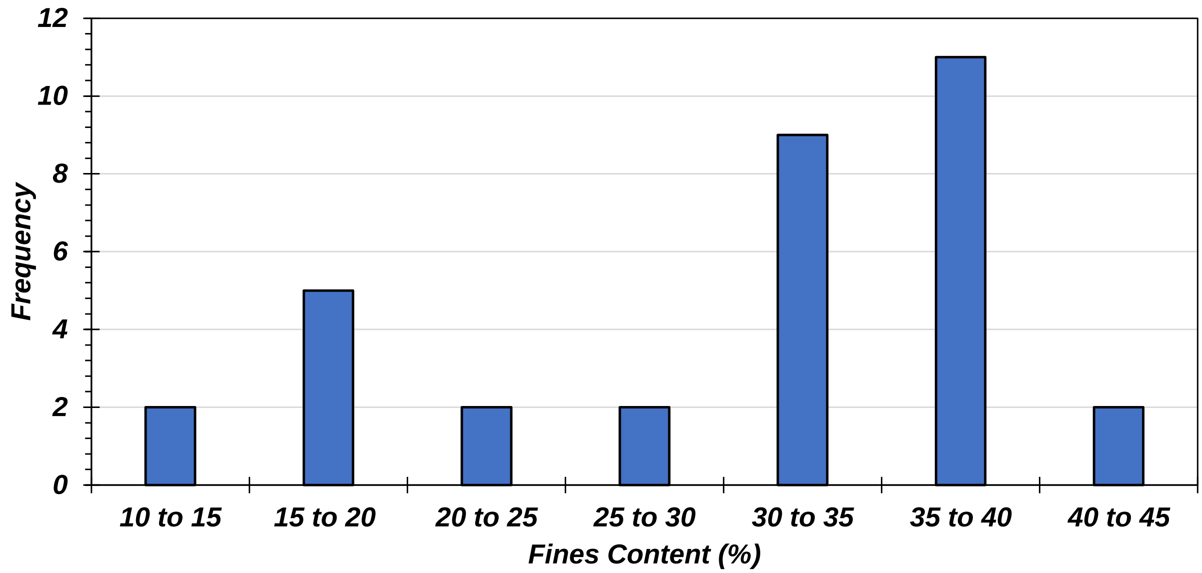

Figure 3.4 Fines content (in percent) beyond which the fine-grained fraction controls soil behavior (Poll Question #5).

With laboratory testing providing a potential means for characterization of liquefaction susceptibility of transitional soils, the conditions under which good quality "undisturbed" samples can be obtained is of interest. The attendees were asked to provide their view on the fines content above which good quality samples could be obtained. Figure 3.5 shows a very wide range of responses with fines contents ranging from nearly zero to 60%. The average fines content was approximately 30%.

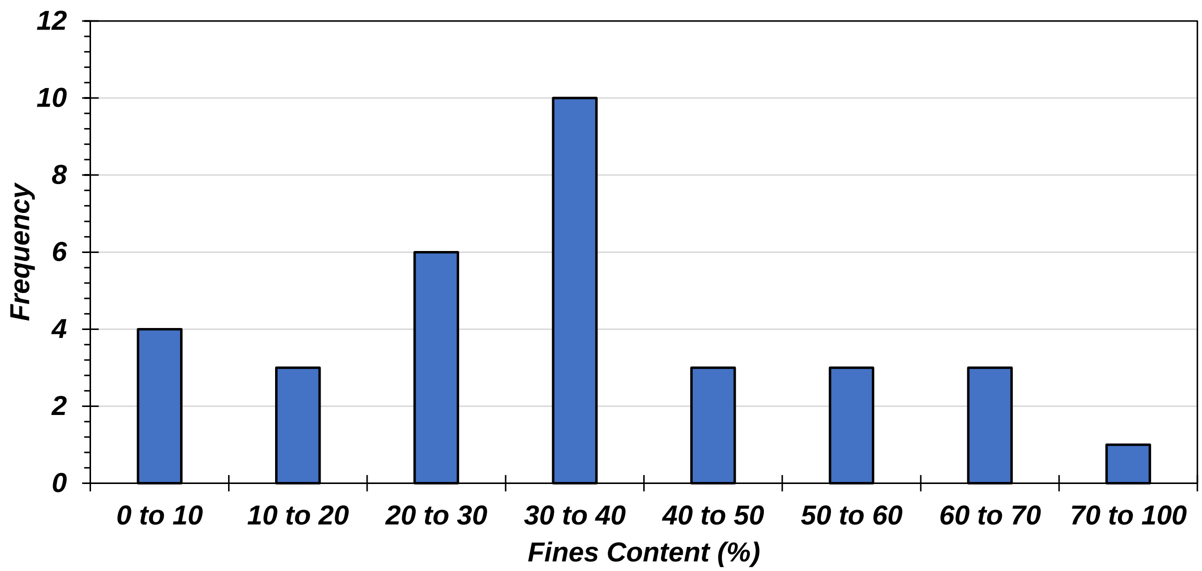

Figure 3.5 Fines content above which good quality undisturbed samples can be obtained (Poll Question #6).

Attendees were then asked a series of questions related to their views on how liquefaction susceptibility should be assessed and characterized. The responses to three of these questions are presented in Table 3.2. The responses show very clear preferences for probabilistic characterization of liquefaction susceptibility and for the use of geologic information and advanced laboratory testing in the assessment of liquefaction susceptibility.

Table 3.2 Responses to questions about susceptibility assessment and characterization.

Poll Question #11	Should susceptibility be characterized in a binary (yes/no) or probabilistic manner?	Binary	Probabilistic
		2	30
Poll Question #12	Should geologic information be quantified and used in liquefaction susceptibility assessment?	Yes	No
		26	7
Poll Question #14	Should advanced laboratory testing be used in liquefaction susceptibility assessment?	Yes	No
		33	0
Poll Question #18	Should NGL develop a database specifically for the study of susceptibility?	Yes	No
		27	5

Building on the previous questions, attendees were asked to state their opinions on the factors that susceptibility *should be* related to. A set of factors ranging from material characteristics, state, and cyclic behavior was provided and the respondents asked to indicate which of these factors susceptibility should be related to, with the option of indicating any and/or all that apply. The intent of this question was to gain insight into whether respondents believed that susceptibility should be treated as a material characteristic or as being influenced by state and environment. The responses, illustrated in Figure 3.6, did not provide much clarity with respect to the question's objective – many respondents checked multiple boxes with the apparent (and not unreasonable) thought that all information is helpful.

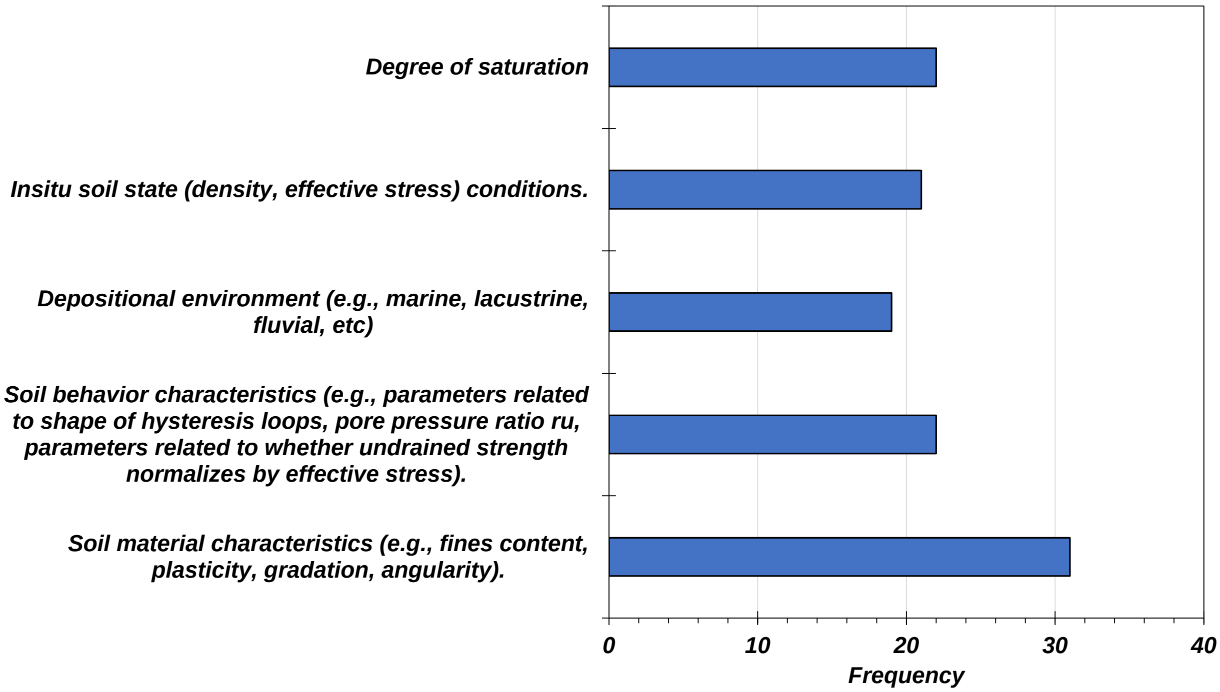

Figure 3.6 Factors that liquefaction susceptibility should be related to (Poll Question #10).

The preceding questions lent themselves well to a tabular summary of responses. Other questions were more open-ended and solicited written responses. The remainder of this chapter will summarize responses to those questions (indicated in **bold font**) in terms of broad categories of common responses supplemented in some cases by representative and/or interesting responses. The responses to all of the poll questions are provided in Appendix C.

How can geologic information be used in liquefaction susceptibility assessment (Poll Question #13)?

Most common responses included:

- By characterizing depositional environment;
- For characterizing soil variability/continuity;
- For constraint/guidance in probabilistic models; and,
- Only qualitatively.

Representative and/or interesting responses included:

- Evaluation of stratigraphic continuity and variability to assess the extent of liquefiable soils and liquefaction hazard, and guiding site exploration programs;
- Not sure, other than by crude correlation to nearby tested material. Factors like age are triggering factors, to me; and,

- Essentially as a "prior", i.e. before we even poke holes in the ground. This could be achieved using geospatial models for probability of susceptibility (similar to Zhu et al.'s global model for liquefaction probability).

How should advanced laboratory testing (e.g., test type: monotonic, cyclic; specimen types: reconstituted, intact) be used in assessment of liquefaction susceptibility (Question #15)?

Most common responses included:

- Cyclic favored over monotonic; both when possible;
- Intact samples favored over reconstituted; difficulty/expense of sampling noted; and,
- Cyclic simple shear favored over cyclic triaxial.

Representative and/or interesting responses included:

- A combination of monotonic and cyclic testing can be used to demonstrate whether the soil behavior will be sand like vs clay like. I think this type of testing is applicable for critical infrastructure projects and research efforts to develop more simplified relationships for use in general geotechnical engineering practice;
- Get the best samples possible with the soil type of interest. If good intact samples are not possible, reconstitute in manner that approximates actual depositional processes. Examine shapes of hysteresis loops, highest r_u achieved, tendency for dilation upon phase transformation, rate of stiffening upon dilation.
- The key is not whether testing would be useful, but how to incentivize/require it on routine (or not so routine) projects. If very few people are willing to pay for it, this discussion isn't very purposeful. The incentive should be worked out before the specific test details.

How should such tests be interpreted in terms of the potential for susceptibility (Question #16)?

Most common responses included:

- In terms of reduction of stiffness observed;
- In terms of excess pore pressure level reached in tests; and,
- In terms of shapes of hysteresis loops.

Representative and/or interesting responses included:

- The hysteresis loop at large strains is the single most important piece of information which can definitively establish the susceptibility to liquefaction;
- Significant stiffness reduction (near zero) under the anticipated seismic loads; and,

- Pore pressure generation, stiffness degradation characteristics with r_u, hysteretic behavior, and post-seismic tests should be evaluated and compared with established literature.

What information should Next Generation Liquefaction susceptibility models provide to the user that current models aren't providing now (Question #17)?

Most common responses included:

- Most comments mentioned need for the probability of susceptibility; and,
- Many triggering-related comments.

Representative and/or interesting responses included:

- Better understanding of transitional soil response and system response of a deposit that may have partial saturation or interlayering; probabilistic estimates and integration with triggering models and consequences;
- Three classes: susceptible, transitional, not-susceptible; and,
- A probabilistic liquefaction susceptibility model, material characteristics based, that is pegged to cyclic hysteresis behavior observed in the laboratory.

How can new technologies be applied to susceptibility assessment (Question #19)?

Most common responses included:

- Use machine learning;
- Improved sampling, *in-situ* testing; and,
- Use drones in reconnaissance to identify sites with and without manifestation.

Representative and/or interesting responses included:

- New technologies allow for better collection of large datasets and should be used for transparent dissemination of data. Using new technologies for more efficient collection and publication of geotechnical *in-situ* data should also be a priority;
- The development of a cheap, downhole (borehole?) based *in-situ* cyclic testing apparatus could improve the ability to establish liquefaction susceptibility;
- Perhaps machine learning could be used to parse out trends/material characteristics which give rise to certain hysteretic features; and,
- Develop a database with: (1) lab index tests; (2) I_c values from CPT; and (3) advanced testing. Perform advanced regression, perhaps including machine learning, to relate susceptibility to different indicators.

What do you view as the most significant challenge to advancing liquefaction susceptibility assessment (Poll Question #20)?

Most common responses included:

- Difficulty and cost;
- Collecting data needed for new models; and,
- Inertia – professional resistance to using new procedures.

Representative and/or interesting responses included:

- Complexity/uniqueness of soil composition;
- Being able to assess susceptibility in a way that is economically feasible for typical engineering projects;
- Utilizing multiple CPT-based criteria in a way that allows us to capture both aleatory variabilities and epistemic uncertainties; and,
- Settling on a clear definition of liquefaction susceptibility. Although we might consider a probabilistic treatment as convenient, this definition ought to be binary for maximum clarity given that liquefaction can either occur given sufficient loading intensity and duration, or not.

3.3 DISCUSSION

The pre-Workshop poll was successful in providing an indication of the thoughts and opinions of workshop participants prior to the Workshop. It effectively pointed out that the term "susceptibility" meant different things to different respondents. Most respondents appeared to consider susceptibility to be a function of material characteristics, but many use the term in relation to triggering considerations. However, the respondents also indicated a strong desire to have a clear and unambiguous definition of susceptibility.

The poll also confirmed the types of sites where susceptibility considerations are important but difficult to deal with: sites with transitional soils, sites with interbedded soil layers, and sites with gravelly soils. Each of these types are encountered frequently for large and small projects and the judgement of susceptibility can have significant consequences on project cost and schedule.

Responses to the poll indicated a strong belief that susceptibility assessment is fraught with uncertainty and there is a strong desire to see it characterized in a probabilistic manner. Geologic information and advanced laboratory testing were also viewed as having significant potential benefit for the assessment of liquefaction susceptibility. Finally, strong support was expressed for establishment of a susceptibility database that could be used to develop improved susceptibility models.

4 SCOPE AND SUMMARY OF DISCUSSIONS

4.1 SESSION 1: STATE-OF-PRACTICE AND LIMITATIONS

4.1.1 Overview

The seven presentations comprising the first session of this workshop aimed to describe the state-of-practice as well as its limitations. The first presentation by Professor Çetin (Middle East Technical University) provided an overview of available methods and approaches for predicting liquefaction susceptibility and was followed by six presentations from practitioners (private companies and federal agencies) who shared their experiences and solutions from projects that have featured challenging soils from a liquefaction susceptibility perspective.

Thomas Weaver (US Nuclear Regulatory Commission, NRC) described NRC regulations for liquefaction evaluation as provided in regulatory guide US NRC 2003 which includes liquefaction susceptibility criteria. Erik Malvick (Division of Safety of Dams, California Department of Water Resources) emphasized the complexities that gravels can pose in liquefaction evaluations and discussed the importance and challenges associated with completing adequate site characterizations including cyclic lab testing. Dr. Malvick cautioned against the use of statistical models without accounting for the quality of the data underpinning the models. Pedro Espinosa (ENGEO, Inc.) presented their experience with the assessment of liquefaction susceptibility of a natural shoal sand unit beneath the fills at Treasure Island. They found that currently available simplified procedures were unable to capture the behavior of these shoal materials, which instead were characterized using material-specific cyclic testing on high-quality samples. This general approach of performing high-quality material-specific cyclic testing to guide assessments of susceptibility was also described for various example sites in the Pacific Northwest by Sam Sideras (Shannon & Wilson, Inc.), Matt Gibson (Clarity Engineering, LLC), and Brice Exley (Haley & Aldrich, Inc.). In many cases, these projects have produced in situ data (CPT) and laboratory data that could be shared as part of a broader research exercise. Refer to the corresponding extended abstracts in Appendix B for additional information on these presentations and other relevant industry experience-based contributions.

The moderated discussion that followed the group breakout addressed participants' responses to four questions. The questions aimed to solicit the participant's opinions on the need to resolve issues of terminology and provide updated definitions, and the mechanics (hysteretic behavior) and/or methodologies (for assessment of susceptibility) that specific terms associated with susceptibility may or may not imply. The questions are presented below and are followed by a summary of the corresponding discussion.

4.1.2 Breakout Questions

1. Should the profession establish a clear and unambiguous definition of liquefaction susceptibility?
2. Should susceptibility be clearly distinct from triggering, i.e., should it be a function of soil characteristics and independent of factors such as soil state (relative density and effective stress), saturation, loading, and other environmental variables that influence triggering?
3. Should susceptibility be judged on the ability for triggering to occur at some state under some intensity of loading, or on the applicability/appropriateness of available/future liquefaction triggering models?
4. Based on your discussion in this breakout session, propose a clear definition of liquefaction susceptibility that has the potential to advance the state of practice.

4.1.3 Summary of Discussions

Workshop participants discussed the questions in a group setting for 60 minutes and reconvened to present their answers and then discuss.

Question #1: There was a broad consensus to establish a clear and unambiguous definition of liquefaction susceptibility. Most of the groups provided additional commentary on the need to also have a clear and unambiguous definition of the term “liquefaction”, which may be used in connection with strength loss due to pore pressure increase in sands, cyclic softening of clays, flow liquefaction, and cyclic mobility. Two groups pointed out the fact that while a delineation would be desirable, it also needs to be viewed within the context and scope of the evaluation or analysis performed. While simpler approaches might require clear terminology, advanced performance-based procedures that apply more advanced modeling of soil responses (e.g., time series of excess pore pressure or shear strain) might not. One group pointed out that ultimately, susceptibility and triggering criteria guide estimates of strength and subsequently inform the selection of the appropriate tools to assess the performance.

Question #2: There was also broad consensus that susceptibility and triggering should be distinct steps in a liquefaction evaluation, although most groups acknowledged that there had been debate regarding the role of seismic loading in drawing the distinction. Several groups proposed a two-step approach wherein: (1) compositional (i.e., material) factors are first accounted for and, if these factors dictate, then (2) environmental factors (soil state, saturation, age, etc.) are taken into consideration. The role of geologic history (through the overconsolidation ratio, aging and/or cementation, and fabric) was identified as a gray zone and could be viewed as either compositional factors or environmental/state factors. It was also noted that a given soil could exhibit different behaviors under different loading intensities. The need for defining triggering was also raised (e.g., is it 100% excess pore pressure ratio or 3% single amplitude shear strain?). The groups that viewed the need for clearly distinguishing susceptibility from triggering or even sequentially tracking composition, environment, and loading, pointed out that the distinction would be helpful towards establishing a probabilistic framework, and would accommodate future changes in design loads or in the perception of hazards overall. One group mentioned that in clearly established Simplified Methods like the CPT-based liquefaction triggering evaluation models, susceptibility and triggering are inherently linked, so there may not be a need to parse them out if one is working with soils that fit within the said methodology, unless the analysis is conducted within a performance-based design framework. However, data presented by several speakers in Session 3 (i.e., Professors Maurer, Moug, and Stuedlein) suggested that soils exhibiting hysteretic behavior or field performance that is associated with liquefaction exhibit a wide range in soil behavior type indices which commonly exceed typical thresholds (e.g., 2.6) selected to inform liquefaction susceptibility assessments. For performance-based design, separating the probability of susceptibility, triggering, and consequences is desirable, so as to explicitly account for the uncertainty in each of the models.

Question #3: The groups expressed diverse views on whether susceptibility of a soil should be judged based on: (1) the ability of the material to trigger irrespective of its current state and the anticipated shaking intensity (i.e., a material behavioral criteria), (2) the applicability or appropriateness of currently available or future liquefaction triggering models, or (3) whether the soil was likely to trigger given environmental factors (e.g., an unsaturated soil would be considered non-susceptible) or whether the consequences of liquefaction were likely to be significant (e.g., a dilatant soil would be unlikely to have large deformations). A point made in connection with option (3) was that susceptibility should not be judged as a function of loading because in some materials cyclic stress-strain loops can have very different shapes under strong vs. moderate imposed stress demands. Moreover, it was argued that if susceptibility is evaluated independent of loading, a cleaner parsing of uncertainties in liquefaction evaluations is possible (e.g., demand uncertainties would be independent of susceptibility uncertainties).

Question #4: Not all groups had the time to develop a definition of susceptibility. Three groups provided the following preliminary definitions, noting the challenge of the task:

- "*[Susceptibility is defined as] material composition that leads to behavior that looks like liquefaction.*" This definition was accompanied by the stated need to study what "looks like liquefaction" through research.
- "*[Susceptibility describes] screening based on material characteristics for soil that has the potential for liquefaction and develop rapid decrease of stiffness and large strain accumulation.*" This group mentioned that they attempted to also mention consequences of liquefaction in their definition, and that a definition of liquefaction would be necessary to implement this definition. The group also supported the development of a holistic framework set within a performance-based design paradigm.
- "*[Susceptibility describes the ability to develop] 100% r_u with instantaneous zero stiffness.*" This group admitted not reaching a consensus on the definition although they agreed on being specific about "susceptibility to *liquefaction*" or "*liquefaction* susceptibility" recognizing the breadth of soils exhibiting various [hysteretic]

behaviors and advocating to honor the potential soil behavior. The group also mentioned they were challenged in decoupling both loading and the types of analyses from the definition of susceptibility, implying that any definition of susceptibility should include a proposed type of analysis (or suite of analyses).

The presentation of the groups' answers was followed by an open discussion, largely focused on the considerations that should be included in a definition of liquefaction susceptibility (e.g., loading, potential consequences, etc.). By the end of this session, it became apparent that a source of confusion is that for some, "susceptibility" means whether or not a soil can liquefy under certain conditions, while for others it means whether a soil is *likely* to liquefy. A summary of the discussion follows, grouped anachronistically by general theme.

Initially, Professor Idriss (University of California, Davis; retired) emphasized the need to define liquefaction before defining susceptibility, and later on proposed that one should not worry about the consequences of a certain behavior but rather about the likelihood for that certain behavior to occur. Professor Scott Brandenberg (University of California, Los Angeles) made two related points (1) susceptibility is a fundamental soil response that should be evaluated probabilistically and not in a binary manner and (2) susceptibility should be distinguished from screening, which is mainly related to anticipated performance (e.g., a structure on dense sand could pass a screening criterion even though the soil is susceptible). Professor Jonathan Bray (University of California, Berkeley) argued that the mechanical behavior of a soil and its consequences should be of most importance in judging susceptibility. Professor Scott Olson (University of Illinois) also argued that the soil properties that one seeks to define depend on the consequences one expects and that consequences need to be tied into susceptibility, particularly because there are different consequences for soils with different composition and states. Professor Brady Cox (Utah State University) promoted adopting a more holistic approach wherein one views the whole profile instead of any one layer, and defining the limit of appropriateness for simplified approaches and corresponding analyses instead of defining a soil as susceptible. Professor Laurie Baise (Tufts University) suggested that liquefaction susceptibility be defined within a geologic perspective which contributes a different scale that becomes important when considering the risk to infrastructure.

A group of participants made a motion suggested to move past the term "susceptibility". Professor Pedro Arduino (University of Washington) proposed defining something different that would be applicable to a broader range of soils, such as quick clays, removing the word "liquefaction" so that the "susceptibility" could represent universal application. Professor Ross Boulanger (University of California, Davis) was in favor of moving past "liquefaction susceptibility criteria" and focusing on the question of how one will obtain material properties, specifically strength, cyclic strength, and post-earthquake strength. Towards this end, he proposed the terms "cyclic strength evaluation criteria" or "cyclic mobility criteria", with multiple criteria which can complement one another in the various stages of an analysis.

Dr. Matt Gibson (Clarity Engineering, LLC) proposed to include considerations related to loading and consequences in the derivation of susceptibility, in order to provide usable advice to clients.

Dr. Andrew Makdisi (US Geological Survey) communicated a concern regarding practitioners with less experience or who deal infrequently with advanced analyses, and their potential reception of more complex definitions and approaches. Professor Jon Stewart (University of California, Los Angeles) argued that current practice suffers from ambiguity in the definition of susceptibility and from the lack of clear and consistent guidelines for its assessment. He suggested that this effort provide clarity by putting forward a material behavior-based definition, indicating that consequences and susceptibility need not be coupled because consequences should be addressed in subsequent stages of a liquefaction risk assessment. Professor Steve Kramer (University of Washington) discussed that from a practical standpoint, having a base definition of susceptibility should come with a set of screening criteria against triggering (e.g., saturation, high densities) so that unnecessary sophisticated analyses can be avoided. In this context, a soil can for example be called "susceptible, but unlikely to liquefy".

The Session 1 discussion substantiated the clear need for conducting the Workshop in view of the lack of consensus on some fundamental aspects of how susceptibility is defined and applied in projects.

4.2 SESSION 2: WHERE DO WE WANT TO BE IN 5 TO 10 YEARS? MODEL DEVELOPMENT, RESOURCE NEEDS AND GAPS

4.2.1 Overview

The focus of Session 2 was to identify improvements in assessing liquefaction susceptibility and its implementation that the profession would ideally achieve in the next 5 to 10 years. Six presenters provided their perspectives on this prompt.

Professor Shideh Dashti (University of Colorado, Boulder) described her vision to incorporate a spectrum of soil behaviors into systems level triggering and consequence models, highlighting a need to separate performance within the profile from surface manifestation and the need for additional case histories, centrifuge experiments, and numerical simulations. Professor Jonathan Bray (University of California, Berkeley) shared lessons learned from liquefaction of silty soil observed in Adapazari, Turkey following the 1999 Kocaeli earthquake and in Christchurch, New Zealand following the 2010-2011 Canterbury Earthquake Sequence, including his recommendations to test soil that can be sampled effectively and to consider depositional environment and soil system response. Professor Dharma Wijewickreme (University of British Columbia) presented a particle fabric imaging technique intended to understand the shear response of silts, indicating that X-ray tomography can provide knowledge about the particulate fabric that could improve our understanding of complex silt behavior.

Professor Laurie Baise (Tufts University) presented global geospatial liquefaction models that provide regional susceptibility evaluations that could be incorporated into local liquefaction assessment as a prior and then updated in a Bayesian framework with local geotechnical information. Dr. Christine Beyzaei (National Institute of Standards and Technology) shared her recommendations for developing susceptibility models to include quantitative site-specific methods and qualitative regional methods, including the development of easily accessible susceptibility maps for each state and more widely available interactive databases of borings and CPTs. Dr. Andrew Makdisi (US Geological Survey) outlined his workflow to incorporate uncertainty in susceptibility criteria into probabilistic liquefaction hazard analysis and highlighted research needs including better estimates of uncertainties at all stages (i.e., susceptibility, triggering, and effects). Refer to the corresponding extended abstracts in Appendix B for additional information on these presentations and other relevant contributions.

Following the presentations, attendees participated in a breakout activity and a moderated discussion. During the breakout activity, workshop participants were invited to respond to questions that were developed as a follow-up to the responses of the pre-workshop poll (Chapter 3; Appendix C). These questions encouraged the participants to consider what liquefaction susceptibility models should be like in the next 5 to 10 years. The questions are presented below, and are followed by a summary of the corresponding moderated discussion.

4.2.2 Breakout Questions

1. Do you agree that liquefaction susceptibility should be incorporated into liquefaction hazard analysis in a probabilistic manner?
2. Do you agree that geologic information should be quantified and incorporated into liquefaction susceptibility assessment?"
3. How can geological information be used?
4. Separating the idea of liquefaction susceptibility from liquefaction triggering and its consequences, what factors should future liquefaction susceptibility models consider (check all that apply)?
5. Which existing and new technologies for the improvement of liquefaction susceptibility assessment hold promise (check all that apply)?

Question #1: This question is similar to Question #11 from the pre-Workshop poll (Appendix C), which asked "Do you agree that liquefaction susceptibility should be incorporated into liquefaction hazard analysis in a probabilistic manner?" One of the purposes of asking this question again was to see if the presentations and discussions in Sessions 1 and 2 had changed participants perspectives on this topic. The responses of the participants after the Session 2 presentations are shown in Figure 4.1. A strong majority of attendees agreed that liquefaction susceptibility should be incorporated in a probabilistic manner (32 compared to six), similar to views communicated within the pre-Workshop poll (30 compared to two).

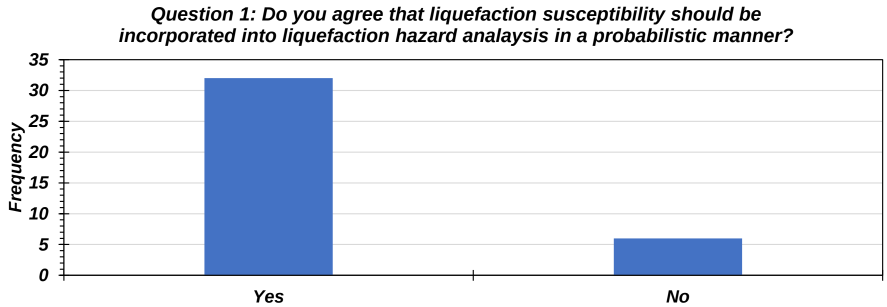

Figure 4.1 Participants' responses to Question #1 during the Session 2 breakout.

Question #2: Some of the presentations during Session 2 addressed the need to incorporate types of information other than site-specific geotechnical data, such as geologic and geospatial information. To assess the participants' perception of the usefulness of geological data, Question #2 asked "Do you agree that geologic information should be quantified and incorporated into liquefaction susceptibility assessment?" This was essentially the same question as Question #12 in the pre-Workshop poll (Appendix C). The participants' responses during the breakout activity are documented in Figure 4.2. In both the pre-Workshop poll and during the breakout activity, it was nearly unanimous that geologic information should be quantified and incorporated.

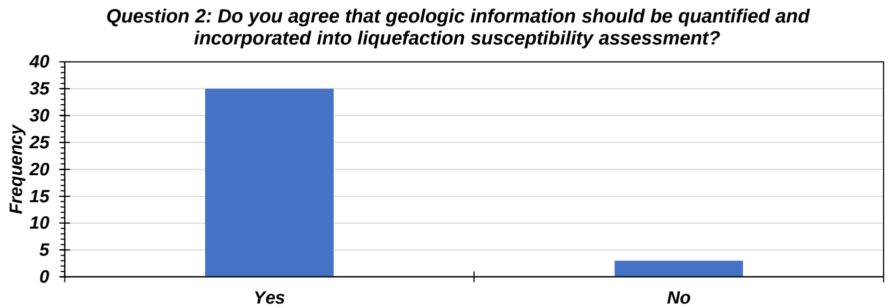

Figure 4.2 Participants' responses to Question #2 during the Session 2 breakout.

Question #3: This question followed up on the second question by asking "How can geological information be used?" Four separate options were provided with the responses shown in Figure 4.3. This question was asked in an open-ended manner in Question #13 of the pre-Workshop poll (Appendix C), and the responses to that pre-Workshop question guided the options provided in Question #3 of the breakout activity. The majority of participants stated that they strongly or very strongly felt that geologic age and geologic information or depositional environment could be used. Many also agreed that geologic information is useful for interpolation or extrapolation. The responses were somewhat more diverse, however, when asked if geologic information was useful when correlated to field or laboratory test results. Many expressed "very strong" agreement with this statement, but there was a nearly uniform distribution across the "low," "moderate," and "strong" responses.

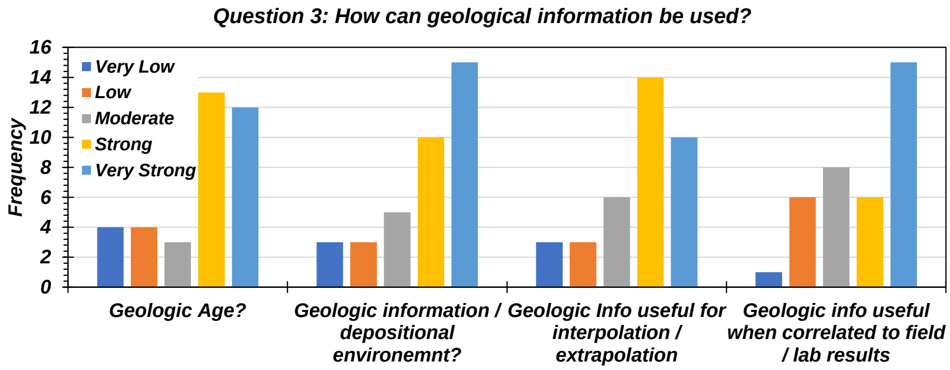

Figure 4.3 Participants' responses to Question #3 during the Session 2 breakout.

Question #4: This question asked the participants: "Separating the idea of liquefaction susceptibility from liquefaction triggering and its consequences, what factors should future liquefaction susceptibility models consider (Check all that apply)?" The list of factors given as optional responses were selected based on responses to Question #3 from the pre-Workshop poll (Appendix C). The responses generated during the second breakout session are presented in Figure 4.4. Plasticity (e.g., plasticity index, *PI*) received the strongest support from the participants. Other factors received moderate support, such as (in order of most to least votes) probability of susceptibility, CPT data, fines content, cementation, probabilistic range of a given predictor variable, mineralogy, and degree of saturation. Clay content and clay activity were selected by a few participants, but generally received little support from most participants, given that these properties are correlated with *PI*.

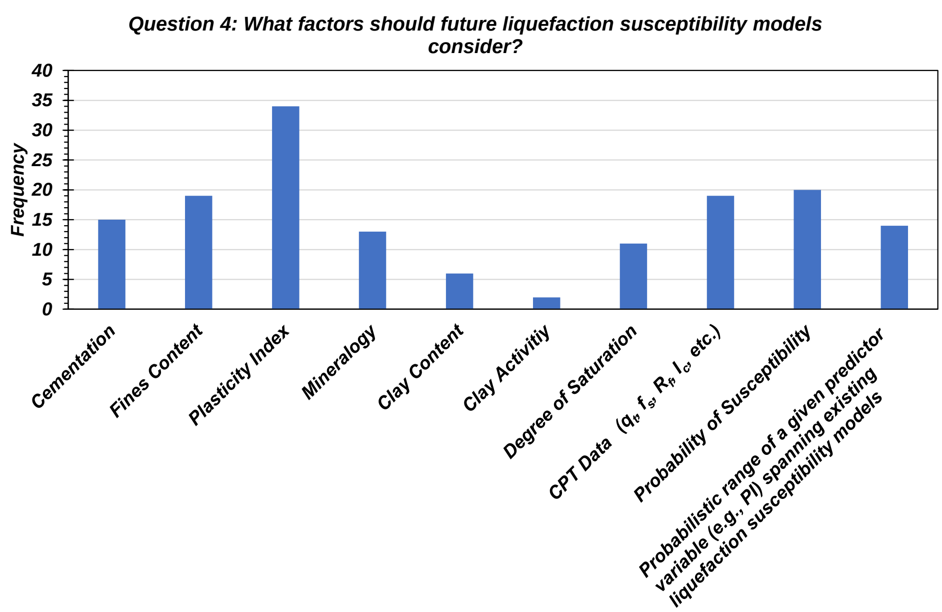

Figure 4.4 Participants' responses to Question #4 during the Session 2 breakout.

Question #5: This question asked the participants to consider a list of existing and new technologies for the improvement of liquefaction susceptibility assessment and to identify "Which do you think hold promise (check all that apply)?" Some of the existing and new technologies that were proposed in this question were selected from the responses to Question #19 from the pre-Workshop poll. The participants' responses are shown in Figure 4.5. The top four technologies that received the most votes, in order of most to least votes, are: (1) improved sampling methods to obtain higher (highest) quality samples, (2) laboratory cyclic testing for the quantification of hysteretic behavior, (3) machine learning/artificial intelligence and/or logistical regression, and (4) X-ray tomography to quantify soil fabric.

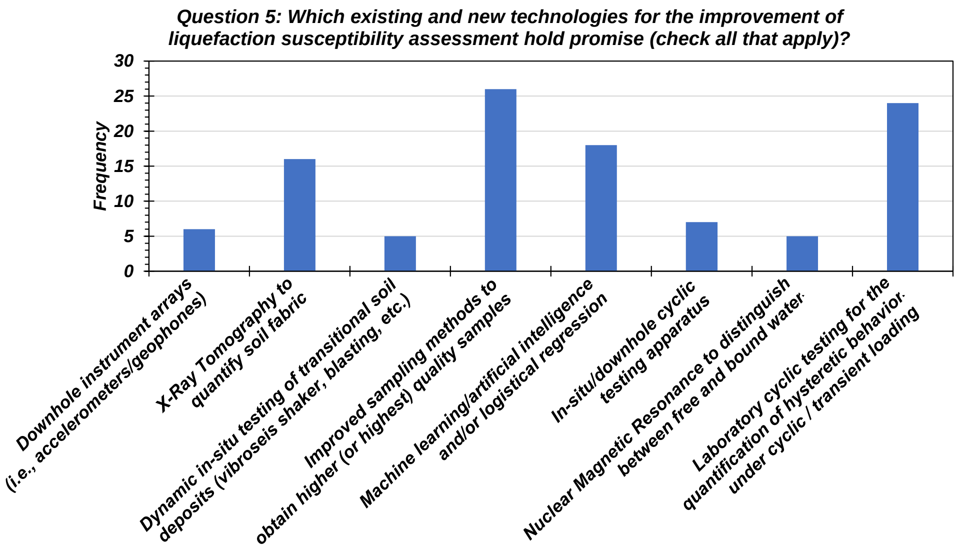

Figure 4.5 Participants' responses to Question #5 during the Session 2 breakout.

4.2.3 Summary of Discussions

During the moderated discussion, the results of the poll questions during the breakout activity were displayed on the screen for participants to review and discuss. Those in the minority who responded "No" to Question #1 regarding the need for incorporating susceptibility in a probabilistic manner were invited to share their perspective. One participant stated that from their perspective, the "susceptibility" question is related to choosing an appropriate analysis to estimate strengths. According to this participant's view, tracking the uncertainties associated with the estimated strengths is appropriate whereas tracking the uncertainty related to the decision of a suitable type of analysis is not appropriate. Another participant said that they had originally answered "Yes" in the pre-Workshop poll, but then answered "No" during the breakout activity, citing a similar concept: if the "susceptibility" question is a decision about an appropriate analysis to use (e.g., a semi-empirical simplified approach for soils with sand-like behavior) then perhaps a probabilistic approach would not be helpful.

This led to a discussion about the perceived differences and/or similarities between the Boulanger and Idriss (2006; B&I06) and Bray and Sancio (2006; B&S06) models. One author from each of these studies, Professor Ross Boulanger (University of California, Davis) and Professor Jon Bray (University of California, Berkeley), shared their perspectives. A summary of their statements is provided below, and an interpretive commentary on this discussion by the OC is provided in Section 5.3.

- Professor Boulanger: The B&I06 model was intended to define: (1) which soils could be analyzed using case history-based relationships using similar soils ("sand-like" soils that can undergo "liquefaction") vs. (2) which soils could be confidently sampled and tested in the lab and should be analyzed for undrained strengths using the suite of methods currently available ("clay-like"). The transition zone between these two categories should be sampled and carefully considered to decide which analysis methods to use. He proposed separate names for the B&I06 and B&S06 criteria, rather than apply the term "susceptibility" to the models.
- Professor Bray: The B&S06 criteria were intended to be used to identify which soils have similar stress-strain curves to soils that "liquefy." The criteria were intended to assess the engineering response of such soils within a strength-based approach near buildings interacting with soil.
- Both agree that sand-like soils cannot be confidently sampled (without expensive and rare procedures like *in-situ* soil freezing and coring) and tested in the laboratory, which means that these criteria are necessary to identify which soils could be analyzed using simplified procedures for sand-like soils. They both agree that B&I06 and B&S06 models are not fundamentally the same.

One comment in response to this discussion was that these differences appear at face value to be more qualitative than quantitative, which can be more difficult for practicing engineers to accommodate in quantitative ways (e.g., weighting each method). Others commented that the lines between "susceptibility," "liquefaction," and "manifestation" were appearing blurry given some example scenarios (e.g., sites in Adapazari, Turkey) where ground deformation was not observed in the free field but was observed under buildings which imposed additional static shear, reflecting a need to carefully distinguish what components of liquefaction evaluations should be considered in each step.

In response to Questions #2 and #3 of the breakout activity (Figures 4.2 and 4.3), several attendees generally agreed that additional information such as geological and geospatial data is helpful in assessing susceptibility. However, the discussion did not yield specific suggestions of what information to use or what is most impactful in assessing liquefaction susceptibility. There was relatively little discussion related to the responses to Question #4 regarding the factors that future susceptibility models should consider. One participant wondered why participants chose fines content, and how they would describe the fundamental aspect of fines content in liquefaction susceptibility. In response, another participant cited that the fines content determines whether coarser or finer fractions dictate the soil behavior. The applicability of the factors proposed in Question #4 were discussed in presentations during Session 3 on the following day (e.g., Professors Maurer, Moug, and Stuedlein).

A participant asked whether efforts should focus primarily on high-end engineering practice that is performed somewhat rarely (e.g., using sophisticated cyclic laboratory tests) vs. relatively routine practice that uses simplified procedures without cyclic laboratory tests. This aspect was also explored by participants in the moderated discussions of Sessions 1 and 3. Another participant suggested that it might be helpful to distribute the pre-Workshop poll to a broader audience to gather feedback from a larger sample size.

There was relatively little discussion related to Question #5 about promising technologies for improving susceptibility assessments. However, it is interesting to note that Professor Wijewickreme's (University of British Columbia) presentation on X-ray tomography may have generated some new interest, as this technology was listed in the top four factors that future liquefaction susceptibility models should consider. There was also some detailed discussion during the moderated breakout for Session 3 about sampling techniques to obtain high quality samples, which was one of the options provided in response to Question #5.

4.3 SESSION 3: OPPORTUNITIES FOR SYNTHESIZING LABORATORY- AND FIELD-BASED OBSERVATIONS

4.3.1 Overview

The six presentations comprising the third session of this workshop ranged from CPT-based interpretations of susceptibility viewed through the lens of critical state soil mechanics, field observations following earthquakes, linkage of laboratory-based observations of cyclic responses to CPT- or dynamic, *in-situ* testing, and linkage of liquefaction susceptibility criteria (or alternatively, criteria for cyclic strength evaluation) to the estimation of cyclic strength for assessment of deformations (i.e., consequences).

Professor Scott Olson (University of Illinois) kicked off the third session by presenting a framework for performing consequence-based susceptibility assessments derived using CPT data, using the Δ_Q approach (Saye et al. 2017). This framework treats soils as susceptible or insusceptible to specific ground failure mechanisms through consideration of both material characteristics and soil state. Professor Olsen identified preliminary limiting boundaries for flow liquefaction, lateral spreading, and post-liquefaction settlement through CPT-based compressibility-adjusted normalized cone tip resistance. Professor Diane Moug (Portland State University) leveraged a recently-developed database of cyclic laboratory test data on transitional soils from sites for which CPTs are also available. She identified the central tendency and dispersion of cyclic resistance ratio of the silt specimens in the context of normalized cone tip resistance-based liquefaction triggering and cyclic softening curves. This work clearly identified that the soils exhibiting sand-like and "transitional" hysteretic behavior can exhibit a very wide range of soil behavior type indices, I_c, which exceeded 2.95 in some cases. Professor Brett Maurer (University of Washington) used insights gained from the assessments of case history data from the 2010-11 Canterbury Earthquake Sequence in Christchurch, NZ to address questions related to: (1) the link between I_c and liquefaction susceptibility, and (2) the role of increased information (fines content, PI, etc.) on improved susceptibility assessments. Professor Maurer concluded that material characteristic-based assessments of susceptibility (e.g., using Atterberg limits) may provide different predictions of susceptibility than the soil behavior type index, and that an $I_c = 2.6$ provides a reasonable median (i.e., probability of occurrence of 50%) threshold for liquefaction susceptibility of Christchurch soils. However, he cautioned that the relationship between I_c and susceptibility is uncertain, and its uncertainty appears to be greater than what is commonly appreciated.

Professor Ross Boulanger (University of California, Davis) led the next set of three presentations. He suggested that available liquefaction susceptibility criteria serve different purposes, with the B&I06 criteria intended to be used to map the outcome of the liquefaction susceptibility assessment to the appropriate means for determining or estimating cyclic strength. See Chapter 4.2.3 for an in-depth summary of the discussion related to this viewpoint. Professor Scott Brandenberg (University of California, Los Angeles) presented a series of cyclic direct simple shear (CDSS) test results of three fine-grained soils with similar *PI* (8 and 9) but differing amounts of certain clay minerals and salinity. He showed that: (1) the shapes of stress-strain hysteresis loops and the rate of strain accumulation with the number of cycles provides the most insight regarding the potential for sand-like and clay-like behavior, and (2) straight and parallel critical state lines (CSL) and normal consolidation lines (NCL) provide another means for determining hysteretic behavior (parallel indicating clay-like, non-parallel indicating sand-like). Professor Armin Stuedlein (Oregon State University) closed the third session of presentations by providing examples of the ultimate hysteretic behavior obtained from CDSS tests on a large number silt soils. This data was used to identify general ranges in both hysteretic metrics and *PI* for which soil might be categorized as sand-like and clay-like. Those ranges are in general agreement with the B&S06 criteria, as summarized in Stuedlein et al. (2023), and use of ultimate hysteretic metrics was justified in view of the large number of cycles of loading associated with the Cascadia Subduction Zone. Refer to the corresponding extended abstracts in Appendix B for additional information on these presentations and other relevant contributions.

The group breakout session immediately following these presentations was designed prior to the Workshop and intended to follow up on themes addressed in the presentations with a focus on data resources that could be leveraged by the NGL Project. The moderated discussion that followed the group breakout addressed participants' responses to six questions. The questions are presented below and are followed by a summary of the corresponding discussion.

4.3.2 Breakout Questions

1. Given your experiences with the pre-Workshop poll and the discussion at this Workshop, has your opinion of how susceptibility should be defined changed or evolved, and if so, how?
2. Discuss the definitions of liquefaction susceptibility proposed yesterday. Rank the definitions in terms of most helpful (i.e., Rank 1) for providing clarity to the state of practice, with or without modifications as your group sees fit.
3. What currently determinable soil characteristics and behaviors are most suited to support judgments of liquefaction susceptibility? What aspects of transitional soil behavior in cyclic tests should be used to judge their susceptibility? How should susceptibility criteria based on laboratory tests be formulated?
4. Should one type of parameter (e.g., CPT I_c) always be backed up with measurements of another (e.g., PI, w_c/LL)?
5. If a database were to be developed to support the development of new, potentially probabilistic, susceptibility models, what information should be included in that database?
6. What could a probabilistic liquefaction susceptibility model look like (e.g., continuous distribution, or discretized into ranges of susceptibility from low, moderate to high) and how would it be informed? Consider for example your level of confidence in CPT-based parameters (e.g., I_c, etc.) relative to index test-based parameters (e.g., PI).

4.3.3 Summary of Discussions

Question #1: This question "…has your opinion of how susceptibility should be defined changed or evolved, and if so, how?" sought to identify how the discussions in the Workshop may have resulted in a shift in the perception of liquefaction susceptibility determinations. One of the groups concluded that whereas prior to the Workshop, they generally felt that susceptibility determinations should be linked to cyclic strength estimation, they now generally felt that susceptibility should be decoupled from assessments of cyclic strength. Another group reflected upon the need for clarity in communication of how a project-specific determination of liquefaction susceptibility will or has been made. This suggestion stemmed from the nuances in liquefaction susceptibility assessment identified over the course of the Workshop. Another group concurred with the need for clarity in communications of susceptibility determination given the critical role of susceptibility determinations in practice.

Question #2: The second question anticipated participants desire for a clear definition of liquefaction susceptibility and attempted to identify a potential consensus on a definition. The first group to report their findings indicated that it was challenging to rank the liquefaction susceptibility definitions, let alone to define liquefaction susceptibility, within the time available at the Workshop. However, this group felt that developing a clear definition is a critical need. At least one other group concurred with this sentiment.

Question #3: Participants identified the plasticity index as the most readily determinable soil characteristic to begin an assessment of liquefaction susceptibility. The water content to liquid limit ratio was also identified as contributing information to liquefaction susceptibility, although it was recognized as largely being associated with soil state (e.g., loose or dense of the critical state) rather than a material composition-type variable. Participants identified the quantification of metrics of the hysteresis of cyclic test data (e.g., maximum excess pore pressure ratio, minimum tangent shear modulus, and other variables described by Professors Bray and Stuedlein) as adding potential value to objective assessments of ultimate cyclic behavior. It was recognized however that cyclic testing was expensive and largely justifiable for a small percentage of typical projects. Participants from industry commented on the need for government and regulatory agencies to drive what is important in liquefaction susceptibility and cyclic strength evaluation criteria.

An example provided during this discussion is that what may be important for a department of transportation may not be as relevant to an agency responsible for regulating dam safety. The range in possible design guidelines or codes which address liquefaction susceptibility (and perhaps more generally, liquefaction assessment), some with respect to performance-based design, were identified by industry consultants to include:

- ASCE 7 - Minimum Design Loads for Buildings and Other Structures;
- ASCE/SEI 41 - Seismic Evaluation and Retrofit of Existing Buildings;
- ASCE 61 - Seismic Design Standard for Piers and Wharves; and,
- Department of Transportation Geotechnical Design Manuals (e.g., WSDOT).

Question #4: The fourth question intended to identify the need for using interrelated variables obtained through disparate means (i.e., “should one type of measurement always be accompanied by another?”). The discussion groups appeared to uniformly agree that assessments of liquefaction susceptibility should always include disparate measurements of composition (e.g., CPT-based soil behavior type index and the plasticity index). One of the driving reasons for this sentiment appeared to be associated with the need to assess the spatial variability of the various strata at a given site, typically achieved using relatively inexpensive CPTs, the information of which can be interpreted through the lens of soil indices (e.g., Atterberg limits) obtained from generally more sparsely distributed soil samples which require relatively expensive drilled boreholes. Participants pointed to the findings presented earlier in the session, which in aggregate identified strong regional discrepancies between the CPT-based soil behavior type index and either inferences of liquefaction from observations of case histories (Professor Maurer) or the results of cyclic laboratory tests (Professor Moug and Professors Stuedlein and Evans). Specifically, relatively strong correlation of the soil behavior type index and plasticity index to observed/lack of observed manifestation of liquefaction in Christchurch, New Zealand, was noted by Professor Maurer (University of Washington), whereas trends between CPT q_c and cyclic resistance by Professor

Moug (Portland State University) and between CPT I_c and hysteretic metrics quantifying degrees of strength and stiffness loss in cyclic direct simple shear tests by Professors Stuedlein and Evans (Oregon State University) for the transitional soils of the Pacific Northwest could not be established. In particular, I_c approaching and exceeding 2.95 were identified as exhibiting transient loss of stiffness and excess pore pressure ratios of 100% in laboratory test results (Professors Stuedlein and Evans). Finally, participants noted the potential for using multivariate analyses to reduce the uncertainty in the probabilistic assessments of liquefaction susceptibility which are beginning to appear in various publications.

