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Behavior of Granular Soils under Dry and Saturated Conditions in Cyclic Torsional Shear Tests

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Abstract

This paper presents results from drained cyclic torsional shear tests on Toyoura sand and a residual soil under dry and saturated conditions. The relationships of shear strain, $\gamma_{z\theta}$ *with shear stress,* $\tau_{z\theta}$*; normalized shear stress,* $\tau_{z\theta}/\sigma'_z$*; vertical strain,* ε_z*; and equivalent shear modulus,* G_{eq} *are compared. The investigation of granular decomposition with respect to its influence on accumulation of vertical strains and shear stiffness were of major interest. It is concluded that the strength and deformation response of granular soils, if decompose with time due to water action, are largely different from what we expect from conventional soils of durable grains. It is anticipated from this study that the laboratory tests on residual soils can provide more reliable and realistic parameters for site characterization and as an input for numerical models.*

Key Words: Granular material; Weathering; Particle breakage; Cyclic shear; Shear modulus;

1. Background

In many regions of the world, population growth, economic needs, and environmental constraints necessitate construction of structures on widespread deposits of soils produced by weathering of soft rocks and use of such cheap but highly degradable gravelly material for construction of embankments. In such scenario, the detailed knowledge on the mechanical behavior of residual soils is essential in geotechnical analysis and design for better serviceability over the lifetime of geotechnical structures and risk analysis.

Due to high sensitivity of residual soils to water-induced degradation and loss of properties with time, it becomes vital for long-term stability of natural slopes, settlement of embankments, bearing capacity of foundations and durability of aggregates as a construction material. The stress-strain response of such soils becomes very complex, as different fundamental features, such as anisotropy, creep, drainage conditions, and granular decomposition largely affects the overall mechanical behavior of the aggregates. Conventional geotechnical design practice relies on simplified theories and mostly the methods used are very crude and conservative which may not be valid for such widespread weathered soil deposits.

2. Focus of the Study

Only few studies are known to exist concerning the time-dependent degradation of granular materials under saturated conditions. Many researchers have reported negligible influence of presence of water on strength and deformation properties of conventional granular soils (Towhata & Aiz, 2011; Aziz et al., 2010; Youn et al., 2008; Laudahn et al., 2005; Wichtmann et al., 2005). This paper compares the effects of dry and saturated test conditions on dynamic properties of conventional Toyoura sand with a residual soil using drained cyclic torsional shear tests on hollow cylindrical reconstituted specimens.

The investigation of granular decomposition with respect to its influence on accumulation of vertical strains and shear stiffness were of major interest in this study.

2. Test Procedure

2.1 Materials Property

Cyclic torsional shear tests were carried out on two granular materials: Toyoura sand (TS), a Japanese standard silica sand; and a residual soil (DS), weathered sandy mudstone from Pakistan. The physical properties of materials are shown in Table 1 and grain-size curves in Figure 1.

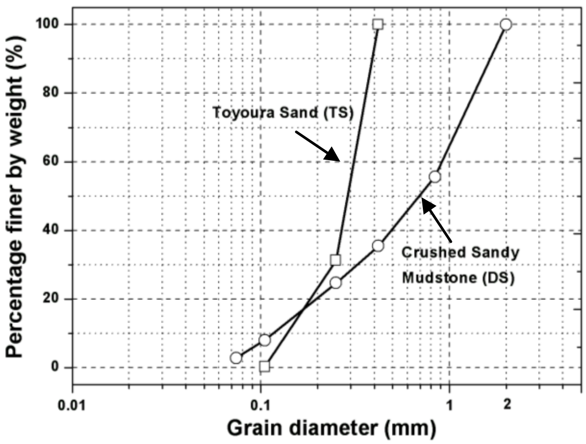
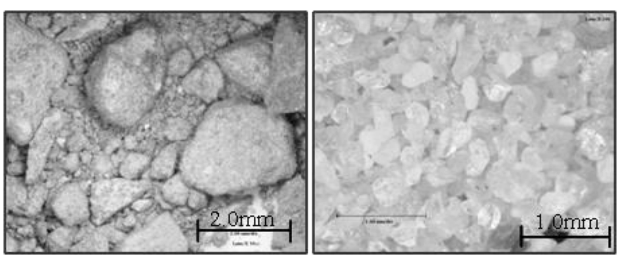


Fig.1: Grain-size distributions.

