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Small And Large Strain Dependence On Cyclic Behavior Of Silts And Silt-Clay Mixtures

De Petite Et Grande Dépendance Sur Le Comportement Cyclique Des Sables Et Des Mélanges De Silt-D'argile

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ABSTRACT: The 1999 Kocaeli earthquake in Turkey caused great destruction of structures and lifelines in the city of Adapazarı. The city of Adapazarı, which is mostly located on a deep alluvial basin in the near field of the ruptured North Anatolian Fault. The soil underlying in the Adapazari is dominantly silts, clays and silt-clay mixtures. In Adapazari, many buildings collapsed or were heavily damaged, hundreds of structures tilted and penetrated into the ground due in part to liquefaction and ground softening. In this study, both cyclic torsional shear and cyclic triaxial shear tests were performed on the specimens of silt and silt-clay mixtures. Tests conducted on reconstituted and undisturbed sample from the city of Adapazarı. The main objective of this study was to investigate the cyclic failure mechanism of these type of soils and to determine the small strain behaviour of soils. In conclusion, the ground failure and liquefaction potential of each of the site categories and failure mechanisms that might have led to the observed building performance were discussed in the study.

RÉSUMÉ: Le tremblement de terre de 1999 à Kocaeli en Turquie a provoqué de grandes destructions de structures et de lignes de vie dans la ville d'Adapazarı. La ville d'Adapazarı, située pour la plupart dans un bassin alluvial profond, dans le champ proche de la faille nord-anatolienne déchirée. Le sol sous-jacent dans l'Adapazari est principalement constitué de limons, d'argiles et de mélanges de limon et d'argile. À Adapazari, de nombreux bâtiments se sont effondrés ou ont été lourdement endommagés, des centaines de structures se sont inclinées et ont pénétré dans le sol, en partie à cause de la liquéfaction et de l'adoucissement du sol. Dans cette étude, des essais de cisaillement en torsion cyclique et triaxial cyclique ont été effectués sur des échantillons de mélanges de limon et de mélanges de limon et d'argile. Tests effectués sur des échantillons reconstitués et non perturbés de la ville d'Adapazarı. L'objectif principal de cette étude était d'étudier le mécanisme de défaillance cyclique de ce type de sols et de déterminer le comportement des sols en petites déformations. En conclusion, l'étude a porté sur les défaillances du sol et le potentiel de liquéfaction de chacune des catégories de sites et sur les mécanismes de défaillance qui auraient pu conduire à la performance observée du bâtiment.

Keywords: Cyclic behavior; Liquefaction, Silt-clay mixture.

1 INTRODUCTION

After the 1999 disastrous Kocaeli earthquake, much structural damage and many casualties have occurred as a result of ground failures generated due to the softening and the liquefaction of foundation soils (Bray et al., 2001, 2004a, 2004b). The determination of cyclic undrained shear strength reduction plays an important role for low plastic silty clays and clayey silts. The observations of the field conditions and damaged areas after the earthquakes showed that under cyclic loadings, bearing failure occurs in low plastic silty and clayey soils due to the rapid increase in shear strains and the limited amount of pore water pressure resulting from ground softening. The previous studies made by several researchers agreed with the field observations considering the cyclic behavior of low plastic silty and clayey soil.

Although silts are classified as fine-grained soils their cyclic behavior can be different from that of clays. The difference in the cyclic shear strength properties and the pore water pressure response during cyclic loading depends upon the plasticity of fines content. Pore pressure increases up to a certain amount in plastic silty clays, whereas it can reach the effective confining pressure in one cycle of loading in saturated sandy silts and silty sands. Thus, a large amount of deformation occurs in the soils due to the rapid increase of pore water pressure, resulting in the reduction of effective stresses that cause soil liquefaction (Vaid, 1994). The plasticity of fines content is one of the major parameters that affect the cyclic behavior of undisturbed silty soils (El Hosri et al., 1984; Zhu and Law, 1988; Erken and Ansal, 1994). The cyclic strength of undisturbed non-plastic silts is lower than that of plastic silts. Puri (1984) investigated the effect of the plasticity index on the cyclic undrained shear strength of normally consolidated silty soils, conducting cyclic triaxial tests on reconstituted soil specimens. From the results, it was determined that the shear stress ratio causing 5% double amplitude shear strain increases significantly with the increase in the plasticity index at the same number of cycles. Ansal and Erken (1989) discuss the cyclic yield strength level as having a critical cyclic shear strain level above which soils undergo rapidly large deformations at every cycle.