Question #5: The fifth question related to the desired data types for a database that could be used to develop new liquefaction susceptibility models including, for example, the probability of a material being susceptible to liquefaction. The consensus of the participants is that such a database ought to include as many types of information as is possible for the exploration and laboratory test programs associated with a typical project, including but not limited to:

- Water content;
- Atterberg limits;
- Grain size distributions;
- Estimates of, or quantified, mineralogical composition;
- Assessments of age and cementation;
- Oedometric and constant rate-of-strain compression data and indices;
- Monotonic undrained shear strength;
- Cyclic stress-strain curves and post-cyclic undrained shear strength;
- Post-cyclic strength and deformation;
- Penetration resistance (SPT, CPT);
- Shear wave velocity;
- Measurements representing sample quality (e.g., reconsoldiation volumetric strains, compression ratio indices, shear wave velocity) and quality assessment designations;
- Latitude and longitude of explorations; and,
- Groundwater depth and/or elevation.

One discussion group emphasized the need for the provision of an entire record of the testing program, including the protocols used for preparing specimens, conducting the tests, and checks on saturation where truly undrained tests are conducted (e.g., Skempton's pore pressure parameter B). Another discussion group emphasized the need to report the entire dataset including time series of a particular test, which likely include several stages (consolidation, cyclic testing phase, post-cyclic testing phase) for completeness and to understand the history of a given specimen. The need for ensuring the longevity of any such database was identified by participants; that is, steps necessary to ensure that the data doesn't simply vanish from an online repository or become obsolete through updates/versioning of the supporting platform would be critical. Likewise, the need to minimize the complexity of any given database was identified as critical for improving the longevity of a database. Another participant circled back to the need for providing "flags" to database entries to clearly distinguish the particular region from which any given data originated due to the obvious differences in material responses to transient/cyclic loading presented by speakers earlier in the session.

The idea of limiting access to a database to those who made contributions to such a database was raised by a participant following reflection on the structure of the New Zealand Geotechnical Database (http://www.nzgd.org.nz/). This geospatial database of geotechnical exploration data requires that any user accessing the database contribute new subsurface information developed following the access to the database. Members of the NGL database thought that such restrictions may be difficult to impose and manage.

An industry participant commented on the need for the development of guidance on drilling, sampling, and laboratory testing of transitional soils. This comment elicited a fairly comprehensive discussion of the drilling, sampling, and handling protocols used alternatively in the post-Canterbury Earthquake Sequence investigations (Professor Bray; University of California, Berkeley) and those implemented for the regional study of transitional soils in the Pacific Northwest (Professor Stuedlein; Oregon State University). Professor Bray suggested that the protocols used by various research teams be posted to the PEER website as a starting point for practitioners, and that the protocols used could be compared and compiled in a guidance document following acquisition of PEER funding. Participants roundly endorsed this potential future activity.

Question #6: The final question discussed by the workshop participants related to the possible composition of a future probabilistic liquefaction susceptibility model. One discussion group noted that it was necessary to account for the uncertainty of a given variable in such a model (e.g., spatial variability and measurement error in *PI*) as well as epistemic uncertainty in the model. One participant suggested a probabilistic liquefaction hazard analysis (PLHA) framework which treated susceptibility criteria (or models) as a branch in a logic tree, which could be weighted according to a variety of factors, including the epistemic uncertainty of each susceptibility model, and incorporated into the larger PLHA outcome. Discussers noted that the intent of a given probabilistic liquefaction susceptibility model would need to be clearly stated so that an end user would have an appropriate context for the potential use and interpretation of such a model.

Closing Remarks: Professor Idriss closed out the session and the Workshop with observations on the presentations and discussions, noting both the critical importance of the Workshop as well as the struggles of many participants to define liquefaction susceptibility. Reflecting on the need for professional responsibility for design of a given structure, Professor Idriss identified the assessment of susceptibility as a significant concern, noting that the charge of the engineer is to assess the risk of a given facility exhibiting unacceptable performance, if the facility is subjected to a shaking intensity sufficiently large to result in unacceptable performance. Regarding the question on how to quantify the risk of unacceptable performance, Professor Idriss suggested that susceptibility should assessed in terms of "What is the susceptibility of the material to a particular performance?" and "What are the properties we need to describe that material?" At the same time, Professor Idriss noted the usefulness of the B&I06 criteria as it points to the specific purpose of the criteria, namely, determining engineering procedures for estimating cyclic resistance, as well as the B&S06 criteria, which is focused on the displacement potential. Professor Idriss concluded by noting that the discussions in this session emphasized the need to have this Workshop, but also the need to continue to meet in such a manner to continue working through the complexities of liquefaction susceptibility assessment.

5 INTERPRETATION OF KEY ISSUES

5.1 NEED FOR A DEFINITION OF LIQUEFACTION SUSCEPTIBILITY

Both the pre-workshop poll and the discussions during the workshop indicated a wide range of interpretations of the term "susceptibility." While both the plenary and breakout session discussions established a clear need for such a definition, these discussions did not converge to a consensus on what it should be.

The interpretations of susceptibility appeared to fall into two primary camps: one based on inherent material characteristics (independent of soil state and other environment-related characteristics), and one that included triggering- and/or consequence-related considerations, such as the likelihood of observing surface manifestation in different forms. One presentation, for example, suggested the development of different consequence-based susceptibility indices for flow failure, lateral spreading, and post-earthquake settlement. Some participants also suggested that the term "susceptibility" not be used and that hazard assessments involving potentially liquefiable soils move directly to triggering analyses and the models that should be used to evaluate them.

Some of the differences in susceptibility interpretations resulted from the colloquial use of the term in common language; examples of explaining susceptibility to non-technical people such as managers or the general public were given. The material-based interpretation of susceptibility is, in broad terms, based on the possibility of the material liquefying, whereas the consequence-based interpretation suggests its likelihood. The Oxford dictionary defines susceptibility as "the state or fact of being likely or liable to be influenced or harmed by a particular thing." The concept of likelihood implies a degree of conditionality upon loading, saturation, soil state, etc., in order for that influence to actually occur.

A few issues generated considerable discussion during the workshop but did not lead to a consensus among the workshop participants. These issues were discussed by the Workshop Organizers and authors of this report, with input from select Workshop participants, following the Workshop. This chapter represents the authors' interpretation of the discussion of these issues, which are offered in the spirit of clarifying the issues and identifying paths forward to the development of improved models for characterization of liquefaction susceptibility. The authors' interpretations and recommendations provided herein are examples of possible paths forward and do not represent a consensus decision reached during the workshop.

5.2 HOW SHOULD SUSCEPTIBLITY BE DEFINED

Recognizing the differences in procedures and the limited data upon which current susceptibility models are based, the majority of workshop participants indicated a desire for future liquefaction susceptibility models to be expressed in a probabilistic form (30 of 32 in the pre-Workshop Poll, Section 3.2; 32 of 38 in Breakout Session #2, Section 4.2.2). Such a form would also be compatible with the further development of a performance-based framework for liquefaction hazard assessment. Since its inception, PEER has developed, refined, and implemented procedures for performance-based earthquake engineering (PBEE; Deierlein et al 2003). The PEER framework, formalized through its well-known “triple integral,” is fundamentally probabilistic in nature and assumes a Markovian independence between ground motion intensity, engineering demand, physical damage, and loss. In this framework, demands are related to ground motion intensity measures, damage is related to engineering demand parameters, and loss is related to damage measures. The framework is modular, and its components can be updated and improved independently. PEER’s PBEE framework is being used in the development of new performance-based design and assessment procedures and there is general agreement that future developments will also be probabilistically-oriented. Workshop participants reported broad support for this probabilistic approach in the development of future susceptibility models (e.g., responses to Question #1 from the Session 2 breakout activity, Section 4.2.2).

The advancement of liquefaction hazard assessment procedures will also require the probabilistic characterization of predictive models and their parameters. Within a PEER-like probabilistic framework, the introduction of susceptibility into a liquefaction hazard assessment can be made clearer and more efficient by also assuming Markovian independence between susceptibility, triggering, and consequences. In order to establish this independence, the quantities used to establish susceptibility should not be related to those that influence triggering. This format is inconsistent with the consequence-based interpretation of susceptibility since it mixes elements of material, loading, and response characteristics. The material-based interpretation, on the other hand, characterizes susceptibility in terms of inherent material characteristics that are independent of density, saturation, effective stress, and other environment-related characteristics that influence triggering and consequences. It can, however, lead to some counter-intuitive circumstances; for example, a very dense, well-graded, dry sandy gravel would be considered *susceptible to liquefaction* under this definition even though it would be virtually impossible for it to liquefy in that condition. However, it would not liquefy because it would not trigger – not because the material itself was inherently non-susceptible (i.e., the same particles could be rearranged in a different environment to a condition in which it could liquefy).

Environmental variables that may be commonly thought to be linked to or control liquefaction susceptibility, but which are not material-type variables, are better served to be evaluated during the liquefaction triggering assessment. Such variables include the degree of saturation, age, cementation, effective stress magnitude, and relative density (i.e., state). These environmental variables are well-suited to screen various layers for liquefaction as part of the liquefaction triggering assessment. Clear examples of the effects of such variables on cyclic resistance come in the form of available adjustments to cyclic resistance for partial saturation and geologic age. During the first breakout session, representatives from two discussion groups discussed their view of susceptibility assessment as a two-step approach wherein one would first evaluate the compositional factors, and, if those dictate it, then assess environmental factors such as state and saturation. Factors like loading history and overconsolidation ratio were also found to challenge the definitions as they could be interpreted by some as both material and state variables. However, we find such characteristics better suited for screening certain layers during the triggering evaluation stage of analysis.

The pre-Workshop poll identified inherent material-specific characteristics (e.g., plasticity index, fines content, CPT-based soil behavior type, mineralogy, clay content) as being more influential with respect to susceptibility than environment-specific characteristics that include triggering- and consequence-related factors. Throughout the workshop discussions, this trend appeared to persist. However, as noted above, several participants expressed their view that susceptibility should also be related to state and/or loading. For example, according to this view, a tightly-packed, dilative material either would not liquefy, or even if it did experience high excess pore pressures under extreme loading, large deformations would be unlikely. However, this perspective on susceptibility can cause confusion in practice, because state is fundamentally associated with liquefaction triggering assessments.

We support the material-based interpretation of liquefaction susceptibility as being more fundamentally appropriate for the advancement of practice in liquefaction hazard assessment. Some clarity in the application of this material-based definition of susceptibility may be gained by referring to it as “material susceptibility” or possibly “inherent susceptibility” in order to distinguish its use in technical analyses from the more colloquial likelihood-oriented use in common communication. It is clear from the workshop discussions that great care should be taken in the use of technical terminology and that definitions be made explicit in both technical communication and the description of potential hazards to non-technical audiences. A finding of material susceptibility does not indicate whether or not significant liquefaction hazards are likely to occur at a particular site (i.e., that liquefaction is likely to be triggered), it merely indicates that the potential for their occurrence should be evaluated using appropriate laboratory tests, models, and analyses. Similarly, a finding of non-susceptibility does not mean that other hazards, such as cyclic softening, do not exist and should not be carefully evaluated.

The workshop participants broadly agreed that in its current form, the CPT-based Soil Behavior Type Index, I_c, represents a useful parameter for characterization of liquefaction susceptibility, but one for which there can be appreciable uncertainty when applied to a particular soil. Evidence was presented for regions such as Christchurch, New Zealand, and the Pacific Northwest, USA, that I_c is a parameter that varies with the mineralogy, depositional environment, and post-depositional geological processes which give rise to unique soil fabric. This parameter is also influenced by anthropogenic processes such as ground improvement, as a result of changes in the lateral stress state and thus I_c (e.g., Nguyen et al. 2014). Further strong statistical evidence appears to point to $I_c = 2.6$ as an approximate *median* of a distribution of I_c that can separate potential sand-like and clay-like behavior of different soils based on observations of liquefaction manifestation. This implies that a non-negligible percentage of soil materials characterized with an $I_c > 2.6$ could be falsely flagged as non-susceptible to liquefaction (and vice versa), as was documented in presentations during the workshop. It is emphasized here that I_c represents both material and state characteristics, and that the deterministic use of a I_c alone could result in inaccurate determinations of susceptibility. Participants endorsed the discontinued use of $I_c = 2.6$ as a strict cut-off between sand-like and clay-like behavior. This need to avoid the use of strict cutoffs is not unique to I_c but would likely apply to any soil parameter used in liquefaction susceptibility assessments.

5.3 APPLICATION OF CURRENT SUSCEPTIBLITY MODELS

Two widely used susceptibility models, i.e., those of Boulanger and Idriss (2006) and Bray and Sancio (2006), referred to hereafter as B&I06 and B&S06, respectively, were the subject of extended discussion in the Workshop. These models were developed by different researchers based on a varying number of tests on different soil materials and employed somewhat different methods to interpret test results. As a result, the two models have broad areas of agreement in their characterization of soil behavior, but also areas where their results can be interpreted as inconsistent. The discussion centered on the B&I06 and B&S06 models and whether their findings are in fact different in terms of how they should be applied in practice.

Professor Ross Boulanger (University of California, Davis) explained that the B&I06 model had the objective of guiding the choice of analysis method and stated his preference for it to be interpreted as a "cyclic strength evaluation procedure criterion," with the following logic:

- A determination of *sand-like* soil behavior would indicate that semi-empirical procedures for liquefaction triggering (which are dominated by data from granular soil sites and for which sampling in an intact state is relatively impractical) should be applied, and as appropriate, undrained monotonic, cyclic, and residual shear strengths would be obtained via correlations.
- A determination of *clay-like* soil behavior would indicate that procedures for strength characterization for clay, which often include sampling, laboratory testing, and consideration of stress history effects, should be applied with the goal of estimating appropriate undrained monotonic, cyclic, and remolded shear strengths of the material. Ground failure assessment in this domain is referred to as cyclic softening and is principally related to strength and stiffness degradation from undrained cyclic loading.

Professor Jonathan Bray (University of California, Berkeley) stated the B&S06 model was developed under a different framework related to the engineering response and consequences of the material being cyclically loaded. The B&S06 model examined the response of slightly plastic silt soils and concluded that, since their response (i.e., excess pore water pressure ratio, $r_u > 90\%$ and similar 'banana-shaped' cyclic shear stress vs. cyclic shear strain loops) were similar to those of medium dense to dense sands whose response is termed liquefaction, their response should also be termed liquefaction. The B&S06 model did not specify the method to evaluate the engineering response and consequences of these materials.

Both Boulanger and Idriss (2006; 2008) and Bray and Sancio (2006; 2008) have recommended that soils that *can* be reliably sampled *should* be sampled and tested to refine the assessment of susceptibility as well as triggering, and consequences of liquefaction.

Following the Workshop, the report writers discussed whether the B&I06 and B&S06 criteria in fact represent different objectives given epistemic uncertainties associated with the models, how the typical practitioner may use the differing criteria, and how they relate to the development of future susceptibility models. These discussions led to the following conclusions:

- After considerable discussion, the interpretation and applicability of available liquefaction susceptibility criteria appears to hinge entirely on the definition of the terms "liquefaction" and "sand-like" and "cyclic softening" and "clay-like". The report writers therefore identify the critical need for the profession to accompany any liquefaction susceptibility model with a clear statement of how liquefaction susceptibility is defined (i.e., as a material behavior vs. as part of the strength or consequence determination). We also emphasize points clearly stated by Boulanger and Idriss (2006; 2008) and Bray and Sancio (2006; 2008) that the determination of "non-liquefiable" or "clay-like" should precipitate an assessment of cyclic softening potential and its consequences.

- Both models make use of the results of laboratory tests to judge the behavior of cyclically loaded soils, and significantly more test data has become available since the models were published. Epistemic uncertainties (e.g., differences in the *PI* ranges specified by the B&I06 and B&S06 models) may be reduced by continued experimental laboratory research, case history interpretation, and development of refined deterministic and probabilistic models, the latter of which was clearly identified as a need in the Workshop.

- Regarding application in practice, the original papers and closures, as well as discussions in the Workshop, describe how the developers of the B&I06 and B&S06 models view their intended use. Professors Boulanger and Bray present their views on their models in their extended abstracts (see Appendix B). However, practitioners often interpret the end result of both models as indicating whether or not a material is susceptible to liquefaction. It is incumbent upon geotechnical engineers to recognize the differing intent, applicability, and limitations of these models in their use and interpretation in practice.

The existing susceptibility models have been widely and beneficially used since their publication some 17 years ago, and differences in their intents, terminologies, and use in practice have helped illustrate the complexity of cyclically loaded soil behavior over important ranges of soil characteristics. The models are supported by experimental data and the expert interpretation of that data by their developers. Differences in the models can largely be attributed to differences in the data they are based upon, and differences in the developers' interpretation of that data. Future liquefaction susceptibility models should supplement that data with available data generated since their publication, new data that fills gaps in the current state of knowledge, and should define their terms and intended model application in practice carefully and explicitly.

6 RESEARCH NEEDS

There was general consensus among Workshop attendees that improved procedures to evaluate liquefaction susceptibility are needed. Moreover, these procedures should be probabilistic, in that they should capture variability in the underlying data, and should be formulated in a manner that facilitates evaluation of epistemic uncertainties. Here we briefly describe the vision for the research that would lead to the development of such procedures, the research tasks (or scope) that would support the development of such procedures, and the ways in which epistemic uncertainty could be inferred from the results.

Vision: Our vision for next-generation susceptibility models is that they should predict whether a material could exhibit fundamental soil behavior that is characteristic of granular media. This includes a rapid and substantial reduction of stiffness, and potentially strength, associated with the development of high pore pressure, and the potential development of surface manifestation and/or permanent vertical and/or horizontal deformations. A concise phrasing for such characteristics is *material susceptibility*, which emphasizes the soil behavior and thus may be a preferred term to "susceptibility". As such, the models would not reflect environmental conditions (mainly saturation) or information about soil state (such as water content or relative density). The susceptibility models should consider alternate predictor variables, reflecting different levels of information available for different applications. The most basic of these parameters would be routinely available from most professional geotechnical reports, such as I_c or PI. More advanced metrics can and should also be considered. The models should be probabilistic (i.e., the outcome of the model is a probability of material susceptibility) that would reflect aleatory variability. Different levels of aleatory variability could be anticipated when different predictor variables are used.

Scope: The scope of the research that would realize this vision mainly involves the development of a database targeted at susceptibility studies. The current NGL database (Brandenberg et al. 2020) was originally developed for field case histories of manifestations (or lack thereof) of liquefaction from past earthquakes. That database structure is not directly applicable to this problem; however, the structure of the database has recently been adapted for laboratory data (Hudson et al. 2022), without corresponding earthquake information or field performance. Such laboratory test data can be used to study many different aspects of liquefaction problems, including the present focus on material susceptibility. The contents of the database were discussed extensively in the Workshop, and are envisioned to include the following:

1. Each entry would be from a given site. The sites would ideally have wide geographic distribution to capture different geological characteristics;
2. Each site should have *in-situ* CPTs that are essentially co-located with borings with samples. The horizontal separation distance between the CPT sounding and boring should be greater than 1.5 m to limit the effects of drilling on the

sounding or of the sounding on the sampling, respectively, and smaller than 3 meters to minimize differences in material characteristics due to inherent soil variability;

3. Cyclic tests for layers of interest in the profile should have been performed, with the results provided digitally in the database. The results should allow for plots of stress-strain hysteresis and stress paths;

4. Metadata related to the tests should be provided, including method of sampling, method of sample preparation, pre-test consolidation of specimens and B-values (CTX) or normal strain time histories (CDSS), as applicable, and the results of tests to assess sample disturbance (Chapter 4.3);

5. Index tests performed on material from the samples used in (3) should be provided, including Atterberg limits, water content, and gradation curves. These soil indices should be obtained from the cyclic test specimen itself when feasible, and from cuttings or other test specimens within close proximity to the cyclic test specimen; and,

6. Where available, results of monotonic undrained tests should be provided. Ideally, a suite of such tests should be provided to allow strength normalization to be evaluated using established procedures (e.g., Ladd 1991).

A particularly encouraging outcome of the Workshop is that a large amount of data of this type is available derived from field observation studies, research-based laboratory investigations, and design-based laboratory investigations from investigations by professional engineers (Tables 6.1 and 6.2). While further investigations are always welcome, it is likely not mandatory for further data development to occur for the envisioned study to be successful. Rather, what is needed is to assemble and archive the data into a perpetually available and usable form.

Once the database is developed, a research team would interpret the cyclic test results for each specimen to assign a numerical or qualitative indicator of soil behavior (e.g., sand-like, intermediate, clay-like). Alternate variables would then be examined through regression (including AI methods) to investigate their predictive power. Ineffective parameters would have large variability (i.e., a statistical distribution of a model characterized by a large standard deviation) whereas effective parameters would have reduced variability.

In the development of predictive models from the database, several types of epistemic uncertainties could be considered:

1. Models in which a region flag is included (model provides predictions specific to that region, such as Christchurch) versus models in which all global data are grouped. The latter (grouped) data would have larger and quantifiable uncertainties;

2. Different assignments of susceptibility from cyclic tests could be made by different investigators (e.g., see Chapters 4.3.3 and 5.3). Differences between the resulting models is a quantifiable form of epistemic uncertainty; and,
3. Different methods of regression could be used and different forms of probabilistic models could be provided.

Table 6.1 Summary of some available laboratory data derived from field observations.

Basis	Event and Location	Laboratory Testing	Reference
Field Observations	1989 Loma Prieta, Moss Landing, USA	Index, consolidation, cyclic triaxial tests	Boulanger et al. (1998)
Field Observations	1994 Northridge, Los Angeles, USA	Index and laboratory vane shear tests	Holzer et al. (1999)
Field Observations	1999 Kocaeli, Adapazari, Turkey	Index, cyclic triaxial, and direct simple shear tests	Bray and Sancio (2006)
Field Observations	1999 Chi-Chi, Wufeng, Taiwan	Index, consolidation, triaxial, cyclic triaxial tests	Chu et al. (2008)
Field Observations	2010-11 Canterbury Earthquake Sequence, Christchurch, New Zealand	Index, cyclic triaxial tests	Beyzaei et al. (2018)
Field Observations	Controlled blasting	Index, consolidation, monotonic direct simple shear, cyclic direct simple shear	Jana and Stuedlein (2022)
Field Observations	Vibroseis shaking, Port of Longview, USA	Index, consolidation, monotonic direct simple shear, resonant column-torsional shear, cyclic direct simple shear	Dadashiserej et al. (2022)
Field Observations	Vibroseis shaking and controlled blasting, Port of Longview, USA	Index, consolidation, monotonic direct simple shear, resonant column-torsional shear, cyclic direct simple shear	Jana et al. (2023)

Table 6.2 Summary of some available data derived from laboratory investigations.

Basis	Laboratory Testing	Reference
Research	Index, consolidation, cyclic direct simple shear	Sanin and Wijewickreme (2006)
Research	Index, consolidation, monotonic direct simple shear cyclic direct simple shear	Dahl et al. (2014)
Research	Index, consolidation, monotonic direct simple shear cyclic direct simple shear	Wijewickreme et al. (2019)
Research	Index, consolidation, monotonic direct simple shear cyclic direct simple shear	Jana and Stuedlein (2022)
Research	Index, consolidation, monotonic direct simple shear cyclic direct simple shear	Stuedlein et al. (2023)
Research / Design Investigations	Index, cyclic triaxial, cyclic direct simple shear	Dickenson et al. (2022)
Design Investigations	Index, cyclic direct simple shear	Presented by P. Espinosa at Workshop (Appendix B)
Design Investigations	Index, cyclic direct simple shear	Presented by S. Sideras at Workshop (Appendix B)
Design Investigations	Index, cyclic direct simple shear	Presented by D. Moug at Workshop (Appendix B)
Design Investigations	Index, consolidation, triaxial, monotonic and cyclic direct simple shear	Presented by M. Gibson at Workshop (Appendix B)
Design Investigations	Index, cyclic direct simple shear	Presented by B. Exley at Workshop (Appendix B)

7 SUMMARY AND CONCLUSIONS

The typical progression of engineering analysis of soil liquefaction involves three steps: determination of liquefaction susceptibility, evaluation of liquefaction triggering for one or more earthquake scenarios, and the assessment of the consequences of liquefaction triggering. Although each of these steps is associated with considerable epistemic uncertainties, the basic framework for engineering analyses of liquefaction triggering and the consequent deformations or instability have been established. However, these analyses hinge upon whether a particular stratum is deemed susceptible to liquefaction, with considerable risk or cost associated with incorrectly assessing susceptibility. The uncertainty associated with the determination of susceptibility represents a significant contribution to the overall uncertainty associated with the assessment of ground failure risk.

The objectives of this PEER Workshop on liquefaction susceptibility were to identify the means to improve data resources and models related to liquefaction susceptibility to reduce uncertainties in the assessment of liquefaction susceptibility (aligned with the goals of the Next Generation Liquefaction project) and to summarize the outcomes of the workshop discussions on the needed elements of, and steps needed to develop, Next-Generation Liquefaction models. Workshop organizers sought to identify challenges and research opportunities for improved assessments of liquefaction susceptibility, centered on three broad themes:

1. The current state-of-the practice and its limitations;
2. The linkage between laboratory observations, and field characterization and response; and,
3. Options for future susceptibility models that could be used, for example, in conjunction with liquefaction triggering models or hazard mapping.

Workshop participants were invited to submit extended abstracts on the topic of liquefaction susceptibility in response to the following prompts:

1. What is the state-of-the-art?
2. What are the consequences of incorrectly assessing liquefaction susceptibility, and under what conditions are these consequences most acute?
3. What are the relevant geological, material characteristics, in-situ tests, or modeling processes which drive the challenges associated with the methods currently in use?
4. What data resources would help improve understanding?
5. How should the next generation of liquefaction susceptibility models be formulated to advance the state-of-the-art?

6. Have you experienced a case where the determination of susceptibility proved to be pivotal, and what were the considerations associated with the application of typical (i.e., state-of-the-practice) susceptibility procedures?
7. Can you describe a case where liquefaction susceptibility was assessed using methods beyond those typically applied, given the importance of the project and consequences of liquefaction?

The breadth and depth of current perspectives on liquefaction susceptibility and related concerns by Workshop participants are clearly demonstrated in the submitted abstracts included within this report (Appendix B).

A pre-Workshop poll (Appendix C) with questions drawn in part from the information provided by participants in their extended abstracts served to help refine the Workshop Agenda (Appendix D) and focused discussion points. The Workshop discussions (Session 1; Section 4.1) clearly identified that the term "susceptibility" could mean a variety of different things to different participants. Whereas most participants considered susceptibility to be a function of material characteristics alone, many linked the term and act of assessing susceptibility to triggering evaluations. The participants overwhelmingly concurred on the need to have a clear and unambiguous definition of liquefaction susceptibility. Several groups of participants identified preliminary forms of such a definition, however, the Workshop participants were unable to converge on a shared definition in the time available.

Participants clearly indicated a powerful belief that susceptibility assessment is fraught with uncertainty and there is a clear desire to see it characterized in a probabilistic manner (Session 3; Section 4.3). Information derived from geologic investigations and cyclic laboratory tests were also viewed as having significant potential benefit in the assessment of liquefaction susceptibility (Session 2; Section 4.2). Strong support was also expressed for establishment of a susceptibility database that could be used to develop improved susceptibility models (Session 3; Section 4.3).

The Workshop Organizing Committee (OC) synthesized three key issues identified over the course of the discussions and provided their opinions thereof in Chapter 5, including the: (1) need for a definition of liquefaction susceptibility, (2) means by which such a definition should be developed, and (3) the differences between current susceptibility models. The OC suggests that the interpretation and applicability of available liquefaction susceptibility criteria is driven by the definition of the terms "liquefaction" and "sand-like" and "cyclic softening" and "clay-like". Epistemic uncertainties related to differing datasets underpinning the criteria can be treated through additional laboratory testing and field observations. The OC emphasizes that the geotechnical engineer is responsible for recognizing the differing intent, applicability, and limitations of these models in their use and interpretation in practice.

A meaningful outcome of the Workshop is recognizing that a large amount of data that could populate a susceptibility database is available from both researchers and practitioners. The sources identified range from field observation including post-earthquake reconnaissance studies, research investigations deploying *in-situ* dynamic test methods, as well as research- and design-based laboratory investigations (Chapter 6). Workshop participants appeared to agree that the assembly and archival of the available data in a perpetual and usable form is both viable and necessary.

The Workshop facilitated deep, meaningful, and vigorous discussions on a critical component comprising the overall set of steps to assess the risk of seismically-induced ground failure: the assessment of liquefaction susceptibility. Although a broad consensus on how liquefaction susceptibility should be defined was not achieved, Workshop participants expressed that the event added significant value to their understanding of liquefaction susceptibility, that the discussions served to crystalize various perspectives, and identified clear data resource needs and model development goals.

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APPENDIX A: LIST OF PARTICIPANTS

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APPENDIX B: EXTENDED ABSTRACTS

LIQUEFACTION OF SILTY SOIL

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INTRODUCTION

This contribution assesses the current state-of-the-art and linkage between the engineering response of silty soil in the field and laboratory. Insights from the comprehensive investigations of the silty soil sites in Adapazari and Christchurch are shared. Emphasis is placed on the engineering response of silty soils that exhibit cyclic mobility similar to that of clean sands.

RESPONSE TO PROMPTS

State-of-the-art

Ground failure in Adapazari, Turkey during the 1999 Kocaeli earthquake (Bray et al. 2004) led to research that produced the Bray & Sancio (2006) susceptibility criteria (referred to as B&S06). The criteria were developed based on an extensive database of laboratory tests performed on high-quality samples retrieved from natural fine-grained alluvial soil deposits after documenting liquefaction effects at several field case histories sites in Adapazari. Bray & Sancio (2006) performed over 100 CTX tests and a dozen CSS tests. Donahue et al. (2008) then performed about 50 CSS tests on laboratory-prepared specimens of Adapazari silt of various plasticity indices (*PI*). Markham et al. (2018), Beyzaei et al. (2018) and Mijic et al. (2021) each performed dozens of CTX and CSS tests. Observations in other earthquakes (e.g., 1994 Northridge, 1999 Chi-Chi, and 2010-11 Canterbury sequence) and additional research confirmed the applicability of the B&S06 criteria. The total number of tests and case histories from these studies exceeds the number of data points used to develop the current empirically based liquefaction triggering procedures.

The B&S06 criteria (i.e., $PI \leq 12$ & $w/LL \geq 0.85$) are based on the engineering response and consequences of the material that is cyclically loaded. The B&S06 model examined the response of a range of slightly plastic silty soils and found their cyclic shear stress vs. cyclic shear strain curves looked like those of a medium dense to dense sand whose response is termed liquefaction. If the phenomenon is referred to as liquefaction for a medium dense sand composed of angular fine sand particles, then a slightly plastic silt under cyclic loading that generates high excess pore water pressures (i.e., excess pore water pressure ratio, $r_u > 90\%$) that produces similar 'banana-shaped' cyclic shear stress vs. cyclic shear strain loops should also be referred to as liquefaction. Building settlement occurred at both sand and slightly plastic silt sites in New Zealand, Taiwan, and Turkey. Sediment ejecta were produced along the edges of buildings at some sand sites and at some slightly plastic silt sites in the field case histories. The engineering response of the sand and slightly plastic silty soils and their consequences in terms of Performance-Based Earthquake Engineering (PBEE) are similar so they should both be classified as liquefiable. This is especially relevant in evaluating the consequences of liquefaction in terms of displacements.

It is noteworthy that Ishihara (1996) found the cyclic stress ratio causing 5% double-amplitude strain in 20 cycles in laboratory tests of high fine-content soils "*did not change much for the low* *plasticity range*" (i.e., $PI \leq 10$), "*but increases thereafter with increasing plasticity index*." Thus, an independent study categorized cyclic resistance of slightly plastic fine-grained soils based on a PI-based criterion, which in this case was $PI \leq 10$.

Boulanger and Idriss (2006) (referred to as B&I06) employed a different liquefaction susceptibility framework focused on the engineering tools they recommended to be used to evaluate the cyclic strength of sand-like or clay-like materials. Given the different intended outcomes of the B&I06 and B&S06 criteria, the different *PI* ranges associated with the B&I06 and B&S06 criteria do not necessarily constitute different recommendations regarding the assessment of susceptibility. Instead, the B&I06 susceptibility criterion is intended to direct engineers to the use of their CPT and SPT based liquefaction triggering for soils they believe are captured well by their liquefaction triggering CPT and SPT databases, and to direct them not to use their CPT and SPT based liquefaction triggering methods for soils they term to behave clay-like. Conversely, the B&S06 criteria categorizes slightly plastic silty soils with field and laboratory responses like those of some clean sands, in which the term liquefaction is commonly used, as liquefiable without specifying the method to evaluate the engineering response and consequences of these materials. However, they state laboratory testing, if performed on high-quality specimens, would provide the most relevant insight. In fact, Boulanger & Idriss (2008) and Bray & Sancio (2008) both recommend that soils that can be reliably sampled should be sampled and tested to refine the assessment of susceptibility as well as triggering, response, and consequences of liquefaction.

The empirical databases used to develop liquefaction triggering procedures consist primarily of liquefaction triggering data from sand sites. Often clean sand equivalent adjustments are made to penetration resistances to account for the difference between nonplastic silty soil and sand and the differences between slightly plastic silt and sand. The basis for these adjustments is not clear. Recent work by Bray & Olaya (2023) provides data that examine the trends of clean sand equivalent cone penetration resistance (CPT) adjustments to silty soils using soil behavior type index (I_c). Their data are from natural soil deposits in Christchurch. Further research is warranted.

Relevant geological, material characteristics, and in-situ tests

Consideration of geologic processes is crucial in proper site characterization, ranging from its relevance to the composition, fabric and microstructure of soil at a given location in the profile to the spatial variability of the sediments at a site (Bray & Olaya 2023). Often site characterization is performed without consideration of the depositional environment of a site. Most current standard-of-practice in situ test methods are not sensitive enough to detect the fabric and microstructure of sediments. Furthermore, disturbed sampling may cause mixing of fine- and coarse-grained fractions, resulting in an incorrect characterization of the engineering properties of the soil.

Better integration of qualitative geologic information about the soils at a site and the quantitative information from in situ and laboratory engineering tests is essential for quantifying and minimizing the uncertainties associated with site characterization (Beyzaei et al. 2020). At the site scale, one potential way to do this is to use proxies for depositional environments. At the fabric and microstructure scale, use of multiple existing in situ tests that induce different levels of strain (e.g., V_s and CPT) should be used with continuous high-quality soil sampling to characterize soil deposits. New in situ test methods that are sensitive to the fabric and microstructure of soil should be developed.

CONCLUDING REMARKS AND RECOMMENDATIONS

The cyclic response of silty soil is less understood than that of clean sand. Additional field, laboratory, and numerical studies are required to advance the profession's understanding of the liquefaction susceptibility and cyclic response of silty soils, especially those with low plasticity.

ACKNOWLEDGEMENTS

Recent work was supported financially by the U.S. National Science Foundation through Grant CMMI-1956248, CMMI-1561932, CMMI-1407364, CMMI-1332501, and CMMI-1266418. Additional support by the Faculty Chair in Earthquake Engineering Excellence at UC Berkeley.

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SUSCEPTIBILITY CRITERIA FOR SELECTING ENGINEERING PROCEDURES

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PURPOSE OF SUSCEPTIBILITY CRITERIA

Liquefaction susceptibility criteria are used in conjunction with a hierarchy of simplified to complex engineering analysis procedures for estimating seismic deformations in a diverse array of soil and soil-structure infrastructure systems. Liquefaction susceptibility criteria should be developed to be universally applicable across this hierarchy of analysis procedures and systems.

Estimating deformations for a geotechnical structure can require estimating the strains (from small to large) that might develop in a wide range of soil types (from cohesionless to cohesive) across a range of states (from loose to dense of critical state) subjected to a wide range of loading intensities, with the responses described by various terms including liquefaction and cyclic softening. Methods for predicting strains generally require knowledge of the earthquake-induced shear stresses (i.e., demand) and soil shear strength (i.e., capacity). The engineering procedures that are appropriate for estimating a soil's strength (monotonic or cyclic; drained or undrained), or more generally its stress-strain response to earthquake loading, depends on the nature of the soil.

For saturated cohesionless soils, such as clean sands or nonplastic silts, the loss of strength and/or development of strains under earthquake loading is generally referred to as liquefaction. Liquefaction has become a colloquial term that encompasses phenomena such as flow liquefaction, excess pore pressure ratio of 100%, shear strains in excess of a specified failure criterion, and surface manifestations in the field. The potential for liquefaction triggering is commonly evaluated using correlations based on in-situ tests (SPT, CPT, V_s etc.) rather than laboratory testing of field samples because conventional tube sampling techniques cause excessive disturbance to cohesionless soils and frozen sampling techniques are usually uneconomical.

For saturated cohesive soils, such as clays and plastic silts, the loss of strength and development of strains under earthquake loading is generally referred to as cyclic softening. Cyclic softening phenomena share similarities with liquefaction phenomena and can be described using similar soil mechanics theories. Procedures for evaluating cyclic softening focus on estimating monotonic and cyclic undrained strengths using information from laboratory testing, in situ testing, and empirical correlations. In contrast to cohesionless soils, conventional tube sampling techniques can usually be used to obtain reasonably high-quality samples for laboratory strength testing.

Comparisons of different liquefaction susceptibility criteria should begin with clarification of their intended purpose. Is a liquefaction susceptibility criterion intended to differentiate between "liquefaction" and "cyclic softening" on the basis of differences in (1) their phenomenological responses to earthquake/cyclic loading, (2) some fundamental soil mechanics characteristic influencing their responses, or (3) the types of engineering procedures that are appropriate for evaluating potential responses? Different purposes can lead to significantly different criteria, which can lead to problems when the application of a criterion is inconsistent with its purpose.

EXAMPLE OF CRITERIA WITH DIFFERENT PURPOSES

For example, consider the liquefaction susceptibility criteria by Bray and Sancio (2006) and Boulanger and Idriss (2006). Bray and Sancio (2006) used cyclic test results for a wide range of soils from Adapazari and the observed field performances of those soils during the 1999 Kocaeli earthquake to conclude that silts and clays with PI ≤ 12 and water contents (w_c) greater than 85% of the Liquid Limit (LL) are liquefiable, while soils with 12 < PI < 18 and w_c > 0.8LL are more resistant to liquefaction but still susceptible to cyclic mobility (Figure 1a). Boulanger and Idriss (2006) suggested that the emphasis should be put on determining which engineering procedures are most appropriate for evaluating cyclic strengths, and recommended that clays and silts with PI ≥ 7 be evaluated using cyclic softening procedures, whereas silts and clays with lower PI should be considered as likely exhibiting sand-like behavior (and evaluated using liquefaction correlations) unless shown otherwise through detailed laboratory and in situ testing (Figure 1b).

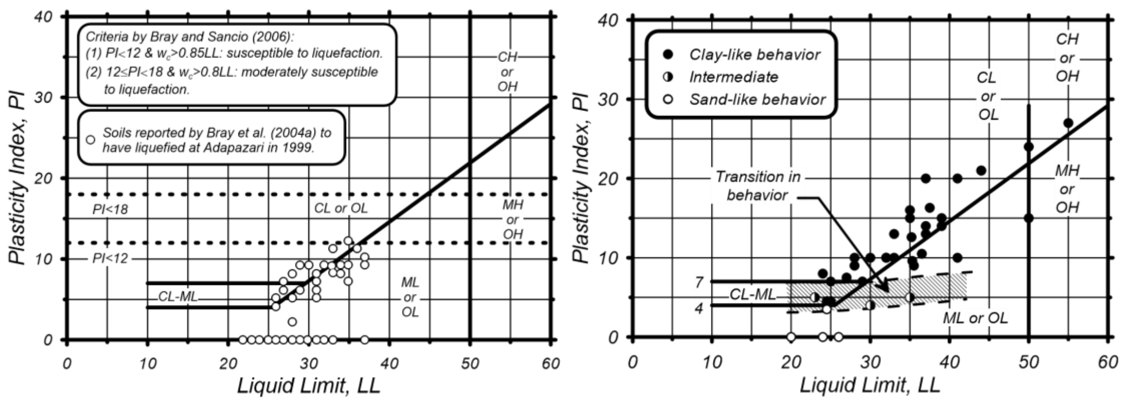

Figure 1. Susceptibility criteria by: (a) Bray & Sancio (2006) and (b) Boulanger & Idriss (2006).

The differences between the guidance provided by Bray and Sancio (2006) and Boulanger and Idriss (2006) have sometimes been perceived in practice as being greater than they really are, in large part because of semantics. The commonality between these two sets of guidance is well illustrated by the following passage from Bray and Sancio (2006),

> "Based on the results of the cyclic testing performed in this study, a soil may be susceptible to liquefaction if the ratio of the water content to liquid limit is greater than 0.85 (wc/LL>0.85) and the soil plasticity index in less than 12 (PI<12). Soils that do not meet these conditions but have plasticity index less than 18 (PI<18) and water content to liquid limit ratio greater than 0.8 (wc/LL>0.8) may be moderately susceptible to liquefaction. These soils, especially those satisfying the first set of requirements, should be tested in the laboratory to assess their liquefaction susceptibility and strain potential under the loading conditions existing in the field. Soils with PI>18 did not liquefy at low effective stresses. However, structures founded on these soils, and for that matter, any soil, may undergo significant deformations if the cyclic loads approach or exceed the dynamic strength of the soil."

Bray and Sancio further clarify their recommendations in their 2008 closure to discussions,

> "The authors contend that field sampling and laboratory testing currently offer the most reliable way to evaluate the liquefaction susceptibility, resistance, and response of fine-grained soils."

The above recommendations are in good agreement with those of Boulanger and Idriss (2006), as illustrated by the following passage from their closure (Idriss & Boulanger 2008),

> "Effective communication regarding issues of liquefaction requires a clear understanding of the technical definitions used by different individuals. For the paper, definitions for terms were chosen such that the names for soil type, soil behavior, and analysis methodology were reasonably consistent: (1) "liquefaction" was reserved for describing the behavior of sand-like or cohesionless soils that would be appropriately evaluated using semi-empirical SPT- or CPT-based "liquefaction" correlations; (2) "cyclic softening" was used to describe the behavior of clay-like or cohesive soils that would be appropriately evaluated using procedures developed for, or modified from those for clays; and (3) the recommended criteria were called "liquefaction susceptibility criteria," because they distinguished between these two cases.

Thus, the two sets of guidance differ in the terminology used to describe cyclic loading behavior (e.g., cyclic softening versus liquefaction), but they both agree in recommending laboratory testing as the preferred basis for evaluating the cyclic strengths and potential strains for low-plasticity, fine-grained soils, regardless of what the behavior may be called. In this regard, there is no significant consequential difference between the practical intent of the two sets of guidance.

The differences in terminology between these two sets of guidance are a consequence of seeking to avoid two common misuses of criteria in practice: (1) equating "nonliquefiable" with the absence of a possible problem, such that no further analysis of potential deformations is performed, and (2) equating "liquefiable" with the requirement that cyclic strengths be evaluated using SPT or CPT based liquefaction triggering correlations, which can be overly conservative for low—plasticity fine-grained soils. The criteria by Bray and Sancio (2006) reduces the potential for the first misuse by including a broader range of soils within the "liquefiable" criteria, after which the fine print says to determine cyclic strengths by performing lab tests. The criteria by Boulanger and Idriss (2006) reduces the potential for second misuse by mapping the criteria to the choice of engineering procedures, after which the fine print says to evaluate potential deformations in "nonliquefiable" soils using appropriate procedures (e.g., cyclic softening procedures).

CONCLUDING REMARKS AND RECOMMENDATIONS

Alternative names for criteria with different intended purposes could provide clarity for practice and avoid legacy issues associated with the term "liquefaction susceptibility criteria." For example, the Bray and Sancio (2006) guidance might be called "Cyclic deformation susceptibility criteria" whereas the Boulanger and Idriss (2006) guidance might be called "Cyclic strength evaluation criteria." A clear distinction between criteria that provide different types of guidance would also help facilitate recognition that they can be complementary tools in application.

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PARTICLE FABRIC IMAGING FOR UNDERSTANDING SHEAR RESPONSE OF SILTS

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INTRODUCTION

The knowledge from experimental research has shown the significant effect of particle structure (fabric) on the monotonic and cyclic shear behavior of silts, in addition to the well understood influence of void ratio (e) and effective confining stress (σ'_{vc}). It has been shown that 3-D imaging can be used to examine the soil fabric of sands (coarse-grained soils). Due to technology advancements, it is now possible to examine the fabric of finer-grained silt size material. With this background, a research program using X-ray μ-CT imaging technology, has been undertaken at the University of British Columbia (UBC) to support characterizing the mechanical response of natural silts. This extended-abstract presents the initial outcomes of this work and demonstrates the suitability of X-ray μ-CT imaging methodologies for understanding the fabric of silt-size particle matrices.

CURRENT UNDERSTANDING

Liquefaction susceptibility of soils under seismic shaking has been studied globally with much of the focus on the performance of saturated loose sands. Mainly as a result of the liquefaction-induced damaged observed in the 1991 Chi-Chi, 1999 Kocaeli, and 2011 Christchurch earthquakes, seismic performance of silty soils has also been receiving increased attention.

Soil fabric refers to the spatial arrangement of individual particles, particle groups, and pore spaces in soils. Initial recognition of this factor was made by Casagrande and Carillo (1944) via the ideas of inherent and induced anisotropy of soils (Arthur et al. 1977). Significant effect of particle fabric and microstructure on the mechanical behavior of soils has been noted by Oda (1972).

Potential effect of fabric on the behavior of silts

Constant volume monotonic direct simple shear (DSS) testing at UBC has shown that reconstituted Fraser River Delta silt specimens prepared using slurry deposition method exhibit lower shear strength (at all levels of confinement) compared to those from counterpart undisturbed specimens; moreover, the undisturbed specimens display a strain hardening response in contrast to the behavior observed for reconstituted specimens. These trends are displayed in spite of the reconstituted specimens having a denser matrix compared to that for relatively undisturbed specimens. The void ratio (e) and vertical effective stress (σ'_v) states after consolidation as well as after reaching relatively large shear strain levels (γ ~15%), as shown in Figure 1 (left side), shows that the lines for the reconstituted silt are at significantly different locations from that noted for the undisturbed silt. Cyclic DSS testing has shown that reconstituted natural undisturbed silt generally exhibits a weaker response compared to that observed from the undisturbed specimens of the same material. (Figure 1, right side). These DSS results are only explainable by the potential differences in the particle fabric between the two specimen types, highlighting the need to account for the effect of particle fabric, in addition to the traditionally well studied effects of e and σ'_{vc}.

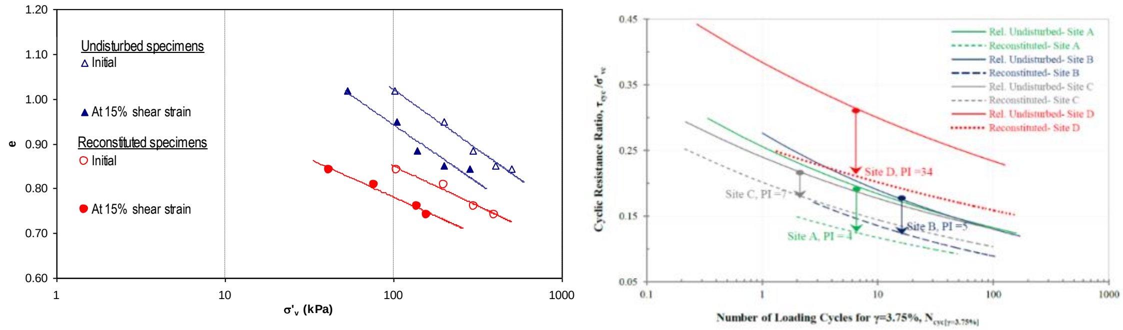

Figure 1. Behavior of undisturbed and reconstituted specimens of Fraser River silt: Left Side - e-log σ'_v curves for initial consolidation versus those at 15% shear strain; Right side - Cyclic Resistance Ratio versus Number of cycles for γ=3.75% (Wijewickreme et al. 2019).

Initial findings towards understanding of fabric

The research herein was undertaken using two silt-sized materials with particle sizes ranging between 2 μm to 74 μm: (i) standard-size silica particles with spherical and irregular shapes; (ii) Fraser and River silt. Imaging was undertaken using ZEISS Xradia 520 Versa equipment (Zeiss International, Germany). A dry specimen of soil containing spherical-shaped silica zone (45 and 63 μm size range) overlying irregular-shaped silica layer (40 and 63 μm size range) was imaged, and the results are shown in Figure 2. The ability of μ-CT imaging to identify/distinguish particle shapes as well as layering in matrices of silt size particles are notable.

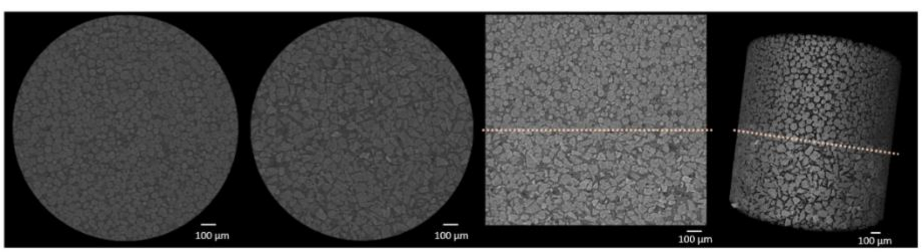

Figure 2. Images from a silica matrix with spherical particles overlying and irregular-shaped grains.

The outcomes from μ-CT imaging of Fraser River silt are presented in Figure 3. The 3D images in Figure 3, do not visually indicate any layering or bedding, confirming the non-segregation (uniformity) expected by the reconstituted specimens formed using slurry deposition. The digital particle size distributions (PSDs) of the silt from the 3 sub-samples taken from the same parent specimen are shown in Figure 3 (Right Side); excellent agreement amongst the PSDs is evidence of very good uniformity within the parent sample. Particle orientation data derived from the same subsamples shown through rose diagrams in Figure 4, illustrates that the principal axes of the particles in the subsamples mainly align in directions close to the horizontal - in accord with the previous observations related to particle orientations for gravity deposited specimens.

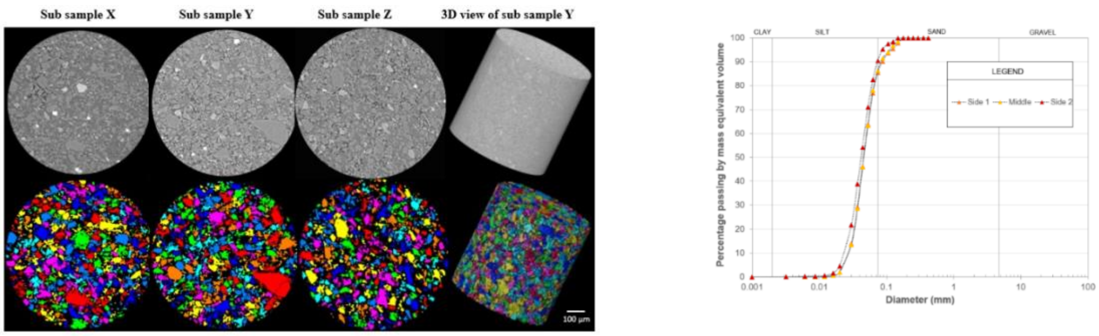

Figure 3. Findings for three subsamples (X, Y, and Z) obtained from the same parent reconstituted specimen of Fraser River silt. Left - Representative raw and processed images; Right - PSDs.