The comparison of grain shape and variability for the two materials is shown in Figure 2. It can be seen that TS particles are sub-rounded while DS particles vary from sub-angular to angular.

Table 1: Physical Properties of the Materials.

Soil	G_s	D_{max} (mm)	D_{50} (mm)	U_c	e_{max}	e_{min}
TS	2.65	0.42	0.22	1.3	0.980	0.610
DS	2.73	2.00	0.69	7.7	1.114	0.586



Sandy mudstone (DS) Toyoura sand (TS)

Fig.2: Grain shape and variability of the test soils

2.2 Specimen Preparation

All tests were performed on reconstituted specimens. Several preparation methods to reconstitute granular soil specimens and their effects on producing samples with different structures and behavioral characteristics are well known (Chaudhary *et al.*, 2002). In order to reproduce density and soil fabric, dry deposition method was adopted in this study. This technique allowed the samples with uniform relative densities and sufficient results in homogeneity and repeatability

2.3 Test conditions and investigation plan

The detailed test conditions and investigation plan is schematically presented in Figure 3. All tests presented in this paper were carried out either under fully saturated or dry conditions. However, volume change measurement during consolidation and drained cyclic loading was carried out only for fully saturated specimens. The volume change of dry soils comes along with a change of the air volume in the voids which is impossible to measure with ordinary volume change measurement devices. Thus, the primary focus of this study was accumulation of vertical strains during cyclic torsional shear.

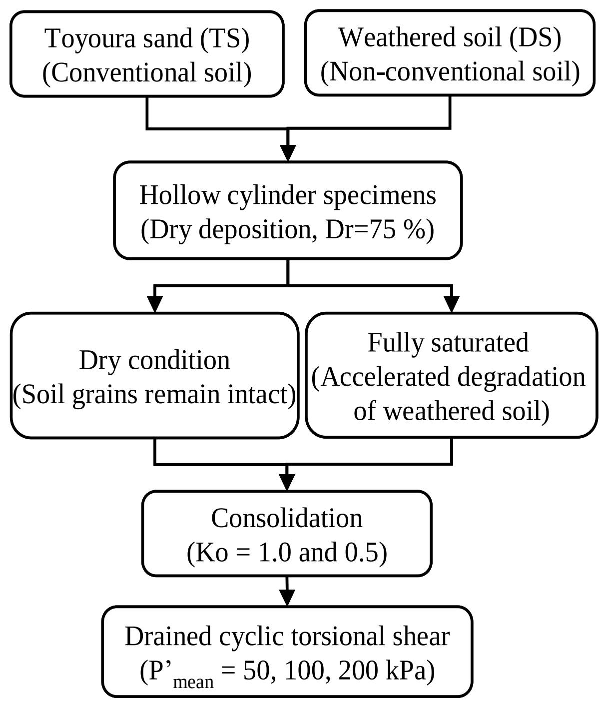


Fig.2: Laboratory testing plan

2.4 Loading Conditions

The strain-controlled cyclic loading with a see-saw wave shape in compression and extension was performed with user defined loading parameters under consolidated drained (CD) conditions (Table 2). The general frequency independency of granular materials under drained conditions was assumed. Application of twenty loading cycles of each strain amplitude was intended for studying the effects of various test conditions on cyclic hardening or softening response of the materials.

