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Effect of Drying-Wetting Cycles on Saturated Shear Strength of Undisturbed Residual Soils

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Abstract: Due to world-wide distributions and extensively used as construction materials, geotechnical engineers are interested in understanding the mechanical behavior of residual soils which are sometimes referred in the literature as problematic soils. The climatic zones where residual soils occur are often experienced by many drying-wetting cycles due to seasonal variations. This seasonal variation in the water content termed as drying-wetting cycle is regarded as the most destructive environmental factor that may cause many foundation diseases. Considering these, the purpose of this study is to understand the effects of drying-wetting cycles on saturated shear strength characteristics of undisturbed residual soil. A series of consolidated drained (CD) triaxial tests are conducted on multiple drying-wetting soil specimens to analyze the saturated shear strength. The test results indicate that the stress-strain relationships appear to be strain-hardening. The deviatory stress and initial stiffness of saturated soils increase and the volume of soils becomes contractive as the net normal stress increases but decrease with increasing drying-wetting cycle numbers. The cohesion (c_d) and internal friction angle (φ_d) decrease with increasing cycle number (N) but the attenuation rate of φ_d is less than c_d. The variations of c_d and φ_d with respect to drying-wetting cycles can be expressed by exponential function. The saturated shear strength and it's attenuation rate due to drying-wetting cycles are analyzed. The effect is more significant for the first cycle and decreases with subsequent cycles and finally reaches to a constant state after 4 cycles. Furthermore, a mathematical function is proposed in this paper which can describe the saturated shear strength attenuation rate of drying-wetting cycle samples. Such studies are useful to understand the possible changes in shear strength behavior of residual soils below the engineering structures that are subject to periodic drying and wetting from climatic variations.

Keywords: Drying-Wetting Cycle, Residual Soil, Shear Strength, Attenuation Rate

1. Introduction

Residual soils are the weathering product of their parent materials. The engineering properties and behavior of residual soils vary widely from place to place even within depth depending upon the rock of origin and the local climate during their formation. These soils are found in many parts of the world (for example in Bangladesh, China, India, Malaysia, Singapore, Thailand etc) and are used extensively in construction, either to build upon, or as construction material of both geotechnical and geoenvironmental structures such as embankments, pavements, earth fills and soil barriers. Therefore, geotechnical engineers are interested in understanding the mechanical behavior of residual soils which are sometimes referred in the literature as problematic soils.

Due to world-wide distributions and extensively used as construction materials, many research worked have already been done on residual soils. For example, the engineering characteristics, microfabric and mineralogical composition, degree of weathering, compressibility and shear strength properties and their controlling factors, bonding behavior and its loading impact, stiffness or yielding behavior of both

natural and compacted residual soils are examined by numerous scholars [1-11]. Several geo-engineering problems associated with residual soils such as landslides, subsidences, damage of road and railway tract, building collapse in many parts of the world have also been reported.

Under extreme climatic conditions such as heavy rainfall, persistent drought and multiple drying-wetting cycles will cause many engineering problems including the weakening of the mechanical properties in consequence foundation diseases. Based on a large amount of investigations, climatic condition, namely drying-wetting, is regarded as the most destructive environmental factor that can induce damage to infrastructures such as highways and pavements [12-13].

A significant number of investigations have been conducted to understand the effects of drying-wetting cycles on soil physical and mechanical properties. It is found that drying-wetting cycle is one of the important factors to impact soil fabric, particle cementation, water content, and void ratio of soils [14-20]. This effect leads to the formation of cracks as well as the development of fissures in soils which significantly increase soil compressibility [21-23]. The hydraulic conductivity or permeability coefficient increases with increasing drying-wetting cycles of compacted clay cover but decreases if the soil is improved with the addition of lime [24-25]. The strength change of expansive soil under drying-wetting cycles plays an important role in the slope stability analysis. The shear strength of expansive soils decreases with the increasing number of cycles, the cohesion of expansive soil decreases obviously and the friction angle keeps a stable value. Furthermore, the slope stability and safety factor decrease with increasing number of cycles [26-27]. Several authors showed that the influence of the first drying-wetting cycle on soil structure is greatest and decreases with subsequent cycles [28-30]. The study on lime or fly ash stabilized expansive soils or solidified sludge found that

drying-wetting cycles may lead to increase in swelling percent, liquid limit and plasticity index, and a reduction in plastic limit and soil strength [31-32].

