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Comparing laboratory-based liquefaction resistance of a sand with non-plastic fines with shear wave velocity-based field case histories

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ABSTRACT

The semi-empirical simplified procedure for liquefaction triggering of level-ground is largely based on correlating post-earthquake field observations such as presence/absence of sand boils to field measurements such as penetration resistance or shear wave velocity (V_s). These correlations could be interpreted in such a way that for a given penetration resistance or V_s, the cyclic resistance ratio (*CRR*) increases as fines content increases. However, some studies have indicated that this interpretation may not be correct, particularly for soils containing non-plastic fines. An experimental research program involving cyclic triaxial tests was undertaken to investigate cyclic resistance of F-75 sand with varying amounts of non-plastic fines (Sil-Co-Sil 125). Bender elements were incorporated in the triaxial cell to facilitate V_s measurements. Other similar data sets found in the literature were used to supplement the laboratory data and evaluate the overall trends implied by the V_s-based field *CRR* curves. The comparison suggests that the laboratory data are generally consistent with the trends embedded in the field curves, with boundary curves shifting slightly to the left with increasing fines content.

1. Introduction

For many years, liquefaction phenomena were thought to be limited to clean sands. Fine-grained soils were considered incapable of generating the high pore pressures commonly associated with soil liquefaction. However, well-documented field case histories (e.g., Bray, et al. [1]; Chu, et al. [2]) have illustrated that intermediate soils previously considered non-liquefiable were found to liquefy. Laboratory cyclic tests have been used extensively to understand the liquefaction resistance of sands with fines, particularly non-plastic fines (e.g., Polito and Martin [3], Xenaki and Athanasopoulos [4], Carraro et al. [5], Kokusho et al. [6]). However, depending on the basis of comparison (e.g. relative density, global or skeleton void ratio), conflicting conclusions have been drawn. Some studies concluded that increasing non-plastic fines content (FC) increases (e.g. Chang et al. [7]; Dezfulian [8]; Amini and Qi [9]), decreases (e.g., Troncoso and Verdugo [10]; Kuerbis et al. [11]; Finn et al. [12]; Lade and Yamamuro [13]), or does not affect (e.g. Ishihara [14]) liquefaction resistance.

Polito and Martin [3] and Xenaki and Athanasopoulos [4] observed that the cyclic resistance of a sand-silt mixture is unaffected by FC up to the *limiting or threshold* FC (typically between 25% and 45% per Polito [15]), at which point the cyclic resistance drops significantly and again becomes constant. Polito and Martin [16] concluded that many of the conflicting trends in laboratory testing mentioned above can be explained qualitatively using relative density of silt-sand mixtures as the basis; and suggested that for soils below the limiting fines content the current fines corrections may be inappropriate, and for silty sands and sandy silts with FC greater than the limiting fines content, the present correlations may lead to dangerous over-prediction of cyclic resistance. While the above mentioned and other laboratory investigations have helped explain many aspects of liquefaction phenomena, cyclic laboratory tests generally are not feasible in typical seismic evaluations because of the difficulty in obtaining undisturbed specimens of sandy soils and economic constraints.

In comparison, a liquefaction potential evaluation based on field measurements of penetration resistance (using standard penetration test [SPT], cone penetration test [CPT], Becker penetration test [BPT]) or shear wave velocity (V_s) often is relatively easier to conduct in practice than a laboratory cyclic testing-based evaluation. The 'simplified procedure' originally developed by Seed and Idriss [17] and Whitman [18] using SPT blow counts has been used widely for evaluating liquefaction triggering. Youd et al. [19] summarized updates to the simplified procedure including guidelines for CPT, BPT and V_s measurements, which are referred as 'existing guidelines' here. The

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existing guidelines reflect the effects of fines in such a way that at constant penetration resistance or shear wave velocity, soils exhibit increased cyclic strength with increased FC of up to 35%, after which the cyclic resistance ratio (CRR) is capped (Seed et al. [20]; Kayen and Mitchell [21]; Cetin et al. [22]; Idriss and Boulanger [23]). Whether this increase is caused by an increase in cyclic resistance or decrease in penetration resistance and V_s is not clear. Indeed, Youd et al. [19] recommended, *"corrections based solely on fines content should be used with engineering judgment and caution"*. Some recent studies supported the present form of fines correction (e.g., Cetin et al. [22]), whereas some showed different trends. For example, Sakai et al. [24] evaluated SPT data from a total of 846 borings from liquefied and non-liquefied sites during 11 earthquakes in Japan. They normalized the cyclic stress ratio (CSR) for various fines contents with the clean sand CSR and plotted against the fines content. Their data seem to support some form of limiting fines content although the overall trend is opposite of the liquefaction curves in the existing guidelines. Green et al. [25] reanalyzed 98 SPT case histories from 14 earthquakes. They concluded that current fines correction factors may overestimate the liquefaction resistance of silty sands with fines greater than 35%. The recent state-of-the-art report on liquefaction evaluation published by the National Academies [26] expressed a concern that different approaches used to adjust for fines content could result in discrepancies among different liquefaction triggering relationships, and recommended continued research to evaluate the different approaches. Therefore, there is continued need to assess the validity of the present form of fines correction embedded in the simplified procedure.

