THE POST CYCLIC SHEAR STRENGTH OF FINE GRAINED SOILS

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ABSTRACT :

In this study the effect of cyclic loads on monotonic shear strength has been studied on torsional test apparatus. Tests have been conducted on both reconstituted and undisturbed fine grained hollow soil specimens with the plasticity index varied from 5 to 18. Stress controlled dynamic tests were performed under different cyclic shear stress ratios, and monotonic tests were conducted on soil specimens controlling the strain rate in order to determine the pre-cyclic and post-cyclic static shear strength. The post-cyclic monotonic shear strengths were evaluated after various numbers of cycles of dynamic loading. If soil undergoes a cyclic shear strain level below the cyclic yield strain, reduction of monotonic strength of reconstituted and undisturbed specimens is limited, but when cyclic shear strain level is larger than yield strain monotonic strength decreases down to 40% of its initial strength.

KEYWORDS: clays, undisturbed soils, softening, post-cyclic monotonic shear strength

1. INTRODUCTION

After the 1999 disastrous Kocaeli earthquake, much structural damages 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; Erken, 2001, 2006, 2007; Yasuda et al., 2001). Earthquake-caused shear stresses result in distinct amounts of deformations in the soil. The main objective of soil dynamics and geotechnical earthquake engineering is to determine the amount and degree of these soil deformations which occur under different kinds of monotonic and cyclic loads.

The determination of static undrained shear strength reduction plays an important role in this study and the primary objective is to systematically determine the post-cyclic undrained shear strengths of low plastic silty clays and clayey silts and to compare the results with the pre-cyclic condition. Also, the effects of soil plasticity and the specimen type on the dynamic shear strength and post-cyclic shear strength behavior of fine grained soils were determined. 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 (Bray et al., 2001, 2004a). The previous studies made by several researchers agreed with the field observations considering the cyclic behavior of low plastic silty and clayey soil.

In this study, cyclic and monotonic tests were conducted on both undisturbed and reconstituted soil specimens, prepared by the air pluviation method, by using the cyclic torsional shear apparatus. The cyclic behavior of silty and clayey soils was determined according to test results, and post-cyclic monotonic shear strengths were evaluated after various numbers of cycles of dynamic loading. Stress controlled dynamic tests were performed under different cyclic shear stress ratios, and monotonic tests were conducted on reconstituted soil specimens controlling the strain rate in order to determine the pre-cyclic undrained static shear strength and also the post-cyclic failure mechanism of fine grained soils.

2. MATERIALS

Tests have been conducted on reconstituted and undisturbed soil specimens. Reconstituted specimen was prepared from soils taken from 3.0-4.0m depths at a site in Istanbul Gümüşdere. Undisturbed soil samples were obtained from boreholes drilled in the cities of Adapazari and Izmir, located on the Aegean Sea shore coast. Liquid limit (w_l), plasticity index (PI), fines content (FC), natural unit weight (γ_n) and percentage finer than 5μm and 2μm of the soils were determined (Table 1). Figure 1 shows the grain size distribution of the soils used in this study. The Gümüşdere soil is low plastic silty clay, having a plasticity index of 18. The plasticity index of Izmir soils varies between 5 and 9. The undisturbed soil obtained from the depth of 3.5m in the city of Adapazarı was lightly overconsolidated (Erken et al., 2007; Bray et al., 2004b). The overconsolidation ratio of the undisturbed soils obtained from depths of 5.5m and 9.0m in Izmir was about 1.0.

Table1 Index properties of soils tested

Field	Sample No	Depth (m)	W_L (%)	PI (%)	FC (%)	5μm (%)	2μm (%)	γ_n (kN/m^3)	γ_{kc} (kN/m^3)	τ_{static} (kPa)	Group
Gümüşdere	M6	3.0	40	18	72	18	11	-	14.3	28.2	CL
Adapazarı*	DO2	3.5-4.0	37	13	95	20	11	18.8	13.9	-	ML
İzmir*	DSO2	9.0-9.5	34	8	63	22	9	18.9	14.4	-	ML
İzmir*	DSO1	5.0-5.5	31	9	55	23	12	18.4	14.4	-	CL
Izmir*	DSO3	5.0-5.5	31	6	52	17	10	18.5	14.0	-	ML
İzmir*	DO3	9.0-9.5	31	5	80	11	9	16.9	14.6	-	ML