Recently, the effects of drying-wetting cycles on soil strength profile of a silty clay are investigated using a micro-penetrometer and found that the strength tends to decrease with increasing cycles and the reduction between the 1st and 2nd drying paths is much higher than that between the 2nd and 3rd drying paths. The pattern of the penetration curve changes from typical mono-peak to multi-peak pattern after the 3rd drying-wetting cycles which reflects that the drying-wetting cycles create more defects in soil microstructure and intensify the heterogeneity of strength in profile [33-34].

Most of the previous investigations on the effects of multiple drying-wetting cycles on engineering properties are based on expansive soil or artificial soils (soil mixed with fly ash, cement, lime or organic polymers) or reconstructed soils for the purpose of slope stability analysis or soil solidification or stabilization. But the effects of multiple drying-wetting cycles on shear strength of undisturbed residual soils are not well understood yet. Therefore, the main objective of this study is to evaluate the effects of drying and wetting cycles on saturated shear strength of undisturbed residual soils.

2. Materials and Methods

Undisturbed residual soil samples of 5.0-7.0m depths collected at areas around Kaiping, Gaungdong, China are used for this study. According to X-ray diffraction analysis, the studied soils are mainly composed of kaolinite with small amount of illite. The non-clay minerals include quartz, pyrite and gibbsite. The basic material properties are measured in the laboratory and given in table 1 and the grain size distribution is shown in Fig. 1.

Table 1. *Basic material properties of the studied residual soils.*

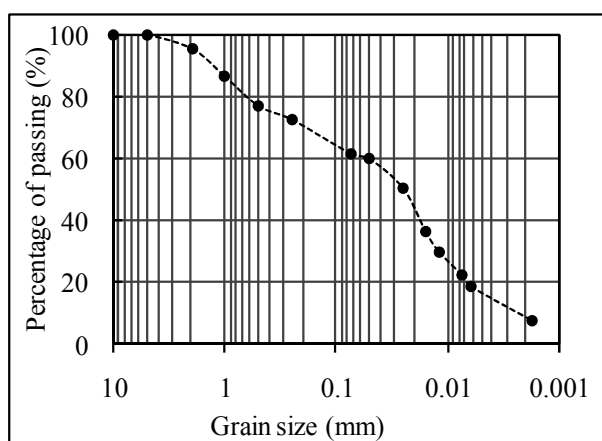| Depth (m)	P_d (g/cm^3)	NMC %	Atterberg limits			Free swell (%)	Grain size distribution (%)			
			L_L %	P_L %	I_P %		Gravel	Sand	Silt	Clay
5.7~6.0	1.30	40.2	57.1	30.7	26.4	9.75	4.6	33.4	45.9	16.1

Figure 1. *Grain size distribution of the studied residual soil.*

The preparation procedures include cutting appropriate size of soil using cutting ring from the core samples. After cutting and weighted, the samples are dried up to moisture content 20% at a constant temperature of 40 ± 2°C (the highest temperature under simulated natural conditions). Remove the specimens from oven and allow 1-2 h for cool at room temperature. The samples are covered by filter paper and water-permeable stone both on top and bottom to prevent disturbance during the saturation process. Then the samples are saturated with distilled water after vacuum seeding about 2 hours and then submerged about 24h. Later the samples are dried up to 20% moisture content oven at a constant temperature of 40 ± 2°C. This is one drying-wetting cycle. The process is repeated until the desired numbers of drying-wetting cycles (0, 1, 2, 4 and 8) are completed.

A conventional triaxial test apparatus is used to measure the shear strength parameters of saturated drying-wetting soil specimens under consolidated drained (CD) conditions following the ASTM D7181-11 [35] standard test method. Prior to the tests, the soil specimens are saturated from the top until a value of B (the pore-water parameter) is 0.95 (± 0.02) and it takes 2-4 days. For this purpose, the cell pressure and saturation water pressure (back pressure) are applied and then increased gradually. A difference of 10 kPa between cell pressure and back pressure is maintained to prevent swelling or consolidation during the saturation process. After completing the saturation process, the soil specimens are consolidated under a confining pressure of σ_3, and pore water is allowed to drain out. The intervals of elapsed time (0.25, 0.5, 1, 2, 3, 4, 5, 10, 15, 30 min and at 1, 2, 4, and 8 h, and so forth) and the corresponding volume change are recorded. The consolidation process is allowed to continue until a steady value of volume change is obtained. At the end of the consolidation, the specimens are sheared at a strain rate of 0.011%/min. For all the samples, the net confining pressures are of 50, 100, 200 and 300 kPa and shear strain upto 20%.

