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Laboratory-based characterization of shallow silty soils in southwest Christchurch

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ABSTRACT

Cyclic triaxial test data are presented to characterize the cyclic response of silty soils at three no-liquefaction case history sites in southwest Christchurch. Stress-strain response and axial strain accumulation demonstrate nuanced, transitional responses of silty soils. Post-liquefaction reconsolidation volumetric strains are within the range expected for clean sands. However, there are clear differences in the post-liquefaction response of silts from that of sands. Low-plasticity silts undergo time-dependent reconsolidation whereas sands undergo immediate reconsolidation. Simplified liquefaction triggering procedures estimate significant liquefaction at these sites; yet, no liquefaction manifestations were observed during the Canterbury earthquake sequence. Laboratory estimates of cyclic resistance are consistent with estimates from simplified liquefaction triggering procedures, and both estimates are well below the estimated seismic demand. Thus, liquefaction is likely triggered at the element-level in the silty soil deposits. Post-liquefaction reconsolidation test results suggest water and ejecta may not necessarily accumulate in these stratified silty soils as they would accumulate in thick deposits of liquefiable clean sands. Thus, manifestations of liquefaction may not be observed at stratified silt/sand sites with delayed reconsolidation responses and lower hydraulic conductivities. Additional mitigating factors may also have contributed to the discrepancy between simplified procedure estimates of liquefaction and the lack of liquefaction observed at these sites.

1. Introduction

During the 2010–2011 Canterbury earthquake sequence, multiple earthquake events triggered widespread damaging liquefaction that affected buildings, infrastructure networks, and critical lifeline systems in Christchurch, New Zealand (Fig. 1a). This degree of extensive repeated liquefaction was virtually unprecedented in a modern urban setting. However, there were also many cases where soil deposits previously thought to be potentially liquefiable did not express surface manifestations of liquefaction (Fig. 1b). At several sites, especially sites with silty soils, state-of-practice cone penetration test (CPT)-based procedures over-estimated the occurrence and severity of liquefaction. Current liquefaction triggering procedures are largely based on observations following earthquakes at sites containing deposits of relatively clean sands. There remains considerable debate regarding the liquefaction resistance of fine-grained soils, such as silts, including how liquefaction of silty soils might manifest damage and the appropriate assessment procedures to employ.

This paper presents laboratory testing data and case histories for three silty soil sites that exhibited discrepancies between state-of-practice liquefaction evaluations and post-earthquake liquefaction observations. A clean sand site, which also contains a shallow layer of silty sand, is included as a point of comparison for the silty soil site characterizations. The primary goals of this paper are to present laboratory testing data for high-quality natural silty soil specimens that provide insight on their cyclic response and to compare the laboratory test results with CPT-based simplified liquefaction triggering procedures to identify consistencies and discrepancies between the two approaches. The findings of the paper provide insights regarding laboratory-based characterization of the cyclic response of silty soils relative to observed earthquake performance. The natural specimen laboratory test data are combined with observational data from post-earthquake reconnaissance to advance the understanding of the cyclic response of silty soils and to improve empirical liquefaction evaluation procedures. Silty soils test data also allow for the development of more robust

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Fig. 1. (a) Liquefaction Site (from GEER Report 27 [10]), and (b) No-liquefaction Site (from Mr. Rick Wentz of Wentz-Pacific, Ltd.) in Christchurch.

numerical models that capture a broader range of soils and their responses. This particular effort is part of a larger study initiated after the Canterbury earthquake sequence to characterize and to understand the seismic performance of silty soil sites. Silty soils warrant additional research; relatively little is known about their cyclic response compared to those of clean sands and plastic clays.

2. Laboratory testing to characterize cyclic response

Characterization of the cyclic response of soils is achieved primarily through observational data and experimental data. Observational data, such as those collected during post-earthquake reconnaissance, form the basis for databases used in developing empirical evaluation procedures. Experimental data, such as laboratory or in-situ testing, informs field case histories and explores cyclic response characteristics that are not readily observed or easily understood in case histories. Most liquefaction cases in the current databases (e.g., Boulanger and Idriss [1]) are for relatively thick deposits of clean sand or sands with fines contents < 35%. Much of the first few decades of liquefaction research focused on field observations for these deposits (e.g., Seed [2]), and laboratory testing also focused on characterization of the cyclic response of clean sands, because available case histories were predominantly associated with clean sand sites. It is difficult to obtain "undisturbed" samples in clean sand, so most laboratory testing was conducted on laboratory-prepared specimens (e.g., moist tamping). Testing of clean sands has formed the basis for our understanding of liquefaction. Considerable research has also been conducted on cyclic softening of clays, albeit significantly less than that on clean sand.