* Undisturbed soils

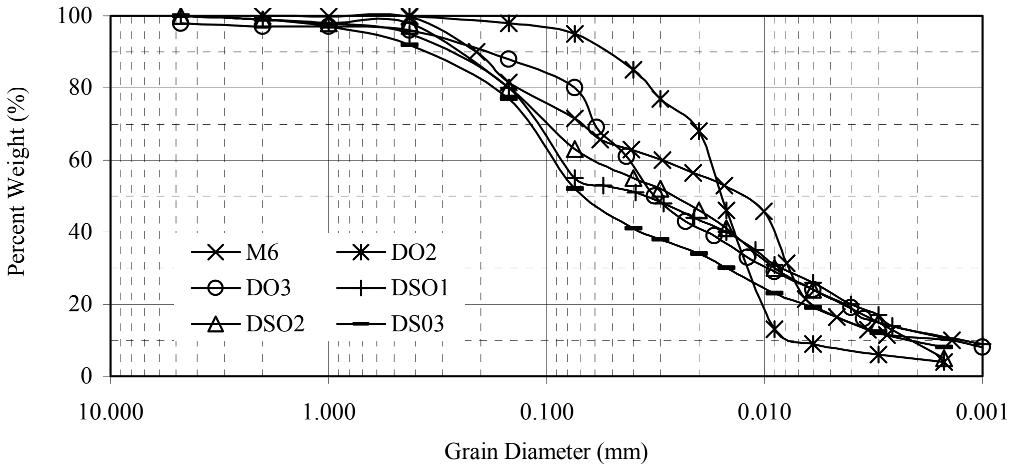


Figure 1 Grain size distributions of soils tested

3. TESTING APPARATUS

Soils were tested using a pneumatic stress controlled system capable of generating cyclic torsional shear stresses at frequencies between 0.01Hz and 10Hz... The size of hollow test samples varies between 70mm to 100mm in outer diameter, 30mm to 60mm in inner diameter and 140mm to 200mm in height. The testing system individually enables the measure and the record of axial vertical load, torque load T, inner confining pressure, outer confining pressure, axial vertical displacement, angular displacement Δθ, inner cell volume change and the specimen volume change. The torque load can be applied at the desired value and rate to the hollow cylinder specimens in one direction in static tests, and cyclically in dynamic tests. The stress-strain relationships and the shear strength properties of the soil specimens can be determined under isotropic and anisotropic conditions by applying sinusoidal loads.

4. SPECIMEN PREPARATION AND TESTING PROGRAM

The reconstitution method used in this study is dry pluviation with low-frequency vibration. All the hollow specimens were prepared with 4 layers, each having the same dry unit weight (initial γ_k, between 12.9-14.3 kN/m^3). Reconstituted specimens have an inner radius of 3cm, outer radius of 5cm and height of 20cm. De-aired water was flushed through the reconstituted specimens, starting from the base cap, for 1-3 days. 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 100kPa was applied to the specimens isotropically, and the consolidation lasted 24 hours 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_{kc}) 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 1.50cm, the outer radius is 3.50cm and the height of specimens was approximately 14.00cm each. After placing the undisturbed specimen into the torsional cell, back pressure of 200kPa 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 100kPa. After the consolidation process, torque loading was applied, cyclically in dynamic tests and monotonically in static tests.