3. Results and Discussions

The drained deviator stress versus axial strain curves for the drying-wetting cycle samples are shown in Fig. 2-6 and it can be seen that the stress-strain relationships appear to be strain-hardening. The curves show a maximum stress level in each case and after reaching the maximum stress level, there is a slight reduction or tends to reach a steady or equilibrium state in deviator stress with increasing strain. The results show that the peak deviatory stresses reduce with increasing drying-wetting cycles. The reduction is more pronounced in the 1st cycle and decreases with subsequent cycles and finally reaches to a constant state after 4 cycles. The axial strains to attain maximum deviator stress for these drying-wetting samples show higher values range from 14.57-18.94% which is a reflection of highly plastic nature of the soil.

The volumetric strain versus axial strain curves are shown in Fig. 7-11. It can be observed that all the samples show contraction behavior because of reduction in volume during drained shearing. It can also be seen that the amount of contraction varied from sample to sample.
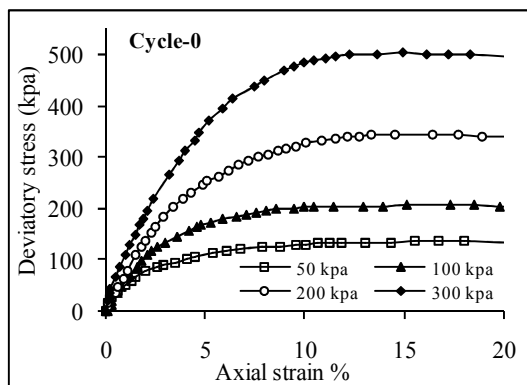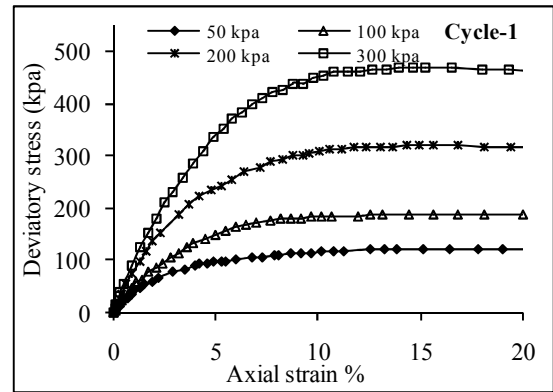

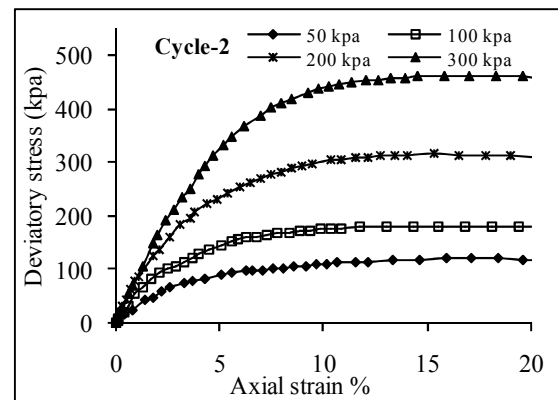**Figure 3.** Deviatory stress versus axial strain of 1st drying-wetting cycle.

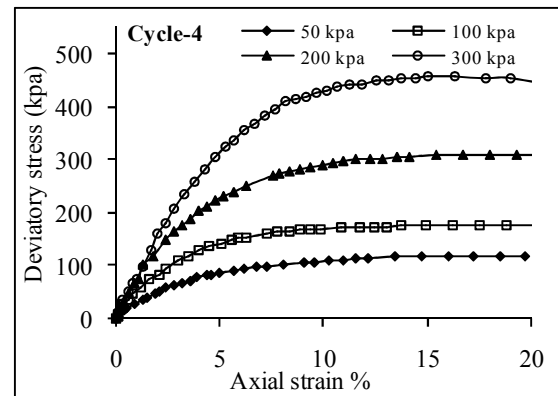**Figure 4.** Deviatory stress versus axial strain of 2nd drying-wetting cycle.