Table 2. Cyclic Torsional Shear-Loading History

Toyoura sand (TS)		Sandy mudstone (DS)	
γ_{SA}	f (Hz)	γ_{SA}	f (Hz)
± 0.0005	0.001	± 0.0005	0.033
± 0.0025	0.001	± 0.0010	0.025
± 0.005	0.0005	± 0.0025	0.014
		± 0.0050	0.008
		± 0.0100	0.005
No. of loading cycles, N = 20			

3. Torsional Shear Test Results

3.1 Toyoura sand (TS)

The drained cyclic torsional shear test results of Toyoura sand under dry and saturated conditions on isotropic and anisotropically consolidated specimens are given in Figures 4 and 5, respectively. It can be noticed that the stress-strain response of Toyoura sand (granular soil with durable grains) at a given confining pressure is unaffected by dry and saturated conditions. Moreover, cyclic hardening become prominent as the confining pressure is increased from 50 to 200kPa.

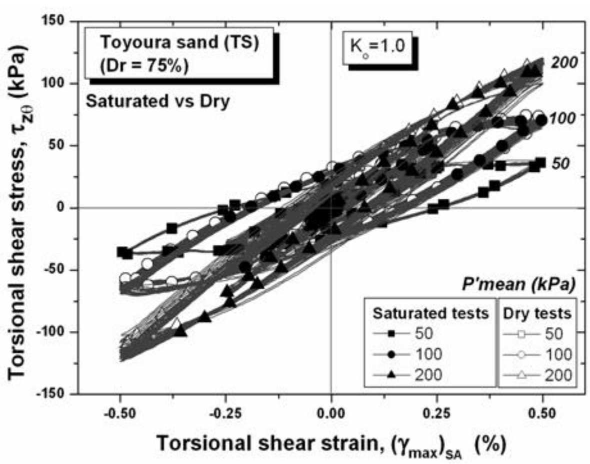


Fig. 3: Hysteresis loops of TS under K_o=1.0.

Figures 6 and 7 show the normalized stress-strain diagrams under isotropic and anisotropic conditions, respectively. It can be seen that the hysteresis loops turn out to be identical after normalizing the torsional shear stress with effective vertical stress. Since, the shear stress is mobilized on

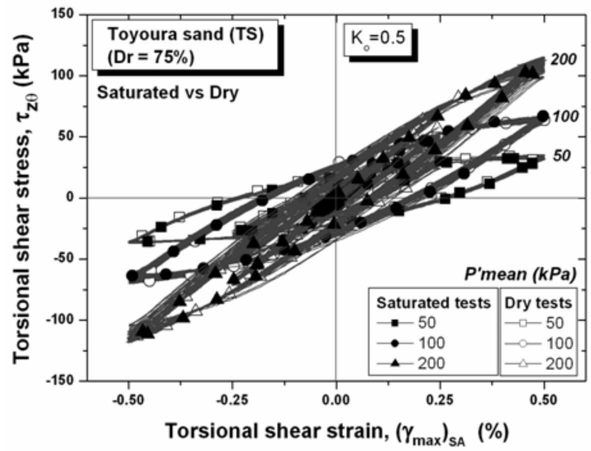


Fig.4: Hysteresis loops of TS under K_o = 0.5.

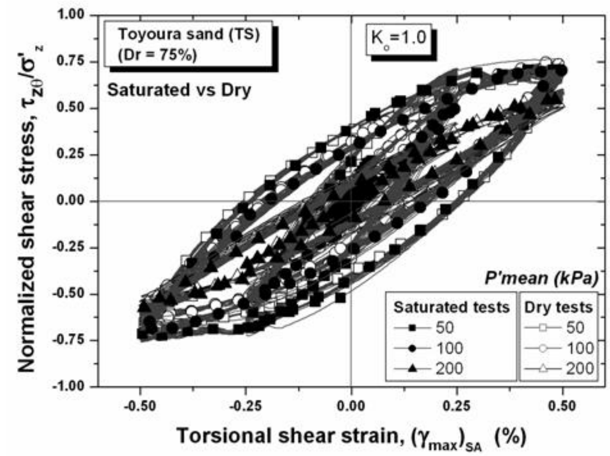


Fig.5: Normalized stress-strain diagrams of TS (Ko=1.0).

