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Fines-content effects on liquefaction hazard evaluation for infrastructure in Christchurch, New Zealand

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ABSTRACT

To assess soil liquefaction hazards for civil infrastructure, several competing liquefaction evaluation procedures (LEPs) are used to estimate the potential for liquefaction triggering, often for use in a liquefaction potential index (LPI) framework. However, due to the relatively uncertain effects of fines-content (FC) on liquefaction behavior, LPI hazard assessments may be less accurate at sites with high FC. Accordingly, this study investigates "fines-content effects" on the accuracy of LPI hazard assessment during the 2010–2011 Canterbury Earthquake Sequence (CES). These effects are resolved into: (1) criteria based on the soil-behavior-type index (I_c) for identifying liquefaction-susceptible soils; (2) FC-corrections inherent to each LEP, used to adjust liquefaction resistance for the presence of fines; and (3) the potential for non-liquefied, high-FC soils to inhibit liquefaction manifestation. This investigation is performed using 7000 liquefaction case studies from the CES, wherein LPI hazard assessments computed with the Robertson and Wride [50], Moss et al. [41], and Idriss and Boulanger [30] LEPs are compared to field observations. For the assessed dataset, LPI hazard assessments were significantly and uniformly less accurate at sites with silty and clayey soil mixtures. For these sites, the existing LPI framework has inherent limitations, such that all LEPs produce erroneous hazard assessments. In particular, the capacity of plastic soils to inhibit liquefaction manifestation by affecting pore pressure development and redistribution should be further evaluated.

1. Introduction

The objective of this study is to investigate fines-content effects on the accuracy of liquefaction hazard assessment for infrastructure using data from the 2010 to 2011 Canterbury, New Zealand, earthquake sequence (CES). This investigation considers the performance of three popular cone penetration test (CPT) based liquefaction evaluation procedures (LEPs) for predicting the severity of liquefaction manifestation within the liquefaction potential index (LPI) framework. Utilizing data from the CES, this study examines the adequacy of commonly adopted liquefaction assessment criteria and methods, with special emphasis placed on silty and clayey soil mixtures. In particular, we examine: (1) criteria based on the soil behavior type index (I_c) used to identify liquefaction-susceptible soils; (2) the correction factors applied to liquefaction-susceptible soils to adjust liquefaction resistance for fines-content; and (3) the potential for inter-bedded, non-liquefied, high fines-content soils to inhibit liquefaction manifestation. Towards this end, the deterministic CPT-based LEPs of Robertson & Wride [50] [R&W98], Moss et al. [41] [MEA06], and Idriss & Boulanger [30] [I&B08] are evaluated within the LPI framework using a database of 7000 liquefaction case studies from the CES.

The 2010–2011 CES induced widespread, severe, and recurrent liquefaction throughout the city of Christchurch, resulting in large-scale damage to civil infrastructure (e.g., [17,18,24,19]). The CES initiated with the M_w7.1, 4 September 2010 Darfield earthquake and was punctuated by the M_w6.2, 22 February 2011 Christchurch earthquake, each of which induced pervasive and damaging liquefaction. Observed manifestations of liquefaction included, among others: (1) spreading- and settlement-induced damage to bridges and bridge approaches (e.g., [58,20]); (2) widespread loss of road functionality due to cracking and fissuring of pavements and inundation by liquefaction ejecta (e.g., [17]); (3) failure of buried lifelines due to flotation or differential settlements, to include water and wastewater distribution systems (e.g., [44]), electric power networks (e.g., [34]), and communication lines (e.g., [53]); (4) damage to levees (stopbanks) caused by spreading,

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slumping, and settlement (e.g., [23]); (4) impairment of port structures caused by ground deformations, to include wharfs, seawalls, and fuel lines (e.g., [13]); (5) slumping- and spread-induced damage to railway embankments (e.g., [17]); and (7) settlement and tilting of residential homes, commercial properties, and high-rise structures, resulting in widespread loss of building stock (e.g., [9]). In addition to direct effects on infrastructure, the ~500,000 t of liquefaction ejecta collected throughout Christchurch posed a threat to stormwater systems and to human health if left unmanaged [57].

As illustrated by the severe liquefaction-induced damage during the CES, there is a critical need to accurately assess liquefaction hazards for civil infrastructure. In current engineering practice, liquefaction hazard is commonly assessed using the liquefaction potential index (LPI) [31], defined by:

$$\mathrm{LPI} = \int_0^{20\ m} Fw(z)\,dz \tag{1}$$

In Eqs. (1), $F = 1 - FS_{\mathrm{liq}}$ for $FS_{\mathrm{liq}} \leq 1$ and $F = 0$ for $FS_{\mathrm{liq}} > 1$, where FS_{liq} is the factor of safety against liquefaction "triggering" computed by an LEP (e.g., [50,41,30]); $w(z)$ is a depth weighting function given by $w(z) = 10 - 0.5z$; and z is depth in meters below the ground surface. Thus, it is assumed that the severity of liquefaction manifestation is proportional to the cumulative thickness of liquefied layers, the proximity of these layers to the ground surface, and the amount by which FS_{liq} in each layer is less than 1.0. Given this definition, LPI can range from 0 to a maximum of 100 (i.e., where FS_{liq} is zero over the entire 20 m depth). Analyzing standard-penetration-test (SPT) data from 55 sites in Japan, Iwasaki et al. [31] proposed that severe liquefaction should be expected for sites where LPI > 15 but not where LPI < 5. This criterion for liquefaction manifestation, defined by two threshold values of LPI, is referred to as the *Iwasaki criterion*.

