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Cyclic and post-cyclic shear behavior of low-plasticity silt with varying clay content

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ABSTRACT

This paper investigates the cyclic and post-cyclic shear behavior of low-plasticity silt and the impact of additional clay content. Bentonite clay was added to the low-plasticity Mississippi River Valley (MRV) silt (PI = 6) to increase the clay content of the soil. A series of triaxial tests were conducted in the laboratory to examine the shear and pore pressure behavior during and after cyclic loading. As the bentonite content in the reconstituted specimens increased, the excess pore pressure developed at a slower rate and the total excess pore pressure decreased at the end of cyclic loading. In contrast to the MRV silt, the specimens modified with bentonite experienced cyclic softening rather than initial flow liquefaction. The cyclic shear strength increased with an increase in bentonite content. The post-cyclic reconsolidation behavior was a similar to a virgin compression process, and not recompression. Adding bentonite to the MRV silt results in changes in permeability, compressibility, undrained shear strength, and initial stiffness. Additionally, the cyclic loading had a marked effect on the shear behavior of low-plasticity soil with a PI < 6, but not noticeable with a PI > 6. This study suggests that the behavior of the Mississippi River Valley silt changes from contractive sand-like material to clay-like behavior at a PI ≈ 6 due to the addition of clay.

1. Introduction

Low-plasticity fine-grained soils, such as silts, are widespread throughout many countries. As noted by Puri [1], one type of low-plasticity silt, loess, occupies the uppermost stratigraphic layer over extensive areas of the central United States; it is found in other parts of the country as well. Usually, the thickest deposits occur adjacent to the Missouri and Mississippi Rivers to the leeward side of the prevailing westerly winds. Liquefaction of low-plasticity fine-grained soils is a common phenomenon during earthquakes. Initially, the liquefaction potential was evaluated according to the Chinese criteria by Seed et al. [2], in which clay content rather than plasticity index (PI) is used. As pointed out by Seed et al. [3] and Bray and Sancio [4], the condition about percentage of "clay-size" particles in the Chinese criteria is misleading and the importance is the percent of clay minerals present in the soil. Therefore, the plasticity index is being used as one of the key parameters in liquefaction criteria to evaluate the liquefaction potential. As presented by Boulanger and Idriss [5], there is a transition zone for cyclic behavior of fine-grained soil, which transitions from sand-like to clay-like as the plasticity index increases. Boulanger and Idriss [5,6] proposed that the soils with PI > 7 can confidently be expected to exhibit clay-like behavior (i.e., cyclic softening, meaning that soil failure develops before excess pore pressure ratio approaches 1.0). The soils with PI < 7 has initial flow liquefaction (i.e., soil failure develops only after the excess pore pressure ratio reaches or is close to 1.0) under cyclic loading.

The effect of plasticity index on the liquefaction resistance of soil has been studied by a several researchers in the Midwest USA. Puri [1] found that the cyclic strength increased with an increase in plasticity index (PI = 1–20), by conducting cyclic triaxial tests on the undisturbed and reconstituted silt from Memphis, TN. Conversely, Sandoval [7] observed that the silt from East Saint Louis, IL had a decrease in cyclic strength when the PI increased from 1.7 to 3.4; but with the PI = 12, the silt had higher cyclic strength than the silt with the PI of 3.4. Izadi [8] added kaolinite to the silt from Collinsville, IL to form soil mixtures having 5% and 10% kaolinite. The tests indicated that the cyclic strength decreased with an increase in clay content, because of a decrease in hydraulic conductivity and no obvious increase in plasticity index. Guo and Prakash [9] stated that the liquefaction resistance increases with a decrease in plasticity index in the low range,

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conversely, the opposite is true in the high range of plasticity index. They suggested that there was a need for further systematic study of the liquefaction behavior of silty and silty clay mixtures.

Other researchers have found other factors affecting the liquefaction resistance, such as the mineralogy and ion content in water. Beroya et al. [10] studied the effect of mineralogy on the cyclic strength of silt–clay mixtures. Three different clays, including kaolinite, illite, and montmorillonite, were used as admixtures to the non-plastic silt. Beroya et al. [10] concluded that the relationships of percent clay fraction, percent clay mineral and PI with cyclic strength are not unidirectional and they cannot be used to evaluate the susceptibility to cyclic failure, because the PI does not adequately encapsulate the effects of clay mineralogy on the cyclic strength of soils. This finding challenges the previous liquefaction criteria, in which the PI is an important indicator to evaluate liquefaction resistance. As a comparison, the work of Gratchev et al. [11] studied the effect of clay content on sands. They studied the liquefaction resistance of clayey sand, concluding that liquefaction resistance increased with an increase in plasticity using pure ware. However, when the clayey sand had a high ion concentration in the pore water, questions are brought on the effectiveness of PI as a measure of liquefaction resistance.