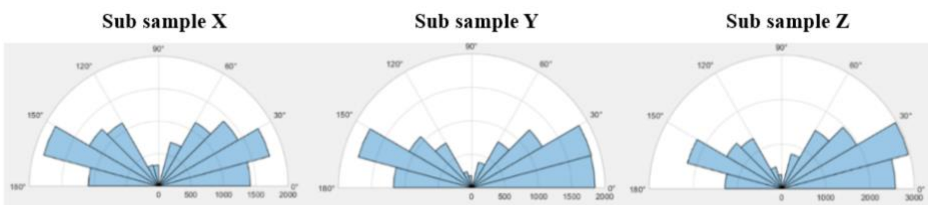

Figure 4. Particle principal axis orientation for three subsamples of reconstituted Fraser River silt.

CONCLUDING REMARKS

The research outcomes highlight the potential of X-ray μ-CT imaging to understand the particle fabric of silt, and in turn, support understanding the mechanical behavior of silts. The findings are in accord with those known from the mechanical laboratory element testing.

ACKNOWLEDGEMENTS

Funding support from the Natural Sciences and Engineering Research Council of Canada (NSERC) and X-ray μ-CT imaging services provided by the UBC Pulp and Paper Centre are gratefully acknowledged.

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LINKING HYSTERETIC BEHAVIOR TO LIQUEFACTION SUSCEPTIBILITY

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Adapted from Stuedlein et al. (2023)

INTRODUCTION

The term "liquefaction susceptibility" has been interpreted differently by various researchers and practitioners, and the potential for confusion is not surprising. Ambiguity stems in part from the need to link the judgement of a soil's behavioral response to seismic loading to its cyclic resistance, which is: (1) commonly estimated using *in-situ* penetration resistance and/or shear wave velocity, in the case of sand-like soils, and (2) then if judged sand-like, the cyclic resistance is estimated based on case histories where surface evidence of liquefaction (e.g., ejecta) was or was not observed. Historically, soil liquefaction has been related to large-deformation flow failure, transient development of zero effective stress, or a particular (though often arbitrary – for transitional soils) cyclic strain failure criterion (Dadashiserej et al. 2022), which injects further potential for ambiguity in the assessment of whether a particular soil specimen or deposit will experience liquefaction. Furthermore, the profession must separate lack of observed ejecta from the possibility that liquefaction has or has not occurred. For example, sites where manifestation of liquefaction has not been documented may include soils at depth which have liquefied. This occurrence could impose the transfer of drag loads to deep foundations, or significant settlement to piled-structures when liquefaction occurs below the depth of piling.

Liquefaction susceptibility should not address whether a soil will liquefy under a given cyclic stress demand; rather, it should identify whether or not liquefaction can occur given *any* seismic demand. Such an interpretation is fully consistent with the recognition that the transient loss of strength (associated with zero effective stress) and stiffness are considered the hallmarks of liquefaction phenomena. Considering transitional soils (e.g., silty sands, clayey sands, sandy silts, silts, low plasticity clayey silts and clays), efforts to quantify the reasonableness in performance of certain CPT-based soil behavior type thresholds (i.e., I_c) coupled with a given liquefaction triggering model have revealed significant uncertainty (Maurer et al. 2019). Thus, it appears that observed hysteretic behavior of high-quality laboratory specimens can shed the clearest light on what characteristics of soils are those which can be correlated to liquefaction susceptibility. This abstract describes some of the findings regarding liquefaction susceptibility based on a series of direct simple shear tests on the transitional soils of deposits found in Southwest Washington and Western Oregon, conducted as part of a long-range study of these materials.

HYSTERETIC SOIL BEHAVIOR: SAND-LIKE, CLAY-LIKE, OR INTERMEDIATE BEHAVIOR?

Identifying the hysteretic behavior of fine-grained soils in term of sand-like, clay-like, and intermediate behavior is important for establishing the potential for transient loss of shear stiffness and strength during seismic loading. However, these assessments have often been made somewhat subjectively. Quantitative hysteretic metrics are evaluated for suitability in the consistent identification of soil behavior. Figure 1a presents selected hysteretic metrics, including the difference in the cyclic shear stress at $\gamma = 0$, $\Delta\tau_{cyc}$, the minimum tangent shear modulus, $G_{tan,min}$, the angle of the hysteresis curves just prior to and following shear stress reversal, θ (computed in the τ_{cyc}–γ plane), and $r_{u,max}$, each calculated for $N_{\gamma = 3\%}$ and the last cycle of each test, N_{max}. Large cyclic shear strain amplitudes (i.e., greater than 5%) are considered in addition to $\gamma = 3\%$ owing to the anticipated intensity and duration of loading associated with the subduction zone events anticipated in the Pacific Northwest.

To minimize the effect of scaling on the interpreted hysteretic behavior, $\Delta\tau_{cyc}$ and $G_{tan,min}$ were normalized by the corresponding maximum cyclic shear stress, $\tau_{cyc,max}$, (i.e., $\Delta\tau_{cyc}/\tau_{cyc,max}$ and $G_{tan,min}/\tau_{cyc,max}$, respectively). Selected $\tau_{cyc,max}$-normalized cyclic hysteretic loops presented in Figs. 1b, 1c, 1d, and 1e are accompanied by the hysteretic metrics for N_{max} and exhibit a range in behaviors which evolve with γ and N. Qualitatively, the hysteretic behavior of Specimen F-2-6 (Fig. 1b) could be described as intermediate for $N_{\gamma = 3\%}$ and sand-like for the last loading cycle (i.e., N_{max}) with its inverted S-shaped cyclic stress-strain hysteresis (indicative of low dissipated strain energy). Quantitively, $\theta = 7$ and 16^{o}, and $\Delta\tau_{cyc}/\tau_{cyc,max} = 0.60$ and 0.47 for $N_{\gamma = 3\%}$ and N_{max}, respectively. Importantly, this specimen exhibits non-zero and zero shear stiffness, with $G_{tan,min}/\tau_{cyc,max} = 10.1$ and 0, and $r_{u,max} = 93$ and 99%, for $N_{\gamma = 3\%}$ and N_{max}, respectively. The evolution in the minimum transient shear stiffness and corresponding maximum excess pore pressure ratio throughout loading is objectively quantified using the hysteretic metrics, which indicate that the ultimate hysteretic behavior is sand-like.

In contrast, clay-like behavior is qualitatively characterized by wide stress-strain loops with non-zero shear stiffness and relatively low generated excess pore pressure. Specimen E-3-2 (Fig. 1c) presents an example with clearly clay-like behavior which did not evolve throughout cyclic loading, quantified with $\Delta\tau_{cyc}/\tau_{cyc,max} = 0.76$ and 1.00, $\theta = 8$ and 23^{o}, $G_{tan,min}/\tau_{cyc,max} = 20.4$ and 1.26, and limited $r_{u,max} = 8$ and 79% for $N_{\gamma = 3\%}$ and N_{max}, respectively. Specimens A-BL-3 and A-BL-5 exhibit frequently-observed evolutionary hysteretic behavior, whereby shear strains of 3% or greater suggested a clay-like response, but upon continued loading the specimen transitioned to sand-like behavior at N_{max} with $G_{tan,min}/\tau_{cyc,max}$ less than 2 and $r_{u,max}$ greater than 95%, indicative of the substantial transient loss of stiffness and strength associated with transient liquefaction.

That the hysteretic behavior of these transitional soil specimens can evolve throughout loading highlights the role of earthquake duration (i.e., N) on the potential for exhibiting sand-like behavior. Thus, short duration crustal earthquakes may not produce sufficient loading cycles to trigger sand-like behavior, whereas longer duration (e.g., subduction zone) earthquakes, which can produce greater than 100 cycles of loading, depending on the power law exponent b describing the *CRR-N* relationship (Boulanger and Idriss 2015; Stuedlein et al. 2021), can lead to the transient loss of strength. Furthermore, it was observed that specimens that exceeded $\gamma = 3\%$ in the first cycle (i.e., subjected to large *CSR*) often required a number of additional cycles to satisfactorily establish the ultimate hysteretic behavior, indicating that significantly larger shear strains than those associated with common cyclic failure criteria are necessary to make determinations of sand-like or clay-like behavior.

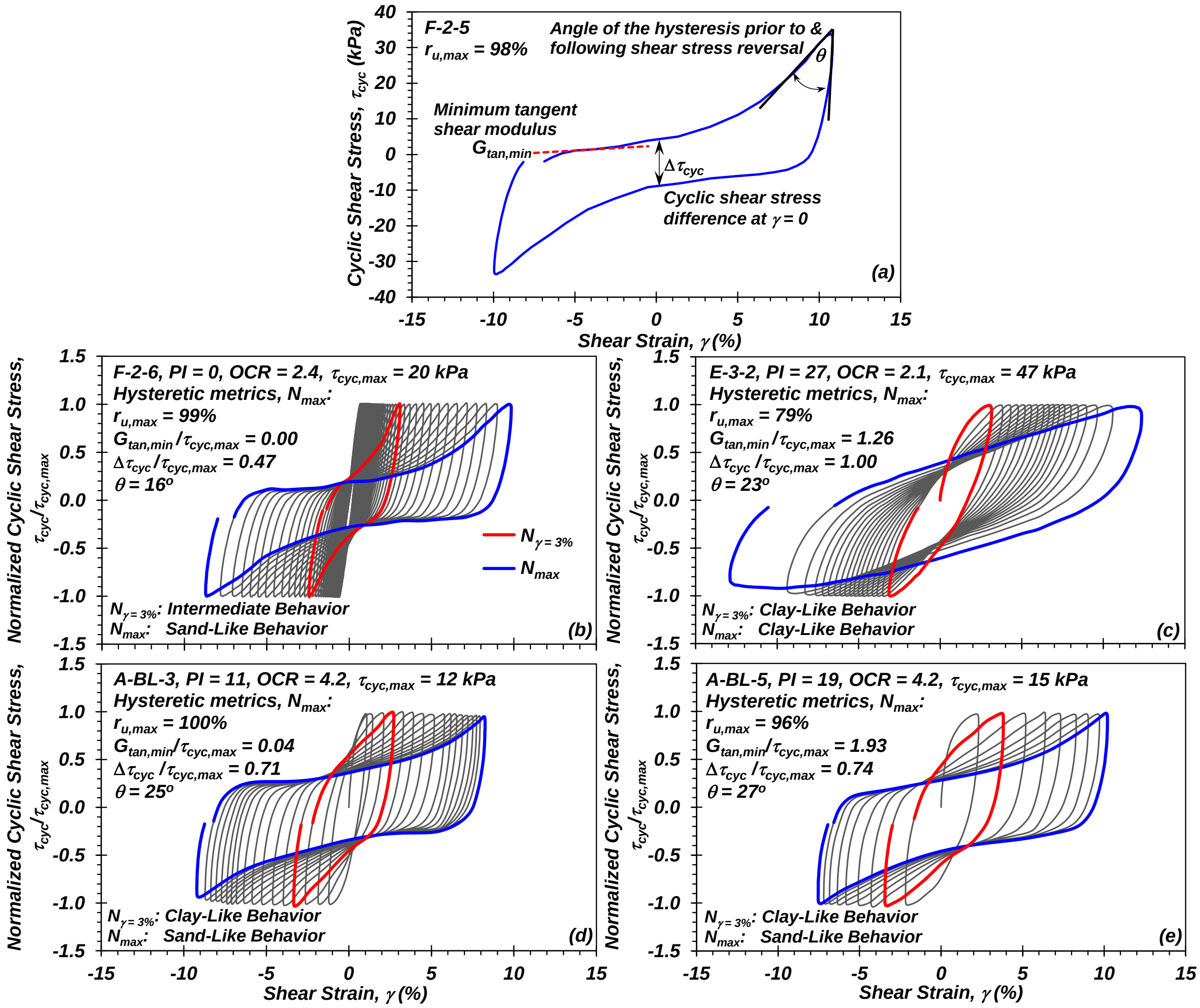

Figure 1. Quantification of hysteretic behavior, including: (a) selected metrics considered for the identification of hysteretic soil behavior at $N_{\gamma = 3\%}$ and N_{max}, and quantified examples of hysteretic behavior from cyclic direct simple shear tests on intact specimens (this study) for N_{max}: (b) initially intermediate behavior transitioning to sand-like, (c) clay-like, and (d, e) clay-like behavior transitioning to sand-like behavior.

The variation of $r_{u,max}$ with $\Delta\tau_{cyc}/\tau_{cyc,max}$ and $G_{tan,min}/\tau_{cyc,max}$ for $N_{\gamma = 3\%}$ and N_{max} are presented in Fig. 2 for nearly 50 representative soil specimens prepared from thin-walled tube samples obtained from mud-rotary boreholes from selected study sites. These data suggest that for the typical strain-based cyclic failure criterion of $\gamma = 3\%$, none of the specimens tested exhibited sand-like behavior, with each exhibiting $\Delta\tau_{cyc}/\tau_{cyc,max} \gtrapprox 0.55$, $G_{tan,min}/\tau_{cyc,max} > 5$, and $r_{u,max} < 95\%$ (Figs. 2a and 2b). The hysteretic metrics for $N_{\gamma = 3\%}$ further suggest that an approximate boundary of $90\% \lessapprox r_{u,max} < 95\%$ is consistent with precedent-based qualitative judgments of intermediate behavior, whereas those specimens with $r_{u,max} \lessapprox 90\%$ also tend to exhibit $\Delta\tau_{cyc}/\tau_{cyc,max} \gtrapprox 0.55$, $G_{tan,min}/\tau_{cyc,max} > 2$ for both $N_{\gamma = 3\%}$ and N_{max}, providing a quantitative basis that is consistent with precedent-based judgments of clay-like behavior. When shear strain amplitudes exceed 3%, the hysteretic behavior of many specimens that previously exhibited intermediate and clay-like behavior transition to sand-like behavior, with $G_{tan,min}/\tau_{cyc,max} < 2$, and $r_{u,max}$ generally greater than or equal to 95%, which quantifies their significant transient loss of strength and stiffness (Figs. 2d and 2e; compare to Fig. 1).

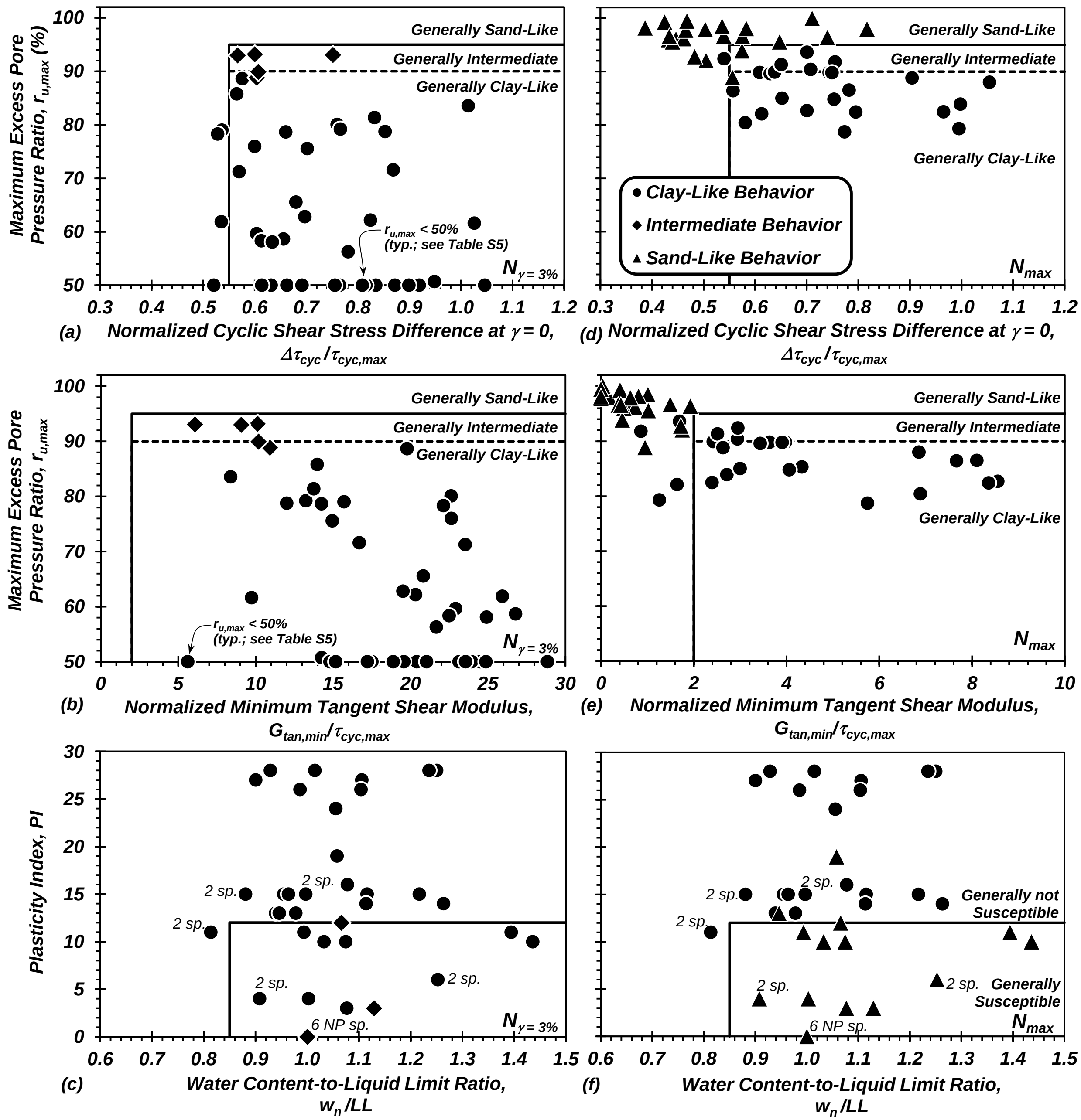

Figure 2. Variation of selected hysteretic metrics with excess pore pressure ratio and liquefaction susceptibility assessment for: (a - c) $N_{\gamma = 3\%}$, and (d – f) N_{max}, indicating variation of maximum excess pore pressure ratio with: (a, d) normalized cyclic shear stress difference at γ = 0, (b, e) normalized minimum tangent shear modulus, and (c, f) the plasticity index-water content-to-liquid limit ratio of selected specimens. Note: (1) the number of specimens where markers coincide is indicated, and (2) non-plastic (NP) specimens assigned w_n/LL = 1.0 for plotting purposes.

Based on the large-strain observations associated with N_{max}, approximate quantitative guidelines for identifying cyclic behavior may be summarized as:

- Clay-like behavior: transitional soils with $r_{u,max} \lessapprox 90\%$, $\Delta\tau_{cyc}/\tau_{cyc,max} \gtrapprox 0.55$, and $G_{tan,min}/\tau_{cyc,max} \gtrapprox 2$;
- Sand-like behavior: transitional soils with $r_{u,max} \gtrapprox 95\%$ and $G_{tan,min}/\tau_{cyc,max} \lessapprox 2$; and,
- Intermediate behavior: transitional soils with $90\% \lessapprox r_{u,max} < 95\%$, $G_{tan,min}/\tau_{cyc,max} \gtrapprox 2$ and $\Delta\tau_{cyc}/\tau_{cyc,max} > 0.55$.

LINKING HYSTERETIC METRICS TO SOIL INDEX-BASED LIQUEFACTION SUSCEPTIBILITY CRITERIA

The liquefaction susceptibility and framework for evaluating transient cyclic characteristics discussed above recognize that judgments of anticipated hysteretic behavior in the absence of site-specific cyclic data are necessary. Accordingly, the specimen behavior deduced using the quantitative criteria for $N_{\gamma = 3\%}$ and N_{max} are assessed in terms of correlation to mineralogy and state through the PI and w_n/LL ratio, similar to the Bray and Sancio (2006; B&S06) criteria. Comparison of Figures 2c and 2f serves to reinforce the need to assess hysteretic behavior of transitional soils at large strain amplitudes (i.e., greater than 5%) given the lack of sand-like behaviors for $N_{\gamma = 3\%}$. Figure 2f shows that no specimen determined to exhibit clay-like behavior using hysteretic metrics is characterized with $w_n/LL > 0.85$ and $PI < 12$. In contrast, only one sand-like specimen with $PI = 19$ notably deviates from the $PI = 12$ boundary separating the susceptible and moderately susceptible soils from not susceptible using the B&S06 criteria, whereas eight sand-like specimens are characterized with $PI > 7$ associated with the clay-like threshold proposed in the Boulanger and Idriss (2006; B&I06) criteria. Based on the large-strain cyclic responses of specimens exhibiting sand- and clay-like hysteretic behavior (i.e., associated with N_{max}), it appears that in the absence of site-specific cyclic test data, transitional soils with $PI > 12$ and/or $w_n/LL < 0.85$ may be reliably judged as clay-like, whereas soils with $PI \lessapprox 12$ and $w_n/LL > 0.85$ may be reliably judged as sand-like provided that the associated soil deposit experiences sufficient loading cycles to trigger large-strain behavior.

CONCLUDING REMARKS AND RECOMMENDATIONS

Evaluation of seismic risk associated with soil liquefaction follows three general steps: evaluation of liquefaction susceptibility, assessment of cyclic resistance and liquefaction triggering, and estimation of the consequences of liquefaction. Given that the second and third steps are inextricably linked to the first step, a clear definition of soil liquefaction, constrained to the transient loss of stiffness and strength, is necessary to complete the liquefaction hazard analysis. The occurrence of liquefaction, and therefore liquefaction susceptibility, of transitional soil may be quantified objectively using hysteretic behavior, as demonstrated by the results of the study discussed herein, independent of the engineering procedure which may be recommended for estimation of cyclic resistance or the consequences of liquefaction triggering.

ACKNOWLEDGEMENTS

Mr. Ali Dadashiserej, lead student researcher, and Dr. Amalesh Jana performed the cyclic direct simple shear tests described in this study; their effort and dedication is gratefully acknowledged. This material is based upon work supported by the National Science Foundation under grant CMMI-1663654, the Oregon Department of Transportation (ODOT) under Grant SPR-304-911 and various ODOT projects, the Port of Portland, the Cascadia Lifelines Program (CLiP), and the Pacific Earthquake Engineering Research (PEER) Center under Grant 1175-NCTRSA. Any opinions, findings, and conclusions or recommendations expressed are those of the authors and do not necessarily reflect the views of the above-mentioned sponsors.

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CYCLIC BEHAVIOR OF LOW PLASTICITY FINE-GRAINED SOILS OF VARYING SALINITY, AND CYCLIC FAILURE DUE TO DYNAMIC SOIL-STRUCTURE INTERACTION

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MOTIVATION

Liquefaction susceptibility of fine-grained soils is often based on plasticity index, with lower plasticity soils considered susceptible to liquefaction and higher plasticity soils considered susceptible to cyclic softening. Pore fluid chemistry exerts a significant impact on the behavior of plastic clay minerals because cations from dissolved salts interact with the negatively charged surface of the clay minerals, thereby suppressing the diffuse double layer and causing a flocculated structure. The presence of dissolved cations also reduces the plasticity for a soil with a given mineral composition. However, very little research has been performed to understand the influence of dissolved cations on the cyclic response of fine-grained soils, and whether plasticity index is a sufficient indicator of susceptibility.

This abstract addresses themes 1. the current state-of-the-practice and its limitations, and 3. options for future susceptibility models that could be used, for example, in conjunction with liquefaction triggering models or hazard mapping. We address theme 1. by presenting direct simple shear test data for fine-grained soils with PI=9, but with varying mineralogy and pore fluid chemistry. These soils behave differently during cyclic loading despite having the same PI, which is not well captured by state-of-the-practice methods that utilize PI to assess liquefaction susceptibility. We then address theme 3. by briefly laying out a vision for a data-driven susceptibility model consisting of field performance observations, geotechnical site investigations, and laboratory tests.

RESPONSE TO PROMPT(S)

Prompt 1. What is the state-of-the-art?

The state of the art in evaluating susceptibility of fine-grained soils is to utilize the soil plasticity index, *PI*. For example, Boulanger and Idriss (2007) indicate that a soil is “clay-like” and therefore not susceptible to liquefaction when $PI>7$, though it is susceptible to cyclic softening which should be evaluated using a separate set of procedures. Bray and Sancio (2006) indicate that loose soils with $PI < 12$ are susceptible, $12 < PI < 18$ and $w_c/LL>0.8$ are marginally susceptible, and $PI > 18$ are not susceptible. Both of these methods utilize *PI* to assess susceptibility, while Bray and Sancio (2006) also use w_c/LL which is related to soil state rather than mineral composition. This raises an important question about whether susceptibility should be a sole function of soil composition, or whether soil state should be included.

Figure 1 illustrates three blends of minerals with the same *PI* (Table 1) that exhibited significantly different behavior under stress-controlled cyclic loading. The blends consisted of a mix of non-plastic silt with either bentonite or kaolinite, and the pore fluid was either fresh water or a 35 g/L NaCl solution. Vertical consolidation stress was 50 kPa, and OCR was 1 for all three blends. The SBSW blend exhibits a gradual accumulation of shear strain and relatively "fat" hysteresis loops that are generally consistent with clay-like behavior, whereas the SKFW blend exhibits a more abrupt increase in strain amplitude and narrower hysteresis loops with a significant flat portion in the middle of the loops, which is more consistent with sand-like behavior. The SBFW blend is intermediate between the other two blends.

Table 1. Properties of mixtures used in experimental program

ID	*% silt*[a]	*% Bentonite*[b]	*% Kaolinite*[c]	*Pore fluid*	G_s	*LL*	*PL*	*PI*
SBFW	95	5	0	Fresh water	2.64	31.2	22.6	8.6
SBSW	90	10	0	Saline water	2.67	31.9	23.1	8.8
SKFW	78	0	22	Fresh water	2.63	30.0	21.4	8.6

[a] Sil-co-sil #45 ground silica, Non-plastic

[b] LL = 455, PL = 40, PI = 416

[c] LL = 66, PL = 36, PI = 30

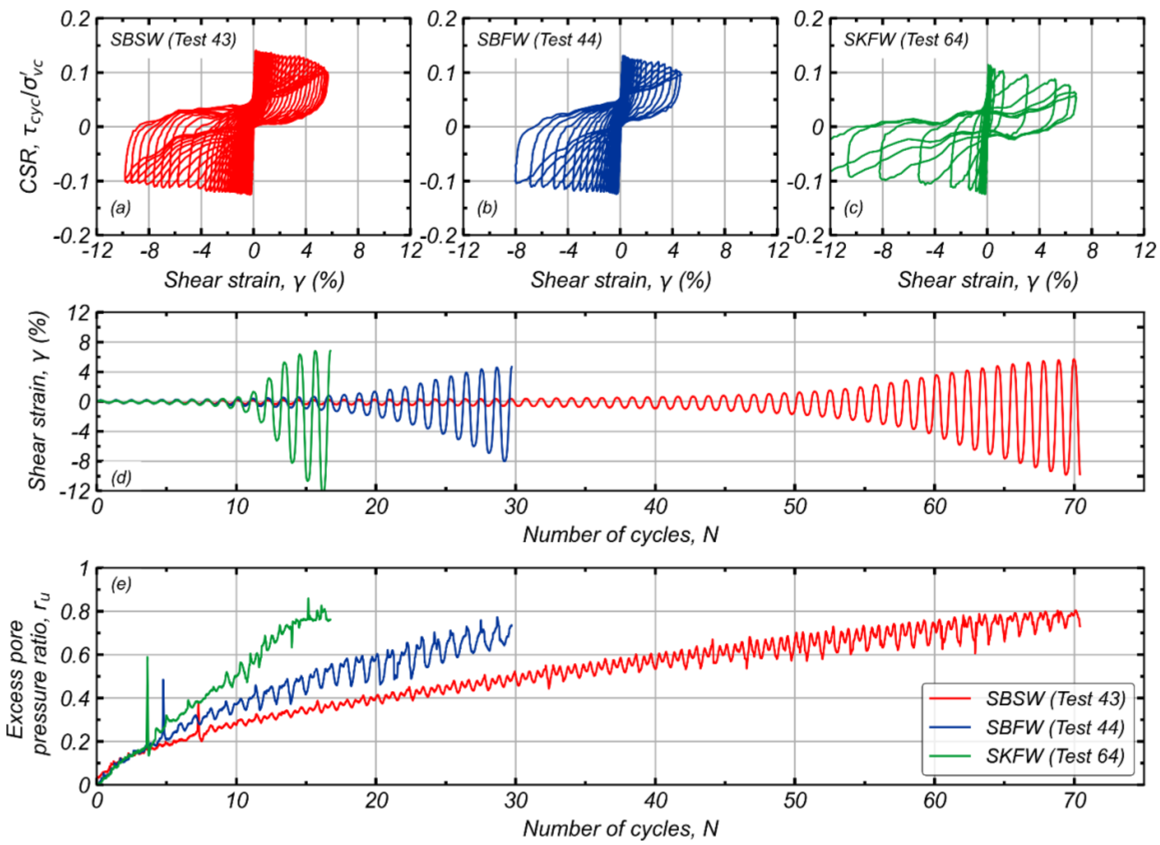

Figure 1. Cyclic behavior of three mineral blends with PI near 9 (Eslami 2017).

Prompt 3. Options for future susceptibility models

Future susceptibility models require data capable of tying together field performance observations from earthquakes, geotechnical site investigation data, and laboratory testing data. Susceptibility cannot be derived solely from field case history data because it is generally impossible to discern whether a particular site did not exhibit surface evidence of liquefaction because it is not susceptible, or because it was not shaken by strong enough ground motion. Laboratory tests provide insights into fundamental behaviors that cannot be gleaned from field performance alone, but laboratory testing alone cannot address system responses and field performance. We suggest that a robust publicly available database that synthesizes field performance, site investigation, and laboratory test data is the best path toward developing new susceptibility models. Furthermore, these models should account for uncertainties in susceptibility assessment. For example, if only soil behavior type index, I_c, is available from a CPT test, there is significant uncertainty with respect to susceptibility, which should be quantified by a large standard deviation. If Atterberg limits are available, uncertainty should be reduced. Finally, if site-specific cyclic testing is performed, uncertainty should be relatively small. Such a framework provides an incentive for engineers to conduct thorough site investigations to reduce uncertainty, thereby generally reducing hazard.

CONCLUDING REMARKS AND RECOMMENDATIONS

Liquefaction susceptibility of fine-grained soils has historically been based upon plasticity index, perhaps in combination with other metrics. We show that soils with the same *PI* may exhibit significantly different behavior during stress-controlled cyclic loading, indicating that *PI* is an insufficient indicator of susceptibility. What remains unclear at this time is whether additional parameters might provide predictive power in addition to *PI*, or whether these deviations in behavior should be handled as aleatory variability and incorporated into a stochastic analysis framework. This finding points to the need for a robust, publicly accessible database of cyclic testing data on fine grained soils to further develop models.

An important issue for our community to clarify is whether the word “susceptible” should refer solely to compositional characteristics (i.e., mineralogy, plasticity), or whether it should also include soil state in some manner (water content, OCR). Our opinion is that susceptibility should be based on compositional characteristics, such that a soil that is not susceptible to liquefaction will not liquefy regardless of how strongly it is shaken. Soil state and shaking intensity should be included to assess whether susceptible soils will liquefy.

Regarding terminology surrounding susceptibility, there is some risk in using the phrase “non-susceptible” without further clarification because engineers may misinterpret “non-susceptible” as meaning “not problematic” or not worthy of additional ground failure evaluation. In reality, a soil that is not susceptible to liquefaction likely is susceptible to another mechanism of strength loss and/or deformation. For future susceptibility models, we suggest clearly stating mechanisms that should be evaluated based on susceptibility of a specific soil to those mechanisms. For example, a soil may be susceptible to liquefaction, susceptible to cyclic softening, or susceptible to other potential mechanisms (e.g., seismic compression).

ACKNOWLEDGEMENTS

This material is based on work supported by the National Science Foundation under award 1563638. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We thank Mandro Eslami and Jason Buenker for their contributions to this work via their PhD studies.

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A DATA ARCHIVE OF CYCLIC AND POST-CYCLIC BEHAVIOR OF SILT-RICH, INTERMEDIATE SOILS OF THE PACIFIC NORTHWEST

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Silt-rich soil deposits are prevalent in the Pacific Northwest (PACNW) region of the USA as well as other parts of the world. While the majority of past research has been focused on the cyclic behavior of sands and clays, few studies have investigated the cyclic response of intermediate fine-grained soils that fall in between classical sand and clay types (e.g., Vaid 1994; Polito & Martin 2001; Bray & Sancio 2006; Idriss & Boulanger 2008; Dahl et al. 2014; Wijewickreme et al. 2019; Jana & Stuedlein 2021.) The cyclic behavior of silt has been documented as intermediate between the generalized and short-hand characterization of soil behavior as either "sand-like" or "clay-like", thereby adding a level of complexity to seismic vulnerability studies involving silt.

This abstract addresses the workshop theme of "*The linkage between laboratory observations, and field characterization and response"* by introducing a data archive compiled of over 200 cyclic shear tests performed on intact soil samples from 37 sites/projects in Oregon, Washington, Alaska and British Columbia. The data archive is comprised of predominantly unpublished test results from Direct Simple Shear (DSS) tests and Triaxial compression (TX) tests. The tests provide researchers and practitioners with a basis for laboratory evaluation of (i) cyclic resistance for a range of reference shear strains, (ii) post-cyclic stress-strain-strength behavior, and (iii) post-cyclic one-dimensional volumetric strain. This data archive will help advance the field by improving our understanding of the effects of stress history and overconsolidation ratio on cyclic resistance, and correlations between cyclic and post-cyclic responses and various soil properties. Figure 1 shows the location of sites/projects included in this data archive. The Data Report will be available under Dickenson et al. (2022) as listed in the References.

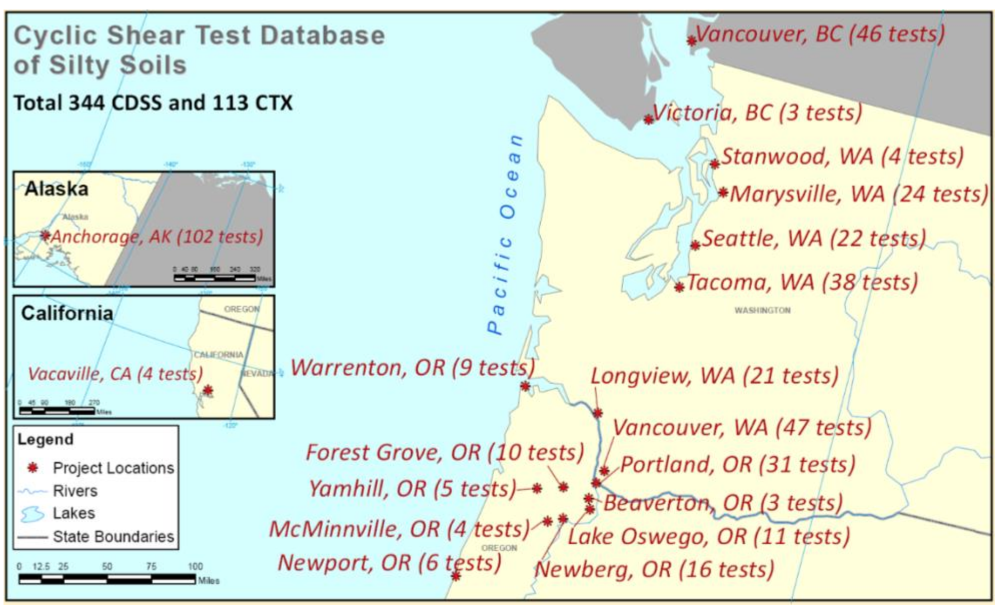

Figure 1. Project site locations.

Data in this study

The data in this archive includes over 200 cyclic shear tests on silt-rich soil deposits from 37 sites in the PACNW of the USA and regions of British Columbia and Alaska. These tests were performed by several soil lab testing facilities in support of various, primarily transportation, projects in these regions. The soil specimens are characterized as low-plasticity silt (ML), low plasticity clay (CL), high plasticity silt (MH), high plasticity clay (CH), and silty sand (SM) based on their USCS classification. Figure 2 shows that the soils presented in this study are characterized as being susceptible to liquefaction or cyclic softening based on screening methods by Idriss and Boulanger (2008) using the illustration method developed by Armstrong and Malvick (2016). The fines contents (FC) for these soils range from 18% to 100% and the plasticity index (PI) values range from nonplastic (NP) to 47. The intact soil samples were extracted from shallow depths down to a depth of 76 m. The depositional environments of the soils in this archive include fluvial (e.g., overbank, floodplain, glacial outwash), estuarine (e.g., mudflat, slough, inter-tidal zone), coastal near-shore (in shallow to intermediate water depths), general alluvial, and mine tailings (e.g., gravel processing and wash tailings). The data archive will be updated as additional projects and test data are provided.

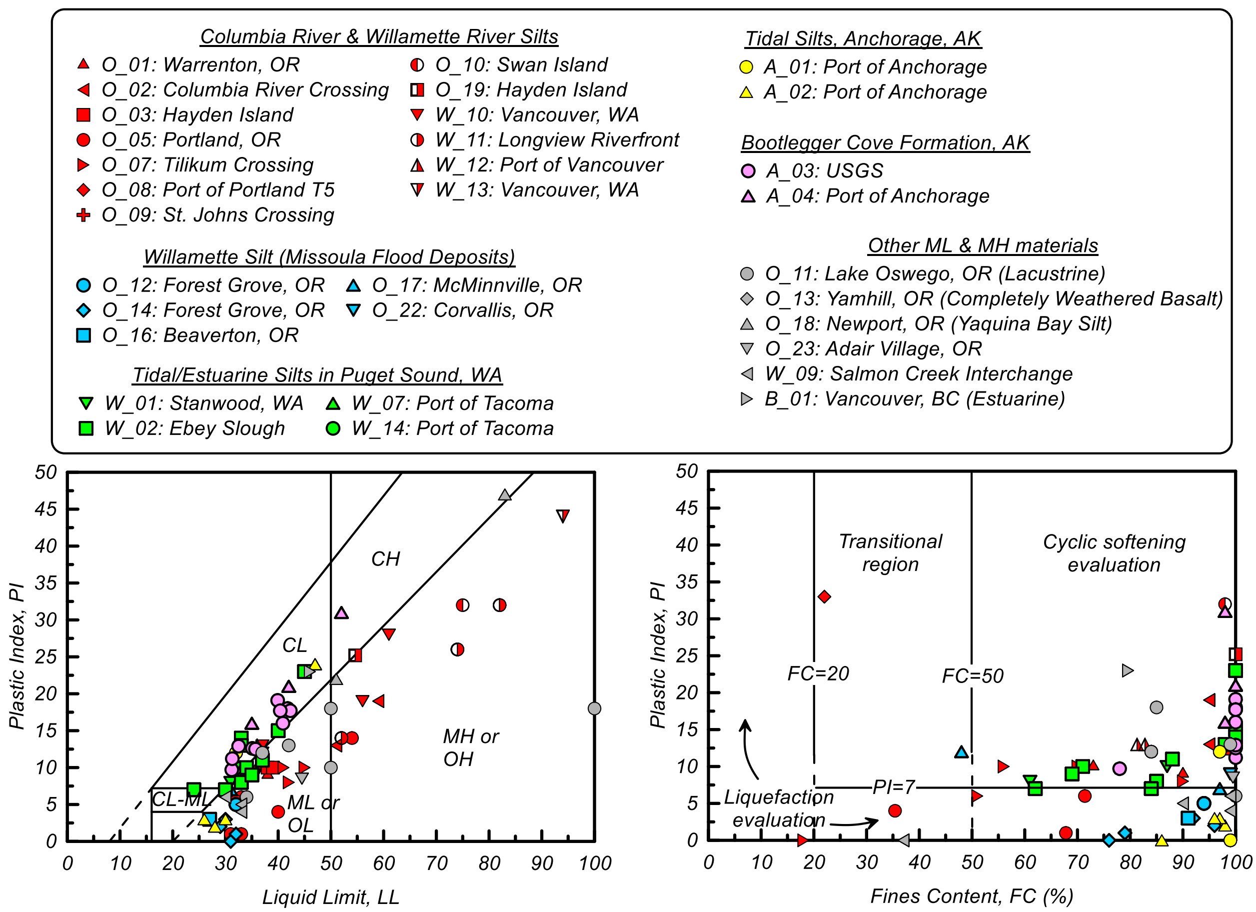

Figure 2. Atterberg limits and fines contents of the soils used in this study and the screening liquefaction and cyclic softening criteria by Idriss and Boulanger (2008) using the illustration by Armstrong and Malvick (2015).

CONCLUDING REMARKS

The data archive presented in this abstract is intended to be used by researchers and practitioners in evaluating the cyclic and post-cyclic response of silt-rich intermediate soils. Considering the scarcity of cyclic shear data on intermediate soils, this data archive provides a benchmark in evaluating the cyclic behavior of silt soils whose cyclic behavior transitions between sand-like and clay-like behaviors. This data archive includes silts from a variety of depositional environments in the PACNW, British Columbia and Alaska, thus the samples support assessment of the influence of factors such as mineralogy, fabric, composition, consistency, density, stress-history, and aging on the cyclic and post-cyclic behavior of the soil.

ACKNOWLEDGEMENTS

The compilation of data was initiated with funding from the Oregon Department of Transportation. The efforts have continued with direct and in-kind support from many organizations and geotechnical consultancies in the Pacific Northwest who shared test data and geotechnical data reports including Jan Six (formerly with the Oregon Department of Transportation), Tony Allen (Washington State Department of Transportation), Scott Schlechter, Jason Bock, and Jack Gordon (GRI Inc.), Don Anderson and Nason McCullough (Jacobs), and Park Piao, Sam Sideras, Bill Perkins, and Bob Mitchell (Shannon & Wilson).

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SUSCEPTIBILITY OF CYCLICALLY-INDUCED DEFORMATION OF LOW PLASTICITY SILTS IN THE PACIFIC NORTHWEST

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CYCLIC STRAIN ACCUMULATION IN LOW PLASTICITY, TRANSITIONAL SOILS

This abstract provides a brief summary of on-going research on the cyclic and post-cyclic behavior of non-plastic to moderate plasticity silt-rich, transitional soils vulnerable to the generation of excess pore pressure. The collection and synthesis of over 200 cyclic Direct Simple Shear (cycDSS) tests on silt specimens from the Pacific Northwest (PACNW), Alaska, and British Columbia (Dickenson et.al. 2022) have facilitated the development of trends for the influence of excess pore pressure generation on the rate of shear strain accumulation, post-cyclic shear strength and shear stiffness, and volumetric strain due to reconsolidation. This effort supports the broad theme of the linkage between laboratory observations and field response. The field response of note in this abstract concerns cyclic shear strain accumulation and modeling of permanent ground deformations due to excess pore pressure generation, with R_u-values ranging from 0 to 0.95.

INFLUENCE OF EXCESS PORE PRESSURES ON CYCLIC STRAIN

Laboratory testing of intact soil and reconstituted specimens has provided the basis for modeling of the rate of shear strain accumulation as a function of excess pore pressure. The work of Tasiopoulou et al. (2020) provides a notable example of shear strain development per cycle of loading for clean sands (Figure 1) loaded to a state of initial liquefaction (i.e., single amplitude shear strain of ~3% during cyclic loading), then subjected to additional loading. The semiempirical relationship illustrated highlights the importance of cyclic demand (τ_{cyc}) and cyclic resistance (D_R) on the post-liquefaction rate of strain. This relationship provides valuable trends for calibration of constitutive models used in two-dimensional nonlinear deformation analysis (NDA).

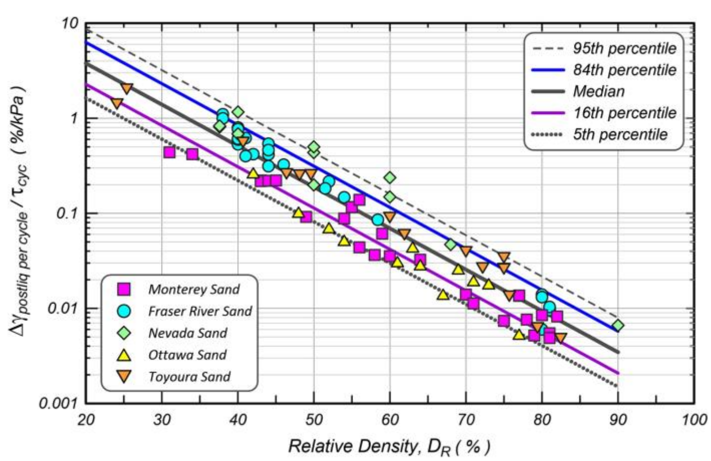

Figure 1. Post-liquefaction shear strain curves for clean sands in cyclic undrained laboratory testing (Tasiopoulou et al. 2020).

In order to develop practice-oriented trends in the rate of shear strain accumulation in low-plasticity silts for calibration of constitutive models such as PM4Silt, the co-authors have evaluated data from the PACNW silt database, as well as from current projects. With the goal of establishing trends that are broadly applicable for a range of cyclic load amplitude and number of cycles, and cyclic resistance, a relationship that included excess pore pressure (R_u) was preferred. This approach has facilitated the development of trends in the shear strain mobilized per cycle for Ru values ranging from < 0.10 to 0.95, thus applicable for situations leading up to, and including, "liquefaction" (or more appropriately "cyclic degradation" for silt that does not exhibit post-cyclic softening behavior similar to that of loose to medium dense sand). Characterization of the strain increment per cycle for silt is important in the PACNW where the seismic hazard is dominated by large magnitude (M 8.5 to 9.2), long-duration Cascadia Subduction Zone earthquakes.

Pore-pressure based models for evaluating behavior such as the post-cyclic shear strength of fine-grained soils have been presented in which the reduction in undrained (constant-volume) shearing resistance is directly related to the maximum R_u during cyclic loading (Ajmera et al. 2019; Dickenson et al. 2022; Egan et al. 1984). A similar approach has been adopted in the current investigation. A curve-fit approximation that includes a function of R_u in cycDSS tests has been applied to model the shear strain per cycle for a silt from the PACNW.

PROJECT-SPECIFIC APPLICATION IN PORTLAND, OREGON

A subset of the cycDSS data presented in the proceedings of this PEER Workshop by the second author is applied in this project summary. Pertinent test results for the 6 specimens include the following; natural water content 34 to 42%, Plasticity Index 0 to 5%, fines content 45 to 60%. The overconsolidation ratio was 1.5 for all specimens. The results of 6 tests are summarized to highlight the general trend of cyclic strain accumulation as a function of; cyclic demand (τ_{cyclic}), cyclic resistance (as correlated with the static undrained shear strength, S_{u_st}), and the excess pore pressure at each cycle (f[R_u]). The influence of progressive softening of the silt on the shear strain per cycle is captured by way of the Ru function, which was obtained by curve fit to the cycDSS tests as previously noted. The trends provided in Figure 2 illustrate that the strain per cycle is well-correlated with both CSR and Ru, and that strain accumulation is small for R_u less than about 0.4, then increases rapidly up to shear strains in excess of 1.0 as the R_u values exceed 0.8.

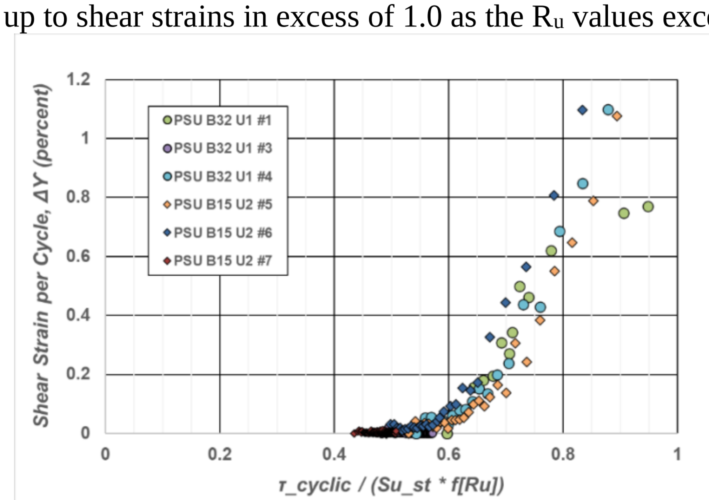

Figure 2. Shear strain per cycle as a function of strength normalized cyclic load amplitude and excess pore pressure function for a low-plasticity silty soil.

CONCLUDING REMARKS AND RECOMMENDATIONS

With respect to the workshop prompts addressing aspects of liquefaction susceptibility and its modeling our observations based on the cycDSS data include the following;

1. Incorrect assessment of the excess pore pressure generation and associated shear strain mobilization per cycle of loading for silt-rich soil commonly results in overprediction of permanent ground deformations due to long-duration earthquake motions.
2. Relevant aspects of hazard assessment that present challenges, or highlight current limitations, in current practice-oriented methods for transitional soils include; (i) characterization of "liquefaction" and "cyclic degradation" type behavior for non- to low-plasticity silt-rich transitional soils, (ii) assessing the timing of cyclic degradation and the associated coupling of kinematic and inertial effects for structures founded on soils subject to permanent seismic deformations, and (iii) for projects involving NDA and transitional soil units, cyclic lab testing is necessary for calibration of constitutive models and has been demonstrated in several cases to reduce inherent uncertainty and conservatism associated with the application of (overly) simplified methods of characterization.
3. The co-authors have experienced numerous cases where the cyclic and post-cyclic behavior of silt-rich soil was pivotal for dynamic soil-foundation-structure interaction of major bridges, port waterfront structures, and buried pipelines. In many cases, the mis-use of liquefaction modeling procedures developed for clean sand with associated fines correction factors has been problematic. There is a pressing need in practice for additional guidance on the post-cyclic behavior of silt-rich, transitional soils.
4. Characterization of rate effects on both static undrained strength and cyclic pore pressure generation in cycDSS testing of low plasticity silt warrants continued research.

ACKNOWLEDGEMENTS

This investigation was initiated with funding from the Oregon Department of Transportation, and has been continued with direct and in-kind support from many organizations and geotechnical consultancies in the Pacific Northwest.

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CPT-BASED PROBABILISTIC PREDICTION OF LIQUEFACTION SUSCEPTIBILITY

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THE CURRENT STATE-OF-PRACTICE AND ITS LIMITATIONS

Cone-penetration-test (CPT) models for predicting liquefaction occurrence and consequences offer advantages over other in-situ tests. However, because soil samples are not recovered, soils are often not characterized directly or tested further in the laboratory. Thus, the standard-of-practice is to infer liquefaction susceptibility from CPT data. Most often, the CPT soil behavior type index, or I_c, is used for this purpose. First proposed by Jeffries and Davies (1993), I_c was modified by Robertson and Wride (1998) to better fit the Robertson (1990) Q – F classification scheme, where Q and F are the normalized CPT penetration resistance and normalized CPT friction ratio, respectively. This modification has become widely used in practice. In the domain of Q and F, circular arcs of constant I_c approximate boundaries between soil behavior types. $I_c = 2.60$, for example, is the commonly assumed boundary between silt mixtures and sand mixtures, and thus, is often used to binomially predict susceptibility, such that soils with $I_c < 2.6$ are inferred to be susceptible. While the $I_c = 2.6$ threshold is common, the I_c boundaries are approximate and warrant continuous retraining, having been established ca. 1990 using an unpublished database that is described neither quantitatively nor qualitatively by Robertson (1990). Moreover, I_c is unlikely to be a perfectly efficient or sufficient predictor of susceptibility. For these reasons, studies have shown the $I_c < 2.6$ criterion to be suboptimal (e.g., Li et al. 2007; Pease 2010).