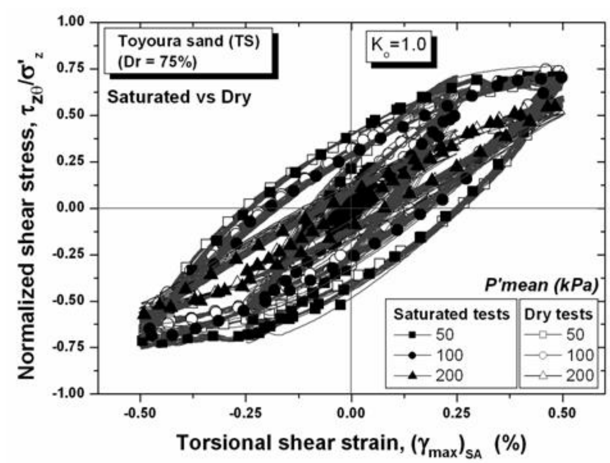


Fig. 6: Normalized stress-strain diagrams of TS (Ko=1.0).

horizontal plane in a torsional shear test, therefore, higher normal stress on this plane leads to higher shear stress and after normalizing the shear stress by effective vertical stress, the stress-strain diagrams superimpose each other with no apparent effects of effective confining pressure as well as dry and saturated conditions.

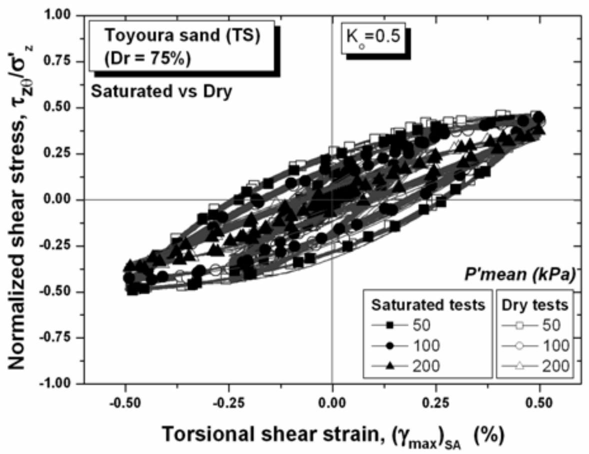


Fig.7: Normalized stress-strain diagrams of TS (K_o = 0.5).

The accumulation of vertical strain due to cyclic shear during typical torsional shear tests under dry and saturated conditions on Toyoura sand specimens is shown in Fig. 8. The relative decrease in accumulation of vertical strain during each successive shearing cycle of given strain amplitude is due to the densification of sand under repeated loads. The presence of pore water in the saturated conditions can cause small variations in the soil skeleton and might be the possible reason of negligible difference in volume change between dry and saturated drained tests. In general, it can be said that the volume change of granular soils with durable grains is independent of saturated and dry conditions.

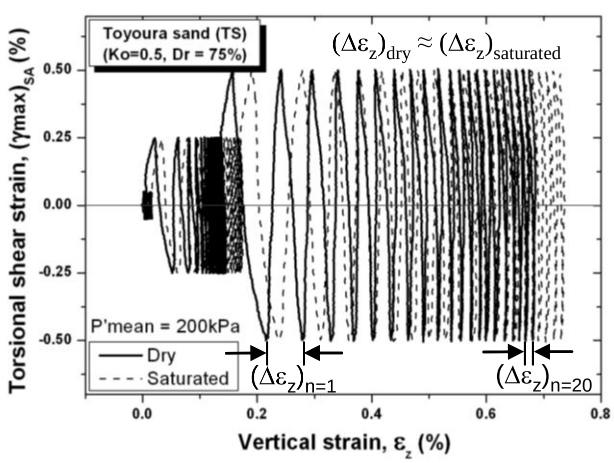


Fig.8: Typical vertical strain accumulation of Toyoura sand during cyclic shear under dry and saturated condition.

Although, similar study had been done by Shahnazari and Towhata (2002) on Toyoura sand on saturated specimens. Nevertheless, from the perspective of current investigations, it was necessary to compare the dry and saturated response of Toyoura sand.