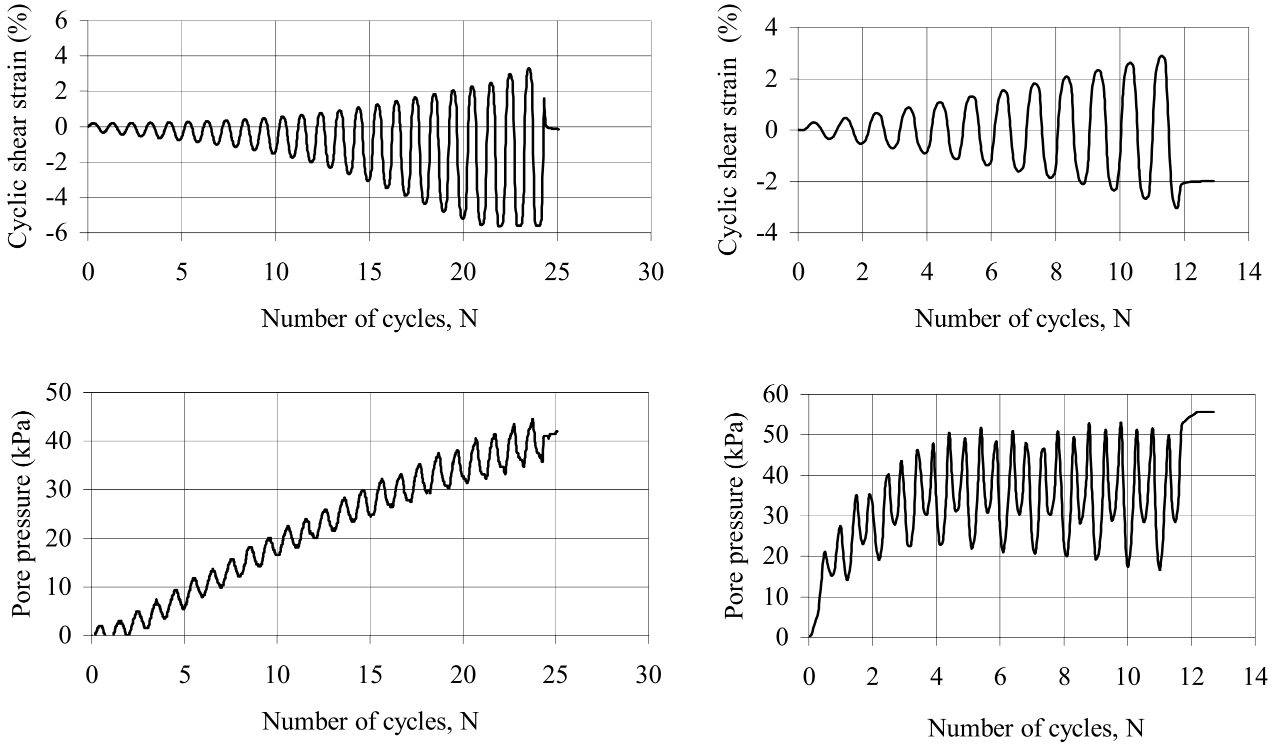
All samples were isotropically consolidated to 100kPa effective confining stress and cyclic tests were performed at a frequency of 0.1Hz under different cyclic shear stress ratios in order to eliminate the effects of consolidation pressure and the loading frequency. The testing program consisted of two test series, each designed to investigate a particular effect of the undrained cyclic and monotonic behavior of the reconstituted and undisturbed silty and silty clay soil specimens. Series 1 included the cyclic tests conducted on both reconstituted and undisturbed specimens. Series 2 included the cyclic tests followed by static loading of all specimens in order to determine the effect of cyclic shear stresses on the undrained static shear strength of fine grained soils. Monotonic loading was applied at a 0.50mm/sec loading rate, and lasted till the soil specimens exhibited a shear strain of 10%.

5. CYCLIC BEHAVIOR OF SOILS

At the first step of this study, cyclic and monotonic tests were conducted on reconstituted and undisturbed silty and clayey specimens. Figure 2.a shows the relationships between shear strain versus the number of cycles, and pore water pressure versus the number of cycles (N) of reconstituted soil specimens having a plasticity index (PI) of 18 under $\tau_d/\sigma_c = 0.185$ cyclic shear stress level. Shear strain increases by the number of cyclic loadings, and exceeds a failure limit in 17 cycles with 5% DA shear strain, allowing the pore water pressure ($\Delta u/\sigma_c$) an increase of only 33kPa and 44 at the end of the test.

Figure 2.b shows a typical cyclic test result of undisturbed silty soil specimen with a plasticity index of 9. Shear strains increase rapidly with the number of cycles, allowing the pore water pressure to remain at 50kPa. The pore pressure behavior of undisturbed soil, with an anisotropic soil structure, was different from reconstituted soil samples. Thus, when the excess pore water pressure increased steadily with each cycle and reached 50kPa, that is smaller than the effective confining pressure, shear strain was 2%DA. Pore pressure remained constant even shear strains already exceeded the failure limit of 5% DA.

Figure 3a shows the cyclic behavior of reconstituted samples by the shear strain and pore water pressure versus number of cycles plot and the relationship between cyclic shear stress ratio and number of cycles. The cyclic tests were conducted at stress ratios of 0.163 and 0.185, respectively. More cycles are required to achieve the same shear strain level with a lower cyclic shear stress ratio. Similarly, at the same number of cycles, pore water pressure increases with the increase in the shear stresses.