The effect of clay and silt content on the cyclic behavior of coarse-grained soils under dynamic loads has been widely investigated since the 1960’s. However, there is some contradiction between previous research efforts in explaining the effect of fines content and the role of plasticity in determining the liquefaction susceptibility of silty soils. Furthermore, the conclusions vary significantly for non-plastic silts. Several researchers found that the liquefaction resistance increased with the silt content (Ishihara et al., 1978; Okusa et al., 1980; Garga and McKay, 1984; Dobry et al., 1985; Finn et al., 1994; Hyodo et al., 1998, Amini and Qi, 2000), while other contrasting studies indicated an increasing effect of silt content on the liquefaction susceptibility (Shen et al., 1977; Ishihara et al., 1980; Troncoso and Verdugo, 1985; Vaid 1994; Yasuda et al., 1994, Chien et al., 2002). A third group of relatively recent research findings reflect a decreasing liquefaction resistance up to a certain limiting silt content followed by an increasing behavior (Koester, 1994 and 1998; Thevanayagam et al., 2000; Polito and Martin, 2001; Bouckvalas et al., 2003; Xenaki and Athanasopoulos, 2003). Guo and Prakash (1999) conclude that the understanding of the cyclic behavior of silts and silty sand mixtures is not very clear and that further research is necessary.

In this study undisturbed and disturbed soil samples were taken from Adapazari sites, and soils were predominantly consisted of fine-grained surface soils of low plastic nature (silt–clay mixtures), defined as silty clays (CL) or clayey silts (ML), according to the Unified Classification System. To investigate the undrained shear and deformation behavior of

Adapazarı silt –clay mixtures, a series of stress-controlled cyclic triaxial and cyclic torsional shear tests are performed in parallel on the natural soil specimens. The specimens were isotropically consolidated, and tests were carried out under both uniform and multi-stage cyclic shear stress to obtain small and large strain behaviour of silty and clayey soils.

2 EXPERIMENTAL STUDIES

Shear and deformation characteristics of Adapazarı silt–clay mixtures are studied through a series of undrained stress controlled cyclic torsional and triaxial tests. The tests were carried out on both reconstituted and the undisturbed specimens, representative of foundation soils, sampled from depth near the surface. Since the surface soils of the Adapazarı basin have highly heterogeneous nature and their engineering properties can vary to a large range, the samples were classified in identical material properties.

In this study, the variation of cyclic strength properties in saturated clayey and silty soils, isotropically consolidated at different confining pressures, was investigated through a series of stress-controlled undrained cyclic torsional triaxial shear tests on cylindrical, hollow-center samples as well as triaxial. Wet tamping samples of non-plastic silts were subjected to a uniform cyclic sinusoidal loading at a 0.1 Hz frequency. Parameters such as the amount of fines by weight within a sample, anisotropic consolidation pressure, applied confining pressure and relative density were varied one-at-a-time while others were held constant. Cyclic shear stress-strain changes, the number of cycles to reach liquefaction and pore pressure variations were recorded during testing. Testing was continued until the measured pore pressures reached 96% of the effective confining pressure and double strain amplitudes exceeded 10%.

An example of test results for a reconstituted silty soil sample is given in Figure 1. Cyclic shear strain ($\gamma_{z\theta}$), cyclic shear stress ($\sigma_{z\theta}$) and generated pore water pressure (u) during undrained cyclic testing at a predetermined confining pressure following consolidation (σ_{mo}) can be measured utilizing the cyclic torsional shear apparatus.