3.2 Weathered soil (DS)

The drained cyclic torsional shear test results of weathered soil under dry and saturated conditions on isotropic and anisotropically consolidated specimens are given in Figures 9 and 10, respectively. The stress-strain response is approximately linear with a very small hysteresis loop at lower strain amplitudes, whereas, at higher strain amplitudes, the response becomes increasingly non-linear with larger loops. Along with the effects of confining pressure, it is quite clear from these figures that the stress-strain response of weathered soil (non-conventional granular soil i.e. soils consisting of weak grains likely to disintegrate upon water submergence) is largely affected by dry and saturated conditions.

Moreover, like in case of Toyoura sand, the cyclic hardening, although to a minor extent, is observed only when confining pressure is increased.

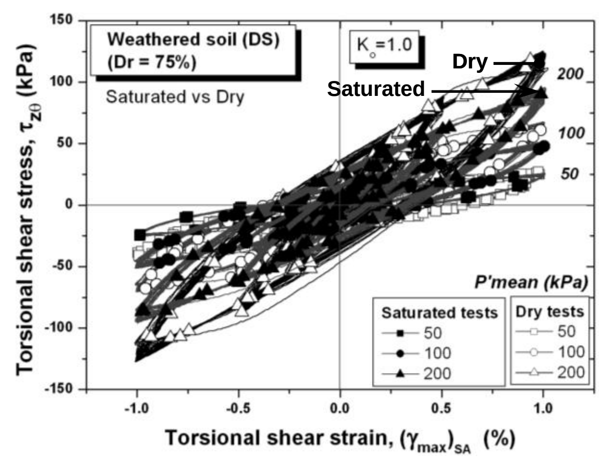


Fig.9: Hysteresis loops of DS soil under K_o = 1.0.

The disintegration of grains during the saturated tests on weathered soils was revealed by doing the grain size analysis of each specimen after torsional shear test (Figure 11). Slight particle rearrangement in the soil skeleton under dry conditions due to confining pressure and cyclic shear is also observed. This particle rearrangement under dry conditions is facilitated by overcoming the particle strength through particle damage of relatively weak grains of the weathered soil. In case of saturated tests, it is important to note that the most of water-induced disintegration process completed during saturation and consolidation stages. Therefore, negligible effects of confining pressure, anisotropic consolidation and cyclic shear on further degradation of soil grains were observed during torsional shear test.

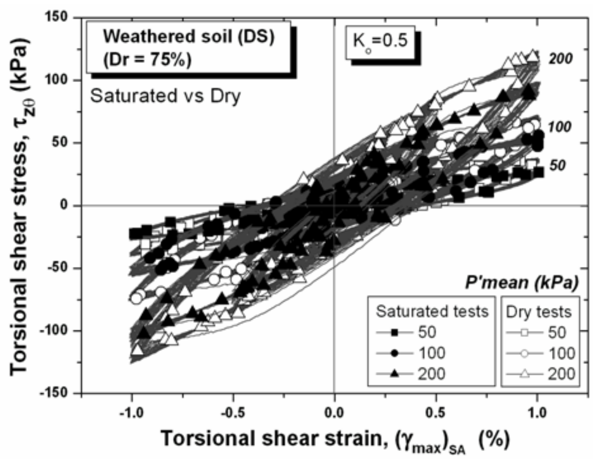


Fig.10: Hysteresis loops of DS soil under K_o=0.5.

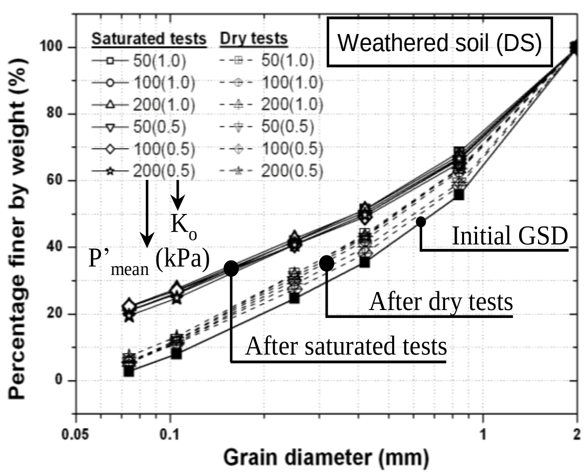


Fig.11: Disintegration of soil grains.