(a) Reconstitute sample PI=18 τ/σ=0.185 (b) Undisturbed sample PI=9 τ/σ=0.240

Fig. 2. Cyclic undrained test results of the reconstituted and undisturbed silty clays

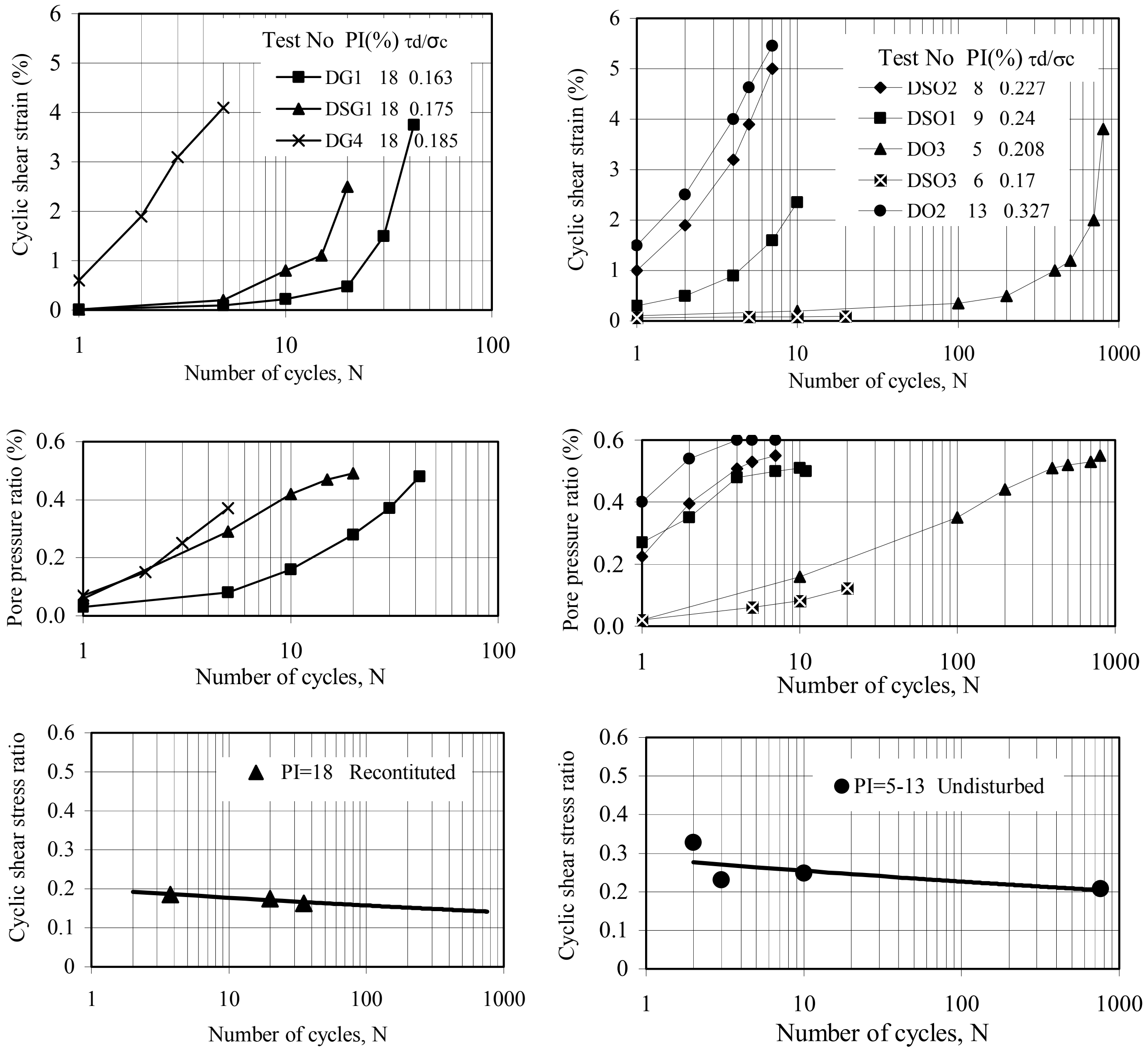
Cyclic behaviors of undisturbed soils obtained from the cities of Adapazari and Izmir are compared in Figure 3b. The undisturbed specimens had fines content between 52% and 95%, and the plasticity index ranged from 5 to 13. As can be seen in Figure 3b, the increased cyclic shear stress ratio causes it to reach the failure limit of DA shear strain of 5% in less loading cycles. Shear strains increase rapidly during initial cycles, and the undisturbed soil specimen loses its cyclic strength following the test. When the ratio of natural water content to liquid limit (w_n/w_l) exceeds 0.90, undisturbed soils become more collapsible due to strain softening within 20 cycles with a pore pressure ratio ranging from 0.52 to 0.60 (Table 2). The silty undisturbed specimens have considerably more cyclic strength resulting from reconstituted specimens with a plasticity index of 18.