This study evaluates the effects of non-plastic fines on V_s and cyclic resistance of sands using laboratory cyclic triaxial and bender element test results. The results are then used to evaluate trends implied by the V_s-based field *CRR* curves proposed by Andrus and Stokoe [29]. Several factors affect V_s in soils, including grain characteristics, void ratio, effective confining stress, stress history, degree of saturation, strain amplitude, shear wave frequency, aging effects, sample preparation procedure, soil structure, and temperature (e.g. Richart et al. [27] and Baxter et al. [28]). These same factors also influence the static and cyclic shear strength of soils, providing impetus for correlating cyclic resistance to V_s (Baxter et al. [28]). Youd et al. [19] adopted the *CRR* (cyclic resistance ratio) – V_{s1} (overburden-stress corrected shear wave velocity) curves developed by Andrus and Stokoe [29,30] for magnitude 7.5 earthquakes and uncemented Holocene-age soils, which are used for general comparison in this investigation. Andrus and Stokoe [30] developed liquefaction resistance curves bounded by FC ≤ 5% and FC ≥ 35% using data from over 70 measurements sites and 26 earthquakes.

There are only a few investigations where cyclic strength of sandy soils was investigated through laboratory tests and correlated to penetration resistance or V_s. Carraro et al. [5] developed liquefaction curves from CRR based on laboratory cyclic triaxial tests versus cone penetration resistance computed using cavity expansion theory for sandy soils with FC ≤ 15%. The trend of *CRR* curves from their study was opposite of the *CRR* curves currently used in practice. Later, Liu and Mitchell [31] developed theoretical CRR-V_{s1} correlations and noted that V_s measurements may be inadequate to reflect all the factors affecting liquefaction resistance. This study however did not employ direct laboratory measurements of V_s and CRR on the 'same' soil. The investigation of Huang et al. [32] is one of the rare investigations that involved measuring CRR and V_s on the same specimens of a natural silty sand with FC ≤ 30%. Huang [33] recently expanded these data by adding two other silty sands with FC ≤ 89%. These data, when compared to the liquefaction curves by Andrus and Stokoe [29], plotted on the left of the clean sand curve and Huang [31] suggest that the data did not necessarily support multiple *CRR*-V_{s1} curves. Baxter et al. [28] investigated CRR and V_s of Providence silts and concluded that existing guidelines (Andrus and Stokoe [30], Youd et al. [19]) could either underestimate or overestimate liquefaction resistance depending on soil type, but it significantly overestimated the liquefaction resistance for Providence silts (FC > 95%). Ahmadi and Paydar [34] investigated uniqueness of *CRR*-V_s relationship curves on Babolsar and Firoozkooh sands (FC < 5%). They concluded that the relationship between V_s and *CRR* is soil-specific and proposed regions on a CRR-V_s relationship chart for initial screening of potentially liquefiable soils. El Takch et al. [35] conducted cyclic ring shear tests along with V_s measurements on reconstituted sand-silt mixtures (Ottawa sand and MIN-U-SIL 40) with FC between 50% and 100%. They observed a unique relationship between CRR and V_s with negligible effect of fines content.

The experimental research presented here examines the effects of non-plastic fines on V_s and cyclic resistance of sands. Cyclic triaxial tests were conducted on a sand by varying FC (0–75%). Other variables included in the testing program were void ratio and relative density. The experiments were designed to measure V_s and the cyclic resistance of the specimens concurrently, and thus it was possible to obtain the laboratory CRR-V_s curves for various FC mixtures. It is recognized here that the CRR-V_s relationship is soil-specific (e.g., Ahmadi and Paydar [34], Baxter et al. [28] Tokimatsu et al. [36]) and cannot be generalized for all sandy soils. Nonetheless, the results from current study provide insight into the trends in CRR-V_s correlations for various sand-silt mixtures based on the framework provided by Andrus and Stoke [30] and adopted by Youd et al. [19]. The results then were compared to trends from laboratory studies reported in the literature.

2. Test materials and methods

A total of 134 stress-controlled cyclic triaxial tests were conducted on specimens of F-75 silica sand at variable densities and FC = 0%, 5%, 15%, 30%, 50%, and 75%. Shear wave velocities were measured during 94 of the tests. The index properties of these sand-silt mixtures and experimental procedures used in this investigation are discussed below.

2.1. Index properties

The host sand was F-75, a silica sand with rounded quartz grains. Sil-Co-Sil 125, a ground silica (quartz), was used for the non-plastic (NP) fines (silt) portion of the mixtures. Both F-75 sand and Sil-Co-Sil 125 silt were procured from U.S. Silica. Fig. 1 shows the grain size distributions of these soils and Table 1 summarizes their index properties. As per the Unified Soil Classification System (USCS), the sand and silt were classified as SP and ML, respectively. The minimum and maximum global void ratios of the sand and silt (Table 1) were determined using the method prescribed by Japanese standard JSF T161–1990 [37]. This method consists of measuring the mass of dry sand-silt mixtures in a stainless-steel mold of 60 mm in diameter and 40 mm in height. To measure maximum global void ratio (e_{max}), the soil is poured in the mold using a funnel without causing any vibrations; and to measure minimum global void ratio (e_{min}), the soil is poured in 10 layers and the mold side is tapped 100 times with a wooden hammer after placing each layer.

2.2. Cyclic triaxial testing

The cyclic resistance of a sand-silt specimen was measured using stress-controlled, undrained cyclic triaxial tests in general accordance to ASTM D-5311 [38] using an updated CKC cyclic triaxial apparatus available at the University of Vermont. The specimens were 71 mm in diameter and about 140 mm in height. All specimens were prepared using moist tamping. Three to five specimens for three to five relative densities (within ± 3% variation) were tested for each of the FC. All specimens were first flushed with carbon dioxide, saturated with deaired water under back pressure as needed. To ensure saturation, all the specimens were required to have a 'B' parameter ≥ 0.95. The specimens were then isotropically consolidated to 100 kPa. The relative densities reported in this paper are at end of the consolidation phase.

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