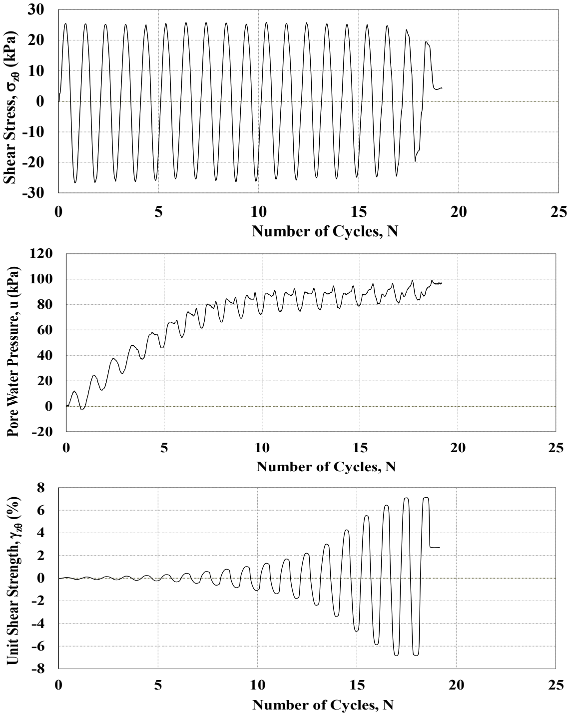

Figure 1. Typical results of liquefaction test

2.1 Properties of testing materials and specimen preparation

The reconstitution method used in this study is the wet tamping. All the hollow and triaxial specimens were prepared with layer by layer. Reconstituted specimens have an inner radius of 3 cm, outer radius of 5 cm and height of 20 cm as a hollow cylindrical specimen. After initial saturation, back pressure was applied to the specimens. The soil samples exhibited a pore water pressure parameter (B) of 0.96 or greater. Then a constant effective pressure of 100 kPa was applied to the specimens isotropically, and the consolidation lasted 24 h prior to cyclic loading. The volume change of the specimen and of the inner cell was recorded, including the change in the axial vertical displacement after consolidation was completed. The dry unit weight (γ_d) of the specimens following consolidation was determined for each test.

Undisturbed soil specimens were prepared using an outer mold to hold the cylindrical specimen, while the inner part of the specimens was carved with a special screw by applying torque. The inner radius of undisturbed hollow cylinder specimens was 1.50 cm, the outer radius is 3.50 cm and the height of specimens was approximately 14.00 cm each. After placing the undisturbed specimen into the triaxial cell, back pressure of 200 kPa with the effective in situ load was applied. Then the back pressure was increased by checking the value of B. All the undisturbed specimens exhibited a saturation ratio greater or equal to 0.96. Then the specimens were consolidated isotropically to an effective stress of 100 kPa. After the consolidation process, torque loading was applied to the specimen cyclically in cyclic tests.

Table 1. Physical Properties of Silts and Clay

Soil Type	**Clay**	**Silt**
USGS Classification Symbol	CL	ML
Specific Gravity, G_s	2.72	2.73
Liquid Limit; ω_L (%)	56-73	27-34
Plastic Limit, ω_P (%)	34-47	18-21
Plasticity Index, PI (%)	22-34	9-14

2.2 Testing programme

All samples were isotropically consolidated to 100 kPa effective confining stress and cyclic tests were performed at a frequency of 0.1 Hz under different cyclic shear stress ratios in order to eliminate the effects of consolidation pressure and the loading frequency. The testing program consisted of four test series, each designed to investigate a particular effect of the undrained cyclic behavior of the reconstituted and undisturbed silty and silty clay soil specimens. Series 1 included the cyclic tests conducted on reconstituted specimens with a plasticity index of 9–27.

In the second series, the cyclic shear strength of the undisturbed silty-clay soil specimens was determined by applying cyclic stress till the failure condition of DA (double amplitude) 5% shear strain occurred. Cyclic shear stress ratios (τ_d/σ_c) were changed in every test, and the number of cycles increased with the decrease in shear stress levels. Series 3 multi-stage cyclic tests were performed in order to determine the small strain behaviour of silty and clayey soils. At the end of the tests, the results of reconstituted and undisturbed soil specimens and the results of silty and clayey soil were compared.