Table 2 Cyclic torsional shear test properties of reconstituted (R) and undisturbed (U) specimens

Specimen	Test No[a]	w_n (%)	w_n/w_l	PI (%)	γ_{kc} (kN/m^3)	B (%)	τ_d/σ_c	N (γ=±2.5%)
U	DO2	37	0.99	13	13.9	100	0.327	1
U	DO3	19	0.61	5	14.6	98	0.208	760
U	DSO1	30	0.97	9	14.4	96	0.240	10
U	DSO2	29	0.85	8	14.4	96	0.227	3
U	DSO3	28	0.90	6	14.0	98	0.170	20*
R	DG4	15	0.38	18	15.2	96	0.185	5
R	DSG1	17	0.43	18	14.9	96	0.175	20
R	DG1	16	0.40	18	15.2	98	0.163	35

[*] The test is continued till 0.18 % DA strain

[a] Symbols define the test conditions; D denotes cyclic test, DS denotes cyclic and post cyclic monotonic test



(a) Reconstituded samples (b) Undisturbed samples

Fig. 3. Cyclic undrained test results of the reconstituted and undisturbed clays specimen

6. POST-CYCLIC UNDRAINED MONOTONIC STRENGTH OF CLAYS

It is necessary to determine the effect of earthquake loads on monotonic shear strength for the design of structures to mitigate earthquake effects. In this part of the research, static torsional tests were conducted after ending the cyclic tests on both reconstituted and undisturbed specimens for a certain number of cycles at constant shear stress amplitude. At first step, the cyclic shear stress ratio of 0.175 as a corresponding stress value of N=20 cycles, which was considered for an earthquake with the magnitude of 7.5, was determined from the relationship CSSR versus N as shown in Figure 3.a. This cyclic shear stress level was applied at different number of cycles to each specimen (Table 3). Following a cyclic shear stress level application of $\tau_d = \pm 17.5$kPa ($\tau_d/\sigma_c = \pm 0.175$), monotonic shear stress was applied. As shown in Figure 4, shear strain level at the end of cyclic loading and monotonic loading was $\gamma_c = \pm 1.5\%$ and $\gamma_s = 10\%$, respectively.