REGION-SPECIFIC MODELS LINKING LAB AND FIELD CHARACTERIZATIONS

Using 574 split-spoon soil samples obtained parallel to CPTs, Maurer et al. (2019) developed probabilistic models for predicting liquefaction susceptibility in Canterbury, New Zealand. This effort provides important insights that are applicable beyond the region of study, with broader implications for liquefaction hazard modeling. Using the measured liquid limit, plastic limit, and natural moisture content of each sample, four different criteria based on Atterberg limits were used to classify susceptibility: Boulanger and Idriss (2006) [B&I06]; Bray and Sancio (2006) [B&S06]; Polito (2001) [P01]; and Seed et al. (2003) [Sea03]. The classifications made by these criteria were then related to the measured I_c. In the following, the Maurer et al. (2019) models are first susceptibly summarized, after which several remarks and conclusions are presented. The model developed using the B&I06 criterion is first shown in greater detail. This criterion is often favored in practice because it was explicitly developed to determine the most appropriate model for subsequent prediction of cyclic behavior, based on whether the soil's expected cyclic response is "sand-like" or "clay-like." It is important to note that the "susceptibility," as predicted by Maurer et al. (2019): (i) is that defined by the developers of the respective criteria; and (ii) that these definitions are not consistent. Shown in Figure 1a are frequency distributions of samples classified by the B&I06 criterion as a function of the measured I_c. The optimal deterministic I_c threshold for binomial prediction of susceptibility, which for this dataset and criterion was $I_c = 2.5$, is also plotted. Shown in Figure 1b is the probability that soil is susceptible, modeled using a cumulative log-normal distribution, as defined in Maurer et al. (2019). Analogous results are shown for all four susceptibility criteria in Figure 2a. These results can also be reconceptualized to represent the probability density of any I_c threshold value, as shown in Figure 2b.

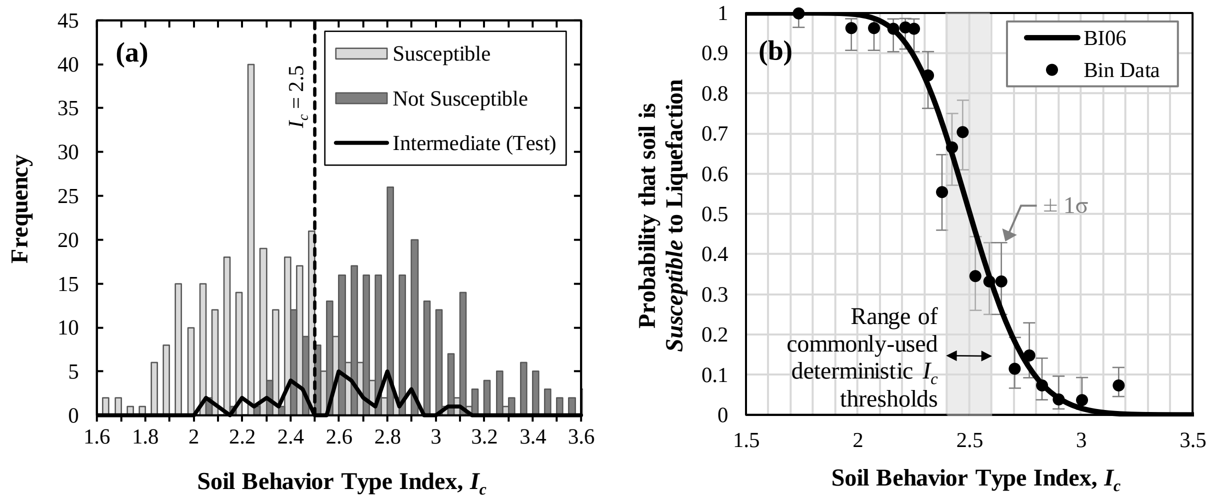

Figure 1. Results using the Boulanger and Idriss (2006) criterion: **(a)** frequency distributions of samples classified as a function of I_c; **(b)** the probability of susceptibility as a function of I_c.

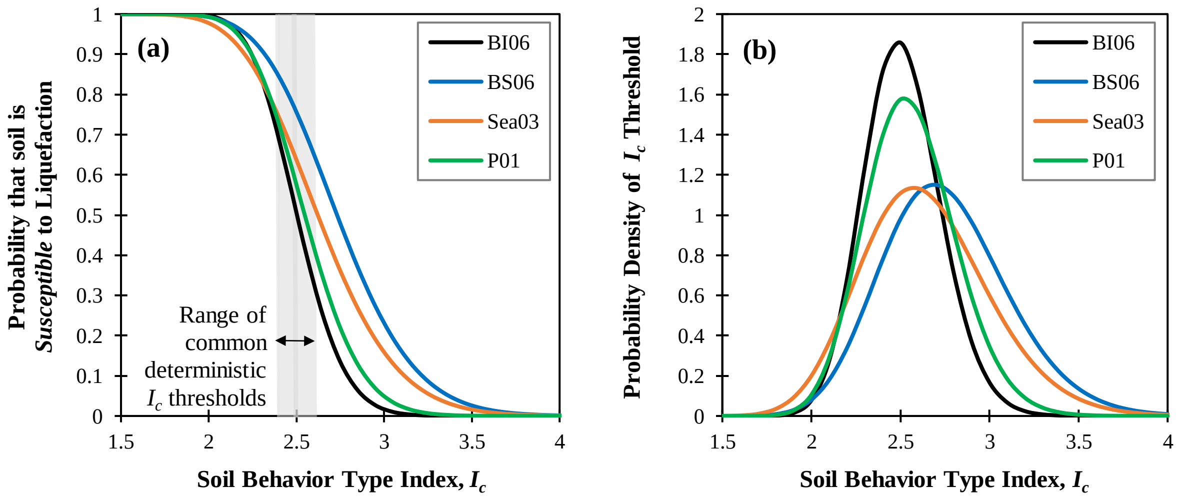

Figure 2. Results using the B&I06, B&S06, Sea03, and P01 criteria: **(a)** the probability of susceptibility as a function of I_c; **(b)** probability density of I_c threshold values.

CONCLUDING REMARKS AND RECOMMENDATIONS

The global applicability of the susceptibility models developed from data in Canterbury cannot be known, and thus, recommendations for or against the use of these models elsewhere cannot be made. Nonetheless, several important conclusions can be derived from these models:

1. While the most common deterministic I_c thresholds for discriminating susceptibility (i.e., I_c = 2.4-2.6) appear to be reasonable medians, the relationship between I_c and susceptibility, as predicted by any of these criteria, is quite uncertain. Using the B&I06 criterion in Canterbury, for example, there is a 15% probability that soil with $I_c \approx 2.3$ is *not* susceptible, and similarly, a 15% probability that soil with $I_c \approx 2.75$ *is* susceptible. It should also be recognized that the

existing criteria based on Atterberg limits do not provide uncertainty quantification, and as such, that component of uncertainty is not accounted for here.

2. Various criteria based on Atterberg-limit data often provide very different predictions of susceptibility. This is of course unsurprising, especially when considering that the definition of "susceptibility" is inconsistent among developers of susceptibility criteria.

3. Given that the uncertainty between I_c and susceptibility is nontrivial, it should arguably be accounted for in any rigorous probabilistic treatment of liquefaction hazard. Accounting for this uncertainty will be most consequential when I_c is asymmetrically distributed within a given soil profile. In these cases, accounting for the uncertainty of the I_c threshold will result in the predicted liquefaction hazard differing from that computed using a median threshold. This assumes, of course, that the median is not systematically unreasonable for the profile (i.e., biased), which would be an altogether different and more consequential problem.

4. The models developed in Canterbury provide a methodology that can be repeated for other regions or at global scale. The uncertain relationship between I_c and susceptibility predicted from Atterberg limits also suggests that predictor variables yet to be determined (i.e., other than I_c) could provide more efficient and/or sufficient predictions of susceptibility. Efforts to better predict susceptibility via CPT data, and to define the uncertainty therein, are needed.

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RELATING CYCLIC BEHAVIOR TO CPT DATA FOR INTERMEDIATE FINE-GRAINED SOILS

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The Cone Penetration Test (CPT) is an established method for evaluating the liquefaction susceptibility of sand and granular soils. However, there remains large uncertainty when evaluating the cyclic strength of soils intermediate to sands and clays (e.g., non-plastic silts, clayey silts). This abstract addresses the workshop theme of *"The linkage between laboratory observations, and field characterization and response"*, specifically by discussing relationships between intermediate soil cyclic behavior, cyclic strength, soil state and CPT data. Developing relationships between the cyclic response of intermediate soils and CPT data currently has several limitations, including: (1) uncertainties in use of CPT-based screening criteria for cyclic behavior and (2) limited understanding of how CPT data responds to changes in intermediate soil properties and state parameters that affect cyclic behavior. This abstract discusses recent work to address these limitations through a database of geotechnical project data from fine-grained soil sites and numerical cone penetration modeling in non-plastic and low-plasticity silt.

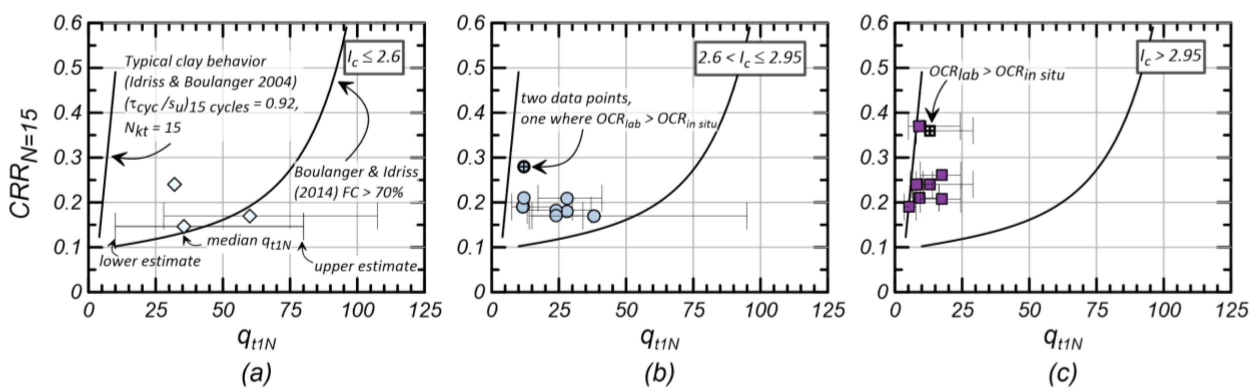

Figure 1. CRR – q_{t1N} data from fine-grained soil projects in Oregon and Washington: (a) $I_c \leq 2.6$, (b) $2.6 < I_c \leq 2.95$, and (c) $I_c \geq 2.95$ (from Moug et al. 2022).

CPT-based intermediate soil liquefaction susceptibility and cyclic strength

The cyclic strength of soil (i.e., cyclic resistance ratio, CRR) is often estimated from the normalized cone tip resistance (q_{t1N}). Estimates of CRR from q_{t1N} vary depending on whether the soil is considered to exhibit sand-like (e.g., Boulanger & Idriss 2014 (2004?)) or clay-like (e.g., Boulanger & Idriss 2006) behavior. Therefore, a reliable CPT-based screening method for intermediate behavior will be a notable step forward for liquefaction evaluation. Soil behavior type index (I_c), as defined by Robertson (1990), is often used as screening criteria: soils with $I_c > 2.6$ are generally not susceptible to liquefaction but should be sampled and lab tested (Robertson & Wride 1998).

A preliminary analysis of 11 fine-grained soil sites in western Oregon and Washington supports use of I_c for liquefaction screening (Moug et al. 2022). Fine-grained alluvial soils are ubiquitous in western Oregon and Washington, therefore, region-specific CPT-based relationships will strongly benefit the region. The data for this study are shown in Figure 1 with CRR-q_{t1N} pairs binned by $I_c \leq 2.6$, $2.6 < I_c \leq 2.95$, and $I_c > 2.95$. The CRR for these soils were evaluated using cyclic direct simple shear tests performed on intact soil samples. The q_{t1N} values were evaluated using CPT data measured in the same soil unit from which the intact soil samples were obtained. The project data indicate that soils with $I_c \leq 2.6$ are consistent with the Boulanger & Idriss (2014) relationship for sand with 70% fines content; $I_c > 2.95$ are consistent with typical clay-like behavior but CRR values are generally lower than expected from the relationship; and, soils with $2.6 < I_c \leq 2.95$ appear to transition between the sand and clay relationships. This analysis provides a basis for in-depth examination of CRR-q_{t1N} relationships for regional soils, and for intermediate soils more broadly, to constrain liquefaction screening criteria and CRR-q_{t1N} relationships.

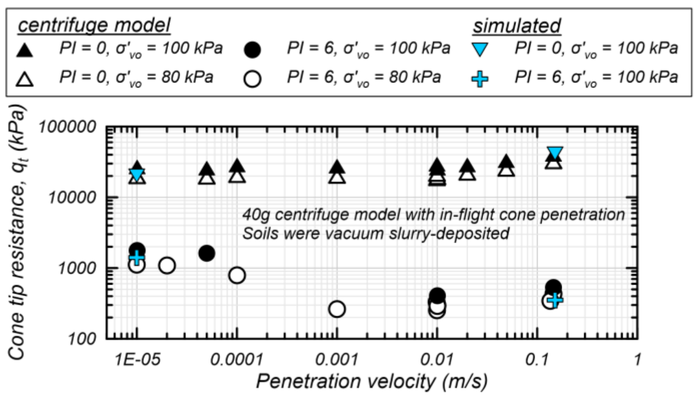

Figure 2. Centrifuge model (Price et al. 2019) and simulated penetration data (Moug & Price 2023) for PI = 0 and PI = 6 silt and clay mixtures.

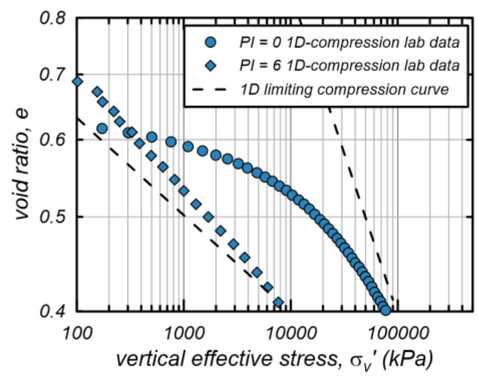

Figure 3. Compression behavior of PI = 0 and PI = 6 silt and clay mixtures (data from Price 2018).

Influence of intermediate soil properties and state on CPT data

Linking cyclic behavior and strength of intermediate soils to CPT data will benefit from investigations into the relationship of CPT data to soil properties (e.g., compressibility, critical state line (CSL) position) and state parameters (e.g., ξ_o). A primary influence of the transition of CRR-q_{t1N} relationships between sands and clays is soil compressibility. Soil compressibility has recently been incorporated by Saye et al. (2021) into a CPT-based liquefaction susceptibility and triggering evaluation procedure. The influence of compressibility is shown in Figure 2 and 3 with geotechnical centrifuge model data, numerical modeling, and laboratory compression data (Price et al. 2019; Moug et al. 2019; Moug & Price 2023). Figure 2 shows centrifuge model-measured q_t at varying penetration velocities for a PI = 0 non-plastic silt (SIL-CO-SIL) and a PI = 6 silt and kaolin clay mixture. Additionally, simulated q_t from a direct axisymmetric cone penetration model with the MIT-S1 constitutive model (Pestana & Whittle 1999) calibrated for the PI = 0 silt and a PI = 6 mixture are shown in Figure 2. It should be noted that the PI = 0 soil is a highly angular and dilative soil, with behavior that likely deviates from naturally-deposited silt soils. The cone penetration data show that q_t values are over an order of magnitude larger for PI = 0 than PI = 6, which is largely attributed to higher compressibility of the PI = 6 soil mixture. The laboratory-measured compression behavior and MIT-S1 limiting compression curves (LCC), are shown in Figure 3. The LCC for PI = 6 is located at much lower mean effective stress (p') conditions than

PI = 0, corresponding to the higher compressibility of the PI = 6 soil. These cone penetration data show the strong influence of compressibility on q_t for intermediate soils. Additionally, compressibility affects the soil's CSL, which is further discussed below.

ξ_o, defined as the difference between the initial void ratio (e) and the equivalent void ratio at critical state conditions for the same p', is considered an indicator for whether liquefiable soil will have contractive ($\xi_o \geq -0.05$) or dilative ($\xi_o < -0.05$) shear behavior. Several researchers have proposed CPT-based methods for interpreting ξ_o (Plewes et al. 1992; Robertson 2009; Been et al. 1986, 1987), however, given challenges to routinely characterizing ξ_o (e.g., obtaining intact high quality samples and characterizing critical state lines), these are generally based on limited data and soil types. Cone penetration simulations, as shown in Figure 4, provide insight into how PI = 0 and PI = 6 soils respond to changes in ξ_o for undrained and drained penetration conditions. It should be noted that for many intermediate soils, the response will be partially drained at the standard penetration rate. Figure 4 shows that the e – p' response for soil around the penetrating cone is related to the CSL position: by the cone tip, soil has loaded to the CSL for drained and undrained penetration conditions. Therefore, CSL position (which is also influenced by compressibility) and ξ_o have a strong influence on q_t. Similarly, stress and porewater pressure conditions at the cone shoulder and friction sleeve, are also influenced by the position of the CSL and ξ_o. This work demonstrates that direct cone penetration simulations across intermediate soil types, ξ_o, and drainage conditions can provide a fundamental basis (i.e., CSL position and shape) to link ξ_o, soil behavior, and soil properties to CPT data.

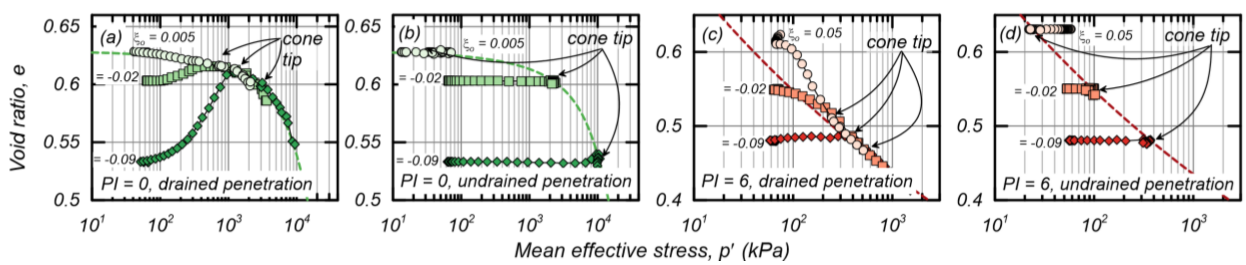

Figure 4. Simulated e – p' paths for soil adjacent to a penetrating cone at initial p' = 66.7 kPa and various ξ_o for (a) PI = 0 drained penetration, (b) PI = 0 undrained penetration, (c) PI = 6 drained penetration, and (d) PI = 6 undrained penetration. Dashed lines are the CSL for triaxial compression loading based on MIT-S1 calibration parameters.

CONCLUDING REMARKS AND RECOMMENDATIONS

The work described in this abstract looks at CRR-q_{t1N} relationships for fine-grained and intermediate soils, including analysis of pairs of laboratory-characterized CRR values and nearby CPT profiles, and numerical simulations of cone penetration in intermediate soils. This abstract recommends additional research into CPT-based liquefaction screening criteria and cyclic strength evaluation for intermediate soils, including how CPT-based criteria and relationships are affected by soil properties, ξ_o and penetration drainage conditions. Compiling and synthesizing data from existing fine-grained soil sites, specifically pairing CPT profiles next to boreholes with high quality intact soil sampling for geotechnical projects, will provide useful data to link intermediate soil behavior to CPT data. Numerical simulations for natural intermediate soils over a range of ξ_o, initial stress conditions, and penetration drainage conditions will provide a critical fundamental understanding for interpreting CPT data.

ACKNOWLEDGEMENTS

Many individuals and organizations that provided data and support for this study: Oregon Department of Transportation, GRI Inc., Northwest Geotech Inc., Geocon Northwest Inc., CH2M Hill, Shannon & Wilson, GeoEngineers, Washington State Department of Transportation, and Portland State University. Support for the numerical cone penetration model and calibration came from Dr. Ross Boulanger and Dr. Adam Price.

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USING CONE PENETRATION TESTS IN WILLAMETTE SILTS

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LABORATORY TEST RESULTS CORRELATED TO *IN-SITU* CPT

This research focused on relating engineering parameters and cyclic resistance of large strain liquefaction triggering of lightly overconsolidated, low to non-plastic silts at seven different study sites. Specific attention was given to preconsolidation (σ'_p), undrained shear strength (s_u) and liquefaction triggering using sand-like, clay-like, and the Common-origin Δ_Q methods. Laboratory tests from undisturbed samples were paired with measured data and relationships from adjacent cone penetration test sounding to develop relationships.

With the use of 24 good quality one-dimensional constant rate of strain consolidation tests, a regional silt-specific σ'_p relationship was developed. A regional silt-specific correlation for Willamette Silt, using the power law, improved the predictability of σ'_p from both Agaiby and Mayne (2019) and Mayne (2007) models which underestimated and overestimated, respectively.

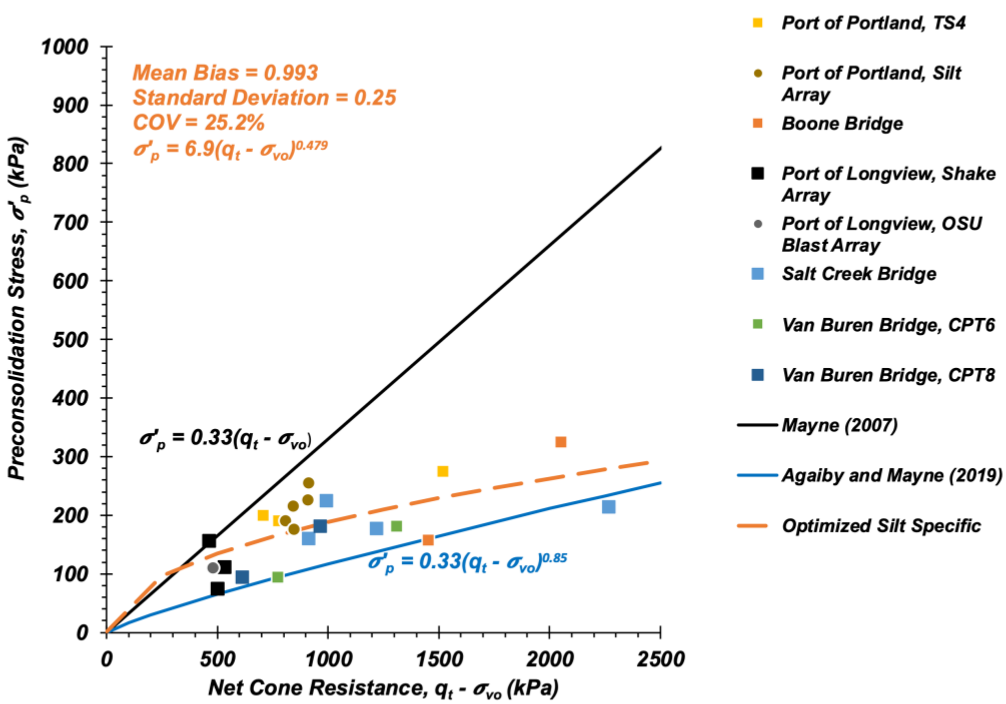

Figure 1. Preconsolidation stress models (Mayne 2007; Agaiby & Mayne 2019; Ortiz 2022).

Using monotonic direct simple shear tests results from Willamette Silts, two approaches were found to be reliable predictors for s_u. A regional silt-specific cone factor was regressed and as well as a regional silt-specific SHANSEP parameters where both methods were found to provide a good estimate of s_u.

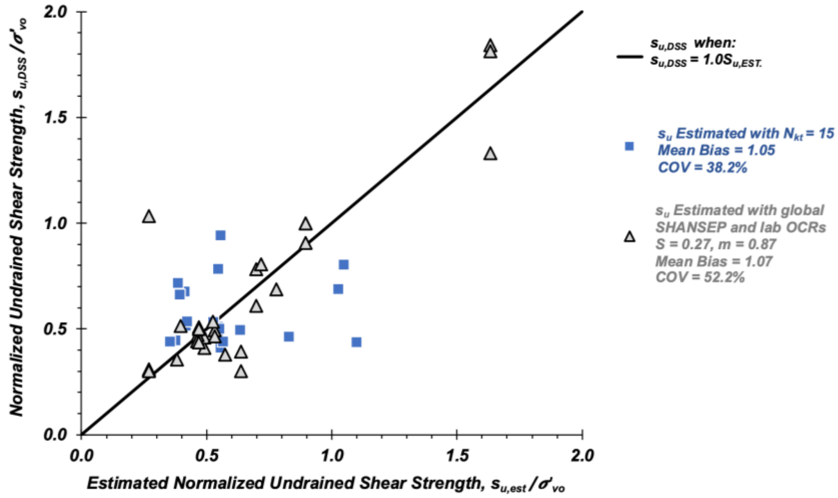

Figure 2. Estimation of undrained shear strength using region silt-specific N_{kt} and SHANSEP parameters (Ortiz 2022).

Assessment of Cyclic Resistance Against Large Strain Triggering

Cyclic resistance of Willamette Silts using both sand-like and clay-like models indicate underestimating and overestimating, respectively (Boulanger & Idriss 2016; Boulanger & Idriss 2007). Investigation of the proposed Common Origin-Δ_Q model (Saye et al. 2021) indicates close approximation to sand-like models and generally underestimates the cyclic resistance.

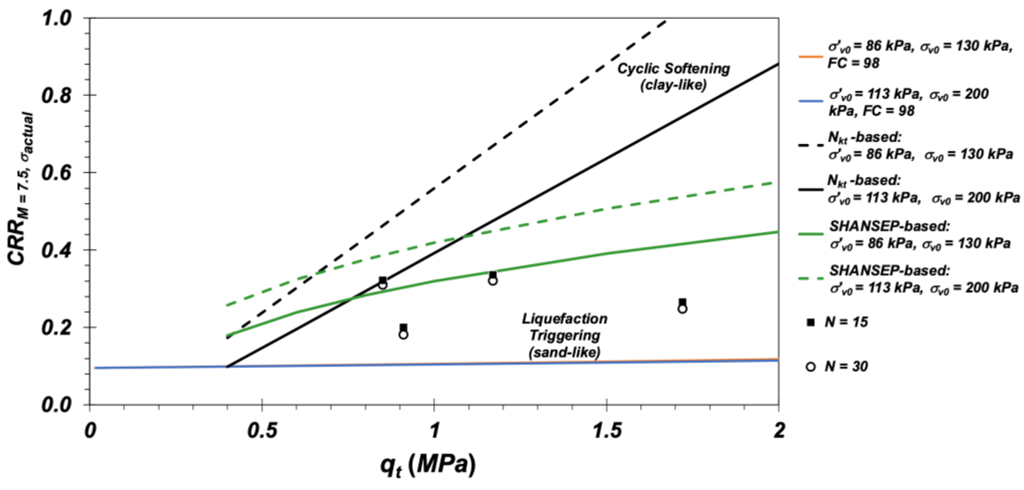

Figure 3. Cyclic Resistance of Willamette Silt using Sand-like and Clay-like models (Boulanger & Idriss 2007, 2016; Ortiz 2022).

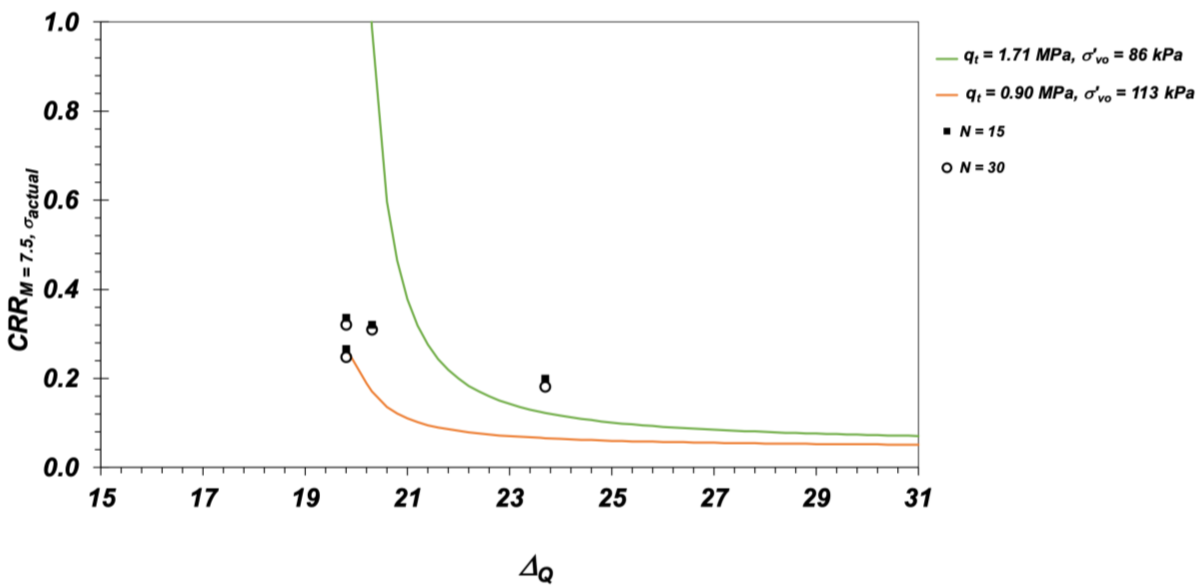

Figure 4. Cyclic Resistance of Willamette Silt using Common Origin-Δ_Q method (Ortiz 2022).

CHALLENGES WITH WILLAMETTE SILT

Soil throughout Southwest Washington and Western Oregon are placed by catastrophic floods known as the Missoula Floods. Repeated flooding of water up to 400 feet, ponding for decades, resulted in deep soil deposits in the Willamette Valley. These flood deposits, Willamette Silts, are low to non-plastic silts which are lightly overconsolidated and generally do not behave like normally consolidated silty sands and sandy silts. Designing projects which are founded in Willamette Silts continue to prove to be difficult to model. Willamette silts show that neither sand-like nor clay-like models for cyclic resistance are particularly good. This is troublesome given that the use of sand-like model results in an over-conservative design increasing the cost of the project and the clay-like models overestimate CRR which compromise safety and long-term performance.

CONCLUDING REMARKS AND RECOMMENDATIONS

Willamette Silts are difficult soils to collect, test and model. Given the stress history and characteristics of the soil, models generated from global databases are not well-suited for use in design. Examples of this include; σ'_p where standard-of practice methods both over- and under-estimate laboratory test results, s_u where regional silt-specific N_{kt} and SHANSEP parameters improve predictability, and assessment of large strain liquefaction triggering where sand-like or clay-like models under- and over-predict cyclic resistance. Lesson learned from this research include: 1) regional specific CPT correlations show promise for improved CPT correlations, 2) an increased dataset would improve the robustness of the proposed models, 3) laboratory testing is best.

ACKNOWLEDGEMENTS

The Oregon Department of Transportation sponsored for this research with Dr. Armin W. Studlein as the principal investigator.

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HIGH-RESOLUTION V_P & V_S MEASUREMENTS FROM DIRECT-PUSH CROSSHOLE (DPCH) TESTING T0 AID IN ASSESSING LIQUEFACTION SUSCEPTIBILITY

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CURRENT STATE-OF-THE PRACTICE AND ITS LIMITATIONS

Currently, in-situ liquefaction susceptibility is primarily evaluated based on results obtained from at least one of the following site characterization tests/methods: (1) the standard penetration test (SPT), (2) the cone penetration test (CPT), and (3) shear wave velocity (V_s) measurements. In simplified terms, the SPT- and CPT-based methods attempt to account for the impact of soil density on liquefaction resistance, while the V_s -based methods attempt to account for the impact of small-strain soil stiffness/modulus on liquefaction resistance. Each method has strengths and weaknesses in regards to evaluating liquefaction susceptibility, and it is beyond the scope of this abstract to elaborate on these points. Suffice it to say that both density and small-strain stiffness are important, and integrating these approaches with one another would be ideal. While sufficient space is not available in this abstract to elaborate on various approaches for integrating penetration-based and Vs-based liquefaction susceptibility methods, some thoughts are provided on how high-resolution measurements of compression wave velocity (V_p) and V_s can be used together to supplement traditional liquefaction susceptibility analyses. Whereas much attention has already been given to V_s in regards to evaluating liquefaction susceptibility, relatively little effort has been put forth regarding the importance of V_p in evaluating liquefaction susceptibility. V_p measurements can be useful in at least two ways: (1) in determining in-situ degree of saturation (or lack thereof), and (2) in determining in-situ soil void ratio. Currently, we neglect the positive benefits of partial saturation below the hydrostatic ground water level in both forward (i.e., design) and backward (i.e., case histories) liquefaction susceptibility evaluations, predominantly because we don't have an easy way to determine degree of saturation in-situ and/or understand if partial saturation will persist over long time periods. Furthermore, given the importance of relative density/void ratio in all of our laboratory testing for liquefaction susceptibility, we have no good way of measuring it in the field, and simply hope that the penetration resistance from either SPT or CPT captures its effects. High-resolution, in-situ measurements of seismic wave velocities can help shed light on both of these issues. The newly-developed direct-push crosshole (DPCH) method is presented as an in-situ testing technique that can provide high-resolution measurements of both V_p and V_s. Several liquefaction case histories from the 2010-2011 Canterbury Earthquake Sequence (CES) are provided to illustrate how these measurements can be used to determine in-situ degree of saturation and void ratio.

SATURATION AND VOID RATIO FROM IN-SITU V_P & V_S MEASUREMENTS

The DPCH test is a new, invasive, near-surface seismic testing method that combines the desirable characteristics of borehole-based crosshole seismic testing with the relative inexpense and speed of direct-push testing methods like CPT (Cox et al. 2019). DPCH allows for higher resolution V_s and V_p measurements than possible with more common methods like seismic CPT (SCPT). In particular, it is very difficult to obtain accurate V_p measurements with SCPT due to compression waves traveling directly down the rods. An example of high-resolution V_p and V_s

measurements made via DPCH is shown in Figure 1, along with a borehole stratigraphy log and CPT results collected within 2m of the DPCH measurements. This particular data is from the Cobra Reserve site in the Halswell suburb of Christchurch, NZ. No observations of surficial liquefaction manifestation were observed at this site after either the September 2010 Darfield or February 2011 Christchurch earthquakes. Standard CPT-based methods predicted moderate liquefaction in both earthquakes, making this site a false-positive liquefaction case history. While the soil is very soft in terms of both q_c and V_p, the V_p measurements indicate the soil is not fully saturated (V_p < 1500m/s) for many meters below the hydrostatic ground water level (GWL). Research by Ishihara and Tsukamoto (2004) indicates that soils with V_p ~700m/s have cyclic resistance ratios (CRRs) that are ~ 24% greater than an equivalent fully saturated soil. Additional information on attempts to refine liquefaction susceptibility predictions at various false positive case history sites from the CES using high-resoluiton V_p and V_s measurements, as well as other refinements like site-specific fines content correction factors, may be found in Cox et al. (2018), Boulanger et al. (2018), and McLaughlin et al. (2019).

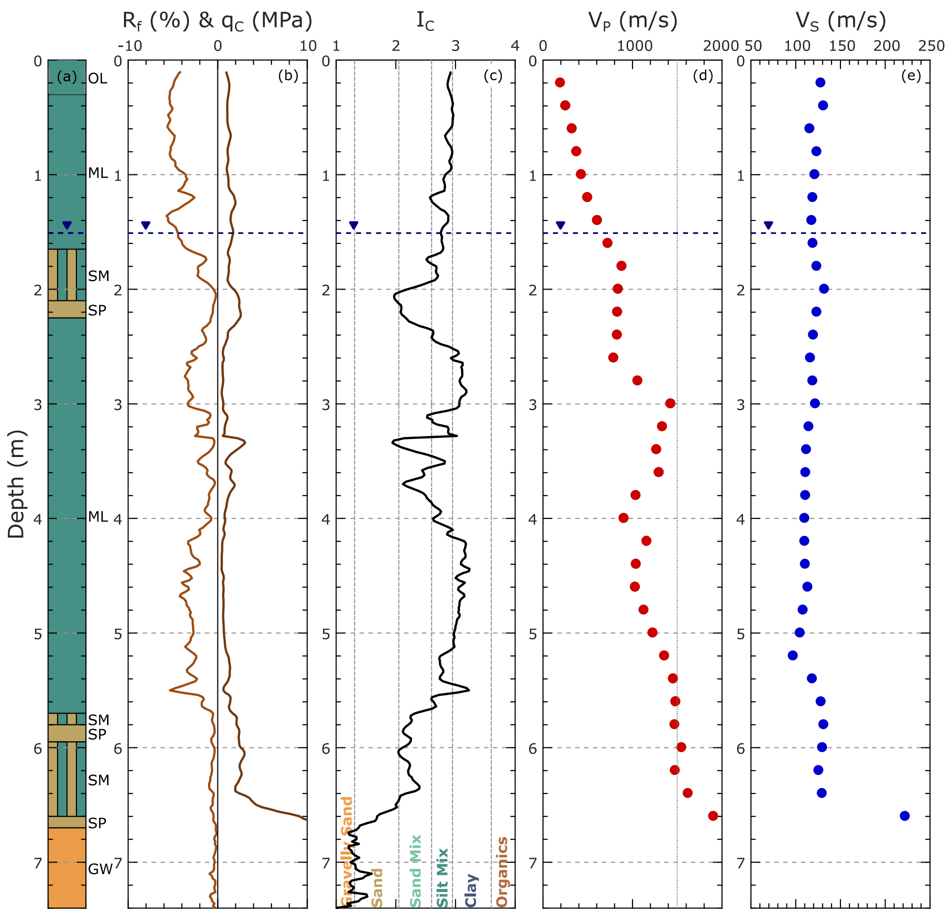

Figure 1. Site investigation data at the Cobra Reserve site: (a) soil classification from sonic borehole samples, (b) friction ratio (Rf) and cone tip resistance (q_c) from CPT testing, (c) normalized soil behavior type index (IC) from CPT testing, (d) V_p from DPCH testing, and (e) V_s from DPCH testing. The ground water table based on piezometer readings is indicated by a horizontal dashed line and an inverted triangular symbol in each panel (Cox et al. 2019).

High-resolution V_p and V_s measurements from DPCH can also be used to directly measure void ratio (e) in-situ based on the theory of poroelasticity (Foti et al. 2002). Stolte and Cox (2019) applied this method at 10 sandy case history sites from the CES and report on its strengths and weaknesses. Results from Rawhiti Domain site are provided in Figure 2.

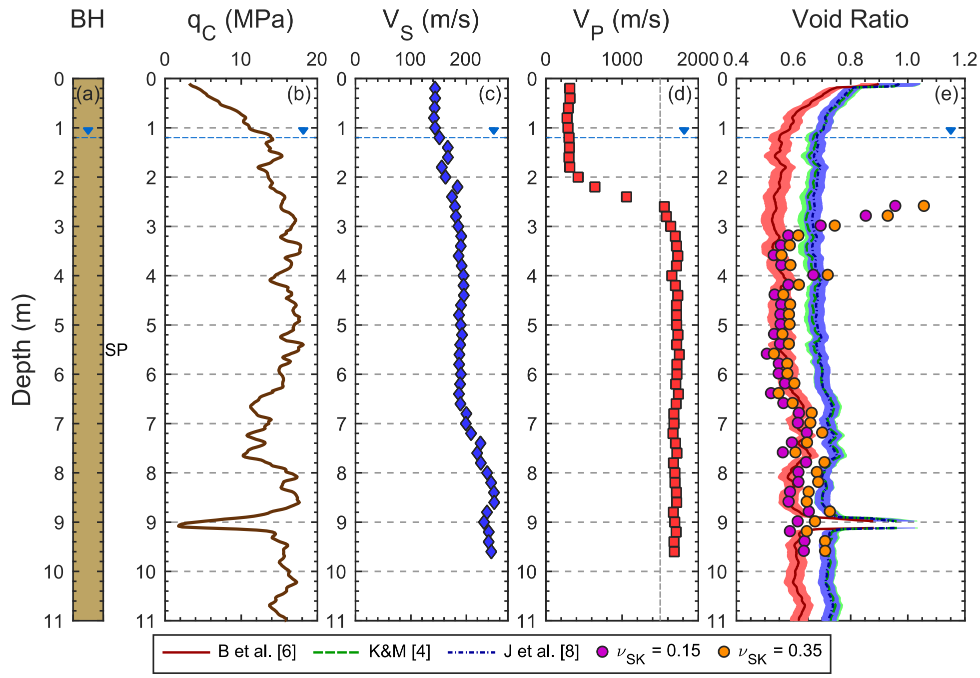

Figure 2. Site investigation data at the Rawhiti Domain site: (a) soil classification from continuous sonic borehole samples, (b) CPT cone tip resistance q_c, (c) V_s, (d) V_p, and (e) in-situ estimates of void ratio from three CPT-based Dr empirical relationships and representative ranges of e_{min} and e_{max} from laboratory testing and seismic-based estimates of in-situ void ratio indicated by circular markers at two assumed values for Poisson's ratio of the soil skeleton, with νSK = 0.15 always yielding lower void ratio estimates than νSK = 0.35. (Stolte & Cox 2019).

CONCLUDING REMARKS

High resolution V_p and V_s measurements from DPCH testing can shed light on important factors like in-situ degree of saturation and void ratio that can strongly influence liquefaction susceptibility. These factors are either ignored or only approximately accounted for in current in-situ liquefaction susceptibility methods based on SPT, CPT, and/or V_s.

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GEOSPATIAL MODELS FOR LIQUEFACTION SUSCEPTIBILITY

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GEOSPATIAL LIQUEFACTION MODELS

As demonstrated in Zhu et al. (2015, 2017), we have developed a geospatial approach to liquefaction modeling that can be applied anywhere in the world rapidly after an earthquake using using globally available datasets. The method relies on geospatial parameters as proxies for important soil properties including soil density and soil saturation and includes shaking intensity through PGA and PGV from the USGS ShakeMap. The models are developed statistically and current models use a logistic regression formulation which results in a probability of liquefaction which is in turn interpreted as an estimate of spatial extent. The global geospatial liquefaction model is described by the following equations.

$$P(x) = \begin{cases} \frac{1}{1+e^{-X}} & \text{PGA, PGV, and Vs30 thresholds (depend on model} \\ 0 & \text{Otherwise} \end{cases} \quad (1)$$

P(x) is the probability of liquefaction which lies between zero and 1; and X includes explanatory variables that describe density, saturation and loading conditions. In Zhu et al. (2017), several candidate models (M) are developed each using a different set of inputs (explanatory variables). As an example, Model 2 has the following model form given by:

$$X = A + b_1.ln(PGV) + b_2.ln(Vs30) + b_3.precip + a_4.dw + a_5\ .wtd \quad (2)$$

This model also includes thresholds by heuristically assigning zero probability when PGV<3 cm/s, V_{s30}>620 m/s, and precip > 1700 mm (the precip threshold was recommended in Rashidian & Baise 2020). Ongoing efforts are updating the geospatial liquefaction database and evaluating new explanatory variables and moving toward a Bayesian modeling approach to quantify parameter and model uncertainty (Baise et al. 2021; Zhan et al. 2022).

OPTIONS FOR FUTURE SUSCEPTIBILITY MODELS

Geospatial Liquefaction Models are designed to leverage geospatial information about the geology and hydrology of any point on the globe. Geospatial proxies exist for soil density (e.g. V_{s30}) and soil saturation (e.g. distance to closest water body). They use global models and datasets as well as geospatial tools to calculate such proxies as distance from or elevation above surface water bodies. Geospatial data captures information about hydrologic conditions and geologic depositional environments are useful for identifying low-lying areas related to alluvial and coastal sediments.. In Zhu et al. (2017), we demonstrated that removing the earthquake loading from the geospatial models results in a map of liquefaction susceptibility as shown in Figure 1 as shown in comparison to a surficial geology-based liquefaction susceptibility map for the San Francisco Bay area. Geospatial liquefaction models are regional in nature and can provide an estimate of liquefaction susceptibility.

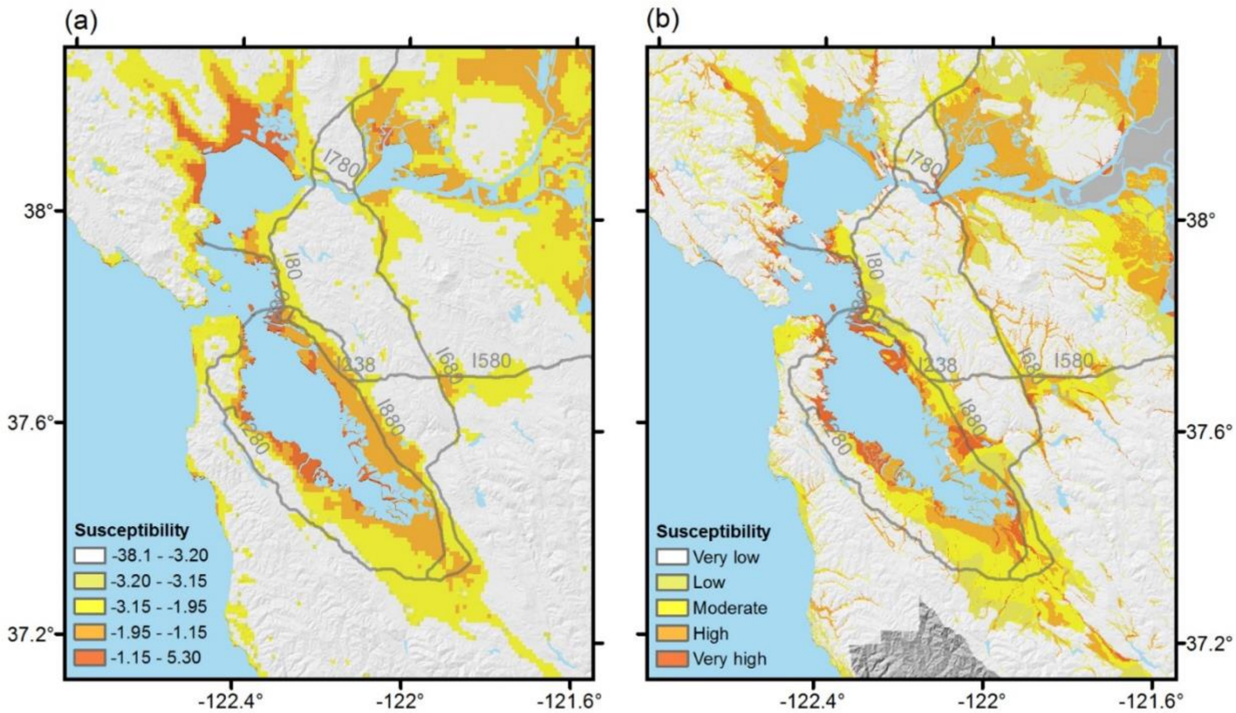

Figure 1. a) Liquefaction susceptibility from a geospatial model (Zhu et al. 2017); b) Surficial geology based liquefaction susceptibility (Witter et al. 2006).

CONCLUDING REMARKS AND RECOMMENDATIONS

The geologic depositional environment and hydrologic conditions of a site have long been understood to be important for determining liquefaction susceptibility as described by Youd and Perkins (1978). The geospatial liquefaction modeling approach provides a mechanism to bring in uniform proxy information for depositional environment and saturation at any location on the globe and should be used in areas lacking more detailed local information as a regional estimate of liquefaction susceptibility.

ACKNOWLEDGEMENTS

The work has been supported by USGS Award G20AP00029 and G22AP00048. Weiwei Zhan, a postdoctoral scholar is currently working on updating the database and enhancing the geospatial models. He has developed the algorithms for adding liquefaction and nonliquefaction samples with geospatial explanatory variables to the dataset. We are also currently working with Prof. Babak Moaveni at Tufts to apply Bayesian Updating as a way of quantifying the model uncertainty and updating the geospatial liquefaction models when new data is available. We have collaborated with Eric Thompson at the USGS on implementation of the model as part of USGS ground failure products.

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ACCOUNTING FOR SOIL AGING IN ASSESSING LIQUEFACTION SUSCEPTIBILITY

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CURRENT STATE-OF-THE PRACTICE AND ITS LIMITATIONS

Geologic age and origin of the soil has been long recognized as having a significant influence on its susceptibility to liquefaction triggering (e.g., Seed 1979), where the soil fabric changes with the age of the deposit, generally resulting in an increased resistance to liquefaction triggering. However, this influence has been largely expressed qualitatively, e.g., relating depositional setting and age to relative liquefaction susceptibility (Youd & Hoose 1977). These qualitative relationships for relative liquefaction susceptibility largely define the current state-of-practice. The lack of quantitative metrics needed to explicitly incorporate aging effects into liquefaction hazard analyses often has resulted in ignoring these effects on liquefaction susceptibility. Alternatively, "engineering judgement" is sometimes used to conclude that a deposit is not susceptible to liquefaction based on its age. This latter approach is often taken when the computed liquefaction hazard with aging effects ignored implies that costly mitigation measures are needed. Unfortunately, "engineering judgement" is not consistently applied across all projects and is sometimes biased towards a desired outcome, rather than being technically well founded.

WHAT IS THE STATE OF THE ART?

Seed (1979) proposed an early method for accounting for aging on liquefaction resistance by computing the ratio of the *CRR* of an aged soil to that of a young deposit of the same soil:

$$K_{DR} = \frac{CRR_{aged}}{CRR_{young}} \tag{1}$$

where K_{DR} is referred to as the "liquefaction strength gain factor" due to aging effects. More recently, several approaches have been developed to compute a numerical index for soil aging. Bwambale and Andrus (2019) provide an excellent overview of the various proposed aging indices. Correlations relating these indices to K_{DR} defines the state-of-art in accounting for aging effects on liquefaction susceptibility. One promising index is the ratio of measured to estimated small-strain shear wave velocities (V_S): *MEVR* (Hayati & Andrus 2009; Andrus et al. 2009).

Hayati and Andrus (2009) argue that the time since last disturbance is more relevant to liquefaction triggering susceptibility than geologic age. To estimate time since last disturbance, Andrus et al. (2009) proposed using *MEVR* as an index:

$$MEVR = \frac{V_{S-measured}}{V_{S-estimated}} \tag{2}$$

where $V_{S\text{-}measured}$ is directly measured, and the estimated V_S (i.e., $V_{S\text{-}estimated}$) is determined using correlations relating V_S and penetration resistance. The underlying premise of the *MEVR* index is that the measurement of penetration resistance mobilizes intermediate to large strains that inherently disturb the soil fabric and, thus, is not that sensitive to aging effects (i.e., penetration resistance correlates to the small-strain shear wave velocity, V_S, of the soil, if the soil were young, regardless of the age of the soil). In contrast, the measurement of V_S directly in the soil is a small-strain measurement and is sensitive to aging effects (i.e., it is the V_S of the aged soil). Thus, the ratio of directly measured V_S to that estimated from penetration resistance should be able to serve as an index for the time since last disturbance.

HOW SHOULD THE NEXT GENERATION OF LIQUEFACTION SUSCEPTIBILITY MODELS BE FORMULATED TO ADVANCE THE STATE-OF-THE ART?

Green et al. (2022) proposed the use of the K_γ-factor to account for intrinsic soil properties and state variables on liquefaction triggering in simplified models. K_γ is used in place of K_σ in simplified stress-based triggering frameworks, but conceptually K_γ and K_σ are very different. Numerically, K_γ and K_σ are similar for young, normally consolidated sandy soils when the factor of safety (*FS*) against liquefaction triggering is close to one, but may differ significantly for other scenarios and/or conditions (e.g., aged deposits and when FS $\neq$ 1).