Recent earthquakes have highlighted the importance of silt liquefaction (e.g., Adapazari during the 1999 Kocaeli, Turkey earthquake; Bray and Sancio [3]). Consequently, researchers have devoted more attention to investigating the cyclic response of "silty soils" (also termed "intermediate" or "fine-grained" soils). These terms describe soils with no-to-low plasticity and fines contents from about 35–100%, encompassing the broad range of soil types after the point at which fine-grained particles control the response of the soil matrix. The variability in silty soil deposits is an inherent challenge in describing and characterizing their cyclic response. There is a large range of silty soil responses possible between those of conventional "sand" and "clay" soils from which most of our understanding and procedures are derived. Currently, the cyclic response of silty soils is characterized in relation to the response of clean sands. Parameters such as fines content, plasticity index (PI), and soil behavior index type (I_c) are used to describe how a silty soil deviates from a typical clean sand and as such, how the cyclic response of a silty soil is anticipated to deviate from that of a clean sand.

Laboratory testing of silty soils has been conducted for both natural "undisturbed" specimens and laboratory-prepared specimens (e.g., Bray and Sancio [3]; Thevanayagam and Martin [4]; Wijewickreme and Sanin [5]). A complicating issue with laboratory testing of natural silty soils is the determination of what constitutes a representative soil specimen. In clean sand deposits, the element-scale test specimen may be more representative of the overall stratum and less subject to within-specimen heterogeneity from layering than a silt specimen. Silty soils are formed in depositional environments such as overbank deposits or swamps, which often lead to the development of highly stratified soil deposits with fine layering sequences. Laboratory-prepared silt test specimens may not capture such in-situ characteristics. Thus, there is merit to performing laboratory tests on retrieved samples of silty soils if they can be retrieved without significant disturbance.

3. Development of no-liquefaction case histories

The silty soil sites presented in this paper are deemed "no-liquefaction" case histories based on the current framework of categorizing sites as "liquefaction" or "no-liquefaction" by observed surface manifestations. It is possible that liquefaction occurred at-depth, but given that no surface manifestations of liquefaction were observed during post-earthquake reconnaissance, the sites are categorized as "no-liquefaction" case histories.

3.1. Canterbury earthquake sequence

The 2010–2011 Canterbury earthquake sequence consists of four main events: the 4 September 2010 M_w 7.1 Darfield earthquake, 22 February 2011 M_w 6.2 Christchurch earthquake, 13 June 2011 M_w 5.3 and 6.0 earthquakes, and 23 December 2011 M_w 5.8 and 5.9 earthquakes. Subsequent research programs have focused on the Darfield and Christchurch earthquakes, which caused the most significant liquefaction damage throughout greater Christchurch (Fig. 2) and were the focus of more comprehensive post-earthquake reconnaissance investigations. The June and December 2011 earthquakes require more judgement in the interpretation of their effects, owing to the paired earthquake events both occurring approximately 80 min apart and due to them being less studied. Much research has been published on the effects of the Canterbury earthquake sequence (e.g. [6–11]). Relevant details are provided in this paper.

3.2. Christchurch geologic setting

Christchurch, New Zealand is located in a complex geologic and geomorphic environment, with dominant influences from alluvial, coastal, and swamp or lagoon-type depositional processes [12,13]. Bound closely to the north by the Waimakariri River, greater Christchurch is located in a coastal setting within the Canterbury Plains. The braided Waimakariri River flows eastward from the Southern Alps to the Pacific Ocean, depositing gravel, sand, and silt sediments in alluvial fan and floodplain deposits throughout the Canterbury Plains. Small rivers and streams meander through the inland areas of Christchurch, with the Avon River flowing east through the Central Business District toward the eastern coastal suburbs, and the Heathcote River flowing east through the southern suburbs of the city before