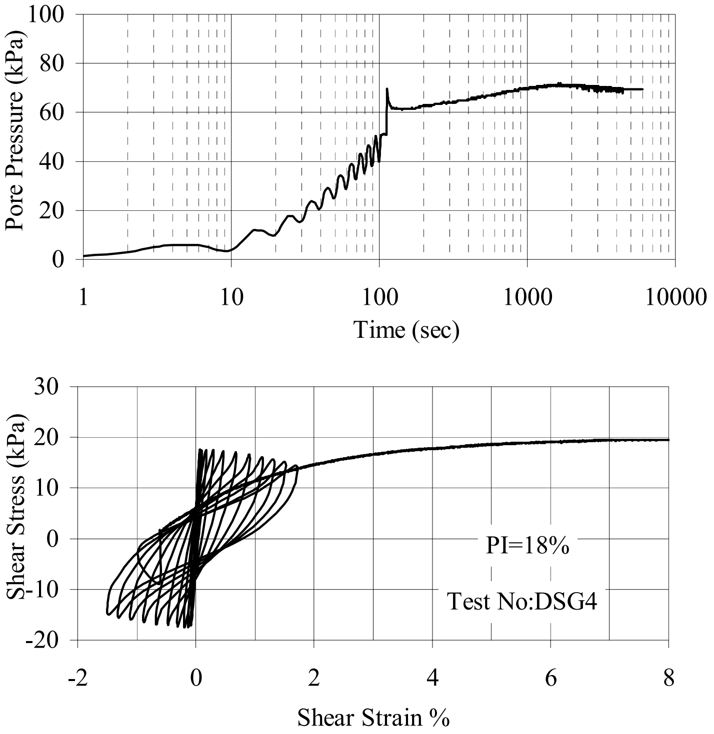
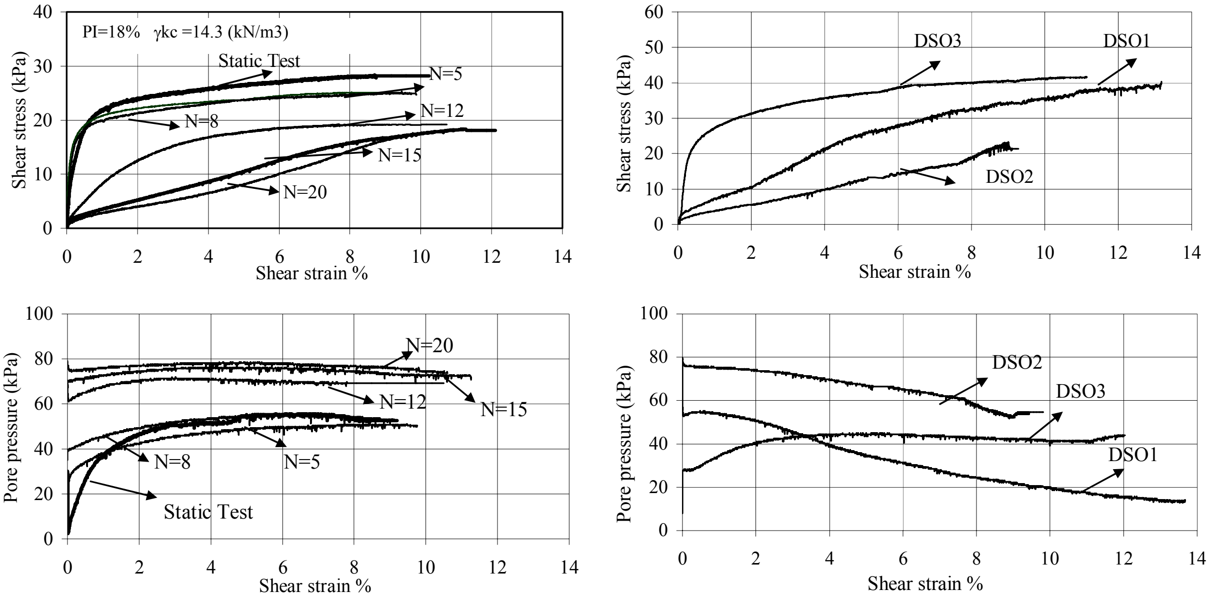


Fig. 4. Monotonic tests following cyclic torsional test

Figure 5a presents the post cyclic monotonic test results of the reconstituted specimens tested to the cyclic shear stress level of 0.175 at increasing number of cycles for each test. The first two tests were conducted at 5 and 8 cycles, respectively, without allowing the specimen to reach the threshold shear strain of $\gamma_{cr} = \pm 0.75\%$ that the shear deformations increase rapidly (Erken et al. 2007). Finally, the tests were continued by monotonic loading till the specimen exhibits 10% shear strain in the undrained condition. The third cyclic test was performed at 12 cycles, and then it was stopped to change the loading type to static undrained with a rate of 0.5 mm/sec. It was observed that the static undrained shear strength decreased significantly after 15 loading cycles. The specimen that was tested at 5 and 8 loading cycles exhibited ± 0.19% and ± 0.36% shear strain, but softening behavior occurred after 12 cycles at which the specimen exhibited ± 1.5% shear strain (Table 3). Excess pore water pressure responses obtained from the cyclic part of this test series are also shown in Figure 5a. The pore pressure generation seems to depend on the different shear deformation levels in cyclic tests to which the specimen was exposed. Pore pressures that reach about 60kPa during the cyclic loading, in which the specimen was loaded till the residual strains started to develop, stay nearly at the same value, and preserve this trend through the monotonic test till the specimen exhibited 10% shear strain. On the other hand, if soil has experienced cyclic shear strain below cyclic yield shear strain level, excess pore pressures in monotonic tests reach nearly 53kPa as was obtained from the static shear tests.

