Soil Dynamics and Earthquake Engineering 104 (2018) 372–377

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Liquefaction resistance of fibre reinforced low-plasticity silt

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ARTICLE INFO

Keywords:
Low plasticity silt
Liquefaction resistance
Cyclic triaxial
Fibre

ABSTRACT

This study sought to investigate the effect of bulk continuous filament (BCF) on the liquefaction resistance of low plasticity silt by performing a series of cyclic triaxial tests on the reference (unreinforced) and reinforced specimens. The effects of BCF contents and length (*BL*), relative density (D_r), and effective confining pressure (σ'_3) on the liquefaction strength of the reinforced specimens were investigated and the results were compared with the reference tests. The results showed that increasing the BCF content improved the liquefaction resistance of the silt. Also, it was noted that increasing the fibre length from 5-mm, to 10-mm and 15-mm respectively, increased the liquefaction resistance of the specimens. The results in the next stage showed that by increasing the relative density (D_r), liquefaction resistance of a reinforced specimen is more pronounced than that of an unreinforced specimen. Finally, investigations on the effect of effective confining pressure (σ'_3) on the liquefaction resistance of the reinforced specimens showed that increasing the effective confining pressure reduced the liquefaction resistance of the specimens due to suppression of the dilatancy.

1. Introduction

Silt is known as a fine-grained soil that is vulnerable to liquefaction during the event of an earthquake [1]. Primarily, Seed et al. [2] noted that a fine-grained soil requires the fulfilment of three conditions in order to be counted as a non-liquefiable soil, based on the Chinese criteria. The constraints involve factors such as having a fines content less than fifteen percent, a liquid limit (*LL*) less than thirty-five percent and a water content (W_c) higher than ninety percent of liquid limit. The liquefaction assessment using Chinese criteria was later challenged by observation of some examples of liquefaction in silty and clayey soils [3]. Some other studies highlighted the importance of the plasticity index (*PI*) as a more crucial set of parameters in studies of fine-grained soil [4–8].

Boulanger and Idriss [9] also discouraged the use of Chinese criteria in the liquefaction investigation of a fine-grained soil and studied mechanical criteria in the liquefaction susceptibility of fine-grained soils. They recognised two groups of the clay-like (when $7 \leq PI$ and $5 \leq PI$ in *CL-ML* soils) and sand-like soils in studying the cyclic behaviour of fine-grained soils and proposed using the term “cyclic softening failure” instead of “liquefaction” for fine-grained soil with clay-like behaviour. El Takch et al. [10] also studied the cyclic behaviour of a silt and a sandy silt soil and reported that non-plastic silts are susceptible to liquefaction and they behave similarly to sand in terms of excess pore water generation and strain. They also indicated that the cyclic stress ratio (*CRR*) of the soil increased with the increase of silt content at the same void ratio.

Application of fibre in ground improvement originated from the reinforced soils by the roots of trees. Many studies have been performed to investigate the effect of the fibre reinforcement. For instance, Boominathan and Hari [11] investigated the effect of fibre reinforcement on the liquefaction strength of fly ash. They indicated that the addition of fibre increased the liquefaction resistance of fly ash due to the provision of interlocking behaviour and dissipating excess pore water pressure amongst fly ash particles.

In another case, Noorzad and Amini [12] investigated the effect of fibre reinforcement on the cyclic strength of silty sand and reported that the addition of fibre reduced the liquefaction susceptibility of the soil. They also indicated that reinforcement is more effective in specimens with medium density than in loose samples [12]. In another study, Vercueil et al. [13] investigated the effect of the addition of woven and non-woven geosynthetics with different mechanical characteristics to the sand and reported that the cyclic strength of the soil increased when geotextiles were included in the sand. Maher and Ho [14] investigated the behaviour of fibre-reinforced cemented sand under cyclic loading. The results indicated that the addition of fibre improved the cyclic strength of the cemented sand.

The liquefaction vulnerability of the fine-grained soil was discussed in the aforementioned literature and it was proven that low plasticity silt is a type of fine-grained soil that is prone to liquefaction, and has a behaviour similar to that of coarse-grained soils such as sand. Also, according to the literature, it was noted that fibre reinforcement is an

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https://doi.org/10.1016/j.soildyn.2017.11.004
Received 26 September 2016; Received in revised form 23 August 2017; Accepted 4 November 2017

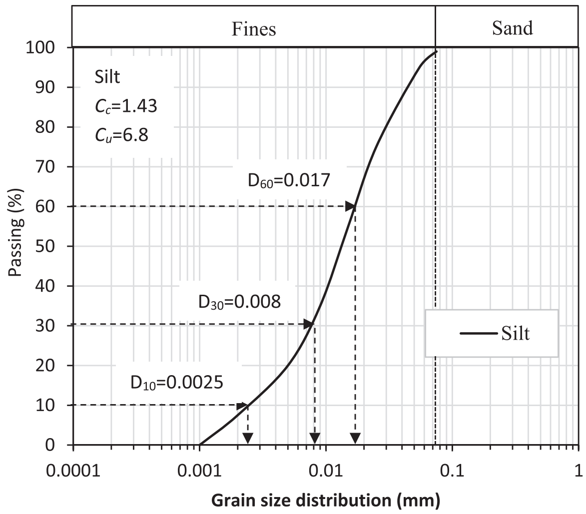

Fig. 1. Particle size distribution (PSD) of the used silt.

accepted approach in liquefaction mitigation. Therefore, this study investigates the fibre reinforcement of low plasticity silt. This research is in continue of the Liquefaction study [15] at Curtin University.