3 TEST RESULT AND DISCUSSION

In this study, cyclic tests were conducted on reconstituted and undisturbed silty and clayey specimens. Figure 2 shows the relationships between shear stress versus the number of cycles to cause liquefaction of reconstituted soil specimens having same plasticity index (PI). Shear stress ratio increases by the increasing of the clay fraction to reach the liquefaction or strain softening.

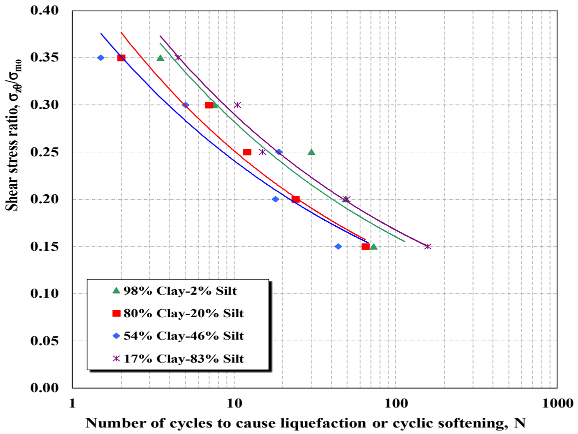

Figure 2. Cyclic test result conducted on different soil sample

Excess pore water pressure can easily increase and effective stresses decrease significantly in silty soil under cyclic stress. This decrease would be more pronounced in the low plastic range, because the pore pressure increases significantly in low plasticity silty soils (Figure 3). The contractive behavior of low plasticity silty soils seems to be the same as for clean fine sands under cyclic loading (Ishihara, 1985; Lade and Yamamuro, 1997).

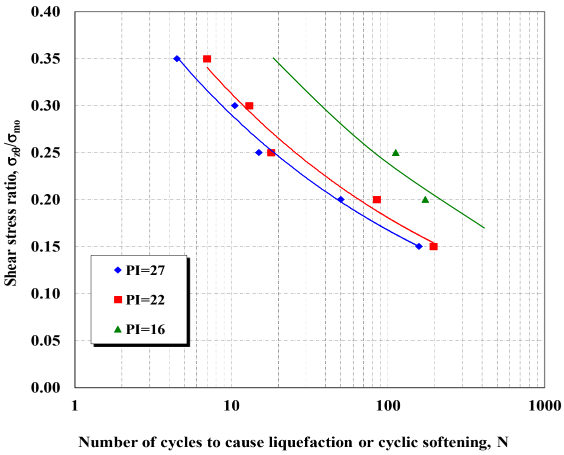

Figure 3. Cyclic test result conducted on silty soil samples having different PI

Figure 4 shows the cyclic behavior of low plasticity silty soil reconstituted and undisturbed samples by a shear stress versus number of cycles to cause liquefaction. It can also be concluded that the different test techniques result from these figures. The cyclic tests were conducted at stress ratios of 0.150 and 0.350, respectively. Undisturbed specimens have considerably more cyclic strength, and show more resistance to earthquake loading with respect to the reconstituted specimens depending on the actual fabric having an in-situ stress history and less fines and limited disturbance, according to in-situ frozen samples (Yoshimi et al., 1989) even though they are softer than reconstituted specimens.

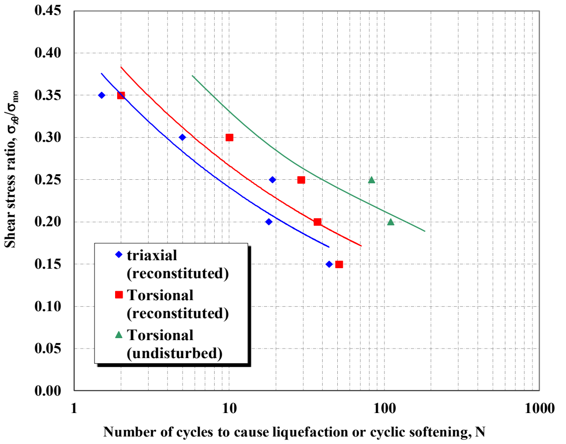

Figure 4. Cyclic test results conducted on undisturbed and reconstituted samples by torsional and triaxial shear apparatus