K_γ is based on equating the shear strain induced in a given soil at given initial stress state and subjected to a given shear stress to that induced when the soil is confined at a reference initial stress state, all else being equal. The same concept can be applied to assess the strength gain due to aging effects by equating induced shear strains in young and aged soils, where young soils represent the reference condition. As can be surmised from Figure 1, the ratio of the cyclic resistance ratio (*CRR*) in the aged and young sands corresponding to a given induced shear strain (γ) is equal to the ratio of small-strain shear modulus (G_{max}) of the aged and young sands, with this ratio being independent of γ. Thus:

$$K_{DR} = \frac{CRR_{aged}}{CRR_{young}} = \frac{G_{max-aged}}{G_{max-young}} = \frac{Vs_{aged}{}^2 \cdot \rho_t}{Vs_{young}{}^2 \cdot \rho_t} = \frac{\left(MEVR \cdot Vs_{young}\right)^2 \cdot \rho_t}{Vs_{young}{}^2 \cdot \rho_t} = MEVR^2 \qquad (3)$$

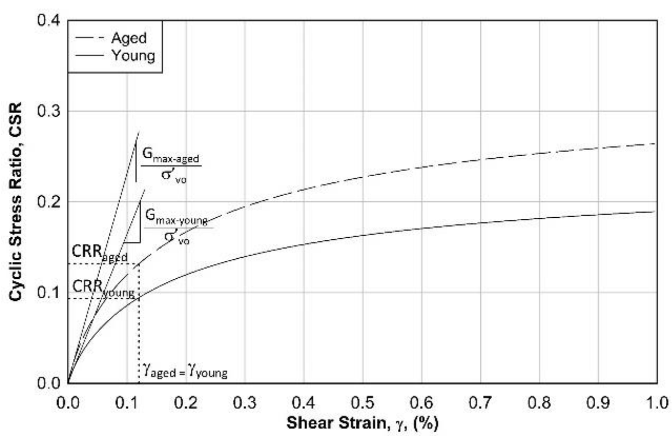

Figure 1. Shear stress–shear strain (τ - γ) response of soil for the same soils, one aged and young. The ratio of the *CRR* corresponding to the same γ for the two soils is K_γ.

Figure 2 shows a comparison of K_{DR} computed using a relationship derived from regressing compiled soil aging case histories (Saftner et al. 2015) and one derived based on the K_γ-factor, per Eq. (3). As may be observed from this figure, the two are in amazingly close agreement, especially given the large uncertainty in aging data. This comparison gives credence for accounting for aging effects on liquefaction susceptibility via the K_γ-factor, without the need of using the K_{DR}-factor or qualitative judgement regarding liquefaction susceptibility of aged deposits.

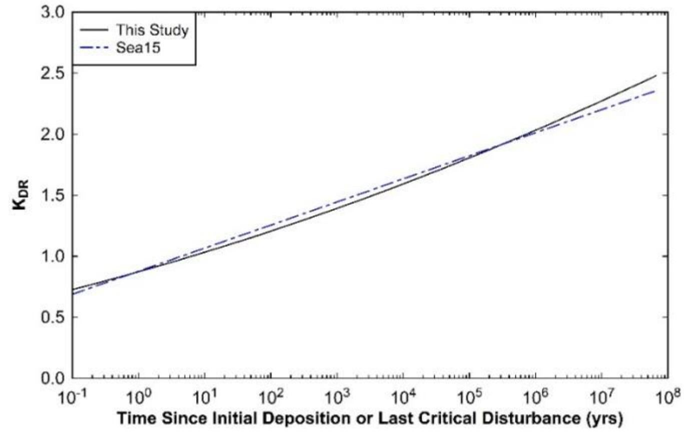

Figure 2. Comparison of the liquefaction strength gain factor, K_{DR}, regressed by Saftner et al. (2015) [Sea15] from compiled case histories and an expression derived using the K_γ-factor.

CONCLUDING REMARKS AND RECOMMENDATIONS

The use of the K_γ-factor in place of K_σ to analyze liquefaction case histories to develop new cyclic resistance ratio curves would advance the state-of-the art in assessing the liquefaction susceptibility of aged deposits, among other advances in the state-of-the art of assessing liquefaction triggering potential.

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CONSEQUENCE-BASED SUSCEPTIBILITY INCORPORATING COMPRESSIBILITY

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THEME 3: A FUTURE NEW LIQUEFACTION SUSCEPTIBILITY MODEL

Traditionally, liquefaction susceptibility has focused solely on material-specific criteria, including composition (gradation, plasticity, etc.), state (density and effective vertical stress; often as reflected in an overburden stress-normalized penetration resistance), depositional environment, and historical performance. However, disparate methods have developed to examine nonplastic and plastic soils and to examine level-ground liquefaction and flow liquefaction.

This extended abstract outlines a new, universal, consistent consequence-based approach to assess liquefaction susceptibility. When combined with the work presented by Prof. Kevin Franke, this deterministic approach can be extended to performance-based (probabilistic) design for static and seismic loading conditions.

PROMPT 5: CONSEQUENCE-BASED LIQUEFACTION SUSCEPTIBILITY

Although not a comprehensive list, the chief consequences of static and seismic liquefaction are settlement, lateral spreading, and flow failure. Liquefaction flow failure generally is limited to sloping ground, while lateral spreading can occur in mildly sloping ground or level-ground incised by a river, stream, or other depression. Settlement can occur in all conditions (i.e., level and sloping ground) and can occur in much denser soils than the former two consequences.

As noted above, disparate methods have been developed to evaluate the liquefaction susceptibility of nonplastic and plastic soils and to examine level and sloping ground conditions. However, nearly all of the material-specific criteria above can be combined using critical state soil mechanics (CSSM) concepts. The position and slope of the critical state line (CSL) in void ratio (e) – effective stress (σ') space is a function of the gradation and plasticity (i.e., compressibility) of a soil. The susceptibility of a soil to various consequences (settlement, lateral spreading, and flow failure) depends on soil density and geostructure geometry (or "depositional environment"). Figure 1 schematically illustrates this concept. The CSL for a given soil tends to be curved in e – σ' space and represents a boundary between soils that are contractive and dilative at large shear strain (Fig. 1a). Although flow failure may occur at soil states slightly below the CSL, the CSL generally provides a reasonable separation between states for a given soil that are and are not susceptible to flow liquefaction (Fig. 1a). As discussed by Jefferies and Been (2016), soils with denser states are susceptible to lateral spreading and liquefaction-induced settlements. Thus, similar boundaries in e – σ' space could be developed for a given soil to identify states that are susceptible to other consequences (Fig. 1b).

As defining in situ void ratio remains difficult, knowing that void ratio (at a given effective stress) is inversely related to normalized penetration resistance (e.g., normalized CPT tip resistance, q_{c1}/p_a) allows one to revise the e – σ' axes to become q_{c1}/p_a – σ' axes and define consequence-based liquefaction susceptibility boundaries in this space (Fig. 1c).

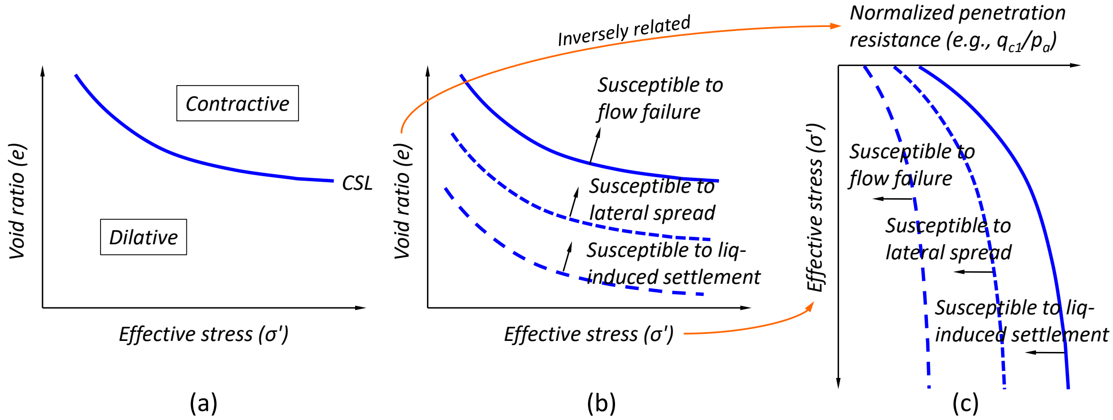

Figure 1. Schematic illustrations of: (a) critical state line (CSL) in $e - \sigma'$ space; (b) consequence-based liquefaction susceptibility in $e - \sigma'$ space; and (c) consequence-based liquefaction susceptibility in $q_{c1}/p_a - \sigma'$ space.

Case histories corresponding to different liquefaction consequences can be used to develop the boundaries illustrated schematically in Figure 1(c). For this purpose, I have initially utilized the CPT-based case history datasets from Saye et al. (2021) for level-ground liquefaction, Olson and Johnson (2008) for well-documented lateral spreads, and Olson and Stark (2002) for flow failures. Using these datasets, Figure 2 presents consequence-based liquefaction susceptibility boundaries for: (a) level-ground settlement; (b) lateral spreading; and (c) liquefaction flow failure.

It is widely known that soil compressibility affects penetration resistance, and as shown by Ishihara (1993), increasing plasticity (generally for PI > ~10; which typically corresponds to increasing compressibility) increases liquefaction resistance. As such, the susceptibility boundaries presented in Figure 2 represent limiting boundaries corresponding to low-compressibility, non-plastic soils. As compressibility increases, these boundaries should shift left.

Olson (2009) proposed a tentative adjustment for the flow liquefaction boundary as a function of the slope of the CSL in $e - \log \sigma'$ space, termed λ_{10}. Generally, λ_{10} can be used as a proxy for soil compressibility. Similarly, the soil behavior type index, Δ_Q (Saye et al. 2021), is inversely related to soil compressibility. With Kevin Franke and Steve Saye, I currently am developing an interim adjustment to q_{c1}/p_a as a function of Δ_Q. Based on these concepts, Figure 3 presents ***tentative*** consequence-based, liquefaction susceptibility/compressibility boundaries for: (a) level-ground settlement using a Δ_Q-based adjustment; (b) lateral spreading using a Δ_Q-based adjustment (*possible – under investigation*); and (c) flow liquefaction using the using a λ_{10}-based adjustment. As noted, these boundaries required further investigation and the λ_{10}-based adjustment for flow liquefaction needs to be reconciled with the Δ_Q-based adjustment. This work is ongoing.

CONCLUDING REMARKS AND RECOMMENDATIONS

While further study is needed to validate these concepts, the ***tentative*** liquefaction susceptibility boundaries considering compressibility presented herein represent a new universal, consistent concept to evaluate susceptibility to the various consequences of liquefaction including level-ground settlement, lateral spreading, and flow failure.

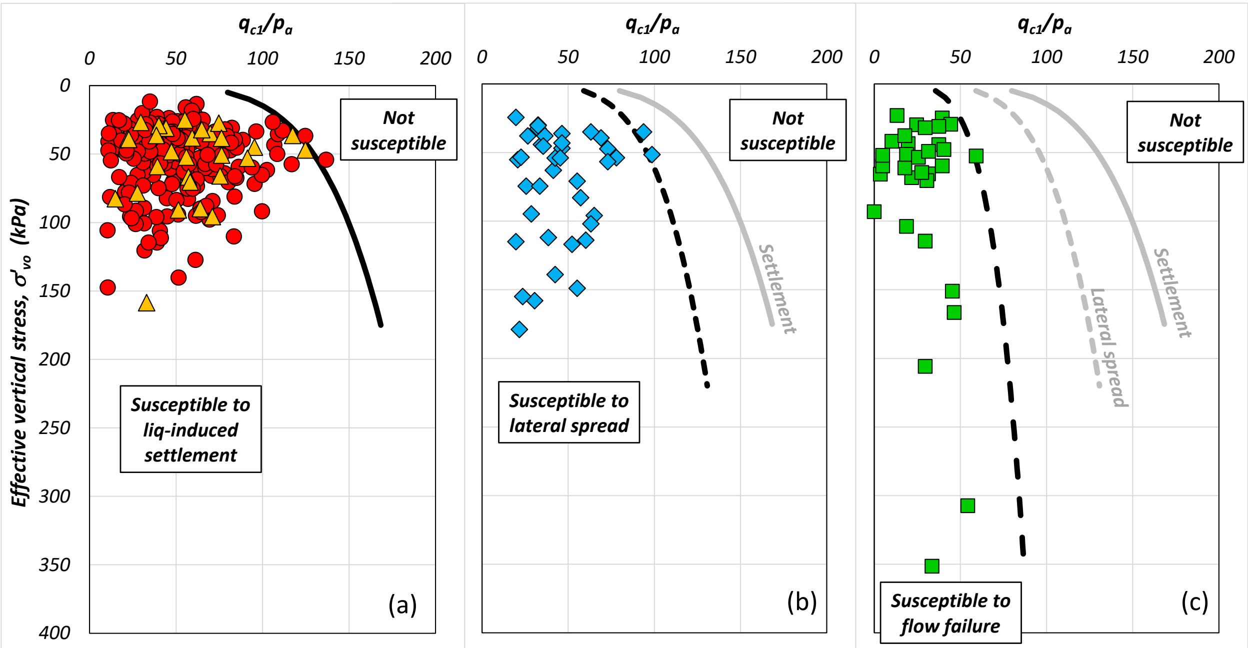

Figure 2. *Tentative* liquefaction susceptibility boundaries for: (a) level-ground settlement; (b) lateral spreading; and (c) liquefaction flow failure.

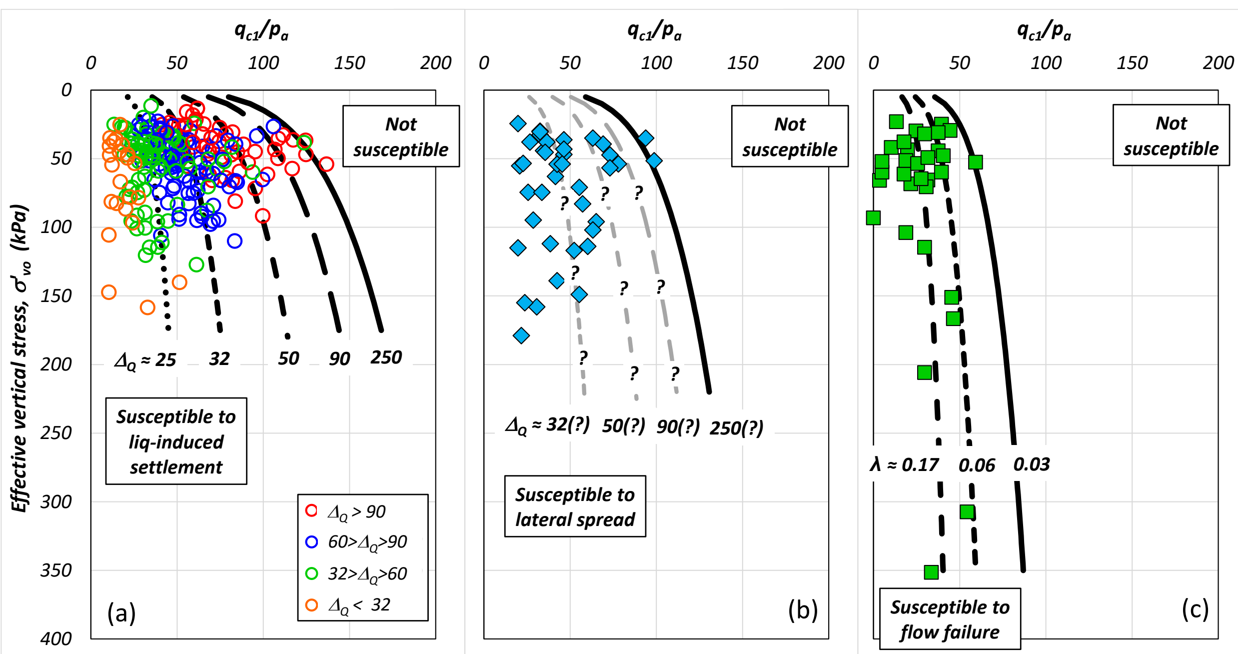

Figure 3. *Tentative* liquefaction susceptibility boundaries incorporating compressibility for: (a) level-ground settlement; (b) lateral spreading; and (c) liquefaction flow failure.

ACKNOWLEDGEMENTS

The author acknowledges and appreciates the detailed discussions on this topic with Mr. Steve Saye and Profs. Kevin Franke, Bret Lingwall, and Armin Stuedlein.

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THE IMPACT OF INCORPORATING LIQUEFACTION SUSCEPTIBILITY INTO A PERFORMANCE-BASED DESIGN FRAMEWORK

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INTRODUCTION

Not all soils are susceptible to liquefaction and its effects. When evaluating liquefaction hazard, it is important to have reliable criteria to predict if the occurrence of liquefaction is even possible given a particular soil. I have been involved in numerous consulting projects where the susceptibility to liquefaction initiation quite literally was the determinant factor in the installation/non-installation of $10s of millions in engineering ground improvement. Like liquefaction initiation itself, liquefaction susceptibility has traditionally been assessed and assigned in a binary manner: either the soil is susceptible, or it is not. Furthermore, developed methods to assess liquefaction susceptibility from observed empirical case histories from the field are arguably more of an assessment of the soil's susceptibility to ground surface disruption than a true assessment of liquefaction triggering susceptibility because there has historically been no practical way (outside of recorded ground motion frequency analysis, trenching, or "geoslicing") to assess if liquefaction occurred subterraneously and did not manifest itself at the ground surface.

Few phenomena related to hazards and engineering, however, are truly binary, and liquefaction is no exception. For example, the recent inclusion of fine-grained "liquefaction" triggering case histories (and some likely cyclic softening case histories) in the Saye et al. (2021) Common-Origin liquefaction triggering method shows empirical evidence that a gradual gradient from sand-like liquefaction behavior to clay-like cyclic softening behavior likely exists (see Figure 1). Susceptibility to liquefaction based on Δ_Q, a CPT-based parameter related to soil type and compressibility, currently shows an approximate boundary at Δ_Q of about 20. However, if more cyclic softening case histories were available and plotted at Δ_Q values less than 20, perhaps the m_{CRR} line (i.e., the blue boundary line between "Surface Manifestation" and "No Surface Manifestation") might extend higher. Therefore, to limit the consideration of susceptibility to seismic-induced ground surface disruption to only sand-like soils may be a risky proposition.

LIQUEFACTION SUSCEPTIBILITY AND PERFORMANCE-BASED DESIGN

The idea of performance-based design is to predict as closely as possible the actual performance of the soil (or infrastructure) during the specified design life or exposure time. Such an effort requires the consideration and incorporation as many of the uncertainties as possible that are associated with the seismic loading, the soil's response to that seismic loading, and the infrastructure's response to the soil's response. Thus, confinement of any aspect of the seismic loading, soil response, and/or infrastructure into convenient "bins" like "sand-like" or "clay-like" may not necessarily be conducive to accurately predicting the actual performance of the system.

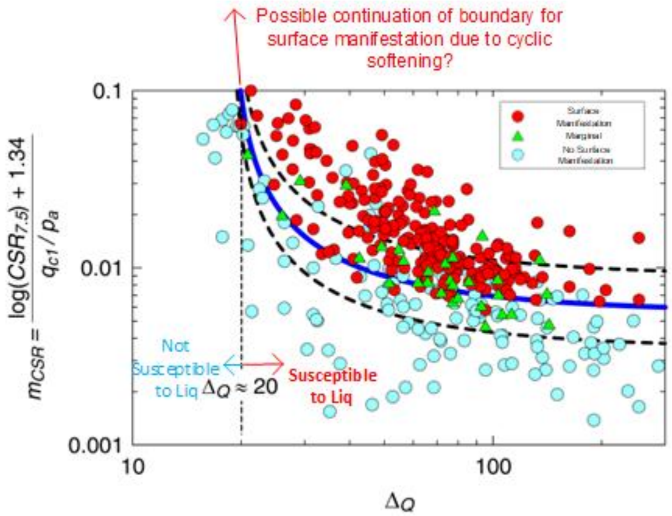

Figure 1. CPT-based liquefaction case histories from the Common-Origin method plotted against their respective values of Δ_Q (modified from Saye et al. 2021).

In a performance-based framework such as that developed by PEER, susceptibility becomes an additional conditionality in the hazard integrals. For example, the Kramer and Mayfield (2007) formulation for the hazard curve for N_{req}, defined as the SPT resistance needed to prevent liquefaction triggering, can be modified to include liquefaction susceptibility as:

$$\lambda_{N^*_{req}} = \sum_{j=1}^{N_{M_w}} \sum_{i=1}^{N_{a_{\max}}} P\left[N_{req} > N^*_{req} \mid a_{\max_i}, m_j, P\left[Suscept = "yes"\right]\right] \Delta\lambda_{a_{\max_i}, m_j} * P\left[Suscept = "yes"\right] \tag{1}$$

Due to space limitations, detailed description of the terms in Equation (1) will not be presented here, nor is such description necessary. The term of interest for this discussion is the susceptibility term $P\left[Suscept = "yes"\right]$. To use such a term would require the use of a probabilistic susceptibility relationship for liquefaction triggering, which does not currently exist according to my knowledge. Previous researchers have only developed and experimented with various heuristic approximations of the probability of susceptibility to liquefaction triggering (e.g., Huang 2008).

Additionally, and as will be discussed by Prof. S.M. Olson in this workshop, there also arguably exists susceptibility criteria for various effects of soil liquefaction (i.e., strength loss and ground deformation). For example, it is possible for certain soils to experience liquefaction triggering and seismic strength loss, but not lateral spread displacement, even if the geomorphological and geometric conditions required for lateral spread are present (Youd et al. 2009). Performance-based formulations for computing hazard curves for these various effects would also include conditional susceptibility terms in the hazard integrals similar to Equation (1).

WORKSHOP RESPONSES TO PROMPTS

The brief discussion presented above could apply to several of the PEER Susceptibility prompts. However, I will focus my attention here on only one prompt that I believe applies significantly to the incorporation of susceptibility into a performance-based design framework.

What are the consequences of incorrectly assessing liquefaction susceptibility, and under what conditions are these consequences most acute?

Due to the lack of available probabilistic susceptibility relationships for liquefaction triggering and its effects, most applications of performance-based liquefaction hazard assessment that I am aware of apply the consideration of susceptibility in a deterministic "Go/No-Go" manner prior to implementing the hazard integrals. However, what would be the effect if probabilistic susceptibility relationships existed and could be incorporated into the hazard integrals themselves, as suggested in Equation (1)?

This question can be indirectly explored by looking at the recent Bray and Macedo (2020) model for Newmark sliding block displacements. Many engineering practitioners today use such models with liquefied soil conditions to develop estimates of lateral spread displacements at bridge abutments. While most models have traditionally recommended computing probabilities of exceedance (i.e., fragility relationships) using a formulation such as $P\left[D > D^*\right]$, Bray and Macedo recommend computing fragility relationships with their model using the formulation of $P\left[D > D^* \mid P\left[D > 0\right]\right] P\left[D > 0\right]$. In this formulation, $P\left[D > 0\right]$ is defined in Bray and Macedo (2020) and is akin to a probabilistic susceptibility relationship. For a simple demonstration using K_y=0.3, M_w=7.5, and a displacement to be exceeded of D^*=3cm, the fragility curves from the Bray and Macedo (2020) rigid sliding block model as a function of *PGA* for both the traditional fragility calculation and the susceptibility-included fragility calculation are presented in Figure 2. As can be seen in Figure 2, neglecting the susceptibility results in substantially larger probabilities of exceedance being computed. This effect repeated millions of times in the performance-based hazard integrals will have a substantial impact and reduction in the final displacement hazard curves that are predicted. This impact could easily be much more substantial to the analysis results than the impact from modifying other terms in the triggering models such as K_σ or *MSF*, which is where many of us researchers have historically spent much of our time and focus.

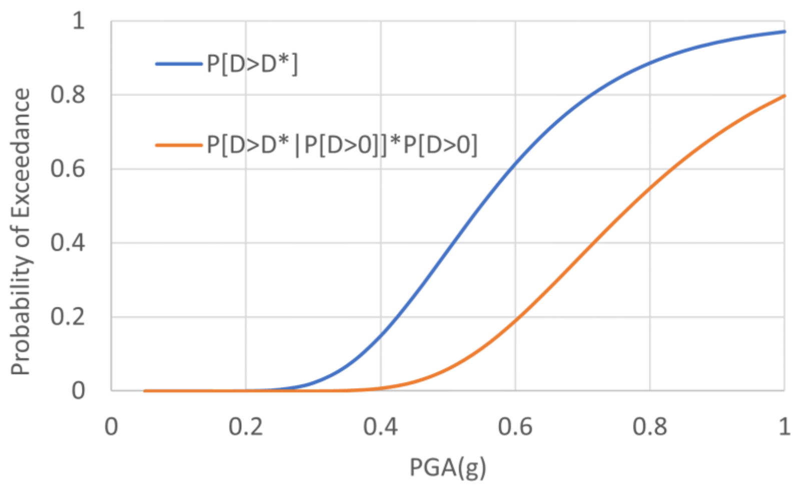

Figure 2. Demonstrative fragility curves from the Bray and Macedo (2020) model. The blue line neglects susceptibility to displacement, and the orange line includes the susceptibility to displacement.

CONCLUDING REMARKS AND RECOMMENDATIONS

Probabilistic relationships for quantifying susceptibility to liquefaction triggering, cyclic softening, and their effects are needed for implementation in a performance-based design framework. Inclusion of such relationships in a performance-based framework will substantially alter and reduce the computed hazards. I recommend a community collaborative effort to develop probabilistic susceptibility models for triggering, cyclic softening, and their effects.

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PROBABILISTIC MODELS FOR SEISMIC SOIL LIQUEFACTION SUSCEPTIBILITY

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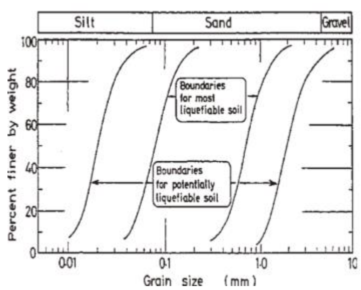
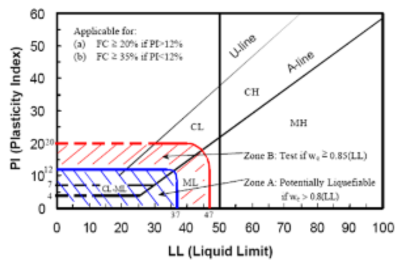
THE STATE OF THE ART IN LIQUEFACTION SUSCEPTIBILITY ASSESSMENTS

Seismic soil liquefaction is commonly defined as significant reduction in shear strength and stiffness due to increase in pore water pressure. Consistent with this definition, susceptibility to liquefaction is defined as the state of being likely to experience significant shear strength and stiffness losses, triggered by increase in pore water pressure. Ideally, susceptibility criteria are expected to be independent of liquefaction triggering parameters of intensity and duration of loading, and density state of soils; and more specifically linked to soils' intrinsic characteristics. A good and pioneering example of it is given by Tsuchida (1970), where a set of grain size distribution boundaries, identifying "the most liquefiable" and "potentially liquefiable" fully saturated coarse-grained soils was proposed. Unfortunately, the boundaries were subjectively and deterministically defined, with limited to no reference to confidence levels of the proposed boundaries as given in Figure 1 (a).

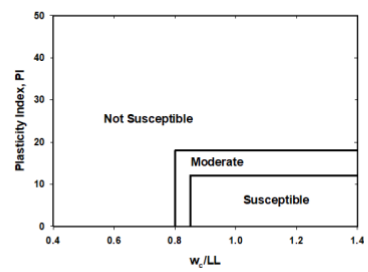


a)

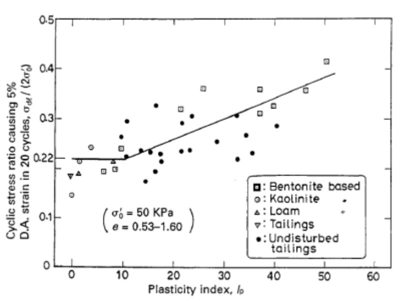
a) Tsuchida (1970)

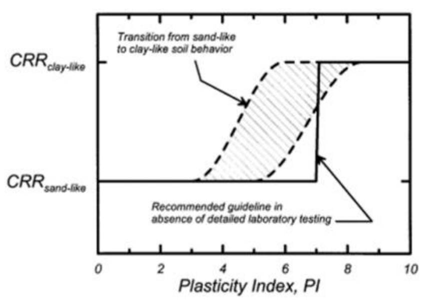


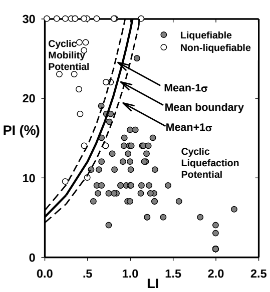
b) Seed et al. (2003)



c) Bray and Sancio (2006)







d) Ishihara (1996)

e) Boulanger and Idriss (2006)

f) Cetin and Bilge (2014)

Figure 1. Liquefaction susceptibility criteria for a) clean, coarse-grained soils, and b-f) fines containing soils and their mixtures.

As shown in Figure 1 (b) through (f), for the susceptibility assessment of mixtures of varying percentage of fines with sands and gravels, Ishihara (1996), Seed et al. (2003), Bray and Sancio (2006), and Boulanger and Idriss (2006), Cetin and Bilge (2014) proposed criteria based on consistency limits and fines content, based on field performance or laboratory test data. Ishihara (1996) proposed that up to the PI value of 10, cyclic resistance ratio (CRR) exhibits a constant trend, followed by a linear increase with increasing PI>10. The susceptibility criteria by Seed et al. (2003), and Bray and Sancio (2006) were developed mostly based on joint evaluation of field performance case histories and the results of cyclic laboratory tests performed on undisturbed soil samples retrieved from Adapazari after 1999 Kocaeli earthquake. As part of their cyclic testing program, the stress and density states were chosen to simulate the field conditions in Adapazari during 1999 Kocaeli earthquake. Hence, the recommendations based on these are more correctly classified as Adapazari-Kocaeli earthquake criteria, and a good example of a hybrid susceptibility-triggering assessments. Boulanger and Idriss (2006) suggested that CRR of soils beyond PI > 4 % sharply increases. Due to reference to CRR in their proposed relationships, Ishihara (1996), and Boulanger and Idriss (2006) criteria are classified as liquefaction triggering screening criteria rather than a susceptibility one. Cetin and Bilge (2014) proposed a probability-based susceptibility criterion based on cyclic triaxial tests performed on a wide range of high quality “undisturbed” fine-grained soil specimens. Liquefaction susceptibility was judged with the onset of banana shaped stress-strain cycles. Accordingly, the probability of susceptibility to liquefaction triggering of fine - grained soils is assessed as given in Equation 1, where LI and Φ are the liquidity index of fine-grained soils and standard normal cumulative distribution function, respectively.

$$P[Liq- \ susceptibility] = \Phi\left[\frac{LI - 0.578 \cdot ln(PI) + 0.940}{0.101}\right] \tag{1}$$

This criterion is independent of the cyclic loading intensity and duration and refers to two intrinsic properties of fine-grained soils: LI and PI. Hence, it fulfills the requirements of a true “susceptibility” criterion; and moreover, expresses the susceptibility boundary in a probabilistic sense, addressing the uncertainty of the problem. The major drawback of it is that it is developed based on cyclic laboratory test data only, and common to all laboratory-based recommendations, calibration with field performance case histories is needed.

RELIABILITY-BASED SUSCEPTIBILITY MODELS

As outlined in the previous section, an ideal liquefaction susceptibility assessment framework should i) refer to intrinsic characteristics of soils, ii) be independent of liquefaction triggering parameters (intensity of shaking, duration, relative density state, etc.), iii) address the uncertain nature of susceptibility assessments (i.e.: probability-based), iv) benefit from both laboratory and field case history data (i.e.: a verified and calibrated model). With the aim of fulfilling these requirements, SPT and CPT-based liquefaction triggering case histories, documented as part of Next Generation Liquefaction database (https://nextgenerationliquefaction.org/) were studied. The grain size distribution curves of the critical soil layers from liquefied, or none-liquefied, or marginally-liquefied SPT-based case histories, were compiled, as given in Figure 2(a). The median liquefaction susceptibility grain size distribution curve, along with its standard deviation was probabilistically assessed benefitting from the maximum likelihood framework. The resulting median, and plus and minus 1,2,3 sigma bands, along with confidence intervals are shown on Figure 2(b) as compared with the recommendations of Tsuchida (1970).

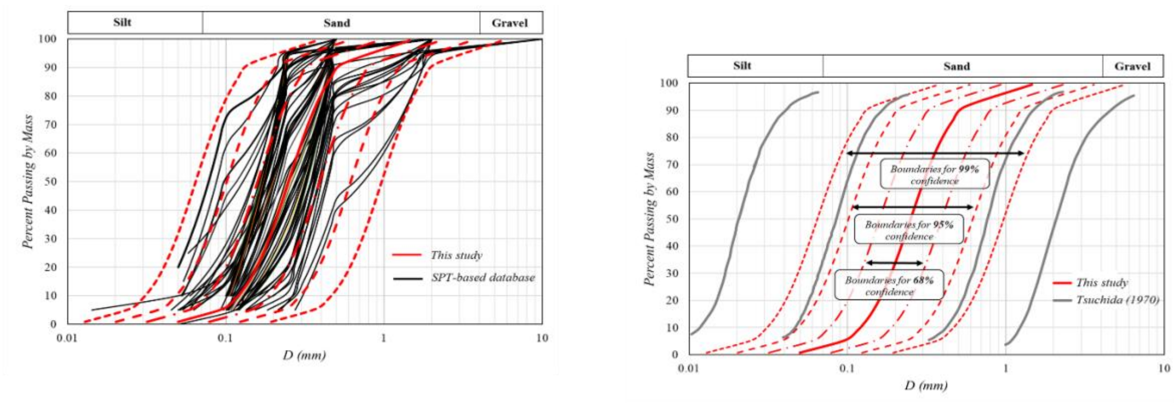


Figure 2. a) Grain size distribution curves of susceptible, coarse-grained soils from SPT database, **b)** the proposed probabilistic boundaries for susceptibility assessments.

A similar exercise was performed CPT-based liquefaction triggering case histories. The median soil behavior index I_c, along with its standard deviation were probabilistically assessed benefitting from the maximum likelihood framework. In Figure 3(a) through (c), the resulting database and the I_c boundaries corresponding to different confidence levels are also comparatively shown with CPT-based soil classification boundaries of Robertson (2010), and Cetin and Ozan (2009).

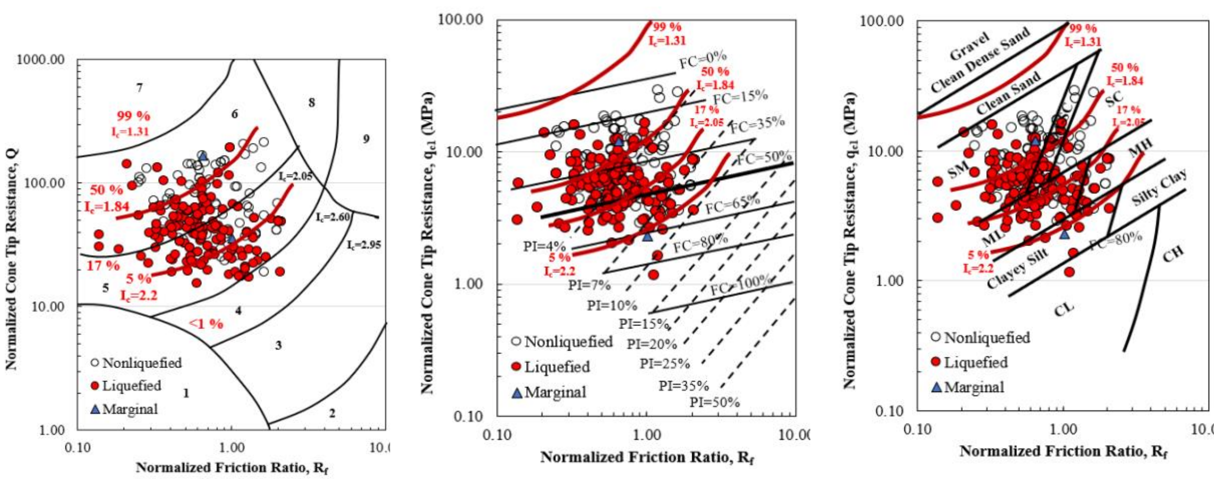


Figure 3. CPT-soil classification-based liquefaction susceptibility boundary curves.

CONCLUDING REMARKS AND RECOMMENDATIONS

Most of currently available liquefaction susceptibility boundaries were subjectively and deterministically defined, with limited to no reference to confidence levels of the proposed boundaries. Also, some of them refer to triggering parameter of CRR; hence, better to be called as screening criteria, which combining both susceptibility and triggering assessments. Within the scope of this study, a set of probability-based screening boundaries were recommended for coarse- and fine-grained soils. The recommended probabilistic boundaries were expressed as probabilistic confidence intervals in the % fines by mass vs. particle size (D), and CPT q vs R_f domains. Fine grained soils with I_c>2.6 are concluded to be **not susceptible** to soil liquefaction with more than 99% confidence. Moreover, fine grained soils with PI > 12% were judged to be again not susceptible to liquefaction with confidence levels of 99 %. Based on these, a flow chart scheme is proposed to assess the susceptibility of soil mixtures with varying % of fines, which could not be presented herein due to page limitations.

ACKNOWLEDGEMENTS

Some of the data presented herein is compiled as part of the NGL project, which is acknowledged and appreciated.

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INCORPORATING THE SPECTRUM OF SOIL BEHAVIORS DIRECTLY INTO SYSTEMS LEVEL TRIGGERING AND CONSEQUENCE MODELS

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THE CURRENT STATE OF PRACTICE AND LIMITATIONS

Current procedures for assessing soil susceptibility to seismically-induced liquefaction focus on identifying the transition point in soil behavior from sand-like to clay-like based on plasticity index and water content. These guidelines were developed based on laboratory tests, backed by observations of surface manifestation (typically in the form of sand boils or ejecta) in prior case histories. The subsequent evaluation of liquefaction triggering and consequence followed by design of mitigation typically ignore the presence of soil layers that are judged unsusceptible at the first step. Nevertheless, these so-called "unsusceptible" soils may still experience cyclic softening as well as excessive lateral and vertical deformations resembling those in liquefied deposits. Alternatively, with their lower permeability, such layers may strongly influence the redistribution and net generation of excess pore pressures in other susceptible or sand-like layers. Not considering such "unsusceptible" layers in the profile at the systems level may lead to notable underpredictions of the likelihood of liquefaction triggering or propagation of damage at the site and hence, inadequate planning of mitigation strategies.

OPTIONS FOR FUTURE SUSCEPTIBILITY MODELS

As the community reimagines the next generation of susceptibility criteria, it might be advantageous to move past a binary judgement of whether a soil is susceptible to seismic liquefaction in the classical sense. In place of categorizing soil behavior as either sand- or clay-like, a spectrum of behaviors can be considered, focusing on quantification of cyclic softening and fluid flow at a systems level. Boundary value centrifuge experiments under controlled conditions followed by 2D and 3D, fully-coupled, effective stress analyses conducted collectively and in a coordinated and open environment can shed light on the spectrum of behaviors in layered granular soils with varying fines contents and plasticity levels. The results can and must be compared with the existing case history database in terms of manifestation of damage, particularly where in addition to detailed in-situ testing, disturbed and undisturbed samples were obtained. The generated experimental, numerical, and empirical database can directly feed into triggering and more importantly consequence procedures that include the entire spectrum of soil types and profiles at a systems level, without the binary exclusion of clay-like soils.

EXPERIMENTAL EVALUATION OF LIQUEFACTION-INDUCED FOUNDATION SETTLEMENT CAUSED BY SAND EJECTA

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1G SHAKE TABLE TESTING TO STUDY LIQUEFACTION-INDUCED SEDIMENT EJECTA

Liquefaction-induced sediment ejecta and its role in the free-field and building settlements were briefly discussed during the 2016 US-Japan-NZ Liquefaction Workshop at UC Berkeley (Bray et al. 2017a). Bray et al. (2017b) describe the three key mechanisms that control liquefaction-induced building settlement: (1) Shear-induced deformation; (2) Volumetric-induced deformation, and (3) Ground loss due to ejecta. Although there have been simplified procedures developed to estimate the first two mechanisms such as Bray and Macedo (2017) for the shear-induced and Ishihara and Yoshimine (1992) for the volumetric-induced components of settlement, there is a lack of simplified procedure to quantify the last mechanism which is attributed to the loss of ground beneath a building's foundation due to the formation of "sediment ejecta". As a result, this abstract contributes to this workshop toward the theme of (1) the current state-of-the-practice and its limitations.

Contrary to the prior experimental studies using centrifuge tests, 1g shake table testing can reliably produce ejecta at different scales. Figure 1 presents liquefaction-induced sediment ejecta examples from 1g shake table tests at different scales, in which the height of model grounds ranged from 20 to 290 cm.

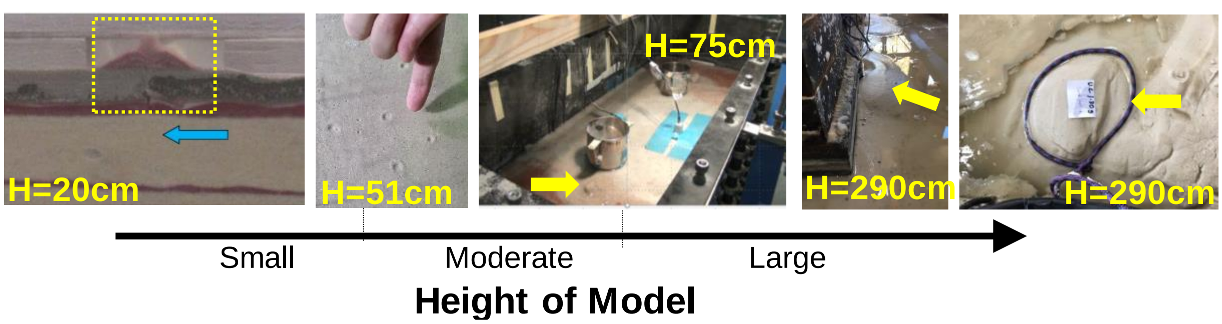


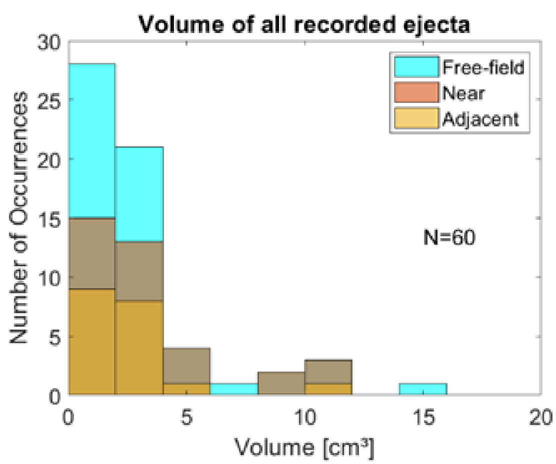
Figure 1. Observed ejecta in 1g shake table tests.

This abstract presents the preliminary results obtained based on a series of scaled shake table tests at UNR to explore the significance of sediment ejecta on liquefaction-induced foundation settlement. It highlights the limitations of current methods for estimating liquefaction-induced settlement and the missing component of sand ejects which can yield unreliable predictions of soil-foundation system response.

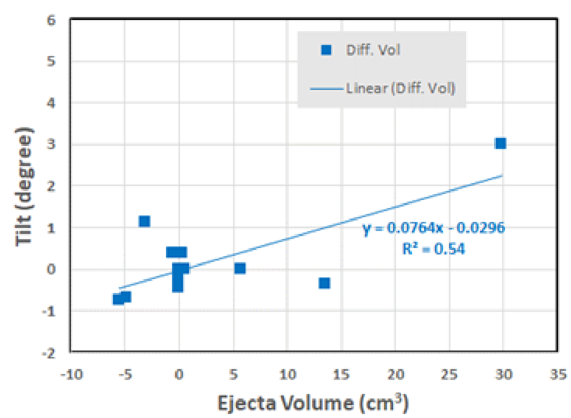
RESPONSE TO PROMPT 1. WHAT IS THE STATE-OF-THE-ART?

The current practice lacks a simplified procedure to quantify the loss of ground beneath a building's foundation due to the formation of "sediment ejecta". Although the occurrence of sand ejecta has been reported in many past earthquakes, the first systematic survey of sand ejecta was conducted by Bardet and Kapuskar (1991) in the Marina District of San Francisco after the 1989 Loma Prieta earthquake. In recent work, we have collected and analyzed 56 cases of observed ejecta near residential buildings or commercial structures during 20 earthquakes since the 1989 Loma Prieta earthquake to develop some statistical understanding of ejecta occurrence (Buhl & Motamed 2020). The effort generated some insight on the ejecta occurrence, though it didn't yield any substantial findings on the relation to the observed foundation settlements mainly as a result of insufficient information about the sub-surface soil conditions, key soil properties, earthquake ground motions, and pore water pressure responses. Therefore, this abstract suggests a laboratory-based approach to reproduce this phenomenon by conducting scaled shake table tests that will produce significant sediment ejecta, thus enabling its effects to be studied.

Over the past several years, we have performed a series of exploratory mid-scale shake table tests at UNR on liquefaction-induced model building settlements to generate preliminary data which are briefly presented hereafter. For example, Figure 1 demonstrates the capabilities of 1g shake table tests to reliably produce ejecta-induced building settlements in models with heights ranging from 20 to 290 cm. In addition, according to the histogram presented in Figure 2(a), the measured ejecta volumes were mainly smaller than 10 cm³ and larger ones were rarely observed. The smaller ejecta volumes were more commonly observed especially in the free-field and adjacent to the foundation. Figure 2(b) shows the observed correlation between the volume of ejecta and the tilt of the foundation indicating a direct correlation.



(a)



(b)

Figure 2. (a) Distribution of recorded ejecta with their distance categories free-field, adjacent and near the foundation, (b) differential ejecta volume versus tilt of the foundation (Buhl et al. 2021).

CONCLUDING REMARKS AND RECOMMENDATIONS

The preliminary work presented in this abstract suggests the following findings on the effects of sand ejecta on liquefaction-induced foundation settlement: (1) the use of field observations to study the significance of sand ejecta requires a more rigorous measurement of the ejecta foundation which can be incorporated in databases such as NGL when documenting future earthquakes, (2) there is a need for complementary laboratory tests using 1g shake table in the area of surface manifestation of liquefaction and sand ejecta.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support of multiple sponsors including PEER (Pacific Earthquake Engineering Research Center), DFI (Deep Foundations Institute), and Ram Jack to conduct the presented shake table tests.

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METRICS FOR USE IN EVALUATING LIQUEFACTION POTENTIAL AND CONSEQUENCES UNDER SEISMIC LOADING CONDITIONS

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ABSTRACT

Since the early 1960s, when systematic approaches for evaluating liquefaction during earthquakes were initiated, the emphasis has been on using the shear stress for both demand and capacity when evaluating the liquefaction potential during earthquakes. This was driven by the fact that the only information regarding capacity available at that time was from triaxial cyclic tests, which had been started by H. Bolton Seed and Kenneth L. Lee at the University of California at Berkeley[1]. The first analysis of liquefaction was for the Niigata site in 1965/1966, in which the demand was estimated in terms of shear stresses induced during shaking using recently developed site response procedures. Up to that point there was no mention of acceleration (PGA), at the ground surface or at any depth.

Therefore, the metric for what has been called "the stress approach" for evaluating the liquefaction potential during earthquakes is shear stress and not PGA.

The PGA at the ground surface came into the picture, circa 1967, when developing a means to estimate the shear stress (and not the acceleration) at a given depth so that, again, the demand can be compared to the capacity, which was still being measured in either cyclic triaxial or cyclic direct simple shear tests. Only the surface PGA was involved; never the PGA at any depth. That lead to the development of the Seed-Idriss simplified liquefaction evaluation procedure, which necessitated "invoking" the use of a "stress reduction factor, r_d". That allowed estimating the shear stress induced by shaking at the depth where liquefaction was estimated to have been triggered for the then few available[2] case histories having or not having surface evidence of liquefaction.

Dobry and colleagues in 1981 proposed the use of shear strain as an alternative metric. While fundamentally strain is a "superior" metric than stress, it was difficult to estimate the strain level at the depth at which liquefaction had or had not been triggered for the case histories available then.[3] Other metrics have been proposed over the years for evaluating liquefaction triggering or its consequences, the earliest of which is the Arias Intensity (AI), then the cumulative absolute velocity (CAV), and more recently the Housner spectral intensity, using the pseudo relative velocity or the pseudo absolute acceleration, among others.
The other aspect to consider in this regard is the fact that the natural case histories noted earlier have increased significantly in the past 25 or so years and have been augmented by additional "case histories" obtained through testing of physical models, particularly in the centrifuge.

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[1] References are not included in this Abstract but will be included in the presentation.
[2] In 1967, there were only 23 cases with observed surface evidence and only 12 cases with no observed evidence of liquefaction.
[3] By the early 1980s, the number of case histories had more than quadrupled.

Except for a few, the available natural case histories have no recording below the ground surface and many have no recordings within a few kilometers. The physical models are typically well instrumented vertically and laterally.

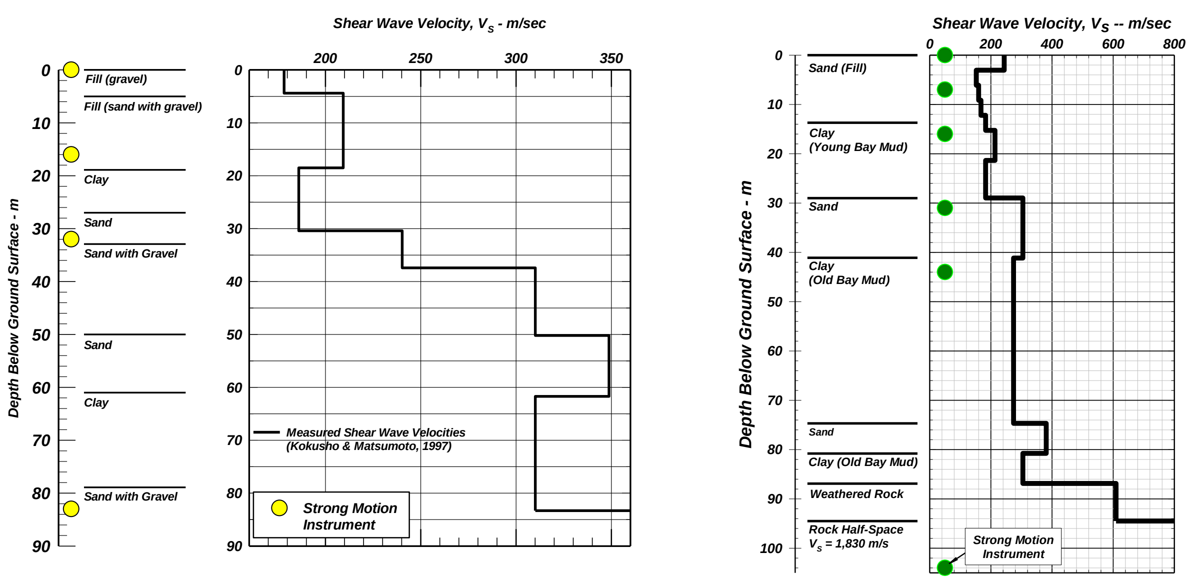
Whatever metric is to be used, it is essential that there be means to estimate the value of that metric at the depth at which liquefaction is considered to have been triggered, or not triggered.

Therefore, it would be useful to examine the recordings available from downhole arrays, such as the array at Port Island (Figure 1a) and the array at Treasure Island (Figure 1b), where recordings were obtained at 4 and 6 depths, respectively. Many other arrays are also available from California, Japan, Alaska etc. It is hoped that colleagues who have completed relevant centrifuge tests will make a number of their case histories available.