The normalized stress-strain diagrams of weathered soil under isotropic and anisotropic conditions are shown in Figures 12 and 13, respectively. It can be seen that the hysteresis loops are not identical after normalizing the torsional shear stress with effective vertical stress. It can be seen in these figures that the normalized shear stress-shear strain, ($\tau_{z\theta}/\sigma'_z$)-$\gamma_{z\theta}$. relationship for dry conditions shows relatively stiffer response than the saturated tests. This is possibly due to the disintegration of soil grains and particle rearrangement under saturated conditions because as a result of such degradation the material becomes closer to a silty/clayey soil.

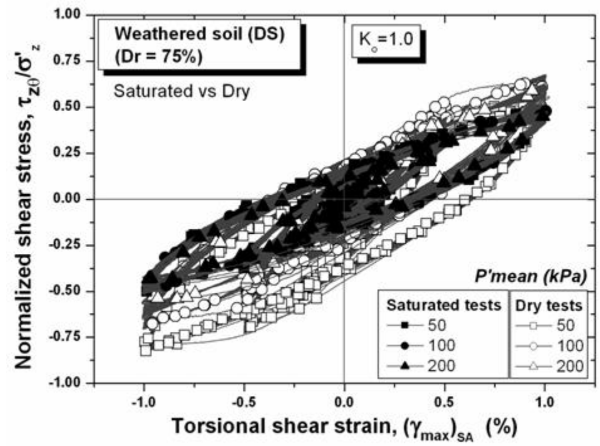


Fig.12: Normalized stress-strain diagrams of DS (K_o = 1.0)

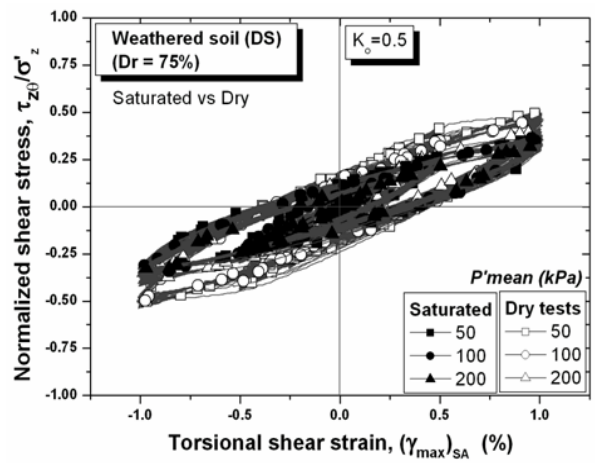


Fig.13: Normalized stress-strain diagrams of DS (K_o = 0.5).

Figures 14 and 15 show that the development of vertical strains in the weathered soil during cyclic shear under dry and saturated conditions is always contractive mainly due to: 1) relatively large intrinsic void ratio; 2) particle rearrangement of weak soil grains; and 3) water-induced disintegration under saturated conditions. It can be seen in these figures that the anisotropically consolidated specimens (K_o=0.5) experienced large vertical contraction both under dry and saturated conditions during cyclic shear which is due to relatively high effective vertical stress, σ'_z as compared to the horizontal normal stresses σ'_r and σ'_θ.

Furthermore, small effects of cyclic hardening are quite evident only in dry tests as the accumulation of vertical strain during cyclic shear decreases with number of loading cycles for particular shear strain amplitude. Whereas, in case of saturated tests $\Delta\varepsilon_z$ interval remains more or less constant during cyclic shear mainly due to the excessive volume changes during saturation and consolidation stages. Therefore, no cyclic hardening is observed in saturated tests.