2. Test materials

The silt used for this study was sourced from Canning River, Perth, Western Australia. The particle size analysis conducted on the low-plasticity silt and the results were presented in Fig. 1 (ASTM D4221 [16]). The analysis showed that the used silt has a coefficient of uniformity (C_u) and a coefficient of curvature (C_c) of 6.8 and 1.43 respectively. Also, the particle size distribution (PSD) analysis showed that this soil has a mean grain size (D_{50}) of 0.014 mm, and a D_{10} and D_{60} equal to 0.0025 and 0.017-mm respectively. The index properties tests were performed according to ASTM D4318 [17], and the results showed that the used silt has a liquid limit (*LL*) of 26%, plastic limit (*PL*) of 21.4%, and a plasticity index (*PI*) of 4.6%. The used silt is classified as the *ML* according to the Unified Soil Classification System (USCS) (ASTM D2487 [18]). The fibre used to reinforce the specimens is known as bulk continuous filament (BCF) fibre, and has a tensile strength, and an elastic modulus of 415 MPa and 3.12 GPa respectively. Also, the proportion of mass to length and the specific gravity was equal to 0.96 g/cm and 1.25 respectively. Fig. 2 presents a typical BCF used in this study.

3. Sample preparation

The "wet tamping" and the "slurry deposition" methods are two main sample preparation techniques in triaxial testing, and selection of

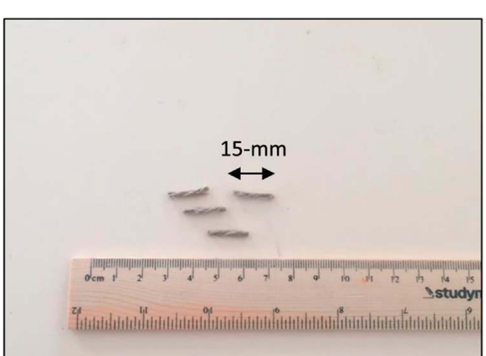

Fig. 2. Bulk continuous filament (BCF) cut in 5, 10, and 15-mm lengths.

each method would affect the results of the study [19]. During the testing phase, it was figured out that the wet tamping technique (i.e., under-compaction) works better, since in this method the uniformity of the reinforced specimens is maintained rightfully. In contrast with the wet tamping technique, the specimen is unable to stand alone during the trimming due to its inability to hold suction in the slurry deposition method [20]. The sample preparation using the under-compaction technique is a well-accepted and applicable method for silt as indicated by Ladd [21] and Prakash and Sandoval [8]. In this method, the lower layer becomes denser by compaction of the upper layer, and each layer becomes compacted to a lower density than the previously targeted. Therefore, the under-compaction rate of each layer linearly varies from the bottom to the top of the specimen, and the required under-compaction can be estimated [22]. Application of this fabrication technique helps the user to have good control of the density of each layer while the BCF is not segregated, and a situation similar to the real condition has been simulated for a reinforced specimen. In this study, specimens with uniform density and identical BCF distribution by moist tamping the silt mixture in 5 layers was obtained using the under-compaction technique. The cylindrical specimens with 120-mm height and 62.5-mm diameter were prepared for each test. To prepare the specimens initially, the silt was mixed with BCF and/or clay and thoroughly stirred. Then, a water content equal to 8% of the weight of the mixture was added to the mixture for ease of mixing, and thoroughly stirred [8,12]. The specimens were fabricated in three initial relative densities (D_r) of 40%, 60%, and 80%. Also, the recorded maximum and minimum relative density was of 0.76 and 0.52 respectively.

4. Methodology

A series of stress-controlled cyclic triaxial tests were performed in accordance with ASTM D 5311 [23] to investigate the effect of BCF reinforcement on the silt specimens using a Geocomp cyclic triaxial apparatus. To conduct the tests, CO_2 gas was injected through the specimen for about one hour [22]. Then, the distilled and de-aired water was passed through the specimen using a low pressure. After that, the distilled and de-aired water was injected through the specimen using a minimum amount of 500-kPa back pressure. The saturation stage was then completed when the ratio of the pore water pressure (Δu) to the variation in cell pressure ($\Delta\sigma_c$), or simply B_{value}, was equal or greater than 0.95 ($0.95 \leq \Delta u/\Delta\sigma_c$). In the consolidation stage, the desired effective confining pressures (σ'_3) of 50, 100 and 150-kPa were applied to the specimens. The variations of the axial displacement and pore water pressure were recorded with a symmetrical sinusoidal pulse frequency of 0.5-Hz and cyclic stress ratio (*CSR*) of 0.18, 0.25 and 0.35 were selected according to Eq. (1).

$$CSR = \frac{(\sigma'_{max} - \sigma'_{min})}{2\sigma'_{min}} \quad (1)$$

where σ'_{max} = maximum principal effective stresses; and σ'_{min} = minimum principal effective stresses. Table 1 illustrates the experimental program which followed to conduct the tests. The post-consolidation relative densities ($D_{r,\ p}$) were recorded based on the pre-consolidation relative densities (D_r), and the occurred volumetric strain after the consolidation stage.

5. Results and discussion

5.1. Typical test results

A typical result of the cyclic triaxial test for a silt specimen reinforced with 0.3% BCF, and a post consolidation relative density ($D_{r,\ p}$) of 42.2% at a CSR value of 0.25 was shown in Fig. 3. It is seen from variation of the deviator stress versus number of cycle to liquefaction (q-N_L) that a harmonic loading pattern with ± 75-kPa of deviator stress (q) is applied to the specimen [see Fig. 3(a)]. This harmonic deviatoric