The values of the metrics listed above – shear stress, shear strain, AI, CAV, spectral intensity etc. – will be calculated from as many arrays as possible prior to the start of the Workshop in September. Shear strain and shear stress will be computed from array recordings using the procedure introduced by Zeghal and colleagues in 1995 when the vertical spacing is adequate and if a strain-compatible shear modulus can be reasonably estimated.

Plots, observations, summaries, conclusions and recommendations will be presented at the Workshop.

The intent of this effort is to gain insight about how these metrics vary with depth and with other parameters to facilitate their use in interpreting case histories and in developing procedures for forward evaluations of liquefaction potential and consequences.



(a) Port Island ***(b) Treasure Island***

Figure 1. Soil profile, measured shear wave velocities and depths at which strong motion instruments had been installed at the (a) Port Island Site and (b) Treasure Island Site.

TOWARD IMPROVED ASSEMSSMENTS OF LIQUEFACTION SUSCEPTIBILITY AND SEVERITY

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INTRODUCTION

This extended abstract addresses partly "1. The current state-of-the practice and its limitations" and partly "3. Options for future susceptibility models that could be used." More specifically, this abstract discusses issues somehow related to: PROMPTS 2, 5, and 7.

RESPONSE TO PROMPT 5: How should the next generation of liquefaction susceptibility models be formulated to advance the state-of-the-art?

The current liquefaction susceptibility evaluations are based on field case histories of occurrence or nonoccurrence of soil liquefaction. Those case histories, therefore, sometimes lack information regarding the degree/severity of soil liquefaction which is more important for seismic design of soil structure systems. Moreover, any data from those case histories plotted far above the boundary line separating occurrence and nonoccurrence in the correlation between cyclic stress ratio and either normalized SPT N-value, CPT resistance, or shear wave velocity, do not play an important role; and only those close to the marginal condition control the position of the boundary.

The next generation of liquefaction case history datasets should, therefore, include information regarding not only the occurrence or nonoccurrence of soil liquefaction but also the degree/severity of soil liquefaction such as, for example, liquefaction-induced ground settlements for level grounds, permanent displacements for inclined grounds, and settlement or tilting of buildings. This enables one to establish a more advanced field performance estimate with emphasis placed not only on susceptibility but also on degree/severity of liquefaction. This also enables all field case histories much effective, regardless of their positions relative to the boundary line. An attempt along the line but using centrifugal experiment data can be found elsewhere, e.g., for estimating liquefaction-induced settlement and tilting of buildings with spread foundations on sandy deposits (Tokimatsu 2019).

RESPONSE TO PROMPTS 2 & 7: What are the consequences of incorrectly assessing liquefaction susceptibility, and under what conditions are these consequences most acute? Can you describe a case where liquefaction susceptibility was assessed using methods beyond those typically applied, given the importance of the project and consequences of liquefaction?

We sometimes assess liquefaction susceptibility of Pleistocene sandy deposits given the importance of the project, although liquefaction is unlikely, generally because their SPT N-values are high due to long-term stress-strain history and aging effects. Nonetheless, they occasionally show N-values lower than thought, leading to unexpected estimation where soil liquefaction is likely during very strong shaking if based only on any of the current SPT based correlations. In those cases, we tried to use Vs in addition to SPT for liquefaction evaluation and to make a comprehensive decision regarding the susceptibility and consequences, as Vs can reflect somehow the stress-strain effects on liquefaction resistance (Tokimatsu & Uchida 1990).

Uchida et al. (2019) compiled recent geotechnical and geophysical field tests in Japan and examined the relation between SPT and Vs, and showed that Pleistocene sands have V_s about 10-70% higher than Holocene sands for the same SPT N-value, e.g., 180-420 m/s versus 160-250 m/s, for N=20. The increase in V_s of Pleistocene sands suggests that the shear wave velocity may indeed reflect the long-term stress-strain history and aging effects more than the SPT N-value. The larger variation in V_s of Pleistocene sand, at the same time, indicates that the effects of the long-term stress-strain history effects may significantly vary depending on local site conditions. Although further studies are needed to confirm this tendency, a new liquefaction susceptibility method using both SPT N-value and Vs may be useful to somehow compensate for the stress-strain history effects not fully reflected in the SPT N-value.

It is important to note that not only incorrectly assessing liquefaction susceptibility but also inexperienced dynamic response analysis may lead to a wrong estimate of design strong motions and spectra occasionally far different from those actually expected for structures and buildings to be constructed at the site. It is therefore useful to create a website compiling worldwide downhole strong motion datasets including soil liquefaction and cyclic mobility, if not exists, which can make available to anyone who would like to enhance his skill for estimating design strong motions and spectra for liquefiable sites.

CONCLUDING REMARKS AND RECOMMENDATIONS

The next generation of liquefaction case history datasets should include information regarding not only the occurrence or non-occurrence of soil liquefaction but also the degree/severity of soil liquefaction in order to establish a more advanced and comprehensive field performance estimate with emphasis placed not only on susceptibility but also on consequences of liquefaction. In order to enhance the reliability in liquefaction estimates particularly for sands having experienced long-term aging effects, a hybrid use of both SPT N-value/CPT resistance and V_s may be useful to compensate somehow for the resulting increase in liquefaction resistance not fully reflected in the penetration resistance. It is desirable to create a website compiling worldwide downhole strong motion datasets including soil liquefaction and cyclic mobility, which can make available to anyone who would like to enhance his skill for estimating design strong motions and spectra for liquefiable sites.

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CHALLENGES AND LIMITATIONS OF LIQUEFACTION ASSESSMENT IN THE PACIFIC NORTHWEST

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Seismic hazard assessments in the Pacific Northwest present several challenges in practice when evaluating native soil deposits for the potential and effects of liquefaction. There are many sites where deep (greater than 80 feet), loose silty and/or sandy soils have the potential to liquefy and affect the performance of our civil infrastructure. Though pore pressure generation or liquefaction of these deeper deposits may have minimal surface manifestations, pore pressure generation and liquefaction may play a key role in the assessment of the performance of deep shafts or driven piles at the deeper depths. Not only do these deep soil deposits have the potential to affect the performance of structures due to pore-pressure generation, such as loss in capacity and post-seismic settlement, but these deeper deposits present challenges in sampling and minimizing disturbance when laboratory testing is required to confidently evaluate pore pressure generation.

This presentation summarizes Jacobs' experience in the Pacific Northwest when evaluating pore-pressure generation and liquefaction of deep sandy and silty deposits to assess their impact on the seismic performance of structures. For our projects, we regularly test soil samples in Cyclic Direct Simple Shear (CDSS) to evaluate the performance and calibrate CDSS results to advanced numerical models (such as PM4Sand and PM4Silt in FLAC) used to estimate the performance of structures. This presentation will present a summary of our findings from select projects.

The presentation will also summarize the challenges we have encountered in performing this work, including sampling and minimizing the disturbance of samples, confirming quality samples prior to testing, evaluating stress histories, discussion on stress- versus strain-based testing, and the calibration of advanced constitutive models. One example is in regards to the occurrence of deep clean sand deposits, which being a clen sand precludes typical relatively undisturbed sampling methods. Therefore, in order to calibrate numerical models for these deposits, more reliance is given to empirical charts, which themselves were not intended for depths greater than 50 feet. We will share our experiences of doing these calibrations, as well as present on the similarities, as well as differences, that we have observed in the performance of silty sands compared to clean in regards to pore-pressure generation, post-cyclic strength, and post-cyclic volumetric strain, and the uncertainties with these values.

DYNAMIC BEHAVIOR OF THE TREASURE ISLAND NATURAL SHOALS

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BENEFITS OF DETAILED CHARACTERIZATION OF GEOLOGICAL UNITS

Treasure Island is located in the central San Francisco Bay, immediately north of Yerba Buena Island, between the active San Andreas and Hayward faults. Treasure Island was constructed by placing hydraulic sand fill within a perimeter of rock dikes. The hydraulic fill consists of loose to medium-dense sand and its dynamic behavior is captured well by simplified conventional analytical methods. The fill was placed over a natural shoal deposit consisting of varying layers of silty to clayey sand with interbedded lenses of highly plastic clay. Standard-of-practice post-vibro-compaction CPTs demonstrated that the fill can readily be densified. The underlying shoal, which was of the same origin as the hydraulic fill, was not densified by high-energy vibro-compaction. This study was undertaken to further investigate the dynamic behavior of the shoal deposit.

The objectives of this study are: (1) to evaluate the potential for pore-pressure generation and characterize the stress-strain response in the shoal deposit and the resulting lateral movements, and (2) to estimate the magnitude of settlement which may occur due to post-cyclic reconsolidation of the shoal deposit. The results of this study demonstrate that the dynamic behavior of the shoal differs from that of the fill and is controlled by variations in clay content, unique soil structure due to the site-specific depositional environment, and biological activity.

Field testing included vibro-compaction using Direct Power Compaction (DPC) in an instrumented test section. Geologic characterization of the shoal included detailed logging (SEM, optical microscopy, thin sections and descriptions of sedimentary structures) of continuous samples recovered using Dames-and-Moore sampling equipment. Laboratory analyses on high-quality samples included cyclic direct simple shear testing, constant-rate-of-strain consolidation testing, and triaxial testing with shear-wave-velocity measurements. Evaluations included seismic site-response analyses, lateral deformation analyses using two-dimensional finite-element and finite-difference models, and comparisons with observed seismic performance of similar sites during past earthquakes.

The study found that the shoal deposit possesses commonly overlooked characteristics such as clay cementation, irregularly distributed clay inclusions, a variable amount of silty to clayey fines forming a matrix between sand grains, and unique structure caused by depositional processes and biological activity (i.e., bioturbation). Figure 1 shows a detailed geological logging of the shoal sample.

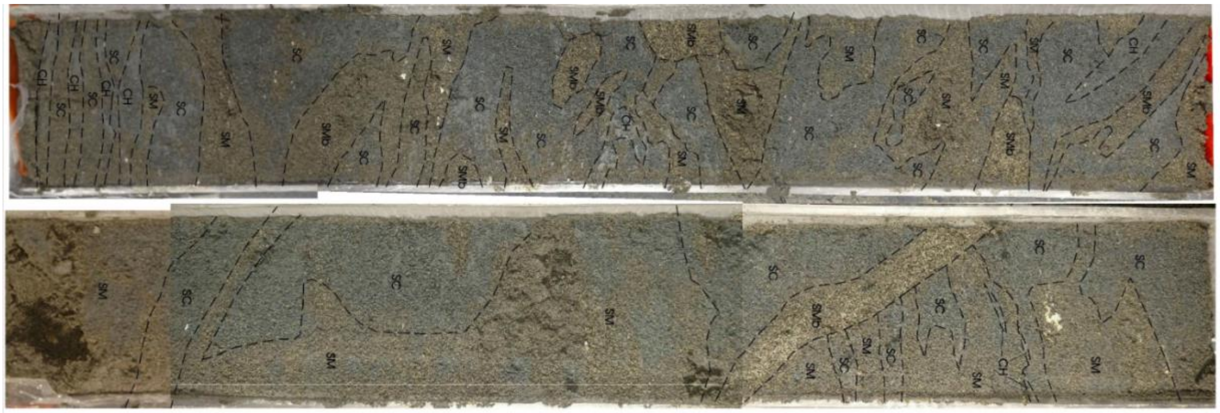

Figure 1. Detail from about 40.75 feet in the lower shoal unit showing variation in fines filling pores. Some areas contain significant fines (upper left) while other regions contain few fines in pores (lower left).

Independent 2D dynamic simulations were performed with the finite-difference program FLAC and the finite-element program PLAXIS, resulting in very similar and consistent results. The shoal is found to be more resistant to seismically induced lateral deformation than would be predicted by simplified models. The work included a comprehensive program to select seven input ground motions representative of the relative contributions of faulting scenarios determined from the probabilistic hazard assessment for this site.

Based on site-specific field investigation programs, full-scale field vibro-compaction testing, laboratory testing, geological interpretations, dynamic numerical analyses using PLAXIS and FLAC, empirical data, and review of earthquake effects on similar waterfront sites during past earthquakes, the estimated lateral movement would be insignificant at distances exceeding approximately 250 feet from the shoreline.

Additional testing and evaluations

On-going development at Treasure Island has allowed further testing of the dynamic behavior of the shoals. The Treasure Island ground improvement program included surcharging to compress soft bay deposits which underlie the shoal. These soils are locally known as Young Bay Mud (YBM). Following the surcharge program the project team investigated whether further, incidental improvement of the shoal was achieved. The same sampling techniques were used as in the original shoal study. Additional cyclic simple shear testing was also carried out. Figure 2 shows the results of the cyclic testing plotted against number of cycles to initiate liquefaction.

As shown on Figure 2, in general the surcharge improved the resistance of the shoal against excess pore built-up. In addition, using the results of site-response analysis to calculate cyclic stress ratios (CSR), instead of the empirically based standard of practice CSR, it was demonstrated that the shoal will not undergo widespread softening and volumetric strain under the Maximum Considered Earthquake (MCE)

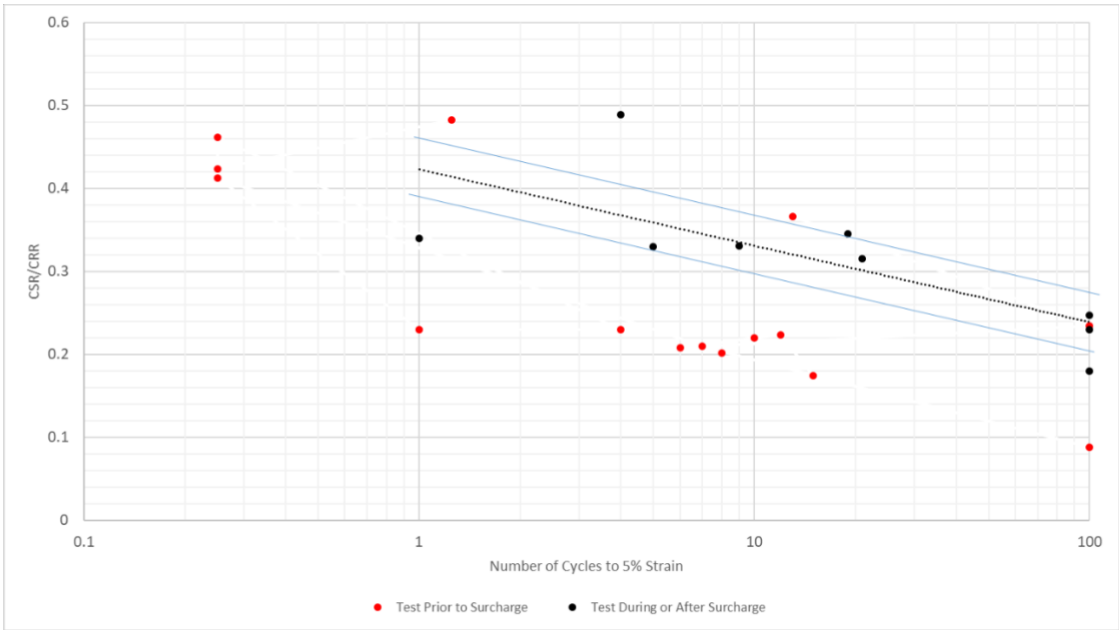

Figure 2. Resulting CSR/CRR for Shoal Samples Before and After Surcharge.

CONCLUDING REMARKS AND RECOMMENDATIONS

Based on our findings at Treasure Island, we believe that the industry will be well served by not over-relying on CPTs and CPT-based software alone to determine the performance of a site under seismic loading. On projects where excessive conservatism creates a substantial financial burden, we recommend introducing very detailed geological characterization of potentially liquefiable materials, cyclic laboratory testing of materials which can be sampled, and site-response analysis calibrated with historical data. These evaluations, although more expensive and time consuming than the current state of practice, can improve the financial viability of projects and create designs that allow resources to be redirected to sustainable construction.

ACKNOWLEDGEMENTS

Special thank you to Treasure Island Development Group for supporting technical excellence and advancement, and to our technical contributors Dr. Michael Beaty, GE, Dr. Steve Dickenson, PE, Dr. Juan Pestana, UC Berkeley, Dr. Michael Riemer, UC Berkeley, Dr. Jonathan Bray, UC Berkeley, Dr. Nicholas Sitar, UC Berkeley.

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LIMITATIONS OF THE SIMPLIFIED PROCEDURES AND PRACTICE IN THE PNW: A REVIEW OF THE CURRENT STATE OF THE PRACTICE AND RECENT CASE HISTORIES

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THE CONCERN

The last 20+ years have shown extensive growth in liquefaction assessment following the 1996 NCEER and 1998 NCEER/NSF workshops on liquefaction evaluation of soils. These workshops paved the way for the development of many tools practicing engineers now use to evaluate liquefaction. These techniques are firmly founded on a review of case histories from numerous sites both with and without liquefaction, and the simplified procedures and software tools have provided many engineers with a quick tool to estimate liquefaction potential. However, regions of the country such as the Pacific Northwest have areas where many, if not most, of the soils, fall outside the range of the sand and silty sand case histories used to develop the simplified procedures. As described further below, newer procedures are available for fine-grained soils. However, due to budget/time-constrained projects and/or lack of familiarity, many engineers do not perform adequate testing (both in situ and laboratory) to better characterize and estimate soil behaviors. Using sand-based procedures in early stages of a project has had significant impacts on project budgeting and outcomes, particularly for projects where conceptual or preliminary engineering efforts drive decisions for environmental permitting constraints. The paragraph below provides additional detail on the issues related to fine-grained soils.

The simplified procedures are based on liquefaction assessment utilizing either corrected standard penetration test blow counts, cone penetration test (CPT) tip resistance, or shear wave velocities to evaluate a soils resistance to liquefaction. This estimated liquefaction resistance is known as the cyclic resistance ratio (CRR) and is compared to the level of earthquake-induced loading, known as the cyclic stress ratio (CSR). While this method of estimating CRR has shown value and provides reasonable results for cohesionless soils, it ignores the nuances of fine-grained soil behavior, such as the effects of plasticity and overconsolidation (OCR). Several guidelines have been developed (Idriss & Boulanger 2008; Anderson et al. 2007), which aim to provide insights into soil characterization and provide methodologies for estimating fine-grained soil CRR while incorporating the effects of OCR. These guidelines set much of the framework needed for incorporating more advanced testing such as cyclic direct simple shear testing into our liquefaction evaluations and provide reasonable lower bounds to CRR trends in fine-grained soils.

RESPONSE TO PROMPT(S)

What are the consequences of incorrectly assessing liquefaction susceptibility, and under what conditions are these consequences most acute?

Following the development of the simplified methods, many conceptual-level evaluations now include screening-level evaluations based on worst-case sand-like behavior. While resulting in safe designs, this approach increasingly drives early decision-making, often resulting in substantially more expensive designs that could have potentially been avoided with the early adoption of more robust in situ and laboratory testing. The consequences of these conditions are most acute in large infrastructure projects where conceptual or preliminary level engineering changes permitting approaches or structure type decisions are commonly made early.

What data resources would help improve understanding?

The large majority of the data currently publicly available comes from areas outside of Oregon/Washington. To alleviate some of the inherent conservatism in liquefaction evaluations, regional trends in fine-grained soil behavior and access to a database of regional information could greatly benefit the geotechnical community. In this regard, the Oregon Department of Transportation, with support from Portland State University and local practitioners, is currently developing a database of cyclic testing for northwest silt soils. The database will include preliminary dataset trends that help form the framework for a better picture of silt behavior.

CASE HISTORIES

Willamette Water Supply Program – Raw Water Facility

The Willamette Water Supply Program (WWSP) is currently in the process of design and construction of a new resilient water supply for several communities near Portland, Oregon, including those served by the Tualatin Valley Water District, the City of Beaverton, and the City of Hillsboro. The project includes the construction of new water treatment plants, tanks, pipelines, and improvements to an existing water intake system in Wilsonville known as the Raw Water Facilities (RWF).

A conceptual-level evaluation of RWF was initially completed and included a liquefaction/lateral spreading evaluation of the slope located between the river and the existing structures (clear well, pumps, etc.). Previous explorations at the site indicated the soils are predominantly Willamette Silt (WS) soils underlain by stiff, higher plasticity silts and clays of the Troutdale Formation. Conceptual-level liquefaction evaluations considered the Willamette Silt as "sand-like" and employed the use of simplified procedures. Results of the analyses indicated the WS soils were susceptible to liquefaction and low factors of safety for slope stability, indicating flow failure type behavior and significant lateral displacements (greater than 10 feet).

The next project phase completed by the final design team employed the use of cyclic direct simple shear testing (CDSS) and the SHANSEP framework (Ladd & Foote 1974; Idriss & Boulanger 2008) as well as Finite Difference Modeling. Results of this next phase of analysis and testing indicated the silt soils would undergo limited cyclic softening and much smaller strain levels than estimated using the simplified procedures. Similar to other case histories in the area, the resulting deformations were closer to an order of magnitude lower than previously estimated.

Bonneville Power Administration Transmission Line Crossing Project

The Bonneville Power Administration (BPA) is tasked with managing power generation on 31 dams in the Columbia River Basin and provides power to local utilities such as Portland General Electric (PGE). Overall, BPA represents approximately 28% of the power generation within the northwest. As part of the agency's seismic resiliency goals, a concept-level evaluation of multiple existing transmission line towers crossing the Columbia and Willamette Rivers in Portland and Troutdale was completed. The various project sites included a wide variation in soils ranging from stiff, high plasticity clays to loose, low fine content sands. Preliminary evaluations utilizing CPT-based simplified procedures characterized the relatively low PI silt as having "sand-like" behavior and high susceptibility to liquefaction and large lateral spreading displacements.

Following the initial screening, a more advanced design phase was contracted to further evaluate the liquefaction and lateral spreading risk as well as provide mitigation alternatives. To evaluate the behavior of the silt and clay soils, the project team performed a robust CDSS testing program. The results of this testing program allowed for the development of project-specific CRR trends for the silt and clay soils as well as site-specific correlations between plasticity and Ic. This additional work to accurately characterize the soil behavior indicated the silt and clay soils were typically not susceptible to liquefaction but would undergo cyclic softening (Beaty et al. 2014). Utilization of the cyclic testing resulted in an overall reduction in the need for ground improvement in the fine-grained soils.

CONCLUDING REMARKS AND RECOMMENDATIONS

As our knowledge of liquefaction and cyclic softening continues to grow, we recommend that the engineering community is strongly encouraged to actively adopt new methodologies and techniques for fine-grained soils. We recommend the engineering practice focuses first on adequately characterizing cyclic behavior of soils at early stages of the project if these behaviors are likely to drive decision making. The current practice of using a sand-like screening approach often leads to expensive decisions that can often be avoided. As a secondary recommendation, development of regional data trends and correlations could greatly benefit the local engineering practices as well as reduce uncertainty for owners.

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LIQUEFACTION SUSCEPTIBILITY OF A LOW PLASTICITY SILTY SOIL UTLIZING CYCLIC DIRECT SIMPLE SHEAR TESTING

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CYCLIC TESTING FOR LIQUEFACTION EVALUATIONS IN TRANSITIONAL SOILS

The liquefaction susceptibility of transitional and intermediate soils is commonly evaluated based on soil index properties (e.g. Boulanger & Idriss 2006; Bray & Sancio 2006) which generally classify a soil's dynamic behavior and potential for pore pressure-induced strength loss as liquefiable (sand-like) or nonliquefiable (clay-like). However, as noted by Armstrong and Malvick (2016), the differences in the soil indices and soil behavior thresholds utilized by the various soil index test-based methods can lead to inconsistent evaluations of liquefaction susceptibility in typical practice. In addition, the available case history and laboratory database is limited with respect to transitional soils.

This paper describes a comprehensive laboratory testing program that was utilized to evaluate the liquefaction susceptibility and the dynamic behavior of a low plasticity silty soil for a major infrastructure project in the Portland Oregon area. The following sections detail the soil index test-based liquefaction susceptibility evaluations typically performed in practice and the results of the cyclic laboratory tests. The results of the laboratory testing program illustrate the benefits of site-specific cyclic laboratory testing for transitional soils that are not well defined in literature.

SOIL INDEX TEST-BASED LIQUEFACTION SUSCEPTIBILITY EVALUATIONS

Soil index tests including Atterberg Limit, water content, and fines content testing were performed on 47 select samples obtained from the transitional soils encountered at the site using Standard Penetration Test split-spoon and Shelby-tube samplers. The index test results for the transitional soils included natural moisture contents that ranged from 29 to 51 percent (average of 42 percent), plasticity indices that ranged from nonplastic to 19 (average of four), and fines contents that ranged from 35 to 83 percent (average of 61 percent). The soil was generally characterized as a low plasticity sandy silt to silty sand.

A summary of the index test data is provided in Figure 1 which plots the plasticity index as a function of the ratio of the water content to the liquid limit. Also included on the plot are zones delineating the liquefaction susceptibility criteria thresholds of Boulanger and Idriss (2006) and Bray and Sancio (2006). Based on the criteria of Boulanger and Idriss (2006) approximately 80 percent of the tested samples would classify as "sand-like" and can be evaluated with typical simplified semi-empirical-based liquefaction methods. Per Bray and Sancio (2006), approximately 98 percent of the samples would be susceptible to liquefaction and strength loss due to generation of excess pore pressures during cyclic loading.

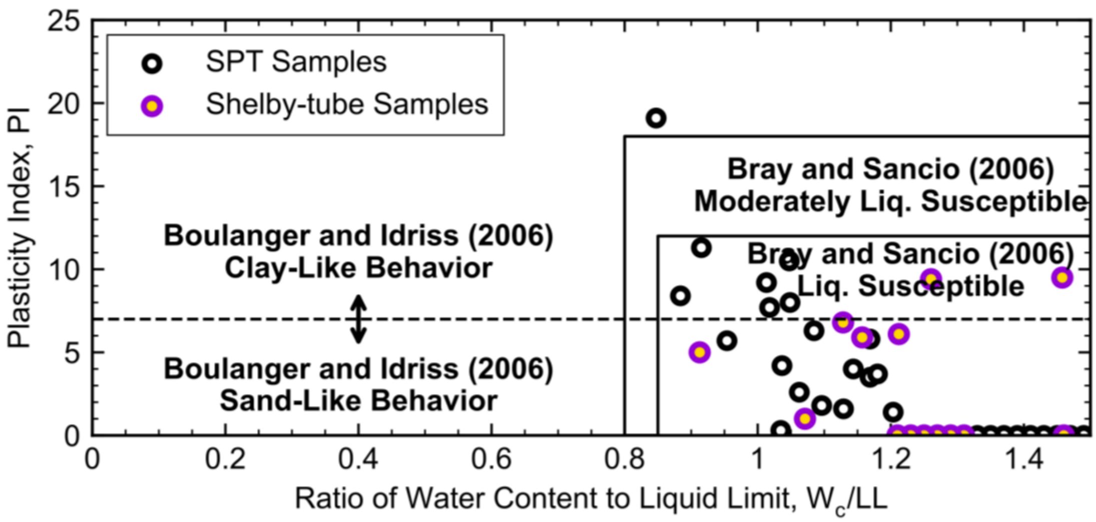

Figure 1. Summary of soil index test data and Boulanger and Idriss (2006) and Bray and Sancio (2006) liquefaction-susceptibility criteria

Both index test-based methods typically used in practice suggest that the transitional soils at the site are predominantly composed of liquefaction-susceptible soils. However, both Boulanger and Idriss (2006) and Bray and Sancio (2006) note that index test-based procedures should be considered as general screening guides and should be supplemented with cyclic laboratory testing of field samples if the seismic behavior of the soils in question are a critical aspect of the project design. Cone penetration tests (CPTs) were used to evaluate the resistance to liquefaction using the semi-empirical liquefaction triggering framework of Boulanger and Idriss (2015). The soils had an average normalized corrected CPT tip resistance, q_{c1ncs}, of approximately 85, indicating a low resistance to liquefaction. Given the prevalent nature of the transitional soils at the site and to reduce the uncertainty in seismic deformation analyses performed for the project, a cyclic laboratory testing program was performed as described in the following section.

CYCLIC LABORATORY TEST RESULTS

The cyclic laboratory testing program included harmonic stress-controlled cyclic direct simple tests (CDSS) performed on select Shelby-tube samples. The index properties of the Shelby-tube samples selected for CDSS testing included samples with natural moisture contents that ranged from 35 to 51 percent (average of 43 percent), plasticity indices that ranged from nonplastic to ten (average of three), and fines contents that ranged from 44 to 83 percent (average of 64 percent). The samples used in the CDSS test program were obtained between depths of 20 to 90 feet below the ground surface. Tests were performed at confining pressures ranging from approximately one to three atmospheres with applied cyclic stress ratios (CSRs) between 0.15 and 0.3.

A summary of the CDSS test results is provided in Figure 2 which plots the CSR as a function of the number of cycles (N) to reach a single amplitude shear strain of three percent for each test that reached the given peak shear strain threshold. Also included in Figure 2 is the CSR vs N relationship for clean sands derived from Boulanger and Idriss (2015) assuming a q_{c1ncs} of 85 and overburden effective stresses ranging from 1 to 3 atmospheres. The site-specific CDSS program shows the soil has significantly more resistance to strain accumulation under cyclic loading than implied from semi-empirical methods developed for clean sands. The site-specific cyclic laboratory testing program indicated that the seismic behavior of the transitional soils at the site were best represented by cyclic softening type evaluations (e.g. Boulanger & Idriss 2007) as opposed to the clean sand liquefaction analyses framework as suggested by the index test-based liquefaction susceptibility evaluations.

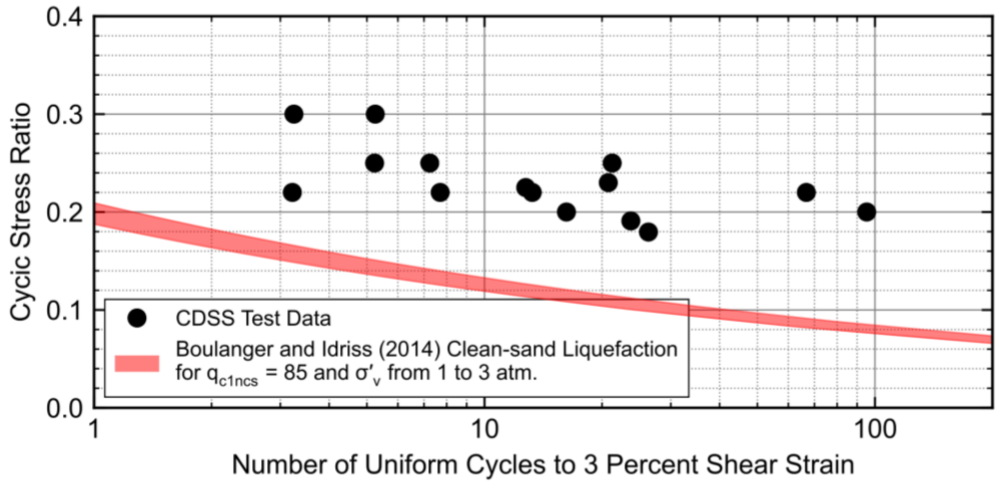

Figure 2. CSR vs number of uniform cycles to 3 percent shear strain from CDSS tests with comparison to Boulanger and Idriss (2015) clean-sand semi-empirical relationship

CONCLUDING REMARKS AND RECOMMENDATIONS

This paper described the use of cyclic laboratory testing to characterize the dynamic behavior of a transitional low plasticity silty soil in practice. This example highlights the known limitations of index-test based liquefaction susceptibility evaluations currently used in practice and the utility of performing site-specific cyclic testing in soils that are not well defined in literature. The practicing geotechnical community would benefit from additional research in the cyclic response of transitional and intermediate soils.

ACKNOWLEDGEMENTS

The presented CDSS tests were performed by Oregon State and Portland State Universities.

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LIQUEFACTION SUSCEPTIBILITY OF GRAYS HARBOR SILTS

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INTRODUCTION

A pontoon casting basing was constructed in 2010 in the town of Aberdeen, Washington as part of the SR 520 Floating Bridge Replacement project. The project site is located within the Aberdeen tidelands on the north shore of Grays Harbor near the lower reach of the Chehalis River at latitude 46.9648, longitude -123.8337. Subsurface conditions along the river are typical of a fluvial depositional environment with embedded sand channels amongst silt and clayey silt deposits. Given the liquefaction and lateral spread hazard form a Cascadia Subduction Zone earthquake, an extensive geotechnical exploration program was conducted yielding borehole/CPT pairs, index testing, and cyclic direct simple shear tests. This data set is presented here to demonstrate the performance of various methods to assess liquefaction susceptibility and cyclic mobility of silts with plasticity indices ranging from 11 to 94 and soil behavior type index (I_c) greater than 3.0. In addition, the data set illustrates boundaries for transitional behavior that is dependent on PI, CSR, and shear strain cycles.

SITE LOCATION AND SUBSURFACE CONDITIONS

32 borings and 26 CPTs were performed at the site resulting in 27 boring/CPT pairings (Landau 2009; SW 2011). The subsurface soils consisted of 10 to 15 feet of fill underlain by about 90 to 110 feet of very soft to stiff silt with embedded sandy stream channels occurring at various elevations and is further underlain by very dense gravels and sandstone. Laboratory tests consisted of moisture contents, sieve analyses, hydrometers, Atterberg limits, 1D consolidation tests, undrained unconsolidated and consolidated triaxial tests, direct simple shear tests, cyclic direct simple shear (CDSS) tests, vane shear, pressure meter tests, and shear wave velocity testing.

LIQUEFACTION SUSCEPTIBILITY ASSESSMENT

Simplified methods

Cone penetration test data was interpreted using procedures outlined by Robertson (2016) resulting in the derived parameters normalized tip resistance (Q_{tn}), normalized friction ratio (F_r), and soil behavior type index (I_c). A comparison of plasticity index versus I_c for paired borings and CPTs was made where no trend is observed between, however, per the Bray and Sancio (2006) liquefaction susceptibility criteria, some silts are classified as potentially liquefiable while others require further testing (See Figure 1A). The Boulanger and Idriss (2006) susceptibility method indicates all soils would exhibit clay-like behavior. Robertson's (2016) large strain soil behavior descriptors indicates that all silts at the site would exhibit fine-grained contractive behavior (see Figure 1B).

CDSS testing

A CDSS test program was performed to further assess the liquefaction susceptibility of the silts (See Table 1). Cyclic stress strain curves were interpreted at 10, 20, and 30 cycles to evaluate trends in excess pore pressure ratio (R_u) and maximum cyclic shear strain amplitude versus plasticity index and cyclic stress ratio (See Figure 2).

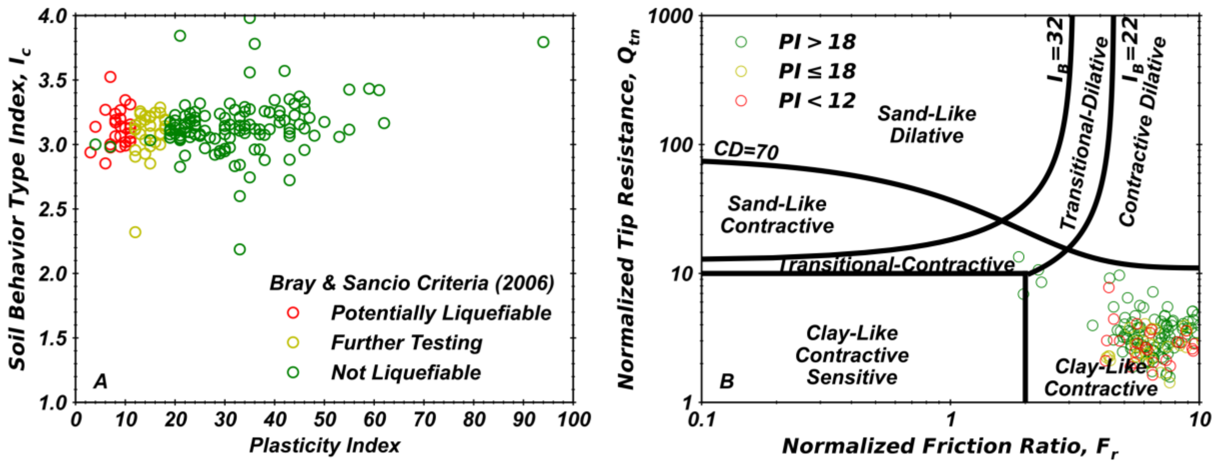

Figure 1. A) Silt cyclic susceptibility to liquefaction on cyclic softening per Bray and Sancio (2006), and B) large strain behavior index per Robertson (2016).

Table 1. Summary of CDSS test program

Sample	Depth (m)	PI	LL	PL	MC	Ic	CSRs
H-08p-09, S-15	13.95	11	45	34	45	3.02	0.12, 0.2, 0.24
H-18-09, S-15	15.42	14	41	27	40	2.93	0.25, 0.3, 0.34
H-07-09, S-15	15.4	17	42	25	41	3.08	0.25, 0.3, 0.34
H-29p-09, S-13	11.95	23	59	36	59	3.06	0.2, 0.3, 0.34
H-16-09, S-13	12.25	94	173	79	173	3.80	0.29, 0.34, 0.39

For a CSR demand of 0.3 and 15 cycles, the Bray and Sancio (2006) liquefaction susceptibility method was able to identify silts susceptible to classic sand-like liquefaction and silts transitioning towards cyclic mobility. However, as CSR and shear strain cycles are increased, higher plasticity silts begin to show liquefiable behavior (Figure 2A and 2C). This suggests that existing susceptibility models may contain a level of inherent triggering criteria based on the limits of empirical data. The data also suggests a relationship between PI and a threshold CSR at which R_u and shear strains rapidly increase and liquefiable behavior is exhibited (Figure 2B and 2D).

CONCLUDING REMARKS AND RECOMMENDATIONS

This data set confirms that CPT based liquefaction susceptibility and cyclic mobility evaluations based solely on I_c are potentially unconservative especially for moderate to large magnitude earthquakes. However, the CPT was able to identify potentially liquefiable silts based on the large strain behavior index. Further research to expand empirical data in susceptibility models, susceptibility models based on large strain behavior, and CSR/PI threshold behavior is recommended. It is also recommended that practitioners and researchers using CPT data evaluate initial liquefaction susceptibility consider large-strain, contractive and transitional boundaries in addition to I_c criteria. CPT data plotting in the translational and contractive regions signify that in-situ sampling for Atterberg Limits and/or CDSS testing should be performed. This is especially important for small to medium sized projects in which CPT is the first and sometimes last investigation tool used to determine soil behavior during site-specific seismic hazards.

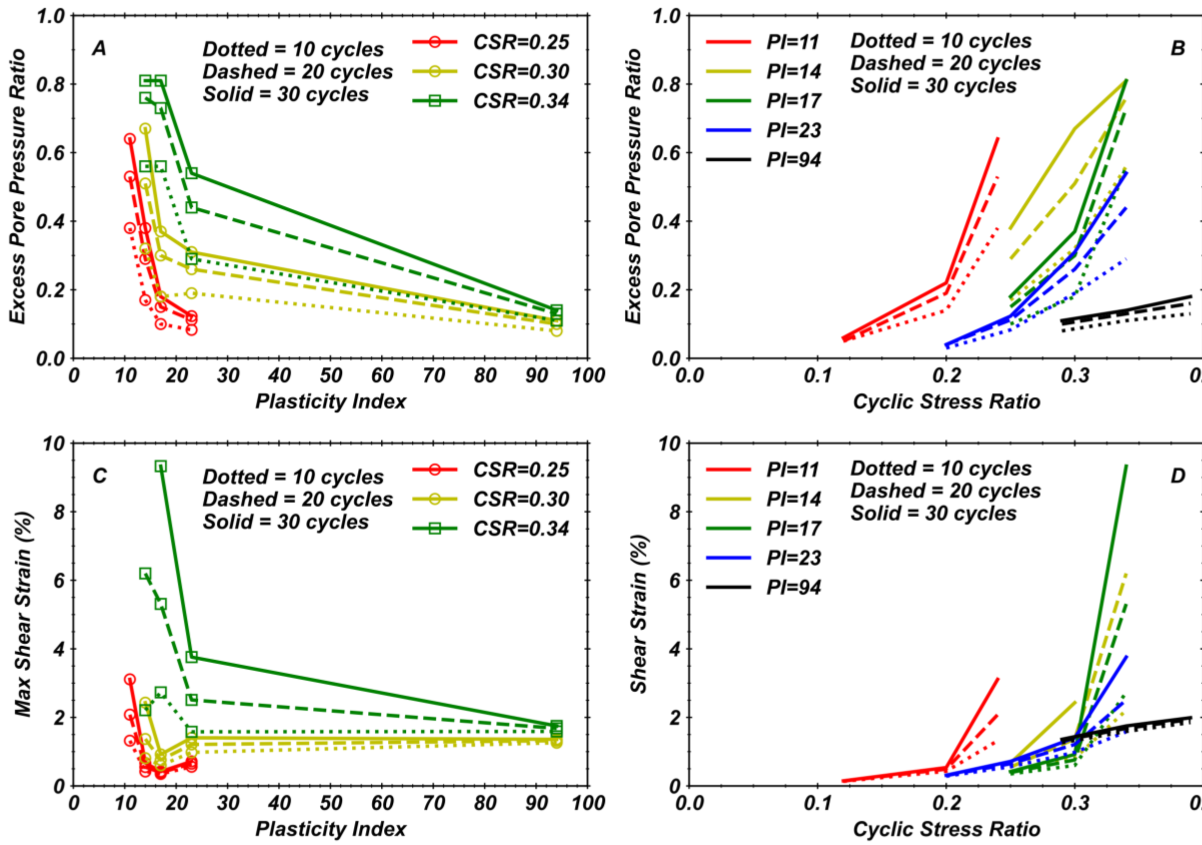

Figure 2. Results of CDSS test program.

ACKNOWLEDGEMENTS

All site data was collected by exploration programs executed by Landau Associates and Shannon & Wilson, Inc. for The Washington Department of Transportation. The author appreciates discussions with Claire Gibson that improved this manuscript.

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THE IMPACTS OF ANALYZING DEEP SAND AND TRANSITIONAL SOIL PROFILES WITH STATE OF THE PRACTICE METHODS

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STATE-OF-THE-PRACTICE METHODS, AND THEIR LIMITATIONS

When assessing the potential for liquefaction triggering, most engineers rely solely on stress based simplified methods such as Boulanger and Idriss (2014). These methods are then applied broadly to sands of any fines content. If fine grained soils are considered at all, the penetration resistance based simplified methods are also applied to low plasticity fine grained soils that may qualify as “sand-like” using simplified screening methods such as Boulanger and Idriss (2006). Correspondingly, when relying on cone penetration tests, the application of sand-like behavior often occurs up to a soil type behavior index, I_c, of 2.6 (Robertson & Write 1998). Treating these transitional soils as sand-like may under predict the cyclic resistance of these soils, therefore over predicting the resulting impacts of cyclic loading on the soil profile.

If an engineer does identify that a transitional soil may have a cyclic behavior that is distinctly different than a sand deposit, it is often difficult to reliably characterize the monotonic shear strength of the soils which would facilitate the use of methods such as Jana and Stuedlein (2021). The impact of the potential mischaracterization of the cyclic behavior of these soils is magnified when they are part of a deep soil profile (e.g. 100+ feet of sand) where the cumulative effects of predicted liquefaction can be quite large and expensive to mitigate.

These deep soil profiles are particularly problematic to the practicing engineer as the simplified methods do not currently lead them to consider either the system response or explicitly capture the horizontal variability of a soil deposit, which may play a significant impact on the seismic performance of the site (Cubrinovski et al. 2019).

These limitations in combination with compounding factors of safety and hazard levels will often leave an engineer with a design soil profile that is generally predicted to liquefy until a very dense bearing layer is encountered. While partial saturation has been documented to significantly increase the cyclic resistance of soils, there is limited precedence or documentation on the long-term reliability of maintaining partial saturation below a water table. Engineers therefore do not account for this behavior in practice. This often leaves the engineer with needing to provide recommendations for deep foundations or significant quantities of ground improvement that may not be necessary.

Deep foundations of an economical size can quickly become unfeasible due to the requirement in the International Building Code (ICC 2017) to treat “deep foundation elements standing unbraced in air, water or fluid soils” as columns without lateral support until they are 5 feet into stiff soil or 10 feet into soft soil. A soil deposit that that has a thick continuous layer of predicted liquefaction can quickly be controlled by buckling. Even if a project is not subject to the IBC, the current state-of-the-practice often results in excessive deep foundation lengths depending on how liquefaction induced downdrag is handled.

The use of ground improvement can be problematic as well. Terminating ground improvement in a liquefiable soil profile is often met with resistance from both building officials and engineers who are uncertain on how to analyze the performance of such a system. The use of economical ground improvement is further impacted by the loss of the assumption of strain compatibility for discrete elements such as aggregate piers, and the resulting cost associated with jet grouting or soil mixing.

RESPONSE TO PROMPT(S)

Have you experienced a case where the determination of susceptibility proved to be pivotal, and what were the considerations associated with the application of typical (i.e., state-of-the-practice) susceptibility procedures?

The susceptibility of a site to liquefaction has been pivotal on many projects I have participated in. These are often impacted by deep interbedded alluvial soil profiles where the assumed behavior of transitional soils can be critical. For the transitional soils we will at times evaluate them with a combination of the CPT and advanced laboratory testing resulting in cyclic resistance profiling based on yield stress ratio profiles (YSR) and the monotonic undrained shear strength. In these cases, the CRR is evaluated using a power law as presented by Jana and Stuedlein (2021) or Dickenson et al. (2021) and as shown in Figure 1 for a low plasticity fine grained soil deposit. However, even if clay-like behavior is identified, determining an accurate profile of the YSR is problematic in silts.

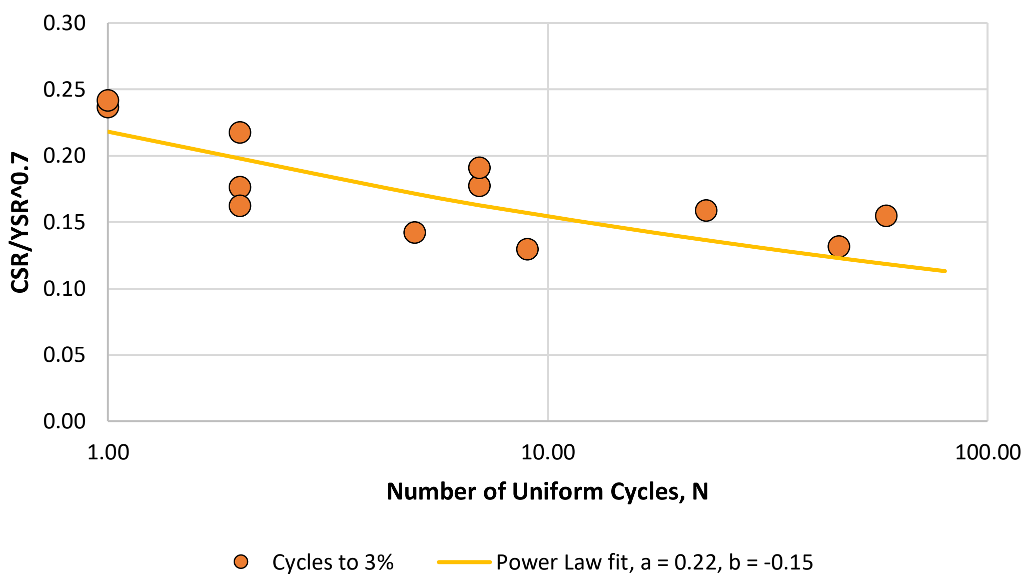

Figure 1. Cyclic Resistance Curve Varying CSR with N for γ= 3%. These are not corrected for rate effects.

For generally deep profiles, typical susceptibility procedures are often applied with some acknowledgement about their limited applicability for depths greater than about 80 feet. However, they are generally still used over the full soil profile.

Can you describe a case where liquefaction susceptibility was assessed using methods beyond those typically applied, given the importance of the project and consequences of liquefaction?

We have used both 1D and 2D site response analyses with models such as PM4SAND and PM4SILT to capture the system response of a site. However, the use of 1D analyses in soft or loose soil deposits is often met with concerns of potentially overdamping due to an incorrect assumption of horizontally infinite and continuous layers.

CONCLUDING REMARKS AND RECOMMENDATIONS

The application of sand-like liquefaction susceptibility criteria to low plasticity fine grained soils can often result in an underestimation of the cyclic resistance and post-cyclic strength of the soil. When coupled with deep profiles that have a significant system response this may result in a design profile consisting of a large degree of false positives, significantly increasing construction costs. This has a cascading impact on all of the resulting analyses involving the impacts of liquefaction. With further refinement of the applicability of transitional soil behavior to the CPT and improved methods of characterizing the yield stress ratio in these soils a reliable estimation of the CRR may be readily estimated without site specific advanced testing. However, the system response of a soil profile remains a challenge for practitioners to address reliably and efficiently. Development of simplified methods that can capture the system response or more explicit guidance on the appropriate application of equivalent one-dimensional analyses using soil models intended to capture this behavior would be beneficial. Finally, further study on the long-term reliability of partial saturation in various environments may support increased cyclic resistance ratios for use in design.

ACKNOWLEDGEMENTS

While no direct research funding has attributed to these observations, several private organizations have patiently worked with project teams over several projects to address many of the limitations presented herein.

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CHALLENGES OF LIQUEFACTION ASSESSMENT AT CALIFORNIA'S DAMS

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INTRODUCTION

The California Division of Safety of Dams (DSOD) regulates over 1240 dams in California. The program was established in 1929 to protect life and property with respect to dam safety. Our authority extends to dams owned by individuals, companies, utilities, local governments, and the State. Over 70-percent of the dams regulated are over 50 years old. The total population at risk for all dams exceeds 5,000,000. Given the high risk, DSOD relies on independent evaluations to provide dual verification of dam safety. Eighty-percent of the dams are earthfill, which makes, liquefaction assessments critical to dam safety.

While liquefaction evaluation techniques continue to evolve and improve, DSOD finds there to be challenges that limit the confidence in our reviews. The most critical issues relate to geology and materials at our dams, specifically the presence of gravel or soils (soils with moderate fines contents, 20–50 percent or moderate plasticity, plasticity indices 12–20). The challenges lead to inconsistent results and contrasting results that can have significant impacts on the final determination for a dam. The most critical issue is the potential bias that can occur due to gravels when they are at a high percentage or too large and impact in-situ measurements. Conversely, it is uncertain what the potential maybe for over-conservatism with intermediate soils that may not be susceptible to any strength loss.

The discussion that follows focuses on these topics and their impact on dam safety. While specific case histories are not presented, DSOD has numerous to support most scenarios described. This will be closed with recommendations towards goals and research that can help achieve more consistency in practice related to liquefaction.

DETAILED RESPONSES

Most common drivers of challenges related to gravel

Gravel is a significant challenge for liquefaction evaluations at California's dams. Methods for characterizing gravels in-situ were standardized starting with the Becker Penetration Test (BPT) work by Harder and Seed (1986) and have continued progress to modern instrumented BPTs (iBPT) (e.g., DeJong et al. 2017 and Ghafgazi et al. 2017). While progress should lead to consistency in techniques, DSOD find evaluations can be inconsistent due to an expectation that early methods should give the same results as new methods. This leads to hesitation in practice and lack of consensus regarding BPT tests overall and variable conclusions when multiple techniques are considered. However, the inconsistencies are likely indicative of the complication of characterizing gravels versus sands, which have generally been more studied and understood.

Specifically, we see limited trust in the applicability of BPTs because the core correlations are derived from and tied directly to sand while the methods are intended for gravel. It is understood this limitation was born of necessity given the limited availability of case histories of gravel liquefaction. In practice, however, the BPT becomes an extrapolation when used with gravels since a reliable correlation with Standard Penetration Tests (SPTs) are not likely with gravel presence. Thus, BPTs may be limited in their ability to capture the real impact of particle size, gravel content, coefficient of uniformity (C_u), and deposition processes that may impact their behavior. Each of those factors may not only affect the in-situ resistance (e.g., CRR) but also the loads needed to trigger liquefaction (e.g., CSR).