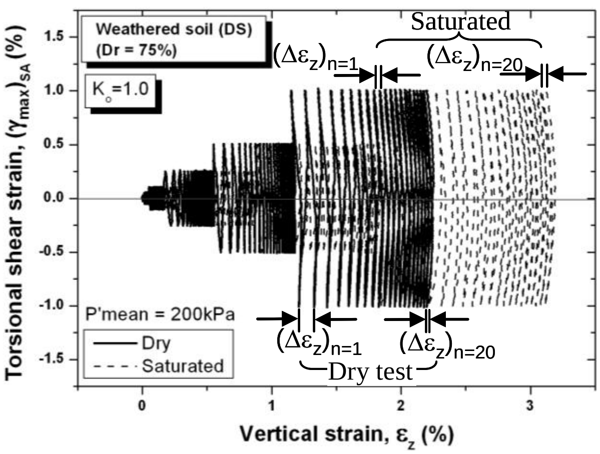


Fig.14: Typical vertical strain accumulation in weathered soil during cyclic shear under isotropic conditions.

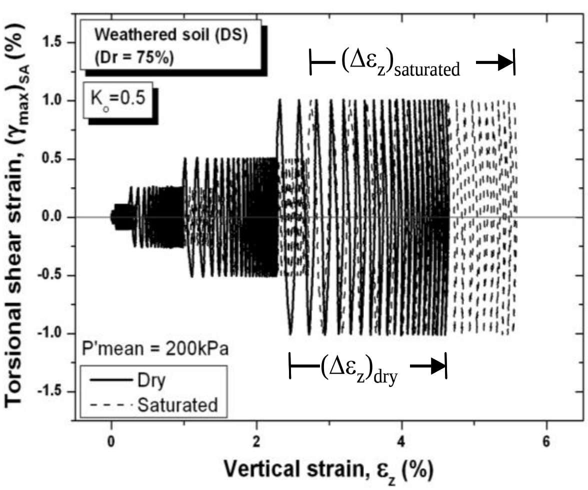


Fig.15: Typical vertical strain accumulation in weathered soil during cyclic shear under anisotropic conditions.

4. Effects of Various Test Conditions on Shear Modulus

Based on the test results presented in the preceding sections it can be stated that the behavior of conventional granular soils (i.e. soil consisting of relatively durable grains) under saturated and dry states is all together different from non-conventional granular soils (i.e. soils likely to disintegrate with time due to wetting). This hypothesis is further supported by comparing the shear modulus of the two soils under various test conditions.

The cyclic shear strain-shear modulus relationships of Toyoura sand and weathered soil derived from drained cyclic torsional shear tests are presented in Figures 16 and 17, respectively. Equivalent shear modulus is defined as the slope of the straight line passing through the peak shear stress points of given strain amplitude for the 10th cycle. Equivalent shear modulus represents an average of modulii in the two loading directions.

It is quite clear from Figure 16 that the dynamic deformation characteristics of granular soils with durable grains are unaffected by the presence of water. In addition, no effects of anisotropic consolidation are observed. Whereas, Figure 17 clearly shows the effects of dry and saturated conditions as well as anisotropic consolidation on shear stiffness of non-conventional granular soils undergoing particle rearrangement due to water-induced degradation of soil grains. Isotropically consolidated saturated specimens have shown the lowest value of shear modulus, whereas, anisotropically consolidated dry specimens have shown the stiffest response.

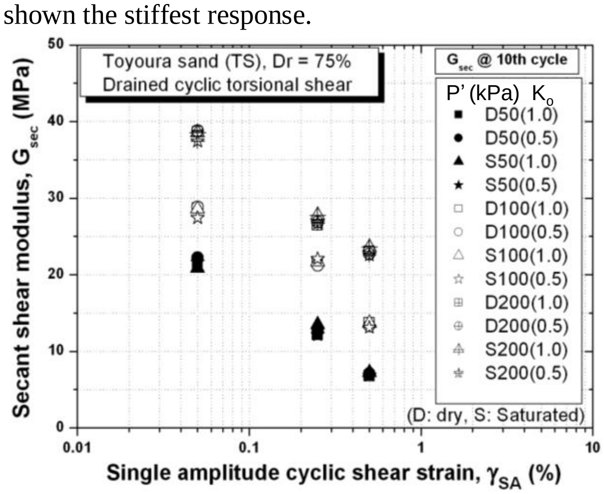


Fig.16: Shear modulus of Toyoura sand.