Logically, the effect of previous cyclic loading on the monotonic shear behavior (post-cyclic behavior) should be different for the soils with different PI. However, few reports address the effect of PI on the post-cyclic shear strength and stiffness due to cyclic loading. Song et al. [12] found that stiffness decreased with the excess pore pressure ratio for non-plastic silt and it was less evident for the Arakawa clay (PI = 17.3). However, case histories presented by Robertson [13] indicate that very young, very loose, non-plastic or low-plastic soils tend to be more susceptible to significant and rapid strength loss than older, denser, or more plastic soils. Alba and Ballestero [14] stated that increasing the fines content decreases the undrained shear strength of soil after liquefaction, but they did not investigate the effect of PI on the undrained shear strength due to cyclic loading. Thus, post-cyclic shear strength decreases with an increase in PI, as static shear strength of low-plasticity soil varies as a function of PI. However, based on the data reported by Song et al. [12] and Robertson [13], there were no consistent results reported on the effect of PI on the post-cyclic shear strength and stiffness of these materials. This paper presents results of the cyclic and post-cyclic shear behavior of low-plasticity Mississippi River Valley (MRV) silt and the impact of added clay content (bentonite).

2. Testing material

The soil material tested herein was obtained from Collinsville, Illinois, which is located in the Mississippi River valley, about 13 miles east of the Mississippi River. The grain size distribution was obtained using sieve and hydrometer analysis (ASTM D 422), and the clay and silt contents were determined as 14.5% and 80.5%, respectively. It is difficult to measure the liquid limit of low-plasticity silt using the Casagrande (cup) approach, because the silt paste cracks easily when cut with a grooving tool. To confirm the validity of the liquid limit obtained from the Casagrande method (ASTM D 4318), the Fall Cone method (BS 1377-2) was also used. The Casagrande and Fall Cone methods indicated liquid limits of 28 and 30, respectively. When comparing these methods, Koester [15], Sridharan and Prakash [16], and Prakash and Sridharan [17] also found the liquid limit slightly lower with the Casagrande method. The liquid limit was determined to be 28 to provide a reasonable comparison with other silts also tested using this method and following the referenced ASTM method. More discussion on the measurement of liquid limit on low-plasticity silt can be found in Wang [18], Wang et al. [19] and Wang and Luna [20].

The minimum and maximum void ratios were determined using the modified compaction method (ASTM D 1557) and allowing silt slurry to settle in a graduated cylinder, following the methods previously described by Polito and Martin [21] and Bradshaw and Baxter [22]. A consolidation test was carried out using isotropic confining pressure in a triaxial chamber to measure the compression and recompression indices. The index properties and compressibility parameters are summarized in Table 1. To increase plasticity index, sodium bentonite was added to the silt. The corresponding index properties for the modified silt are also included in Table 1. The values of LL, PL and PI were rounded to integers according to ASTM standards D 4318. However, to show the small changes of LL, PL and PI, their values are placed with tenths in the brackets in Table 1. It can be found that both LL and PL only increased by 1, and so the PI remained nearly constant, when the bentonite content increased from 0% to 2.5% by weight. However, when the bentonite content increased from 2.5% to 5.0%, the LL increased by 4 and the PL remained constant, increasing the PI by 4. The corresponding clay contents are also listed in Table 1. The clay (portion $< 2\ \mu m$) content increased steadily when the bentonite content increased from 0% to 5.0%.

3. Testing procedure

3.1. Cyclic shearing

The liquefaction resistance of the MRV silt and its mixtures with bentonite were studied by conducting cyclic triaxial tests on specimens reconstituted using a slurry consolidation method, developed by Wang et al. [19]. The specimens were prepared in a split vacuum mold on a special experimental setup and then moved to the triaxial pedestal. Before supplying back pressure for saturation, a vacuum less than the effective consolidation pressure was applied to the top and bottom ends for each specimen to remove as many air bubbles as possible. The application of vacuum helped with the back pressure saturation process of the specimen. The back pressure was increased on increments of about 25 kPa until the Skempton B-value remained constant and reached at least 0.94 for each specimen. All specimens were normally consolidated to an effective consolidation pressure (σ'_c) of 90 kPa, with no initial shear stress. The void ratio (e) for each specimen after consolidation is shown in Table 2. The cyclic triaxial tests followed the procedures in ASTM D 5311-92. Cyclic triaxial tests were conducted with a controlled deviator stress and the applied cyclic stress ratios (CSRs) are listed in Table 2. The frequency of all experiments was 0.1 Hz and the cyclic stress was a symmetrical sine function. For the purpose of post-cyclic testing, the cyclic loading was limited to 9% single-amplitude axial strain for each specimen. After cyclic loading, the deviator stress was slowly reduced to zero for each test, resulting in a small change in axial strain. Table 2 summarizes the testing program used to investigate the cyclic strength of the MRV silt and its mixtures with bentonite, which resulted in a total of 12 cyclic triaxial tests.

Table 1
Index properties of the MRV silt and its mixtures with bentonite.

Bentonite content	0%	2.5%	5.0%
Clay content ($< 2\ \mu m$)	14.5%	16.6%	18.8%
Liquid limit (LL)	28 (28.1)	29 (28.9)	33 (32.7)
Plastic limit (PL)	22 (22.3)	23 (22.7)	23 (23.3)
Plasticity index (PI)	6 (5.8)	6 (6.2)	10 (9.4)
Specific gravity	2.71	2.70	2.68
Maximum void ratio	1.60	NA	NA
Minimum void ratio	0.44	NA	NA
Compression index (C_c)	0.0896	0.1280	0.1991
Recompression index (C_r)	0.0090	0.0096	0.0156