Soil Dynamics and Earthquake Engineering 83 (2016) 98–109

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

journal homepage: www.elsevier.com/locate/soildyn

Cyclic resistance and liquefaction behavior of silt and sandy silt soils

Ali El Takch [a], Abouzar Sadrekarimi [b,*], Hesham El Naggar [c]

[a] Hatch Engineering, Niagara Falls, Ontario, Canada. Formerly MESc Candidate Department of Civil and Environmental Engineering, Western University, London, ON, Canada
[b] Department of Civil and Environmental Engineering, Spencer Engineering Building, Western University, London, ON, Canada N6A 5B9
[c] Department of Civil and Environmental Engineering, Spencer Engineering Building, Western University, London, ON, Canada N6A 5B9

ARTICLE INFO

Article history:
Received 26 November 2013
Received in revised form
28 August 2015
Accepted 9 January 2016

Keywords:
Cyclic resistance
Ring shear test
Shear wave velocity
Silt
Liquefaction
Soil dynamic

ABSTRACT

The liquefaction behavior and cyclic resistance ratio (CRR) of reconstituted samples of non-plastic silt and sandy silts with 50% and 75% silt content are examined using constant-volume cyclic and monotonic ring shear tests along with bender element shear wave velocity (V_s) measurements. Liquefaction occurred at excess pore water pressure ratios (r_u) between 0.6 and 0.7 associated with cumulative cyclic shear strains (γ) of 4% to 7%, after which cyclic liquefaction ensued with very large shear strains and excess pore water pressure ratio ($r_u > 0.8$). The cyclic ring shear tests demonstrate that cyclic resistance ratio of silt and sandy silts decreases with increasing void ratio, or with decreasing silt content at a certain void ratio. The results also show good agreement with those from cyclic direct simple shear tests on silts and sandy silts. A unique correlation is developed for estimating CRR of silts and sandy silts (with more than 50% silt content) from stress-normalized shear wave velocity measurements (V_{s1}) with negligible effect of silt content. The results indicate that the existing CRR–V_{s1} correlations would underestimate the liquefaction resistance of silts and sandy silt soils.

1. Introduction

Following the extensive damage that occurred as a result of soil liquefaction in the 1964 Alaska and Niigata earthquakes [1–3], cyclic liquefaction has become one of the most widely investigated subjects in geotechnical earthquake engineering. This has become even more critical with the increased occurrence of mega-earthquakes around the world. For example, significant liquefaction-related damage occurred following the recent 2011 Tohoku earthquake [4], 2010 Chilean earthquake [5], and the 2010 Haitian earthquake at Port-au-Prince [6].

Cyclic liquefaction behavior has been extensively studied for clean sands [7–9] and sandy soils with less than 35% silt content [10–13], and the existing relationships for liquefaction analysis and the estimation of cyclic resistance of non-plastic soils are often applicable for silty sands with less than 30% silt content [14]. Very little work has been conducted on the liquefaction potential and cyclic shearing behavior of non-plastic silts and sandy silts partly due to the biased perception that fine-grained soils have lower potential to develop excess pore water pressure compared to sands [15]. Nonetheless, a review of past earthquake-induced liquefaction cases indicates that deposits of uniform, clean sand are rare, while liquefaction of sandy silts and silts has been extensively observed in past earthquakes [16–23]. For example, boiling of silt widely occurred following the 1987 Chibaken-Tohooki (Japan) and the 1989 Loma Prieta (United States) earthquakes, and liquefaction of silt vastly occurred following the 1995 Kobe earthquake in the reclaimed coastal areas of Port Island, Japan [24]. Non-plastic mine tailings slimes have also been found to be susceptible to liquefaction [25–27]. Accordingly, there is an urgent need for additional experimental work in order to better understand the liquefaction potential and cyclic behavior of non-plastic silts in order to develop new practical guidelines for evaluating liquefaction susceptibility of primarily silty soils.