Additional challenges using BPT are tied to practicality. Accessibility at dam sites can be a challenge for BPTs related to rig size, road size, dam height, and more. Further, the availability of BPTs can impact schedule and costs. Thus, engineers often rely on extrapolative techniques, such as SPTs measuring blows-per-inch, often without consideration for gravel size or deposition. Cone Penetrometer Tests are often used with visibly damaged probes. Statistics are often relied on to average results and justify the inclusion of all data without thought to what one extreme outlier might have on results. DSOD has seen SPT data used where a shoe has been blocked or recovery is zero despite high blow-counts. SPTs have been used in 60-percent gravel materials and even in cobbles. This leads to widely inconsistent interpretations of liquefaction susceptibility. One evaluation of a hydraulic fill dam had about 25-percent gravel with some SPT blow counts ($N_{1\text{-}60,cs}$) exceeding 60 with many below 20. The consultant concluded liquefaction was not an issue because the mean $N_{1\text{-}60,cs}$ was greater than 30. However, it is hard for DSOD to trust a hydraulic fill to be that competent given 75-percent of the material was finer than gravel.

The challenge comes down to limited guidance regarding the use of samplers versus particle size. In one extreme, a dam recently explored with IBPTs was known to be constructed with gravels approaching cobble sized.

Challenges related to intermediate soils

DSOD also faces lesser challenges with intermediate soils, soils generally thought not to be liquefiable but not clearly in the realm of cyclic softening. Malvick et al. (2014) documented DSOD's protocols for evaluating these "transition" soils for strength loss susceptibility, liquefaction or cyclic softening. Liquefaction and cyclic softening literature were compared to identify areas in common and those where interpretations would vary. As a regulator, it is critical to recognize all valid procedures. Our process focuses on identifying if soil behaviors are clay-like or sand-like and fines-controlled or coarse-controlled. Given the mission to protecting life and property, the absence of literature explicitly noting conditions where strength loss may not occur or how the behavior from liquefaction to cyclic softening can transition, a conservative approach is taken. Yet, these soils can have low $N_{1\text{-}60,cs}$, yet quality samples show high density with $C_u > 4$. We speculate these materials are not susceptible strength loss and in one case concluded so.

Impact on Dam Safety

The consequences of incorrectly assessing liquefaction susceptibility can be catastrophic at dams. The Lower San Fernando Dam incident in 1971 shows us what liquefaction can do at a dam. While there were no consequences, the incident highlights California's major cities and the dams that serve them are often in the state's most seismically active regions. DSOD has focused re-evaluations of dams for seismic loads and liquefaction as engineering methods improve and evolve. In some cases, dams considered safe historically have been found not to be. Yet gravel bias, especially when SPTs are misapplied, can lead to extreme risks and long-drawn-out processes to reach consensus on what needs to be done with a dam. Mitigation and repairs can be costly as $100 million or more repairs become more common.

RECOMMENDATIONS

It is recognized that the Next Generation Liquefaction project is intended to mimic the Next Generation Attenuation (NGA) project used for ground motion parameters. DSOD sees merit in the objective but does have concerns if there is intent for multiple models to be developed towards the same purpose. For instance, there may be more value in one liquefaction susceptibility and triggering model contributed by all potential authors to exemplify a full consensus. With the NGA, DSOD sees inconsistencies related to varying choices of models, applicability, and other biases. With liquefaction, the contrast of methods had been problematic while there may be more acceptance and consistency with a consensus such as that of Youd and Idriss (1997).

In addition, there is a need for supplementary guidance, clarifications, and consensus when dealing with gravel influenced and intermediate soils. Research may be needed or compiled to clarify the conditions where gravelly or intermediate soils can liquefy or lose strength. Consideration may be needed for the impact of C_u, soil matrix, sampler validity, sample quality, and exclusion when strength loss may not need to be considered at all. For practitioners, one inclusive reference may provide an advantage as the number of engineers and projects grow resulting from ageing infrastructure, continued advances in engineering knowledge, and retirement of our respected experts. In dam safety, consistency can make a huge difference in correctly mitigating risks or potentially save a dam owner significant costs.

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EVALUATING LIQUEFACTION SUSCEPTIBILITY FOR NUCLEAR POWER PLANT SITES

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The Nuclear Regulatory Commission (NRC) was established by the Energy Reorganization Act of 1974 with the authority for all licensing and related regulatory functions associated with civilian uses of nuclear materials and facilities. There are currently 93 operating electrical generating nuclear power reactors at 55 sites in the United States, and according to the Nuclear Energy Institute, the Nuclear Regulatory Commission (NRC) could receive 12 or more license applications for advanced reactors per year as early as 2025. Liquefaction susceptibility evaluations are performed for nuclear power plant sites when assessing the possible effects of ground shaking on facility foundations.

10 C.F.R. §100.23 (1997) requires a power plant license applicant to evaluate the site for liquefaction potential. This regulation does not provide details on how to assess liquefaction susceptibility, liquefaction triggering, or consequences associated with liquefaction. Guidance to licensees and applicants on implementing NRC's regulations, techniques used by the NRC staff in evaluating specific problems or postulated accidents, and data needed by the staff in its review of applications for permits or licenses are documented in Regulatory Guides. Specific guidance for evaluating liquefaction at a nuclear power plant site is found in Regulatory Guide 1.198, "Procedures and Criteria for Assessing Seismic Soil Liquefaction at Nuclear Power Plant Sites," (US NRC 2003). The current regulatory position states that the applicant should identify soils that might liquefy and that screening for liquefaction potential should include assessing susceptibility by asking the following question: "Are potentially liquefiable soils present?" Although the regulatory position does not describe specific susceptibility criteria, the Regulatory Guide Discussion Section includes information on susceptibility criteria. Specifically, the discussion in the guide states the following.

- Cohesive soils with fines content greater than 30 percent and fines that either (1) are classified as clays based on the Unified Soil Classification system or (2) have a Plasticity Index (PI) greater than 30 percent should generally not be considered susceptible to liquefaction.

- Sands that have dual Unified Soil Classification system designations such as CL-ML, SM-SC, or GM-GC are potentially liquefiable (Youd 1998).

- Other designations involving the "C" description, if the clay content is greater than 15 percent by weight and the liquid limit is greater than 35 percent and occurs at natural water contents lower than 90 percent (Wang, 1979), can be considered nonliquefiable.

The discussion also notes that gravelly soils are potentially vulnerable to liquefaction and that most liquefaction risk is associated with Holocene deposits and uncompacted fills; however, a few cases of liquefaction have been observed in Pleistocene and Pre-Pleistocene deposits. Some soils considered nonliquefiable according to the criteria presented in the regulatory discussion may be susceptible to liquefaction according to criteria proposed by Seed et al. (2003) and Bray and Sancio (2006). Work is in progress to update Regulatory Guide 1.198. This update will result in modifications to the discussion on liquefaction susceptibility.

There is potential for the NRC to support liquefaction susceptibility research. The NRC provides research grants to develop a workforce capable of supporting the design, construction, operation, and regulation of nuclear facilities. Recently, the emphasis of research supported by grants has been activities relevant to civilian advanced nuclear reactors. Research areas of interests include evaluating technical gaps and major uncertainties in assessing risk for advanced reactors and characterizing low frequency, high consequence natural hazards for advanced nuclear application. Some key information on the grants program from 2022 includes the following. The notice of funding opportunity for research and development grants was issued in February 2022 with a closing date in April 2022. These grants have a project period of performance of three years and an award ceiling of $500,000. Grant applications can be submitted by U.S. public or private institutions of higher education, and all graduate students, faculty, principal investigators, and co-principal investigators must meet U.S. citizenship requirements.

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INCORPORATING UNCERTAINTY IN SUSCEPTIBILITY CRITERIA INTO PROBABILISTIC LIQUEFACTION HAZARD ANALYSIS

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INTRODUCTION

Most conventional approaches for assessing liquefaction triggering hazards generally rely on simplified procedures that involve identifying liquefaction susceptible layers and calculating a factor of safety against liquefaction (FS_L) in each layer. Such procedures utilize deterministic semi-empirical models for standard penetration test (SPT), cone penetrometer test (CPT), or shear wave velocity (V_S)-based subsurface data. This general approach largely neglects considerable uncertainties in ground shaking, as well as aleatory variabilities and epistemic uncertainties inherent to liquefaction susceptibility and triggering prediction. A more robust methodology known as probabilistic liquefaction hazard analysis (PLHA), integrates the full ground motion hazard space with probabilistic forms of liquefaction triggering models (e.g., Boulanger & Idriss 2012) to compute of FS_L profiles with consistent return periods (e.g., Kramer 2008). Multiple PLHA computational platforms have been developed over the years, with the computational framework from Makdisi (2021) serving as the basis for a new Liquefaction Hazard Tool under development at the U.S. Geologic Survey (USGS).

Despite substantial improvements in recent years to the availability of seismic hazard data and probabilistic triggering and effects models, the issue of incorporating uncertainty in characterizing liquefaction susceptibility remains a challenge. Most compositional susceptibility criteria (i.e., whether the soil exhibits sand-like behavior) currently in use are presented as deterministic bounds based on *in situ* or laboratory test data; similarly, determination of soil saturation is often based on a single groundwater level from *in situ* testing. As a result, the same types of binary decisions must be made in PLHA as in more conventional methods. With the expansion and availability of field and laboratory data pertaining to liquefaction through resources such as the Next Generation Liquefaction (NGL) project, an improved set of susceptibility models may be possible for CPT, SPT, and V_s-based applications. Presented here is a brief discussion on how probabilistic susceptibility modeling can be accommodated in PLHA calculations, as well as how the use of multiple models can be leveraged within a logic tree to improve the representation of epistemic uncertainty in liquefaction hazard analysis.

USE OF PROBABILITY OF SUSCEPTIBILITY IN LIQUEFACTION ANALYSIS

The PLHA framework is based on calculating the annualized rate of non-exceedance of a given factor of safety value, Λ_{FS_L}, in a given soil layer, as follows:

$$\Lambda_{FS_L}(fs_L) = \sum_{j=1}^{N_m} \sum_{i=1}^{N_{pga}} \mathrm{P}\left[FS_L < fs_L \middle| susc, PGA_i, M_{w,j}\right] \cdot \mathrm{P}[susc] \cdot \Delta\lambda_{pga_i,m_{w,j}} \tag{1}$$

where PGA and M_w are peak ground acceleration and magnitude, respectively, and are utilized to represent the peak cyclic stress and the effects of loading duration on incremental pore pressure rise. $\Delta\lambda_{pga_i,m_{w,j}}$ is the incremental joint annualized rate of exceedance of *PGA* and M_w, which can be obtained by disaggregating the *PGA* hazard curve at a range of return periods. The probability of susceptibility term $\mathrm{P}[susc]$ involves the joint probability of the soil layer (1) exhibiting sand-like behavior and (2) existing below the groundwater table. However, current compositional and saturation susceptibility criteria are largely deterministic, and therefore $\mathrm{P}[susc]$ is generally implied to be either 0 or 1. Nevertheless, Equation (1) is formulated to accommodate uncertainties in susceptibility as probabilistic criteria are further developed and improved upon. The full PLHA calculation is repeated for a wide range of FS_L values, yielding a soil profile of FS_L non-exceedance hazard curves, from which FS_L profiles of uniform return periods can be extracted to estimate the consequences of liquefaction.

For the purposes of determining soil saturation, it is important to note that groundwater levels can vary over both seasonal and longer-term temporal scales. Shallower soil layers may see higher probabilities of saturation during periods of intense rainfall or due to sea-level rise, and lower probabilities occur during periods of drought. Greenfield and Grant (2020) found that groundwater level uncertainties can be important contributors to uncertainty in liquefaction potential at the regional scale, and that groundwater levels can be modeled as a normally distributed random variable. Groundwater estimates can also come from multiple sources, and site-specific measurements from SPT, CPT, or well data can be supplemented, where available, with regional-scale groundwater models to form a more complete picture of the saturation likelihood in a given soil layer.

Although most compositional criteria are not currently formulated or presented probabilistically, they do acknowledge a degree of uncertainty in the process. For SPT data, Bray and Sancio (2006) identified a zone of "moderately susceptible" materials in their laboratory test-based criteria, whereas Idriss and Boulanger (2008) supplemented their more conservative plasticity index-based (PI) recommendations with a transition zone between sand- and clay-like soils. Using visual approximation, Kramer (2008) quantified these transition zones and presented both criteria in terms of a susceptibility index that varies smoothly between 0 and 1. Such modifications allow for (1) a pseudo-probabilistic representation of the susceptibility that can serve as a starting point for more rigorous statistical models in the future, and (2) the incorporation of multiple models in the characterization of susceptibility criteria via a weighted logic tree, capturing a potentially important source of epistemic uncertainty in liquefaction hazard analysis.

Figure 1 introduces how such a set of susceptibility models could be implemented, along with multiple subsequent models for liquefaction triggering, in a logic tree similar to the approach utilized extensively in the USGS National Seismic Hazard Model (NSHM). FS_L hazard curves can be computed for each logic tree branch, and the overall mean non-exceedance rate of a given FS_L value is computed as the weighted mean of all branches. This framework also allows for FS_L hazard curve fractiles to be calculated to provide more information about the uncertainties surrounding the PLHA calculation. Logic trees are an important tool for uncertainty quantification and are as yet underutilized in liquefaction hazard analysis. Although the current slate of liquefaction models limits our ability to thoroughly quantify epistemic uncertainty in liquefaction-related problems, implementing the logic tree approach when possible is nonetheless important to both motivate and accommodate future expansion in liquefaction model availability in any PLHA framework.

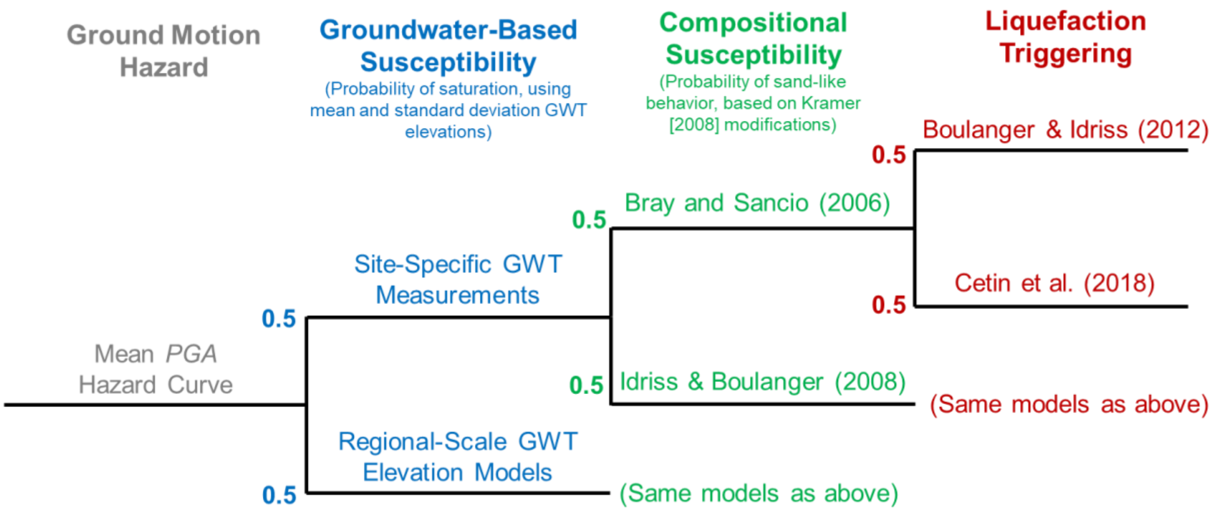

Figure 1. Example logic tree for computing liquefaction triggering hazard curves.

CONCLUDING REMARKS AND RECOMMENDATIONS

The PLHA framework presents an important opportunity to advance liquefaction hazard assessment in engineering practice. To make PLHA calculations more widely available to users, the USGS is developing a computational platform that reflects the best available data and models for capturing important aspects of uncertainty in both (1) ground shaking hazards and (2) liquefaction triggering and effects prediction. At the same time, there is clear and equally important need to formally quantify and incorporate uncertainties in liquefaction susceptibility in the PLHA framework. A simple modification to the classic PLHA equation was presented that accounts for the probability of susceptibility of a given soil layer, and a potential logic tree framework highlighting the need to capture both aleatory and epistemic uncertainty in liquefaction susceptibility characterization was discussed. The expansion of available data and models presents a clear roadmap for developing a new class of susceptibility models that can meet these needs.

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REGIONAL LIQUEFACTION SUSCEPTIBILITY ASSESSMENTS: DATA COLLECTION NEEDS AND A FOCUS ON THE CENTRAL AND EASTERN U.S.

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CURRENT STATE-OF-THE-PRACTICE AND LIMITATIONS

Liquefaction susceptibility assessments can be performed at the site-specific or regional scale. Site-specific assessments typically utilize quantitative methods that rely on geotechnical data from laboratory testing of soil samples retrieved in-situ (e.g., Bray & Sancio 2006; Boulanger & Idriss 2006). Regional assessments are generally more qualitative in nature and are based on factors that influence susceptibility such as groundwater level, geology and depositional environment, age of deposit, and fabric, or are based on applying site-specific methodologies at a regional scale (e.g., Youd & Perkins 1978; FEMA 2020).

Regional liquefaction susceptibility assessments are critical to improving the seismic resilience of communities and infrastructure systems across the country. However, there exists a technical gap between the detailed, quantitative site-specific studies carried out using laboratory testing data, and qualitative, often proxy-based, regional studies. This extended abstract discusses two aspects of regional susceptibility assessments: data collection needs to advance or improve existing assessment methods, and limitations in applying existing state-of-the-practice methods, with a focus on the Central and Eastern U.S. (CEUS).

DATA RESOURCES TO HELP IMPROVE UNDERSTANDING

Liquefaction susceptibility assessment methods are derived primarily from post-earthquake field case histories and laboratory testing. Case histories require an observation, a ground motion recording or estimate, and geotechnical data. However, immediately after an earthquake it is not feasible to visit and photograph the entire affected area in person, due to time and safety constraints. Developing the next generation of liquefaction susceptibility assessment methods, including quantitative regional assessment methods, requires regional data collection and selection of meaningful case history sites for detailed investigations. Extensive high-resolution aerial photography after an earthquake event can provide essential data needed to meet these goals. Consider the 2010-2011 Canterbury earthquake sequence (CES), which led to unprecedented research advances. Within two days after major earthquake events in the CES, the New Zealand government collected extensive aerial imagery throughout Christchurch and the surrounding communities. The imagery was then made publicly available, accessible via Google Earth, and maintained for over a decade following the events (NZGD 2022). Figure 1 shows the extent of aerial imagery coverage and the imagery resolution at the ground scale. Extensive regional coverage with high-resolution aerial imagery has enabled research investigations of CES post-earthquake observations to continue to this day.

In addition to providing regional coverage, extensive aerial imagery allows researchers to "revisit" sites years later and select critical, impactful case history sites for further investigation and collection of quantitative geotechnical data. This is especially important for selecting sites that perform well (i.e., where no ground failure is observed). For example, to investigate observations of "no liquefaction" at silty soil sites in Christchurch, over 30 candidate sites were initially selected and then narrowed down to 8 sites for development of detailed case histories (Beyzaei et al. 2018). High resolution aerial images across the region enabled a large pool of candidate sites from which the most impactful sites could be selected for further investigations. Aerial imagery of this extent ensures that the ephemeral data from post-event observations are not lost and can later be used for either regional or site-specific quantitative analysis.

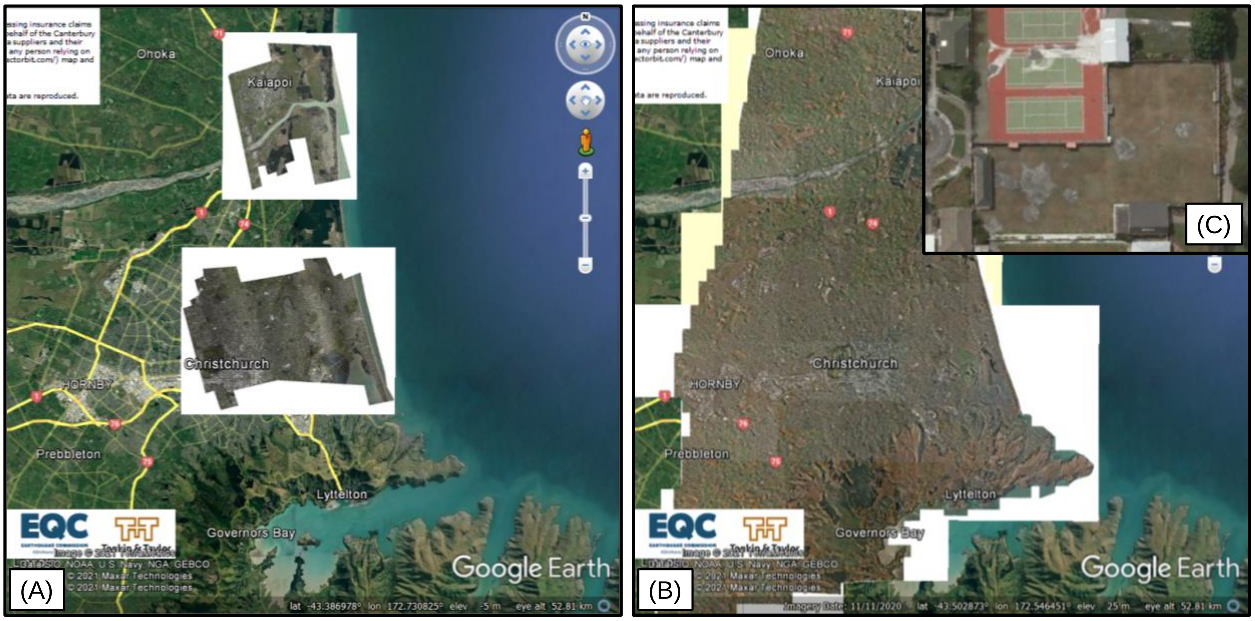

Figure 1. Extent of aerial imagery commissioned by the New Zealand Ministry of Civil Defence and Emergency Management: (A) 4 Sept 2010 Darfield earthquake, acquired on 5 Sept 2010; and (B) 22 Feb 2011 Christchurch earthquake, acquired on 24 Feb 2011 (NZGD 2022). (C) Inset showing resolution of imagery at the ground level.

CHALLENGES WITH CURRENT METHODS AND POTENTIAL CONSEQUENCES

Existing methods and proposed frameworks for regional liquefaction susceptibility assessments are typically based on examples from the Western U.S. and other areas of high seismic hazard. However, there are several challenges in applying existing assessment methods to the CEUS or other areas of low to moderate seismic hazard: 1) limited regional data availability (i.e., publicly available subsurface geotechnical and groundwater data), 2) practitioner and stakeholder liquefaction hazard awareness, and 3) fewer earthquake events leading to the perception of liquefaction hazard not being a "local" issue.

Improving practitioner and stakeholder awareness of liquefaction hazards and existing liquefaction susceptibility assessment methods should be a primary goal, alongside research, to advance technical knowledge and assessment models. Improving awareness and addressing the perception of liquefaction not being a "local" issue increases the opportunities for stakeholder buy-in and higher quality assessments in seismic or multi-hazard resilience planning.

It is critical to get stakeholders onboard now to start planning for climate change impacts affecting liquefaction susceptibility. Sea level rise has the potential to create larger or new areas of susceptible soils, with studies demonstrating the effects of sea level rise on liquefaction vulnerability for the Bay Area in California (USGS 2022) and Charleston, South Carolina (Ghanat 2021). A potential acute consequence of climate change impacts on liquefaction susceptibility is that a region becomes more vulnerable to liquefaction hazard due to sea level rise. In areas of low to moderate seismic hazard, if there is a lack of awareness or view that liquefaction is not a "local" problem, communities may not have mitigation strategies in place and are then unprepared when an earthquake occurs and damage ensues.

CONCLUDING REMARKS AND RECOMMENDATIONS

The next generation of liquefaction susceptibility models should close the gap between current state-of-practice quantitative site-specific methods and qualitative regional methods. Extensive aerial photography is key during post-earthquake reconnaissance and will allow for selection of impactful case histories in the years after an event. Limited regional data availability and practitioner and stakeholder awareness in low-to-moderate seismicity areas are challenges related to the use of existing methods.

ACKNOWLEDGEMENTS

Any opinions, findings, and conclusions or recommendations expressed in this extended abstract are those of the author and do not necessarily reflect the views of NIST.

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SHEAR WAVE VELOCITY SEISMIC SOIL LIQUEFACTION TRIGGERING ANALYSIS–2022 UPDATE

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THE CURRENT STATE-OF-THE-PRACTICE FOR V_S TRIGGERING ANALYSIS

The shear wave velocity (V_s) of soil is a means to assess the triggering of seismic soil liquefaction. Since the early 1990s, the size and quality of these data sets have grown enormously. Based on these expanding data sets, we have actively worked to develop probabilistic models for seismic soil liquefaction triggering using Bayesian analysis and system reliability methods. Critical elements of any update of these triggering analyses involve building a modern case-history catalog of legacy cases (e.g., Kayen et al. 2013 - KEA13) and inclusion of new case histories such as the 2011 M9.0 Tohoku earthquake, 2010-2011 New Zealand-Canterbury earthquake sequence, and other earthquake events less prominent in terms of Vs measurement.

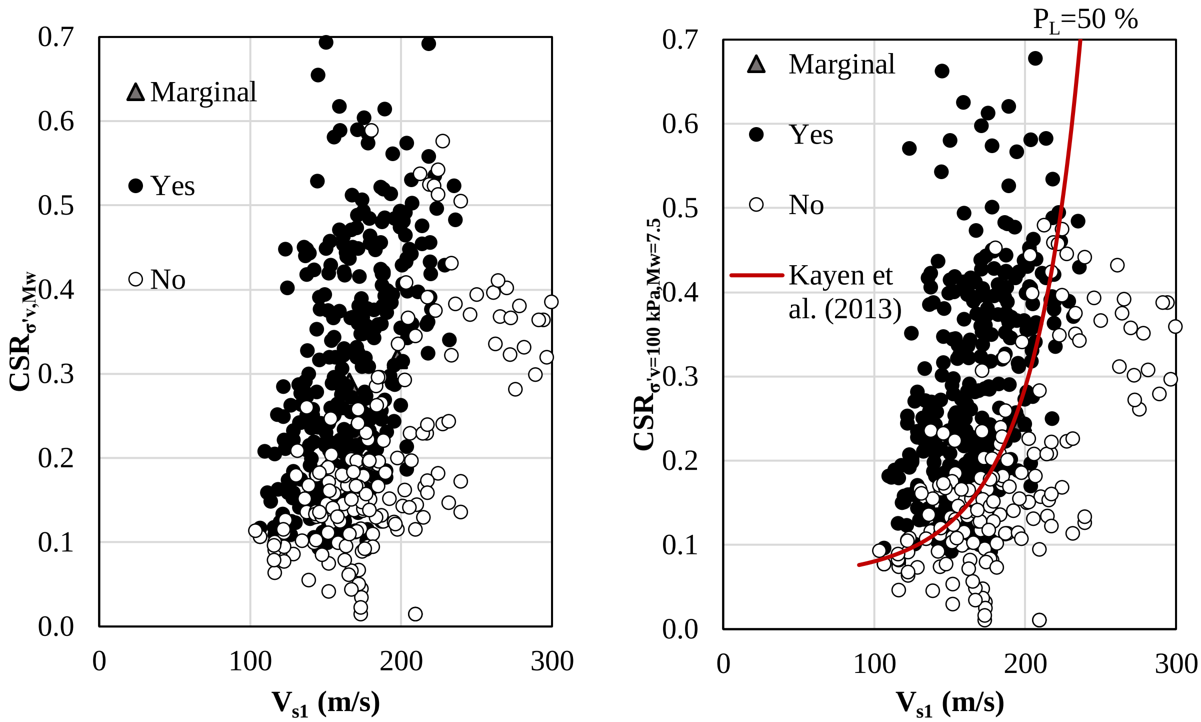
Our current 2022 efforts to update the V_s -based database require characterization of the mean and distributions of all relevant load and capacity parameters and understanding the locations, details, and statistics of each case. The updated database currently consists of 537 case histories (Table 1; Figure 1). When using surface wave data, we have computed averaged velocity profiles of the critical layers using multiple inversion methods applied to the dispersion data. We base the “Critical-layer” susceptibility determination on the analysis of nearby standard penetration test (SPT), cone penetration test (CPT) data, geologic textual information, and the characteristics of the V_s -profile. We digitized V_s profiles from the literature for legacy cases not collected by the authors. Considerable effort has gone into improving the selection of unit weight needed for computing effective and total stresses. One of the benefits of V_s analyses is that other parameters such as V_{s12m} and V_{s30m} are available to model the mass participation parameter r_d and site-specific response analyses. Toward this objective, we developed a standard protocol for processing data to minimize bias and measure the uncertainties of each input parameter.

Table 1. Distribution of earthquake events within the V_s database

Earthquake	# of sites	Earthquake	# of sites
1906 San Francisco	2	1989 Loma Prieta	49
1948 Fukui	11	1993 Hokkaido-Nansei-Oki	27
1964 Niigata	9	1993/1994 Kushiro-Oki/Kushiro	8
1968 Tokachi-Oki	4	1995 Hyogo-Nambu	83
1973 Miyagi-Ken Oki	11	1999 Chi-Chi, Taiwan	14
1975 Haicheng	5	1999 Izmit Earthquake	1
1976 Tangshan	24	2000 Tottori Seibu	3
1978 Miyagi-Ken Oki	8	2001 Geiyo-Hiroshima	5
1979 Imperial Valley	7	2002 Denali Fault	9
1980 Mid-Chiba	2	2005 Sanriku Minami	11
1981 Westmorland	7	2003 Tokachi-Oki	10
1983 Borah Peak	19	2003 Tokachi-Oki Aftershock	1
1983 Nihonhai-Chubu	8	2007 Niigata Chuetsu Oki	2
1983 Nihonhai-Chubu Aftershock	2	2008 Achaia-Elia	2
1986 Chiba-Ibaragi-Kenkyo	2	2010 Darfield	61
1986 Lotung Sequence	5	2010 Jiasian	1
1987 Chiba-Toho-Oki	1	2011 Christchurch	61
1987 Edgecumbe	2	2011 Tohoku	35
1987 Elmore Ranch	7	2011 Tohoku Aftershock	10
1987 Superstition Hills	7	2014 Napa Valley	1
Sum of V_s-based case history data: 537			

This dataset is used to assess the likelihood that a site tips towards liquefaction or away based on prior data and observations to estimate probabilities based on Bayesian inference. We establish a limit state function with initial conditions of mean values of the entire dataset and assess the likelihood of liquefaction occurrence by contrasting the individual site parameters with the prior dataset. An example of a limit state function for shear wave velocity assessment was presented in KEA13, KEA15 and is shown below (Equation 1). The parameters (e.g., a_{max}, V_s, M_w, σ'_v, r_d, etc.) are measured properties of load or capacity, and the Theta's (Θ_1, Θ_2, etc.) are the coefficients modeled through Bayesian analysis.

$$g_{V_{s1}} = \Theta_1 V_{s1}^{\Theta_2} + \Theta_3 ln(CSR) + \Theta_4 ln(M_w) + \Theta_5 ln(\sigma'_v) + \Theta_6 FC + \varepsilon \quad (1)$$



(a) (b)

Figure 1. 2022 V_s-based case history database (Effective stress-normalized velocity, V_{s1} versus magnitude and effective stress normalized cyclic stress ratio, $CSR_{\sigma'v,Mw}$ domain), b) on V_{s1} versus $CSR_{\sigma'v=100\ kPa,Mw=7.5}$ along with Kayen et al. (2013) Fifty-percent Probability of Liquefaction, P_L=50% curve. (dots, circles, and triangles represent liquefied, non-liquefied, and marginal sites, respectively.)

ACKNOWLEDGEMENTS

This research was funded by the TUBITAK 2214-A International Research Fellowship Program for Ph.D. students. Financial support was provided through the United States Geological Survey (USGS), Pacific Earthquake Engineering Research (PEER) Center's Lifelines Program, and Research Center for Urban Safety and Security, Kobe University.

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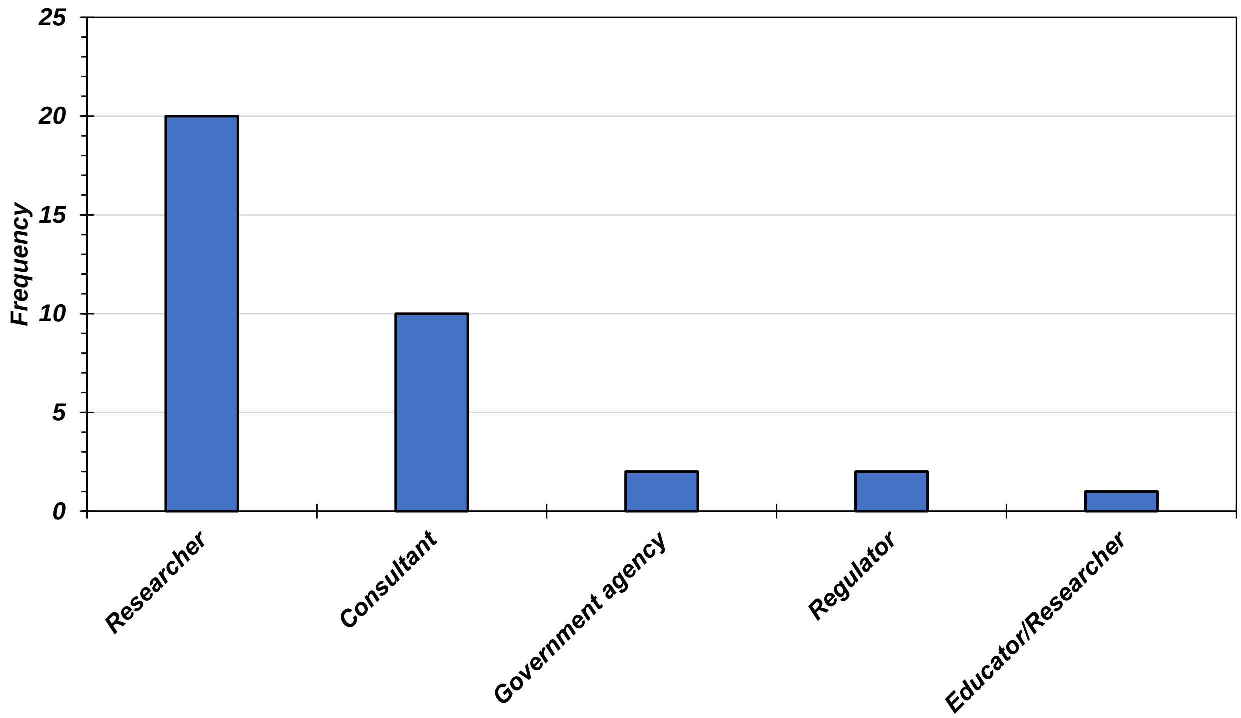
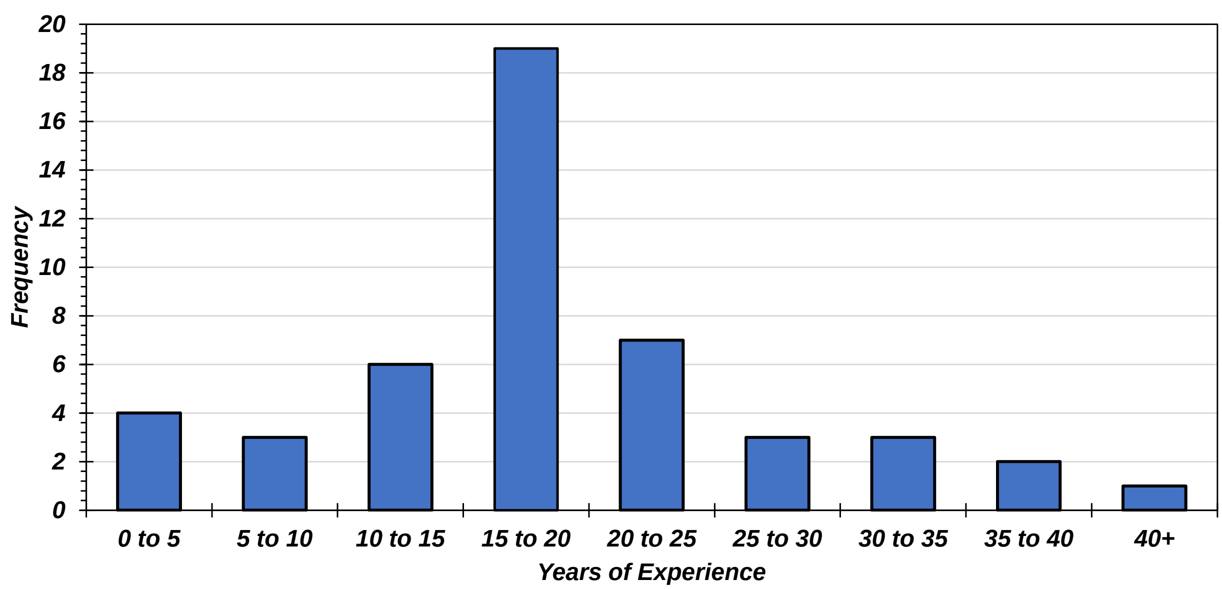
APPENDIX C: PRE-WORKSHOP POLL RESULTS

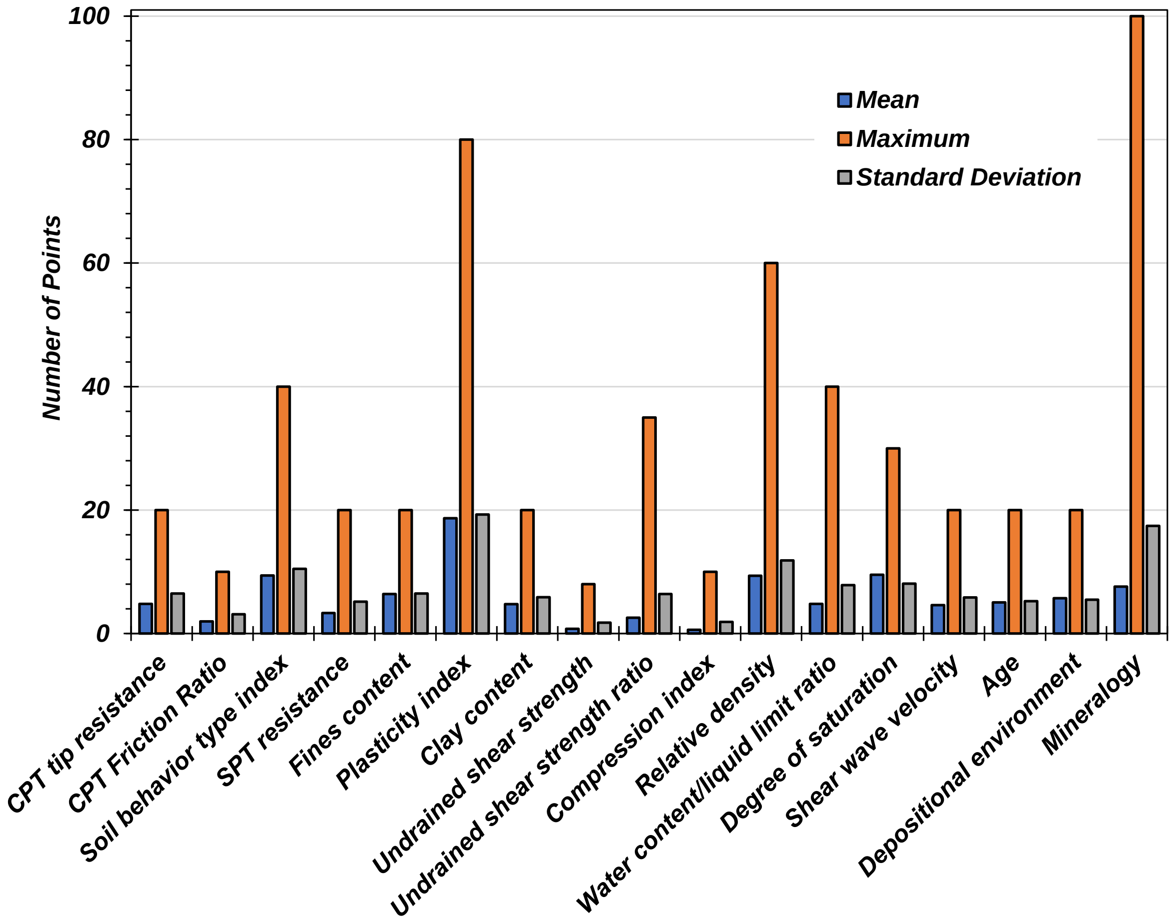
Question 1 – Please indicate your primary roll:



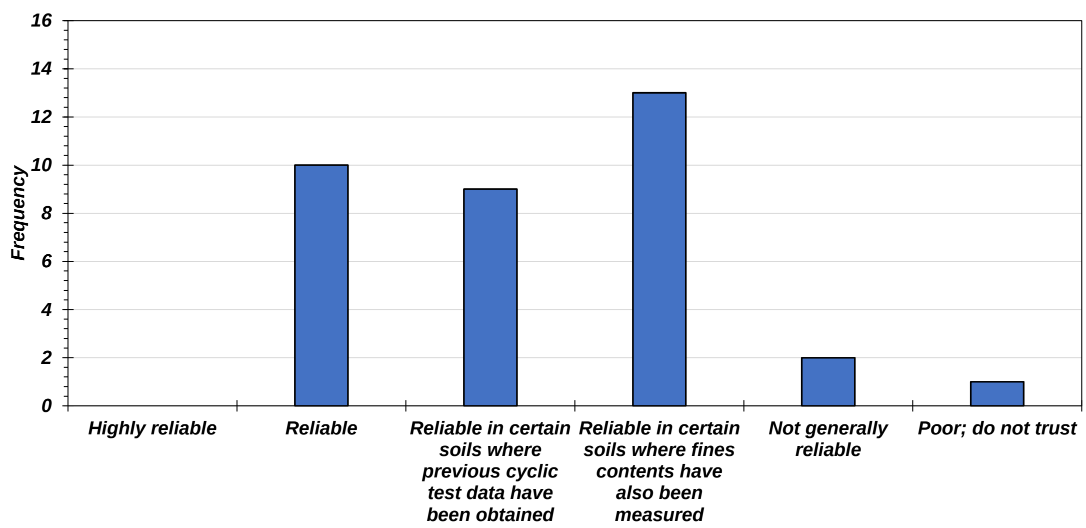
Question 2 – Please indicate your years of experience:



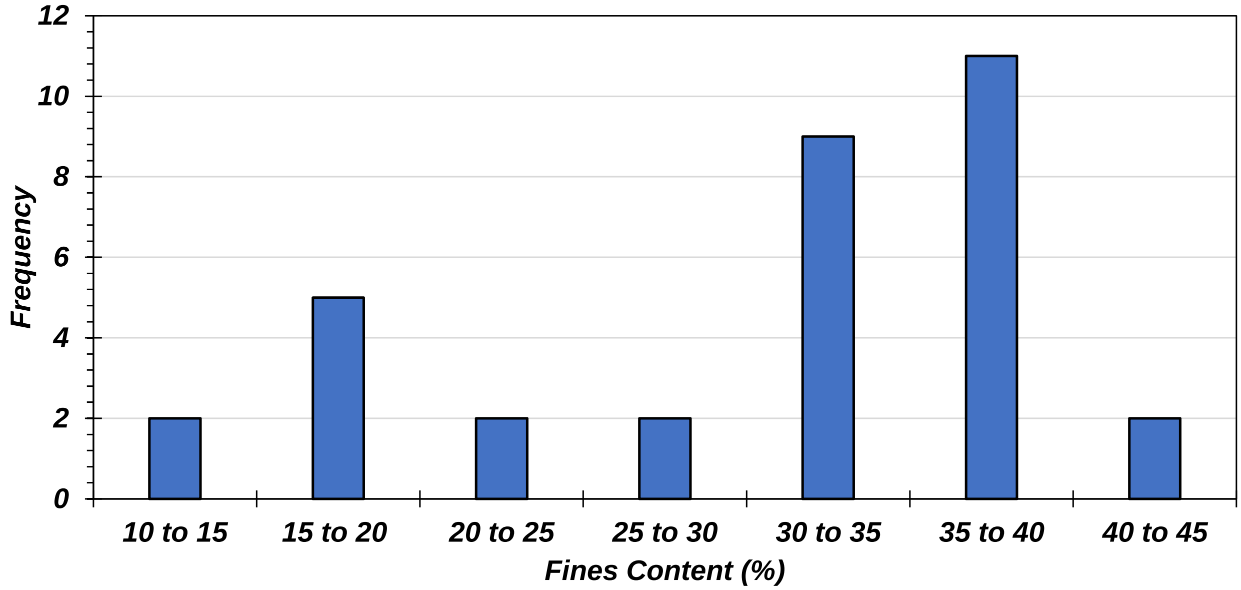
Question 3 – Please distribute 100 points to the following quantities according to their influence on a soil's liquefaction susceptibility, with zero corresponding to no influence and greater points corresponding to greater influence:



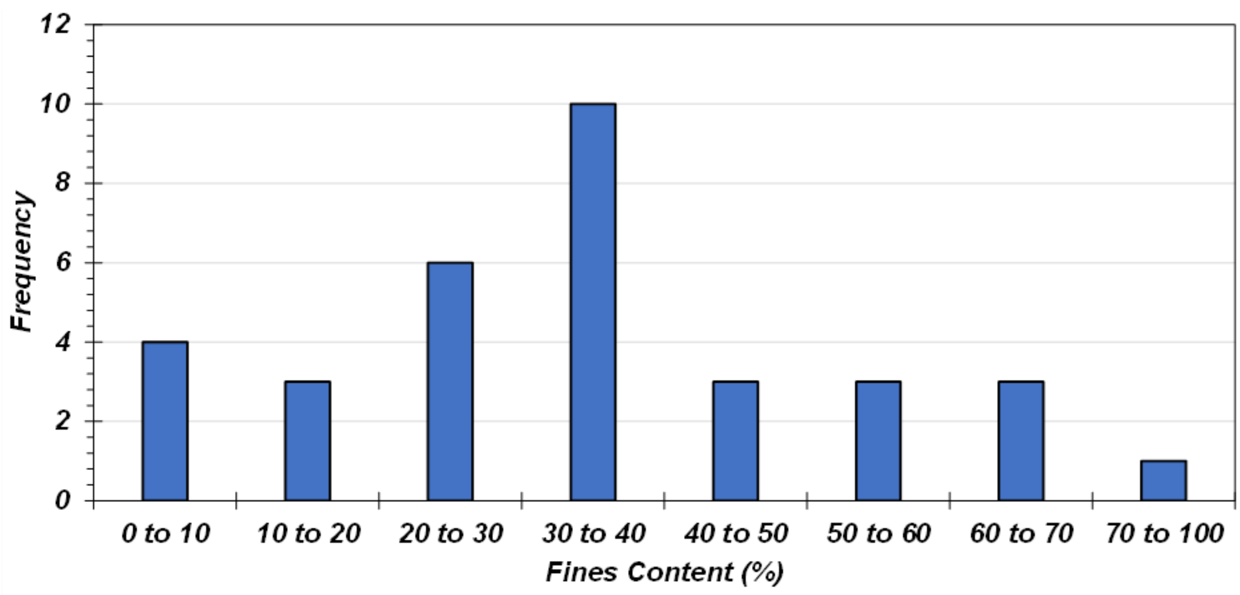
Question 4 – How do you rate the reliability of cone penetration test-based liquefaction-susceptibility interpretations, e.g., using the Soil Behavior Type Index, I_c? (choose one)



Question 5 - Above what fines content do you consider soil behavior to be controlled by the characteristics of fines (please report as percent)?



Question 6 – At what minimum fines content do you believe good quality undisturbed samples can be obtained (please report as percent)?



Question 7 – How do you judge the susceptibility of interbedded soils?

1. Having an understanding of the depositional history, age and historical performance is of outmost importance.
2. Depends on the thickness of the interbeds.
3. Carefully.
4. Depends on thickness of beds.
5. Combination of grain-size and Atterberg characteristics, blow counts, strength, and stress history of soil profile are used. Where the surrounding soils have lower strength and have physical characteristics of susceptible soils then they are considered susceptible and softening and strength loss are expected.
6. It depends, but typically would consider the susceptibility of the different interbedded layers (if samples can be obtained from individual layers) and the nature of the overall interbedding sequence at the site with depth and relative to the groundwater table/zone of partial saturation.
7. I would evaluate susceptibility based on soil characteristics independent of interbedding; however, I believe interbedding would have a significant impact on system response.
8. Depends on the depositional and stratigraphic conditions (layer thickness/length), and consequences of failure. If applicable, use in-situ testing tools and assess susceptibility using engineering correlations.
9. Through use of CPT measurements and SPTs, if possible.
10. Cyclic shear.
11. With and without corrections, i.e. sensitivity to modeling.
12. If we simply talk about susceptibility (intrinsic soil characteristics which do not have anything to do with the current soil conditions (e.g., Dr or water content are not descriptive of susceptibility), I do not see any differences in evaluating susceptibility of a single layer in a homogeneous profile vs that of a layer within an interbedded soil. My opinion is different if we talk about thinly-interbedded soils. For these kind of soils, I do not know whether we can consider a portion of the soil as the mixture of soils part of various interbedded layers.
13. Focus on what appears to be the most continuous soil units, work with geologists to get an understanding of the geologic environment (i.e. 3D continuity, is an interbedded unit an old meandering stream channel), understand the gradation of soil materials (fines and gravel content) and how

they differ from and might be influenced by other beds (will other beds liquefy, help dissipate pressure, etc.).

14. Need to start with high-quality continuous sampling to determine thickness and frequency of interbedding. Then, most likely need to perform effective stress modeling of the layered system. Or, live with conservative predictions (i.e., over-prediction of susceptibility and consequences) based on CPT.
15. Careful sampling and cyclic testing of clearly differing interbeds without mixing of differentiable units; specimens must be uniform w/r/t the interbed in question. How the "system" of interbeds responds is a question of triggering.
16. "Undisturbed" samples to see the stratification then effective stress modeling.
17. Based on the spatial continuity of susceptible layers and evaluation of dominant characteristics of the deposit.
18. Depends on how thinly interbedded.... potentially the same as non interbedded soils.
19. Evaluate the thickness of each soil layer to identify the predominant soil unit and drainage paths to assess the overall behavior of the interbedded soils.
20. Based on the thicknesses of the respective liquefiable and nonliquefiable layers.
21. I have not had a chance to do this in practice, but I think I would do cyclic lab testing if at all possible.
22. I view susceptibility as a material characteristic, so I would tend to judge the susceptibility of the individual materials separately. The interbeddedness would affect triggering to some degree and consequences to probably a greater degree.
23. They are susceptible but different than clean saturated sands.
24. I generally don't expect highly interbedded soils to liquefy in an appreciable manner, at least not such that we would see surface manifestation effects.
25. CPT with layer adjustments when layers are thick enough for representative assessment, otherwise generalized, "homogenized" soil approximation with sensitivity evaluation.
26. I focus on the weakest susceptible layers that are over 0.5m thick.
27. I think you need to first define "susceptibility." If you have interbedded soils, some layers will be susceptible and others won't be susceptible. I would look at the PI of the various layers as a preliminary way to assess their susceptibility.
28. I would judge susceptibility using the granular fraction and consider the interbedding in separate analyses of manifestation.