Figure 5b shows the monotonic shear strength results obtained from three undisturbed silty specimens loaded cyclically at different stress ratios. The cyclic shear strain was increased up to ± 0.09% at the end of 20 cycles of the application of the cyclic shear stress level of 0.170. The post cyclic ultimate monotonic strength value was obtained as 40kPa at 10% shear strain. After a shear strain of ± 2.95%, shear strength decreased to 35kPa and a strain potential of ± 5.04% caused the monotonic strength to decrease to 25kPa. As shown in Figure 5b, the pore water pressure changed according to cyclic shear stress history. So, after the cyclic strain amplitude of ± 0.09%, pore water pressures increase from 29kPa to 4kPa. However, pressures decreased from 55kPa to 14kPa at the cyclic shear strain history of ± 2.95% and from 78kPa to 50kPa in the static test having at the cyclic shear strain history of ± 5.04%.



a) Reconstituted samples

b) Undisturbed samples

Fig. 5. Undrained monotonic shear stress and pore water pressure

From the tests conducted on the reconstituted soil specimen with a plasticity of 18, it was determined that monotonic strengths decreased significantly due to the cyclic stress history at the same cyclic shear stress. Prior to critical yield strain level, the silty clay specimen did not experience a significant deformation, but the stress reduction exceeded nearly 40% after the critical yield strain.

Figure 6 presents the relationship between the post cyclic shear stress and the cyclic shear strain history of the reconstituted soil with PI = 18 and the undisturbed soils with PI = 6-9. When the soil undergoes earthquake loads the induced cyclic shear strain causes a reduction in shear strength of soil. Post cyclic shear stress is around 0.60 of the monotonic shear stress of PI = 18 reconstituted fine soil at the failure state of shear strain of $\gamma_c = \pm 2.5\%$ (Fig. 6.a).

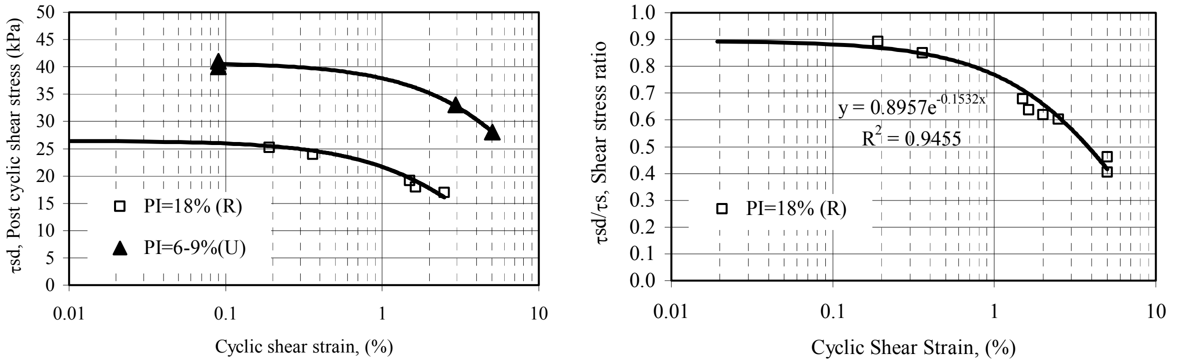
Table 3 Cyclic and monotonic test properties of reconstituted and undisturbed specimens

Test No	σ_c (kPa)	B (%)	PI (%)	γ_{dc} (kN/m^3)	τ_d/σ_c	Number of Cycles, N	Shear Strain at N (±γ%)
DSG1	100	96	18	14.3	0.175	20	2.5
DSG2	100	98	18	14.3	0.175	5	0.19
DSG3	100	100	18	14.3	0.175	8	0.36
DSG4	100	96	18	14.3	0.175	12	1.5
DSG5	100	96	18	14.3	0.175	15	1.63
SG1*	100	96	18	14.3	-	-	-
DSO1	100	100	9	14.4	0.248	12	2.95
DSO2	100	98	8	14.4	0.227	7	5.04
DS03	100	100	6	14.0	0.170	20	0.09

* Static torsional loading

7. CONCLUSION

In this research cyclic behavior and post cyclic monotonic shear strength of reconstituted and undisturbed fine grained soils have been studied in torsional test apparatus. The following results have been obtained.



a) Post cyclic shear stress versus cyclic shear strain b) τsd/τs, Shear stress ratio versus cyclic shear strain

Fig. 6. Reduction of undrained monotonic shear stress due to cyclic loading

1. 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.
2. The monotonic undrained shear strengths of reconstituted and undisturbed specimens decrease with the cyclic shear stress history.
3. The reduction is significant when the soil specimen exceeds a certain yield strain level under the same shear stress amplitude prior to static undrained test, and reaches nearly 40% in silty soil.

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