Several parameters affect the cyclic resistance of soils including: soil fabric, composition, void ratio, and stress level, which also affect soil shear wave velocity (V_s) [28]. Therefore, several investigators have studied the relationship between cyclic resistance ratio (CRR) of soil and V_s [29–37]. For example, Fig. 1 presents empirical relationships of CRR and an overburden stress-normalized shear wave velocity (V_{s1}) developed by Andrus and Stokoe [30] based on the field observations of liquefaction during past earthquakes. Fig. 1 shows that for a certain fines content (FC), CRR increases with increasing V_{s1} and for the same V_{s1}, CRR increases with increasing the amount of fines up to FC=35%. The relationships presented in Fig. 1 only cover the range of 5% $\leq$ FC $\leq$ 35%, and the effect of FC > 35% on CRR–V_{s1} relationship is largely unknown and therefore the existing correlations for the

---

* Corresponding author. Tel.: +1 519 661 2111x80334.
E-mail address: asadrek@uwo.ca (A. Sadrekarimi).

http://dx.doi.org/10.1016/j.soildyn.2016.01.004
0267-7261/

estimation of CRR from V_{s1} are not applicable to silts and sandy silts ($FC \geq 50\%$). Another major drawback of field-based empirical relationships, similar to those presented in Fig. 1, is that the in-situ V_{s1} is often measured after the occurrence of liquefaction and describes the state of the post-liquefied soil. Therefore, these relationships do not represent the initial state of the soil prior to liquefaction and would involve some degree of uncertainty for assessing the liquefaction potential. Accordingly, laboratory shear tests on loose cohesionless soils have been used to develop CRR–V_{s1} relationships. However, most of these studies have been conducted on sands and silty sands with $FC \leq 35\%$ [31,33,38–42]. Only a limited number of studies have investigated higher FC and pure silts [29,36,43].

In the present study, a comprehensive laboratory testing program is conducted using an advanced ring shear apparatus in order to characterize the cyclic behaviors of silts and sandy silts (with $FC \geq 50\%$) based on CRR and V_{s1} measurements. A series of constant-volume cyclic ring shear tests along with bender element shear wave velocity measurements are conducted on silt and sandy silt specimens with different amounts of sand (25% and 50%).

While several studies have investigated the cyclic shearing behavior of silt in axisymmetric triaxial compression tests [27,44–50], field structures (e.g., slopes, embankments, long retaining walls) are often governed by plane strain conditions [51]. In a ring shear test, the sample is laterally confined between pairs of solid rings and therefore the sample is subjected to a plane strain mode of shearing similar to cyclic direct simple shear tests. Furthermore, the in-situ strain condition in an earthquake is predominantly applied on a horizontal plane and normal to the direction of soil deposition, and hence the application of a vertical cyclic load to a cylindrical triaxial specimen may not precisely produce the in-situ dynamic loading condition during an earthquake. Therefore, cyclic ring shear testing can be considered to effectively represent the in-situ stress conditions under seismic loading. Ring shear tests are also particularly effective in obtaining soil shear response at large shear displacements. Accordingly, cyclic ring shear tests are employed in this study.

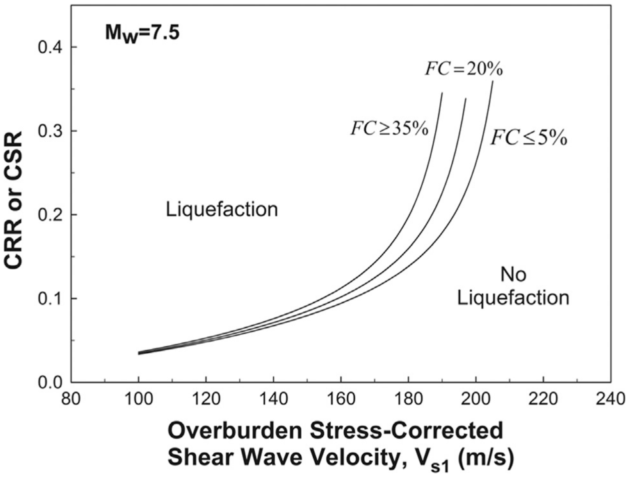

Fig. 1. Empirical CRR–V_{s1} relationships for silty sands ($5\% \leq FC \leq 35\%$) suggested by Andrus and Stokoe [30].