29. Use CPT, get undisturbed or at least sonic samples, consider the layer thickness, relative presence of fine-grained soil layers against coarse-grained, if possible do some cyclic shear testing.
30. Interbedded soils are often mixed together during sampling. If this does not occur, I would recommend testing the individual soil types within the sample separately.
31. It depends on the nature of the interbedding, and the assumed "homogenous" behavior of the soil. If the interbedded materials should be liquefiable in other conditions, or if the interbedding wouldn't significant improve the drainage characteristics we treat the soils as liquefiable.

Question 8 – What are the main limitations of the state-of-the-practice with respect to liquefaction susceptibility assessment?

1. Assessment of transitional fine-grained soils.

   Lack of methods to assess liquefaction susceptibility for soils that are not quartz sands (in particular fine-grained soils); and, lack of methods for post-liquefaction hazard assessment (volumetric strain, shear strength, lateral deformation) for fine-grained soils.
2. Too reliant on CPTs alone.
3. Having a consensus on the approach. Lack of a unified theory that links pore-pressure generation, liquefaction, strength/stiffness reduction, and volumetric strain for all soil (sands, silts, clays). Susceptibility and affects of liquefaction at depths greater than 60-80 ft.
4. Soil layer variability and geologic details.
5. Lack of site specific testing, large variations in state of practice, conservative use of sand trends regardless of soil type.
6. For silts, it can be challenging to have enough explorations, basic sampling testing, and cyclic testing to provide a 3D interpretation of the site such that the extent of susceptible soils can be distinguished. For sands with high fines or plastic fines, it can be challenging to obtain samples for cyclic testing so cyclic behavior can be observed.
7. Hard boundaries for soils we know to have transitional behavior. Relatively small number of in-situ samples that can reasonably be collected relative to the size of a site.
8. We have not quantified uncertainty in our susceptibility evaluation procedures.
9. The community's understanding of the effects of non-zero mean static shear stress, effect of fines, ageing effects.

10. High initial static shear stress and overburden pressures.
11. Research that established susceptibility assessment is generally on "ideal" sands.
12. Complex mixtures (fills); silty soils, relatively wide "gray zone" of soils with transitional behaviour, and lack of comprehensive measures (combination of parameters).
13. The main issue is that we have a boolean approach: (1) soil is susceptible to liquefaction, (2) soil is not susceptible to liquefaction (in which case we expect soil as behaving as a clay-like material and cyclic softening might become an issue that is dealt with separately). Also, there is some confusion (no general agreement) on what "susceptibility" means: soil intrinsic characteristics vs. soil characteristics + current condition. With latter being a mix of susceptibility and triggering.
14. Lack of clarity in dealing with transitional soils and identifying where soils are fines-controlled vs. not. Additionally, lack of clarity on specifically how gradation (coefficient of uniformity) might impact susceptibility.
15. The simplified CPT, SPT and Vs procedures all work quite well for young, clean sand deposits. There are still a lot of questions about susceptibility of interbedded soils, soils with low-to-moderate plasticity, soils with micro-structure due to aging or slight cementation, etc.
16. The source data underpinning the two most common liquefaction susceptibility criteria (B&I 2006; B&S 2006) is relatively low. Since mineralogy and deposition environment/time-dependent processes may affect susceptibility, the databases needed to test these criteria need to be expanded significantly.
17. Delineation of fines-controlled is broader in my opinion than current thresholds typically used in practice. Characterization of deep deposits.
18. (1) Different lab criterion used by different people, (2) Inefficiency of field measurements (e.g., Ic) in relation to lab-based criterion.
19. The lack of case histories for interbedded soils, transitional soils and potentially liquefiable soils at greater depth to validate the mechanics-based approach developed based on centrifuge and laboratory testing.
20. Lack of understanding of the role of compressibility.
21. Currently there's little consensus about what is meant by liquefaction susceptibility and each model inherently means something different. There are also a lot of uncertainties that are relatively undefined at present.
22. Cost of sampling to obtain plasticity index. In cases where only CPT is used, lack of certainty about relationship between parameters like Ic, IB, etc. and

susceptibility and obtaining reliable values of those parameters for thin layers or interbedded profiles.

23. So far a lot of what we know is based on clean saturated sands. Only recently there has been serious work using intermediate soils.
24. We don't have a good sense of the uncertainties inherent to susceptibility characterization, we don't have that many different criteria, and CPT-based criteria are quite simplistic.
25. (1) Assessment of Transitional Soils, especially with respect to cyclic/post-cyclic behavior at the benchmark, Reference Shear Strain of 3.0% to 3.75% developed for sand-like soil, and (2) Unresolved uncertainties in Ru estimation at depth greater than roughly 75 ft (i.e., influence of confining stress, aging, etc.).
26. Linking lab testing to field testing.
27. The ambiguity in what is being referred to as "susceptibility" is the most significant limitation of current susceptibility criteria.
28. Over-reliance on two legacy methods. Poor understanding of the proper definition of "susceptibility."
29. Not considering how difficult it is to get the void ratio right but still estimating state parameter to high accuracy, not accounting for particle fabric, not accounting for principal stress rotation.
30. It's not clear what susceptibility means sometimes. In my opinion, susceptibility is a compositional feature of soil. Soil that is not susceptible to liquefaction will not liquefy no matter how strongly it is shaken. Soil that is susceptible to liquefaction will liquefy if shaken strongly enough. I think there may be too much reliance upon soil behavior type index, Ic, on assessing susceptibility without adequate consideration given to the uncertainty in the relationship between Ic and plasticity characteristics.
31. Capturing the system response of the soils, and behavior of liquefied soils on structures at depth.

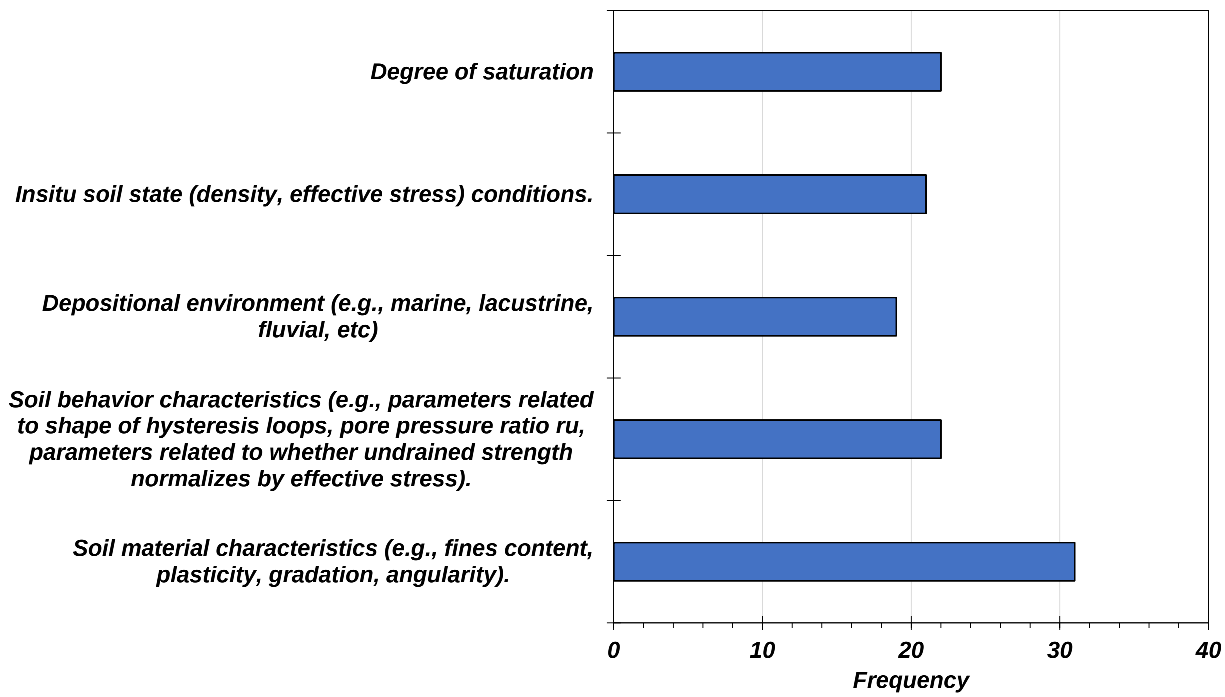
Question 9 – What soil conditions are particularly problematic for diagnosing liquefaction susceptibility, given the state-of-the-practice?

1. Transitional fine-grained soils.
2. Thinly interbedded soils with clay content in the low teens.
3. Soils deeper than 60-80 ft. Silty soil, especially low/non plastic silt.
4. Non-ideal soils (e.g., non-quartz, soils with mica, aged soils).
5. Silts.

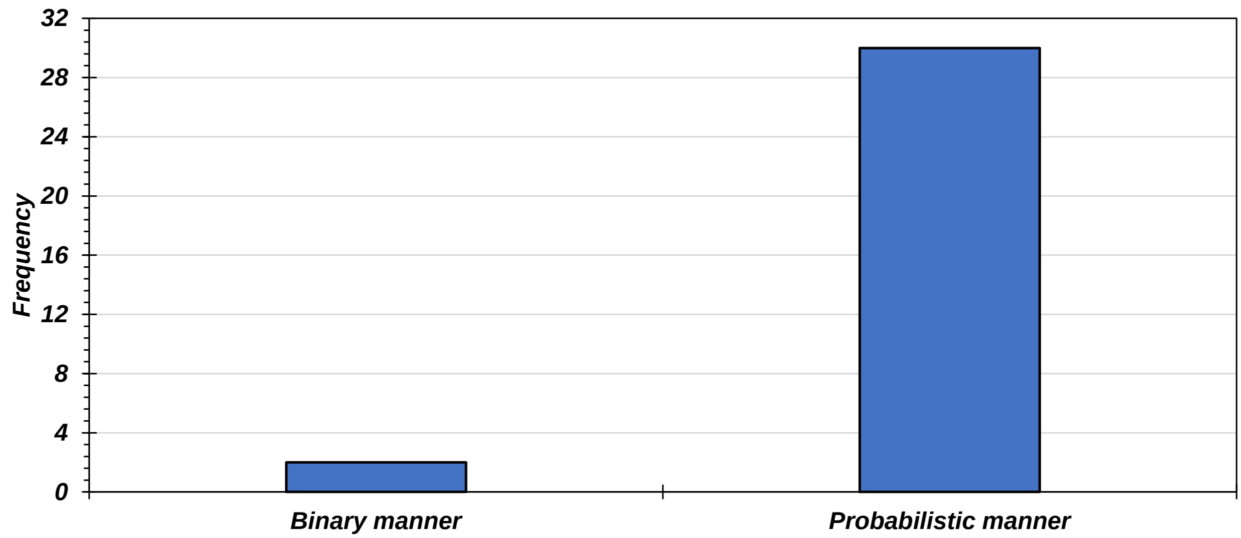
6. Fluvial environments that have varying deposition resulting in complex distributions of PI and fines content that exploration tools such as CPT cannot distinguish.
7. Interbedded soils, partially saturated soils, deposits with fines contents in the transitional range of 15-35% and plasticity indices in the range of 5-15.
8. Mid-range fines content (20 to 50%) with plasticity indices on the order of 8 to 12.
9. Intermediate Soils.
10. Soils with smaller PIs (4-7), soil with gravel contents.
11. Sands with micro-structure and cementation that may undergo cyclic softening rather than flow liquefaction.
12. Thinly interbedded deposits, crushable soils, soils at the threshold between susceptible and not-susceptible to liquefaction.
13. Intermediate plasticity soils and thinly-interbedded soils.
14. The most difficult soils conditions we see related to soils with gravel contents greater than around 10% and with appreciable size. They make gathering samples difficult. We especially find soils that are broadly graded with F/S/G contents nearly evenly distributed (33,33,33) or even if gravels are lower but sized bigger. It again gets to what defines the matrix and limited understanding of gravel liquefaction, especially as gravel contents and size increase (and Cu perhaps gets lower). Currently, it seems "susceptibility" is more on focusing on whether they may trigger or not... i.e. assume they are susceptible and then determine whether they might trigger, which has its own issues.
15. As noted above; interbedded soils, soils with low-to-moderate plasticity, and soils with micro-structure due to aging or slight cementation.
16. Clayey sands and low plasticity silts.
17. Low plasticity silts, low-plasticity fines with FC of 20-45%, finely interbedded deposits, soils at high confinements.
18. Those near the sand-like vs. clay-like boundary, and highly interbedded soils.
19. Transitional and interbedded soils, especially at depth deeper than 60 to 80 feet.
20. Layered nonplastic to low plasticity soils.
21. Transitional soils, highly interbedded and loosely characterized (i.e., sites with only CPT data that rely entirely on correlations with CPT data to determine susceptibility, which have significant uncertainty).

22. Soils of intermediate plasticity. Profiles with thin or interbedded layers (difficult to obtain reliable CPT-based susceptibility parameters).
23. Intermediate soils.
24. Interbedded and transitional soils.
25. Soils that are not similar to the clean sands on which most of the lab-based research has been based. On project applications, regional "unique" soils are routinely problematic due to inherent differences in composition, structure, and cyclic behavior. Examples include; (i) high carbonate, shell-rich or coralline sand, (ii) mine tailings, (iii) Transitional, Intermediate soil, and (iv) sand-gravel mixtures.
26. Silty interbedded layers.
27. Clayey sands with low PI.
28. Materials of high fines content and marginal plasticity, PI =4-12.
29. Gravels, silts, medium density soils.
30. Sand with non-susceptible plastic fines is a tough one. I'm talking about sand-dominated matrix soils here, so less than 35% fines. Another huge problem is the fines correction applied to susceptible fine-grained soils. But this is not a susceptibility problem, but rather an assessment of whether a susceptible fine-grained soil will or will not liquefy under a specified loading condition.
31. Capturing non-homogenous soil profiles, particularly when the soil profile is very deep. Additionally, assessing whether partial saturation is a long term reliable marker for an increased CRR.

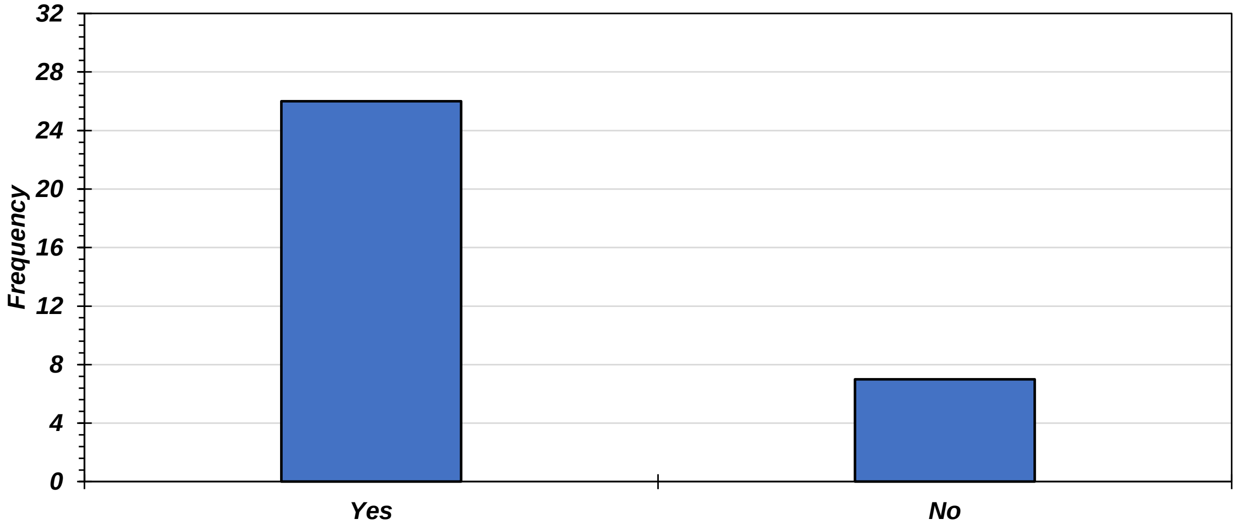
Question 10 – Which factors should susceptibility be related to (check all that apply)?



Question 11 – Should susceptibility be designated in a binary (yes/no) manner or probabilistically?



Question 12 – Should geologic information be quantified and used in liquefaction susceptibility assessment?



Question 13 – How can geologic information be used in liquefaction susceptibility assessment?

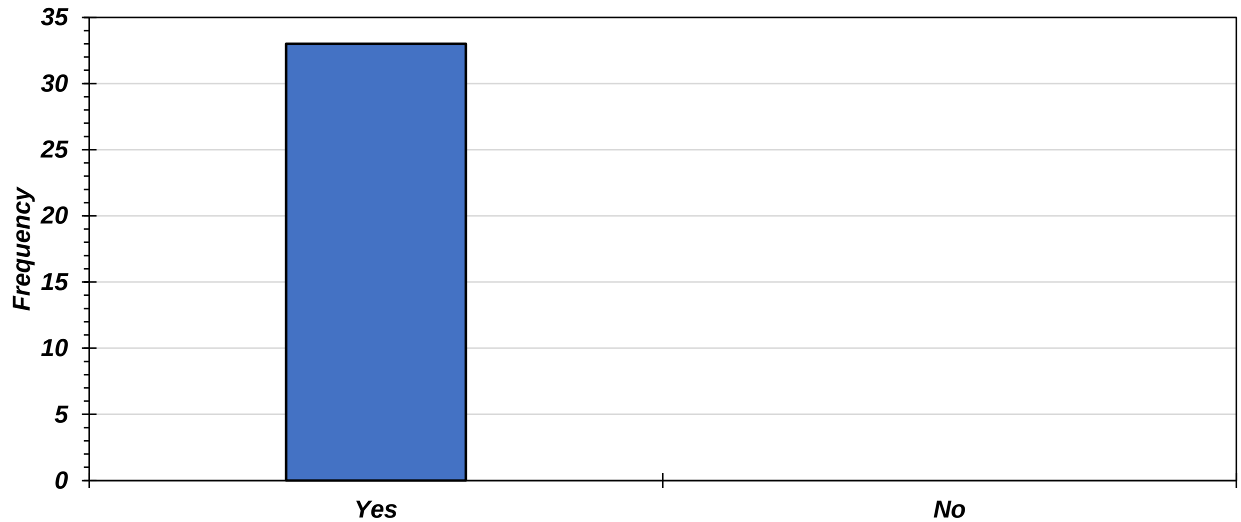
1. Evaluation of stratigraphic continuity and variability to assess the extent of liquefiable soils and liquefaction hazard; and guiding site exploration programs.
2. To assess if additional advanced sampling and laboratory testing would be required to understand liquefaction potential.
3. Depositional environment.
4. Generally no unless site specific testing is incorporated.
5. Known and commonly encountered geologic formations could be researched with high quality testing not feasible for single projects.
6. Best used in regional assessments or areas where in-situ testing is not available or feasible. Type and age of the deposit can be used, and through new case histories with improved regional data collection perhaps more granularity on "type" of deposit (or types of deposits in different parts of the world) can be achieved.
7. I anticipate that geologic information can be incorporated into a statistical regression relationship or qualitatively.
8. By including geologic information the community would have a stronger understanding depositional conditions, mean layer thicknesses/lengths, paleoliquefaction, age.

9. The age of the deposit, how many earthquakes the deposit has experienced, depositional environment in terms of small layers and energy of deposition and mineralogy.
10. Old, cemented sands are less likely to undergo liquefaction.
11. Source, formation and structure of the deposit (macro and micro stratification).
12. Not sure.
13. Geologic information is useful for understanding the geomorphology for a site. In practice, consultants and engineers are often limited by resources to 2D models of their sites. Incorporating and understanding how the geology of a site into their models may help where units might appear to be discontinuous but could be a meandering stream bed. Geologic processes and general understanding can be utilized stochastically, and in combination of data over a site to understand what the statistics might mean. I'd note that straight up probabilistic based evaluations are often impacted by biases resulting from poor data, which we often see in gravel particles impacting data.
14. Generally, to improve liquefaction hazard maps; to understand how mineralogy affects susceptibility; to date soil deposits and assess aging/geochemical processes.
15. In a similar manner as different fault-mechanisms are used in crustal GMPE's as a binary term that increases or decreases the probability of liquefaction susceptibility given other relevant soil information.
16. As a very preliminary screening tool, or to bin field-lab susceptibility correlations on geologic units... I don't think it's of much quantitative use, per se.
17. Geologic information should be used to assist in judging if the liquefaction analysis results are reasonable.
18. Quantifying depositional energy.
19. I am not currently sure how this information can or should be used, but it seems reasonable to me that if it could be used then it might help constrain some of the uncertainty currently in susceptibility models.
20. Not sure, other than by crude correlation to nearby tested material. Factors like age are triggering factors, to me.
21. Depositional history can have an effect on liquefaction susceptibility.
22. Essentially as a "prior", i.e. before we even poke holes in the ground. This could be achieved using geospatial models for probability of susceptibility (similar to Zhu et al.'s global model for liquefaction probability), and could be

a useful way to blend regional and site-specific data in assessing liquefaction potential.

23. Empirically-based scaling factors have been used in several regions to account for the influence of various geologic influencing parameters (e.g., age, cementation, depositional environment). This has been a worthwhile start; however, quantification by way of correlation with geotechnical and geophysical parameters seems warranted.
24. Depositional environment and ageing are key in understanding a soil's susceptibility.
25. Sampling will always be limited. Knowing the depositional environment of the profile allows you to extrapolate the properties of the sample laterally and vertically.
26. Depositional environment could be useful - soils deposited in quiet environments (lakes, bays) are likely fine-grained and non-susceptible. Soils deposited in relatively rapid-flow fluvial environments are more likely to be liquefiable.
27. Determine age, layering, expected fabric.
28. Paleoliquefaction studies could be used to assess whether a marginally susceptible soil has exhibited evidence of liquefaction in past earthquakes. Geology may also be used to assess conditions where soils may be susceptible, not-susceptible, or marginal.

Question 14 – Should advanced laboratory testing (e.g., cyclic simple shear, cyclic triaxial) be used to aid liquefaction susceptibility assessment?



Question 15 – How should advanced laboratory testing (e.g., test type: monotonic, cyclic; specimen types: reconstituted, intact) be used in assessment of liquefaction susceptibility?

1. Need to know OCR. DSS for fine grained soils.
2. Evaluating cyclic strength and hazard for soils where high-quality samples can be obtained.
3. As long as we can have "undisturbed" sampling, cyclic testing on the material in question will provide a better understanding of behavior.
4. Test results provide insight in terms of the shear stress vs. shear strain response of soil and the movement of water within the soil deposit.
5. Intact monotonic and cyclic DSS.
6. Cyclic testing of undisturbed samples can be used to establish cyclic behavior for the range of possible ground motions.
7. Cyclic testing should be used in conjunction with field observations to advance state of knowledge and assessment models, and also used in practice for soils that are not well understood or analyzed using currently available methods. Intact specimens are far preferable to reconstituted specimens for this type of testing.
8. A combination of monotonic and cyclic testing can be used to demonstrate whether the soil behavior will be sand like vs clay like. I think this type of testing is applicable for critical infrastructure projects and research efforts to develop more simplified relationships for use in general geotechnical engineering practice.
9. Laboratory testing can help check or refine correlations for site specific conditions. For in-situ conditions that are on the border line of liquefaction, testing can help confirm predicted soil behaviors.
10. Intact samples are preferred but reconstituted might be useful. Cyclic tests (DSS) would be most useful.
11. Cyclic simple shear.
12. Details of stress-strain behaviour can help to discriminate between susceptible, not-susceptible and transitional soils. Intact specimens are the best choice; reconstituted could be also useful for susceptibility assessment (it depends on the soil characteristics).
13. They would help designing a model. I do not expect models needing advanced laboratory testing to define susceptibility as this would defeat the purpose of having a simple screening criterion/criteria.
14. I will say that advanced laboratory testing should be used to help supplement research data. In practice, most consultants and projects are resource limited

to monotonic testing, while cyclic softening to fill in research gaps at an academic level could help bridge and relate susceptibility to more accessible test types in practice (or other parameters). In practice, it is also extremely challenging to get intact samples, yet those are of most concern at dam sites.

15. Given that we cannot sample and place "undisturbed" specimens of liquefiable-type soils in testing devices, cyclic laboratory testing is primarily valuable for parametric studies and/or for calibrating cyclic response of constitutive models. I do not believe we can accurately evaluate in-situ liquefaction in absolute terms from laboratory testing.

16. In my opinion, the single most reliable means to assess liquefaction susceptibility is to perform cyclic testing. Since cyclic triaxial testing provides the wrong stress path and is biased in extension, the cyclic direct simple shear test is the most appropriate, accessible laboratory test which can establish the potential for transient loss of shear stiffness and excess pore pressure generation potential. Such tests should be accompanied by grain size analysis, Atterberg limits, water content, and overconsolidation ratio in order to understand how the specimen(s) maps to the deposit.

17. Cyclic tests on intact specimens when possible. Reconstituted cyclic tests may be OK to identify general behavior with an appropriately extensive lab program.

18. The key is not whether testing would be useful, but how to incentivize/require it on routine (or not so routine) projects. If very few people are willing to pay for it, this discussion isn't very purposeful. The incentive should be worked out before the specific test details.

19. The advanced lab testing should be used to inform the susceptibility of transitional and sandy soils at depth greater than 40 feet.

20. Reconstituted first to develop a framework and then undisturbed to validate the framework.

21. I think there are aspects to be learned from all types listed in the question. Pros and cons for each specimen type and lab type, but together they may provide sufficient insights to assess susceptibility in challenging soils.

22. Get the best samples possible with the soil type of interest. If good intact samples are not possible, reconstitute in manner that approximates actual depositional processes. Examine shapes of hysteresis loops, highest ru achieved, tendency for dilation upon phase transformation, rate of stiffening upon dilation.

23. Absolutely much more testing using different lab techniques, following different stress paths.

24. First, the use of the term "advanced laboratory testing" requires explicit definition. What specific types of cyclic tests are being referred to as advanced? For example, TX and CycDSS are not considered "advanced" methods of testing and should be treated as routine supplements to a well-planned geotech investigation for soil-types that can be sample with minimal disturbance or for which testing of reconstituted specimens can provide representative behavior. For sand-like soil, lab testing would continued to be viewed as a supplement to, not in lieu of, standard simplified procedures. Also, cyclic testing may be required for the calibration of constitutive models such as PM4Sand. This latter consideration is too often overlooked in practice.
25. By isolating specific variables and assessing their relative contribution.
26. Liquefaction triggering inherently involves the breakdown of the soil skeleton and the transfer of the overburden stress to the pore fluid. As the PI of the soil increases, bonded water fills a larger percentage of the voids, preventing the soil skeleton from collapsing (i.e., bonded water results in the soil to behave more viscously - clay-like behavior) when subjected to cyclic loading. So, cyclic tests are useful in assessing the liquefaction susceptibility of a soil.
27. Identify metrics that indicate soil behavior, which could be max ru, relative tangent moduli at small and large strains, or degree to which undrained strength normalizes. Related those metrics to susceptibilty, through research in the NGL project.
28. Consider all of the above and decide on what is the best approach.
29. Atterberg limits should be performed first. Monotonic strength and consolidation testing can be performed to assess whether the normal consolidation line and critical state line are straight and parallel, which is an indication of clay-like behavior. Cyclic testing can also be used to assess whether the soil reaches ru=1, or stabilizes at a lower value. Cyclic testing is very important for evaluating strength loss potential for non-susceptible soils. I think of them as being susceptible to cyclic softening rather than to liquefaction.

Question 16 – How should such tests be interpreted in terms of the potential for susceptibility?

1. Used to supplement simplified methods.
2. Evaluating CRR, excess porewater pressure generation, and soil stress-strain behavior.
3. Should start with similar interpretations of similar cyclic testing, and include a degree of judgement to the results to modify similar interpretations.
4. If the response of a soil is similar to that of a clean sand that we agree is susceptible to liquefaction it should be considered as susceptible to liquefaction.
5. Ru, strain accumulation, shape of hysteretic loops.
6. Test should be interpreted relative to the range of common design ground motion levels and the ability of those motions to "change" the soil behavior such that "liquefied/reduced strength" properties should be used in analyses instead of "static" properties.
7. Development of strains and pore water pressure vs. number of cycles. Frequency of loading is also a critical consideration for soils in the transitional fines/PI range that may have rate effects.
8. Interpretation can be challenging. For example, I would have judged both soils in Figure 10 from Boulanger and Idriss (2006) as soils that are susceptible to liquefaction based on their stress-strain behavior; whereas, Boulanger and Idriss (2006) characterized the silt with a PI=10.5 as behaving as a clay. This indicates that stress path results may be needed as additional support for justifying the interpretation of the soil behavior.
9. Check correlations, develop site specific correlations, confirm borderline cases of susceptibility.
10. Either Ru approximately 1.0 or single axial strain of 2.5%.
11. Hysteresis loops and excess pore pressure.
12. Level of ru, i.e. residual effective stress levels; characteristics of stress-strain curve (loop);
13. Not sure yet.
14. The quality of the samples is first that should be looked at. How representative are the materials versus what is in the field. Have some percentage of gravels been loss. Confidence in density. From a broader perspective, if a suite of soils are tested, it is best to test them to a similar playing field and perhaps measure their susceptibility as a comparison to

known liquefiable soils, specifically with respect to both excess pore pressure and shear strains.

15. The hysteresis loop at large strains is the single most important piece of information which can definitively establish the susceptibility to liquefaction.
16. Pore pressure generation, stiffness degradation characteristics with ru, hysteretic behavior, and post-seismic tests should be evaluated and compared with established literature.
17. Test results should be interpreted in ways to correlate to the semi-empirical method for top 40 to 60 feet and inform the limitation of the semi-empirical methods for transitional soils and soils deeper than 40 feet.
18. Whether particular consequences can be developed (within a reasonable number of cycles) regardless of the loading intensity.
19. Currently unsure.
20. See last response.
21. Can use # of cycles to reach a certain level of deformation or pwp ratio.
22. With all the usual caveats, i.e. that samples can be disturbed, that they only represent an extremely small proportion of the soil deposit in question. I think there's a lot of utility in generating site-specific FC-Ic correlations using lab data.
23. Interpretation of the lab tests for use in practice will likely be soil specific in the sense that the applicability of the lab data to field conditions requires judgement on the influence of a host of considerations that have been well addressed in the literature (e.g., specimen disturbance, stress path, shear strain localization, 1D and 2D loading considerations, etc.).
24. Excess pore pressure and shear strain potential for a given number of cycles in stress-based tests is a common approach.
25. Liquefaction triggering is not the issue of concern, but rather the consequences of liquefaction triggering is of concern. I would use laboratory tests to assess the soil properties after specified cyclic loading and use these properties to assess the consequences of the cyclic loading.
26. See previous response.
27. Rate of degradation of stiffness, rate of generation of excess pore water pressure, stiffness criteria instead of strain criteria.
28. I answered that in the previous cell.
29. Significant stiffness reduction (near zero) under the anticipated seismic loads.

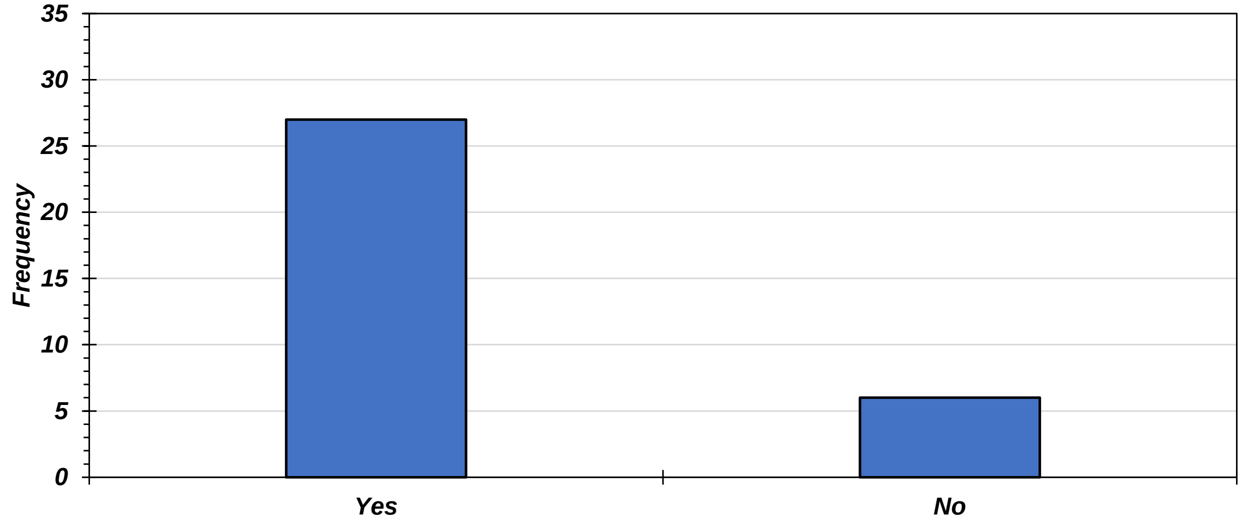
Question 17 – What information should next generation liquefaction susceptibility models provide to the user that current models aren't providing now?

1. OCR correlations.
2. We need to start moving towards modeling of liquefaction using more advanced models (PM4Sand/Silt) that can be calibrated with cyclic testing to help understand the behavior and build a database that can be access by the engineering community.
3. Depends on the NGL model.
4. Calibration with cyclic testing. Inclusion of new recently made empirical data/laboratory testing.
5. Models should use consistent measures of susceptibility. Since susceptibility is often yes/no, multiple criteria may be warranted. Or varying degrees of strength loss, strain potential, settlement potential, etc... should be provided whether deemed susceptible or not. This could help engineers with nuance project specific questions related to consequences, client risk tolerance, and life safety vs cost.
6. Better understanding of transitional soil response and system response of a deposit that may have partial saturation or interlayering; probabilistic estimates and integration with triggering models and consequences.
7. Next generation models should provide the probability for susceptibility coupled with guidance on how to move forward when there is some moderate probability of susceptibility. For example, if there is a 20% probability that the soil is susceptible to liquefaction, should advanced laboratory testing be used to establish cyclic behavior?
8. Better information about sensitivity of inputs. Would additional information reduce susceptibility? Reduced uncertainty and stronger more accurate predictions.
9. Overburden and static shear stresses.
10. CRR increase due to cementation or lamination.
11. Three classes: susceptible, transitional, not-susceptible.
12. Probability of liquefaction for sure and a more careful definition of susceptibility that only considers intrinsic characteristics of soil.
13. The models would be best to come together into one cohesive model (or suite of models) that interrelate to each other so that the practicing world can have confidence that this is an agreed upon model. More technically, the next generation models need to more clearly address how fines content and gradation impact susceptibility, especially as fines contents exceed 20%

towards 50% and PI's range between say 5 and 20. Currently, the models are more binary in nature suggesting soils are no longer liquefiable at some boundary depending on the model you look at. Perhaps something more probabilistic representing the reality that the behavior probably gradually transitions from liquefaction susceptibility (towards cyclic-softening susceptible)... AND perhaps a clear identification of a zone where neither is a possibility. From a theoretical perspective it seems logical that what we call transitional soils, especially those that tend to be well-graded, are not susceptible to liquefaction. Yet, literature rarely tells us that materials are NOT susceptible.

14. Consequences of liquefaction; better estimates of settlement and post-liquefaction shear strength.
15. A probabilistic liquefaction susceptibility model, material characteristics based, that is pegged to cyclic hysteresis behavior observed in the laboratory.
16. Probabilistic evaluation, quantifiable means to account for geologic characteristics,
17. A probability of susceptibility; ensemble predictions of susceptibility.
18. Quantitative measure of variability and uncertainties associated with liquefaction to inform the probabilistic liquefaction susceptibility.
19. Susceptibility related to consequences of liquefaction.
20. Whatever the output from a model, a mean (or median) and an uncertainty term from a probabilistic approach is desirable.
21. Probability of susceptibility.
22. Probability of susceptibility, increased emphasis on using CPT data.
23. A probability of susceptibility.
24. The triggering models should specify the applicable soil types.
25. Probability of liquefaction conditioned on different types of information (simple index tests or Ic vs more advanced indices).
26. Deformation potential as opposed to susceptibility.
27. 1. A clear definition of what susceptibility means; and 2. Probability of susceptibility, and a framework for incorporating it into analysis.
28. System response context, and drainage impacts due to layering.

Question 18 – Should NGL develop a database specifically for the study of susceptibility?



Question 19 – How can new technologies be applied to the problem of susceptibility assessment?

1. Existing tools can be used to characterize those factors that affect soil susceptibility.
2. Develop guidelines for use of cyclic testing data.
3. The state of practice would need to see the technology proven out by rigorous, research level testing. It is otherwise difficult to "sell" either to an owner or peer reviewer.
4. The same properties relevant to susceptibility are also typically relevant to triggering and consequences, so an integrated NGL database will likely enable more robust understanding of the data and development of models. New technologies allow for better collection of large datasets and should be used for transparent dissemination of data. Using new technologies for more efficient collection and publication of geotechnical in-situ data should also be a priority. Drone (or flight) imagery collection over large areas will also enable better coverage for collecting post-earthquake observations of liquefaction and no-liquefaction which can then be used to select sites for detailed investigations.
5. New data analysis methods such as machine learning may be useful.
6. The use of instrumented BPT and SPT looks to be very promising.
7. Use of CSS testing to develop CRR for a soil.
8. Recovery of high-quality samples, index testing and cyclic testing of soils.
9. Not sure.

10. I think to the extent more reliable sampling techniques (again thinking about gravel) can be used to get a better grip on gradation, that might help. Potentially using modern equipment to more closely assess real sites where liquefaction has occurred can be useful.
11. Experimentally: The development of a cheap, downhole (borehole?) based in-situ cyclic testing apparatus could improve the ability to establish liquefaction susceptibility. Analytically: Perhaps machine learning could be used to parse out trends/material characteristics which give rise to certain hysteretic features."
12. More downhole arrays specifically targeting transitional soils and deep potentially liquefiable deposits.
13. Information sharing including advanced lab testing and centrifuge test results for soils with similar characteristics.
14. Unsure.
15. Unsure.
16. NMR techniques (e.g. Vista Clara) can distinguish between free and "bound" water - seems like bound water content could be related to plasticity.
17. There's a lot more data now, which is great, and we're a lot better as a field at formulating things probabilistically and developing models with more statistical rigor than we used to be. Not sure that qualifies as "new technologies" but that's the advantage I think we have now... being more quantitative and less reliant on engineering rules of thumb.
18. A very good question and one that I eagerly look forward to discussing with those who are actively applying "new technologies" to dynamic soil behavior (in the lab and in situ).
19. I don't have a good answer for this.
20. I don't know what new technologies are being referred to here. I think undisturbed sampling and cyclic testing is the best way to assess susceptibility.
21. Develop a database with: (1) lab index tests; (2) Ic values from CPT; (2) advanced testing. Perform advanced regression, perhaps including machine learning, to relate susceptibility to different indicators.
22. Find ways to get spatial variability as well as quantify particulate structure.
23. Methods like machine learning, logistic regression, etc. can be brought to bear to gain insights into this classification problem.

Question 20 – What do you view as the most significant challenge to advancing liquefaction susceptibility assessment?

1. The degree of relative difficulty and cost of the more advanced analysis versus the state-of-the-practices, CPT only evaluations.
2. Thin layering and soil variability.
3. Lack of adopting new methods research and/or willingness to do something different.
4. In general, clients do not understand the topic and can't differentiate between a consultant who thinks attention to susceptibility of certain soils (e.g. silts) is necessary and another consultant that does not. So advancement must come from the academic side. Advancement has a better chance if susceptible soils can be differentiated by their associated consequences of strength loss, strain potential, settlement potential, etc. since many believe that for some soils susceptible doesn't necessarily present a life safety problem which is the key issue to address.
5. Development of community consensus models, or adopting a framework for probabilistic analysis using multiple methods such as was done for ground motions GMPEs. Having the data necessary to use the most current models effectively.
6. I believe the most significant challenge is collecting the data needed to develop new models.
7. Developing or using new procedures/ideas that deviate from the established liquefaction susceptibility assessment tools that are precedent. To reduce uncertainty and advance liquefaction assessment we should ask if our current tools still the best? Does greater parameterization produce better assessment, and why cannot our established approaches capture the information introduced with this parameterization?
8. Not having sites with recorded ground motions. Not having subsurface information for sites that didn't liquefy. The lack of sites with large overburden stress and high initial static shear stresses.
9. Sample quality.
10. Complexity/uniqueness of soil composition, insufficient high-quality sampling and then testing in the laboratory, and subtle differences in soil behaviour.
11. Lack of reliable laboratory data and of a consistent definition of susceptibility.
12. Numerous unknowns regarding gravel is one issue. Another issue that impacts dams in my daily work relates to the complexity associated with deposition or engineered fill where it can be difficult to identify what is the

matrix or not or what is controlling. For instance, it is common in practice to try and subtract gravel influence for assessing susceptibility (and triggering). It is difficult to do this when layers are "well-mixed". Similarly, most liquefaction case histories tend to be in relatively flat sites under limited shear stresses. It is unclear how much of what we base on liquefaction susceptibility is incorporating higher shear stresses. Finally, for dam projects in general, it is challenging to leap from in-situ conditions prior to the construction of a dam to post-reservoir-filling when saturation levels increase and further any geologic properties may be altered (e.g. loss of cementation in older units due to water presence).

13. Settling on a clear definition of liquefaction susceptibility. Although we might consider a probabilistic treatment as convenient, this definition ought to be binary for maximum clarity given that liquefaction can either occur given sufficient loading intensity and duration, or not.
14. Cost and logistics of sampling and testing intact samples with fines contents less than about 50% across a range of PIs, clay fractions, and geologic and depositional environments.
15. The paucity of all the required data types available to researchers (invasive field samples; non invasive field measurements; lab index testing; lab cyclic testing).
16. The lack of consensus among researchers and practitioners on the approach to assess liquefaction susceptibility of transitional soils and interbedded soils, specifically on how the results of the advanced lab testing results should be incorporated in the analysis.
17. Defining a consistent definition of susceptibility that incorporates soil compressibility and consequences of liquefaction.
18. Unsure.
19. In practice, getting budgets for sufficient drilling, high-quality sampling, and laboratory testing. In research, developing reliable methods for measuring parameters that control susceptibility and making them economical.
20. Utilizing multiple CPT-based criteria in a way that allows us to capture both aleatory variabilities and epistemic uncertainties.
21. Coupled assessment of the "susceptibility and consequences" of reaching a given Ru value, or perhaps a Reference Accumulated Cyclic Shear Strain. Alternatively stated; what might the susceptibility of a soil be to significant strength reduction or large strain accumulation given the amplitude and duration of the cyclic loading? Many outstanding and useful procedures exist for uncouple assessment of liquefaction related behavior. Practice-oriented

tools such as PM4Sand / PM4Silt provide a bridge from the lab and empirically-based procedures to a coupled framework.

22. Money. A large suite of full scale field tests at various fully characterized and instrumented sites with a shaker or blasting could provide a robust data base for pinning things down.
23. Being able to assess susceptibility in a way that is economically feasible for typical engineering projects.
24. Resistance to change in practice and over-reliance on legacy models.
25. Reluctance to deviate from conventional approaches.
26. Clearly defining it.
27. Guidance documentation and code requirements.

APPENDIX D: WORKSHOP AGENDA

Wednesday, 7 September

6:30 PM - 8:30 PM **Welcome Reception and Ice Breaker**
Location: The Vue, 517 SW 2nd St, Corvallis, OR 97330
Shuttles from Hilton Garden Inn to venue begin 6:15 PM
Note: venue located 1 mile (20 min. walk) east from Hilton Garden Inn

Day 1: Thursday, 8 September

7:30 AM - 9:00 AM **Workshop Opening**
MU Horizon Room

7:30 AM Check-in, Breakfast
8:30 AM **Armin Stuedlein**, Welcome, Agenda, and Workshop Objectives
8:35 AM **Scott Ashford** (Dean, College of Engineering), Welcome Address
8:40 AM **Steven Kramer**, Overview and Summary of Pre-Workshop Poll

9:00 AM - 12:30 PM **Session 1: State-of-Practice and Limitations**
MU Horizon Room

9:00 AM ***Part A: Presentations*** (12 min talks, 3 min short Q&A)
Önder Çetin, Probabilistic Models for Seismic Soil Liquefaction Susceptibility
Thomas Weaver, Evaluating Liquefaction Susceptibility for Nuclear Power Plant Sites
Erik Malvick, Challenges of Liquefaction Assessment at California's Dams
Uri Eliahu & **Pedro Espinosa**, Dynamic Behavior of the Treasure Island Natural Shoals

10:00 AM *15-minute break*

10:15 AM ***Part B: Presentations*** (12 min talks, 3 min short Q&A)
Sam Sideras, Liquefaction Susceptibility of a Low Plasticity Silty Soil Utilizing Cyclic Direct Simple Shear Testing
Matt Gibson, Liquefaction Susceptibility of Grays Harbor Silts
Brice Exley, The Impacts of Analyzing Deep Sand and Transitional Soil Profiles with State of the Practice Methods

11:00 AM ***Breakout Session, Report, and Discussion***
Part A: Outdoor Breakout: Group Activity
11:30 AM **Part B**: MU Horizon Room: Report on Breakout
12:00 PM **Part C**: MU Horizon Room: Discussion

12:30 PM ***Lunch***

1:30 PM - 5:00 PM	**Session 2: Where Do We Want to Be in 5 – 10 Years? Model Development, Resource Needs/Gaps** *MU Horizon Room*
1:30 PM	***Part A**: **Presentations*** (12 min talks, 3 min short Q&A) **Shideh Dashti**, Incorporating the Spectrum of Soil Behaviors Directly into Systems Level Triggering and Consequence Models **Jonathan Bray**, Liquefaction of Silty Soil **Dharma Wijewickreme**, Particle Fabric Imaging for Understanding Shear Response of Silts
2:15 PM	*15-minute break*
2:30 PM	***Part B: Presentations*** (12 min talks, 3 min short Q&A) **Laurie Baise**, Geospatial Models for Liquefaction Susceptibility **Christine Beyzaei**, Regional Liquefaction Susceptibility Assessments: Data Collection Needs and a Focus on the Central and Eastern U.S. **Andrew Makdisi**, Incorporating Uncertainty in Susceptibility Criteria into Probabilistic Liquefaction Hazard Analysis
3:15 PM	***Breakout Session and Discussion*** **Part A**: Outdoor Breakout: Individual Activity
3:45 PM	*15-minute Break (& compilation of breakout responses)*
4:00 PM	**Part B**: MU Horizon Room: Report and Discussion
4:45 PM	**T. Matthew Evans,** Day 1 Observations and Closing Remarks
5:00 PM	**Group Photograph,** *and adjourn to Reception:* NHERI Coastal Wave/Surge and Tsunami Center, O.H. Hinsdale Laboratory
7:00 PM	Participants shuttled to Hilton Garden Inn or downtown for dining on their own

Day 2: Friday, 9 September

7:30 AM - 8:30 AM	**Breakfast** *MU Horizon Room*
8:30 AM - 12:00 PM	**Session 3: Opportunities for Synthesizing Laboratory- and Field-based Observations, Consensus Recommendations**
8:30 AM	***Part A**: **Presentations*** (12 min talks, 3 min short Q&A) **Scott Olson,** Consequence-Based Susceptibility Incorporating Compressibility **Diane Moug,** Relating Cyclic Behavior to CPT Data for Intermediate Fine-Grained Soils **Brett Maurer,** CPT-Based Probabilistic Prediction of Liquefaction Susceptibility
9:15 AM	*15-minute break*
9:30 AM	***Part B*: *Presentations*** (12 min talks, 3 min short Q&A) **Ross Boulanger**, Susceptibility Criteria for Selecting Engineering Procedures **Scott Brandenberg & Jonathan Stewart**, Cyclic Behavior of Low Plasticity Fine-Grained Soils of Varying Salinity, and Cyclic Failure due to Dynamic Soil-Structure Interaction **Armin Stuedlein & T. Matthew Evans**, Linking Hysteretic Behavior to Liquefaction Susceptibility
10:15 AM	***Breakout Session, Report, and Discussion*** **Part A**: Outdoor Breakout: Group Activity
10:45 AM	**Part B**: MU Horizon Room: Report on Breakout
11:15 PM	**Part C**: MU Horizon Room: Discussion
11:45 PM	**Workshop Closing** **I.M. Idriss**, Observations on Workshop Discussions **Armin Stuedlein**, Closing Remarks
12:00 PM	***Box Lunch** (Shuttles to/from Hotel and Eugene Airport begin)*
1:00 PM	Workshop Organizers Draft Report 311 Kearney Hall

APPENDIX E: SESSION 1 PRESENTATIONS

This electronic appendix contains seven presentations from Session 1, titled "State-Of-Practice and Limitations," which may be found on the PEER report webpage, including:

- K. Önder Çetin: Probabilistic Models for Seismic Soil Liquefaction Susceptibility
- Thomas Weaver: Evaluating Liquefaction Susceptibility for Nuclear Power Plant Sites
- Erik Malvick: Challenges of Liquefaction Assessment at California's Dams
- Pedro Espinosa: Dynamic Behavior of the Treasure Island Natural Shoals
- Sam Sideras: Liquefaction Susceptibility of a Low Plasticity Silty Soil Utilizing Cyclic Direct Simple Shear Testing
- Matt Gibson: Liquefaction Susceptibility of Grays Harbor Silts
- Brice Exley: The Impacts of Analyzing Deep Sand and Transitional Soil Profiles with State of the Practice Methods

APPENDIX F: SESSION 2 PRESENTATIONS

This electronic appendix contains six presentations from Session 2, titled "Where Do We Want to be in 5 to 10 Years? Model Development, Resource Needs and Gaps," which may be found on the PEER report webpage, including:

- Shideh Dashti: Incorporating the Spectrum of Soil Behaviors Directly into Systems Level Triggering and Consequence Models
- Jonathan Bray: Liquefaction of Silty Soil
- Dharma Wijewickreme: Particle Fabric Imaging for Understanding Shear Response of Silts
- Laurie Baise: Geospatial Models for Liquefaction Susceptibility
- Christine Beyzaei: Regional Liquefaction Susceptibility Assessments: Data Collection Needs and a Focus on the Central and Eastern U.S.
- Andrew Makdisi: Incorporating Uncertainty in Susceptibility Criteria into Probabilistic Liquefaction Hazard Analysis

APPENDIX G: SESSION 3 PRESENTATIONS

This electronic appendix contains six presentations from Session 3, titled "Opportunities for Synthesizing Laboratory- and Field-based Observations, Consensus Recommendations," which may be found on the PEER report webpage, including:

- Scott Olson: Consequence-Based Susceptibility Incorporating Compressibility
- Diane Moug: Relating Cyclic Behavior to CPT Data for Intermediate Fine-Grained Soils
- Brett Maurer: CPT-Based Probabilistic Prediction of Liquefaction Susceptibility
- Ross Boulanger: Susceptibility Criteria for Selecting Engineering Procedures
- Scott Brandenberg: Cyclic Behavior of Low Plasticity Fine-Grained Soils of Varying Salinity, and Cyclic Failure due to Dynamic Soil-Structure Interaction
- Armin Stuedlein: Linking Hysteretic Behavior to Liquefaction Susceptibility

The Pacific Earthquake Engineering Research Center (PEER) is a multi-institutional research and education center with headquarters at the University of California, Berkeley. Investigators from over 20 universities, several consulting companies, and researchers at various state and federal government agencies contribute to research programs focused on performance-based earthquake engineering.

These research programs aim to identify and reduce the risks from major earthquakes to life safety and to the economy by including research in a wide variety of disciplines including structural and geotechnical engineering, geology/seismology, lifelines, transportation, architecture, economics, risk management, and public policy.

PEER is supported by federal, state, local, and regional agencies, together with industry partners.

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ISSN 2770-8314
https://doi.org/10.55461/BPSK6314