5. Conclusions

Cyclic torsional shear tests were performed at various drainage conditions, effective confining pressures and K_o-values on a typical highly weathered residual soil from Pakistan and conventional Japanese Toyoura sand. The influence of dry and saturated test conditions on granular decomposition of the material with respect to its influence on accumulation of vertical strains and shear stiffness was investigated. The following main conclusions are drawn from this study.

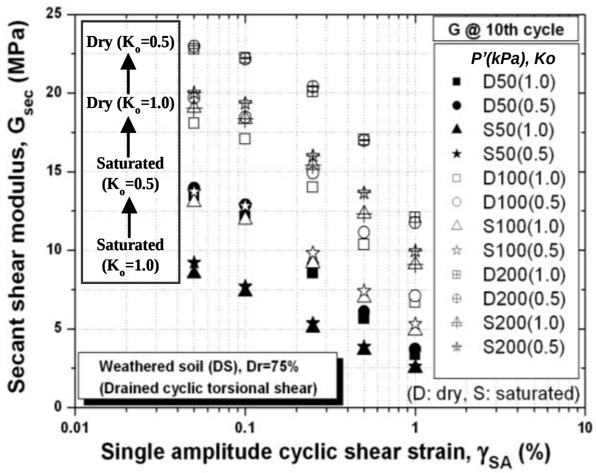


Fig.17: Shear modulus of weathered soil (DS).

The cyclic shear stress-strain response of Toyoura sand (i.e. granular soil with durable grains) at a given confining pressure is unaffected by the presence of water. Moreover, cyclic hardening becomes prominent as the confining pressure is increased from 50 to 200kPa.

The shear strain-shear stress, $\tau_{z\theta} / \tau\sigma_z$, shear strain–normalized shear stress, $\tau_{z\theta} - \tau\sigma_z / \sigma'_z$, vertical strain–shear strain, $\varepsilon_z - \gamma_{z\theta}$ and shear strain–shear modulus, $\gamma_{zq} - G_{eq}$ relationships of residual soils are strongly influenced by dry and saturated conditions. Disintegration of soil grains with time due to wetting and accumulation of excessive vertical compression observed during cyclic loading can be crucial to the collapse of embankments made with cheap gravels and settlement of foundations constructed on residual soils.

It is anticipated from this study that the laboratory tests on weathered soils can provide more reliable and realistic parameters for site characterization and as an input for numerical models.

6. Acknowledgements

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7. Symbols / Abbreviations

CD	=	Consolidated drained
D_{max}	=	Maximum grain size
D_R	=	Relative density
G_{sec}	=	Secant shear modulus
G_s	=	Specific gravity of soil
GSD	=	Grain size distribution
I_D	=	Degradation index
K_o	=	Coeff. of lateral earth pressure
p'_{mean}	=	Mean effective stress = 1/3(□'$_1$+□'$_2$+□'$_3$)
γ_{max}	=	Maximum shear strain
Δ	=	Increment of a quantity
ε	=	Normal strain
ε_{vol}1	=	Volumetric strain
θ	=	Circumferential direction
υ	=	Poisson's ratio
$\mu\varepsilon$	=	Microstrain
σ	=	Normal total stress
σ'	=	Normal effective stress
σ_1	=	Major principal stress
σ_2	=	Intermediate principal stress
σ_3	=	Minor principal stress
□$_z$	=	Axial normal stress
□$_r$	=	Radial normal stress
σ_θ	=	Circumferential normal stress
$\tau_{z\theta}$	=	Shear stress on z-□ plane

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