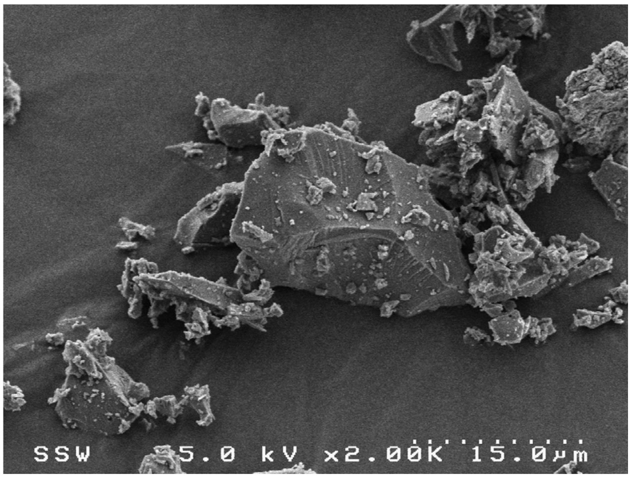

Fig. 2. SEM image of silt particles used in this study.

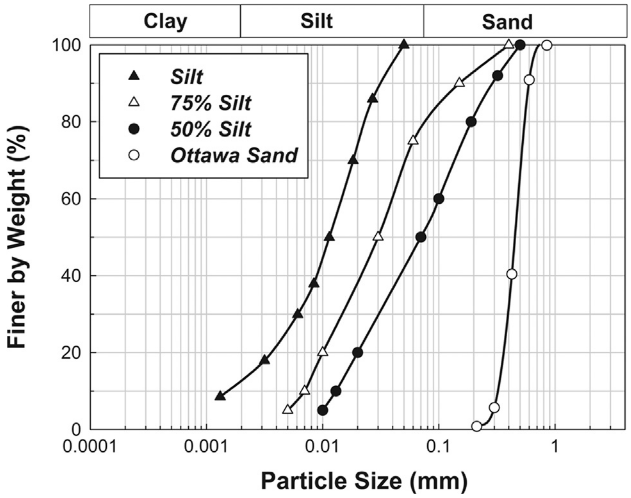

Fig. 3. Average particle size distributions of the soils used in this study.

2. Materials tested and specimen preparation method

Reconstituted specimens of non-plastic silt and sandy silts with 50% and 75% silt content were prepared and tested in the experimental program of this study. The silt used in this study (MIN-U-SIL 40) was produced from the grinding of silica sand by US Silica Company in Berkeley Springs, West Virginia. The silt was mainly composed of white-colored quartz particles. Scanning electron microscopic images of the silt particles in Fig. 2 indicate angular and irregular particle shapes. The added sand was a quartz Ottawa sand with round to subrounded particle shapes. Fig. 3 and Table 1 present the particle size distributions and the index properties of these materials as well as the mixtures.

Because of the large bulking potential, the ASTM standard methods [52,53] are not applicable for soils with more than 15% fines content and therefore the maximum (e_{max}) and minimum (e_{min}) void ratios were consistently determined using a slurry deposition technique [48] and the modified proctor procedure [54] respectively. As illustrated in Fig. 4, e_{max} and e_{min} and their difference increase with increasing silt content which is consistent with similar trends reported by other investigators [55,56].

The moist tamping method was used to prepare all soil specimens in this study, where each specimen was prepared in layers and tamped at a moisture content of 5%. The under compaction technique recommended by Ladd [57] was used to account for the increased density of the lower layers by compaction of the upper layers and produce homogenous specimens. An adjustable clamp on the tamping rod was used during specimen preparation to control the drop height of the tamper and thus specimen void ratio. This technique would provide comparable cyclic shearing