Figure 5 shows typical degredation curves of undisturbed silt-clay mixture soil specimens with a plasticity index of 18-26. 100 kPa consolidation pressure was applied to the specimens, and starting the very small level, multi-stage shear stress was applied to the specimen to obtain small stress-strain relationship. Dynamic shear modulus degradation curves can be drawn at the end of the test. It can be figured out that clay fraction is effective on the stress-strain behaviour of the fine soil.

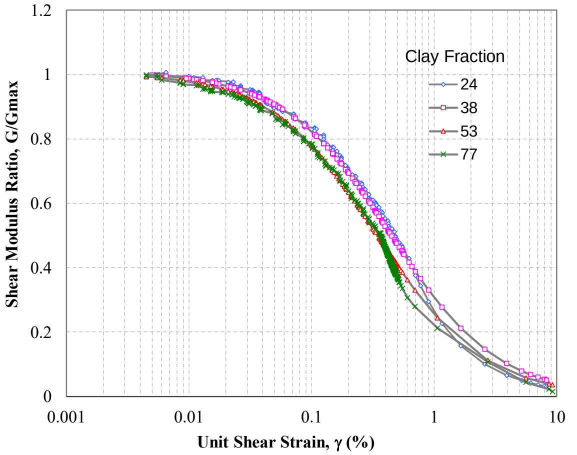

Figure 5. Clay fraction effect on the shear modulus degradation curves of fine grain soil

The cyclic undrained test results can be seen in Figure 6 showing the dynamic shear modulus ratio versus unit shear strain. This figure also represents the cyclic undrained behavior of silt soils. The reconstituted specimens have a plasticity index between 16 and 27. Dynamic shear modulus degradation curves can be obtained at the end of the test. It can be figured out that clay fraction is effective on the stress-strain behaviour of the fine grain soil. As can be seen in Figure 6, a slight difference was obtained between the cyclic behavior of silty (PI=16) and silty clay soil (PI=27).

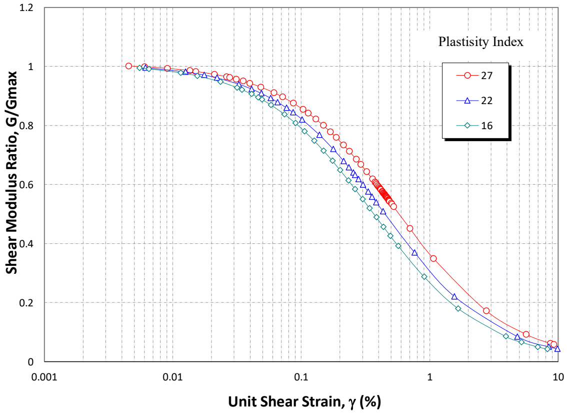

Figure 6. Effect of PI difference on the shear modulus degradation curves of fine grain soil

4 CONCLUSIONS

Stress-controlled cyclic torsional and triaxial shear tests were carried out on undisturbed and reconstituted silty and clayey samples under varying initial and testing conditions. The liquefaction resistance and pore pressure development were measured and compared for different soil properties and experimental settings. The following conclusions can be derived from the analysis of test results and observations made within the context of this study:

1. Experimental results indicate that the liquefaction resistance and pore pressure generation are sensitive to the amount of silt content present within the soil matrix.
2. The results of cyclic undrained torsional and triaxial shear tests conducted on both reconstituted and undisturbed low plastic silty and silty clay soils show that shear strains increase rapidly and steadily until the failure limit described as 5% DA shear strain level, but excess pore water pressures increase only at a limited amount.
3. The cyclic undrained shear strength of undisturbed soft silty soil is considerably higher than that of reconstituted specimens depending on the aging and initial fabric.
4. It can also be concluded that small stress-strain behaviour of the fine grain soils slightly depends on the clay fraction and plasticity index of soil.

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