In the decades since its inception, LPI has been widely adopted as a predictive proxy for liquefaction damage potential and has been used worldwide in hazard mapping, urban planning, and the engineering design of infrastructure (e.g., [52,2,27,28,36,16,26,29,15,33]). However, in using LPI to assess liquefaction hazard in current practice, it is not always appreciated that the efficacy of LPI hazard assessment (and the *Iwasaki criterion*) is inherently linked to the LEP used within the LPI framework. Although the LEPs used in today's practice (e.g., [50,41,30]) are the cumulative result of 4–5 decades of research, it has been shown that they can compute different FS_{liq} values for the same soil profile and earthquake scenario (e.g., [25]), and thus different LPI values. In addition, today's LEPs are vastly different from that used by Iwasaki et al. [31] to develop the *Iwasaki criterion*. These differences have led to confusion as to which LEP is the most accurate, and whether the LPI framework and *Iwasaki criterion* are equally effective for all LEPs.

Maurer et al. [38] addressed these uncertainties by assessing the efficacies of the R&W98, MEA06, and I&B08 LEPs, operating within the LPI framework, for evaluating the liquefaction hazard at 1173 sites during the Darfield and Christchurch earthquakes. Maurer et al. [38] concluded that: (1) the utility of the *Iwasaki criterion* varied amongst LEPs (i.e., the optimum threshold LPI values for predicting liquefaction manifestation were LEP-dependent); and (2) LPI hazard assessments were highly erroneous for some sites, irrespective of the LEP used within the LPI framework.

While there are many potential sources of LEP discrepancy (and erroneous liquefaction hazard assessment), the uncertain liquefaction behavior of silty and clayey soil mixtures may be a predominate factor. For, while the behavior of clean sands is *relatively* established (e.g., [37]), there are many conflicting opinions about the effects of fines-content on liquefaction resistance, and definitive guidance on the matter is lacking (e.g., [22,48]). Uncertainties pertaining to high fines-content soils could affect liquefaction hazard assessment in several ways. First, antecedent to using any LEP in the LPI framework, liquefaction-susceptible soils must be identified. For CPT-based liquefaction assessment (considered herein), the current state-of-practice is to use the soil behavior type index (I_c) for this purpose, defined as [50]:

$$I_c = \sqrt{(3.47 - \log_{10} Q)^2 + (1.22 + \log_{10} F)^2} \tag{2}$$

where Q and F are the normalized cone tip resistance and normalized friction ratio, respectively. A value of $I_c > 2.6$ is commonly considered to imply non-liquefiable soils [50]. However, because the relationship between I_c and soil type is approximate, the $I_c = 2.6$ cutoff may in some cases be inappropriate (e.g., [61]). Accordingly, Youd et al. [59] recommended that soils with $I_c \geq 2.4$ be sampled and tested to evaluate their liquefaction susceptibility. While these guidelines are widely used with I_c to gauge liquefaction susceptibility, their efficacy is uncertain (e.g., [3,37,47]).

Once liquefaction-susceptible soils are identified (e.g., $I_c \leq 2.6$.), the LEPs used in today's practice apply differing correction factors to adjust liquefaction resistance for fines-content. These correction factors, unique to each LEP, were developed from relatively limited data using different approaches. For example, the R&W98, MEA06, and I&B08 procedures respectively use I_c, friction ratio (R_f), and fines-content (FC) to adjust liquefaction resistance for the presence of fines. Greater discrepancies may therefore exist amongst LEP predictions in the assessment of silty sands and sandy silts, relative to evaluations of clean sands. Lastly, field, laboratory, and numerical analyses have suggested that high fines-content soils in the capping or interbedded non-liquefiable strata may inhibit surficial liquefaction manifestations [45,4,39]. Thus, inherent limitations in the LPI framework to account for such effects may lead to erroneous hazard assessments even if the selected LEP is wholly competent. In summary, due to the relatively uncertain effects of fines on liquefaction behavior, referred to herein as "fines-content effects," the accuracy of liquefaction hazard assessment for infrastructure is uncertain.

Accordingly, the objective of this study is to investigate fines-content effects on the accuracy of LPI hazard assessment using data from the 2010–2011 CES. These effects are resolved into (1) criteria based on I_c for identifying liquefaction-susceptible soils; (2) fines-content corrections inherent to each LEP; and (3) the potential for non-liquefied, high fines-content soils to inhibit liquefaction manifestations. This investigation is performed using 7000 liquefaction case studies from the CES, wherein LPI hazard assessments computed with the R&W98, MEA06, and I&B08 LEPs are compared to field observations.

In the following, the high-quality dataset from the CES is briefly summarized. This is followed by a description of how LPI was computed using three CPT-based LEPs. An overview of receiver-operating-characteristic (ROC) curves, which will be used in the analysis of the LPI data, is then provided. Lastly, fines-content effects on the accuracy of LPI hazard assessment are analyzed and discussed in detail.

2. Data and methodology

The 2010–2011 CES resulted in a liquefaction dataset of unprecedented size and quality, presenting a unique opportunity to evaluate fines-content effects on the accuracy of liquefaction hazard assessment (e.g., [17,18,8,5]). The study presented herein uses data from the M_w7.1, 4 September 2010 Darfield and M_w6.2, 22 February 2011 Christchurch earthquakes, which induced pervasive and damaging liquefaction (e.g., [24,25]). Ground motions from these events were recorded by a dense network of strong motion stations (e.g., [8,5]), and due to the extent of liquefaction, the New Zealand Earthquake Commission (EQC) funded an extensive geotechnical reconnaissance and characterization program [42]. The combination of densely-recorded ground motions, well-documented liquefaction response, and detailed subsurface characterization comprises the high-quality