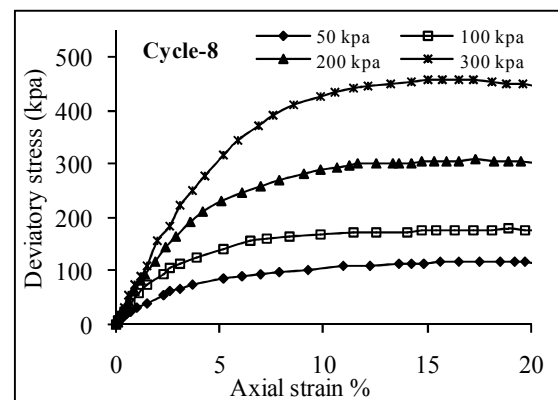**Figure 5.** Deviatory stress versus axial strain of 4th drying-wetting cycle.

Figure 6. Deviatory stress versus axial strain of 8th drying-wetting cycle.

Figure 2. Deviatory stress versus axial strain curve of initial soil samples.
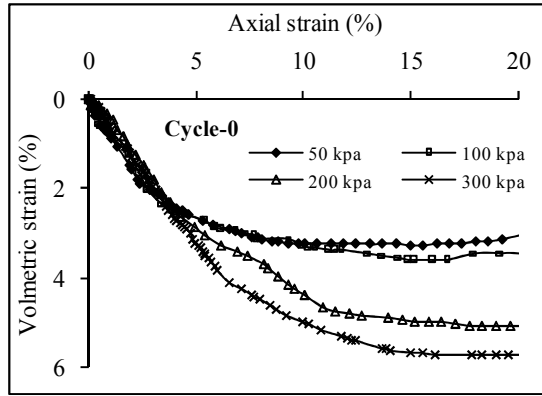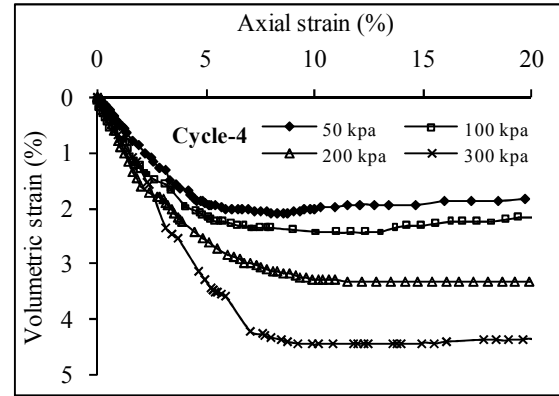
Figure 7. Volumetric strain versus axial strain curve of initial soil samples.

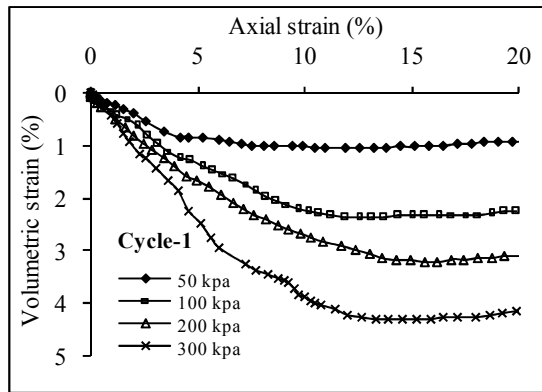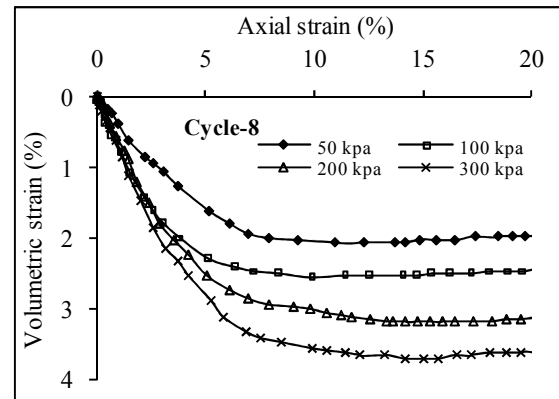*Figure 8. Volumetric strain versus axial strain of 1st drying-wetting cycle.*

After attaining a maximum contraction, the volumetric strain of each sample tends towards a steady value of the volumetric strain at very large strain and there is no distinct dilation behavior which suggesting that they might approach the critical state condition. The effective stress paths of those drying-wetting cycle samples are shown in Fig. 12-16. It is observed that the failure point and end point almost close to each other indicating the hardening behavior of the soil. All the samples failed with a number of indistinct shear planes and by bulging. At high net normal stress, the sample failed with distinct shear planes and prominent bulging. The possible critical state lines (CSL) and the slope of CSL (M) in the plane of deviator stress against mean effective stress of the saturated specimen are also given in Fig. 12-16.
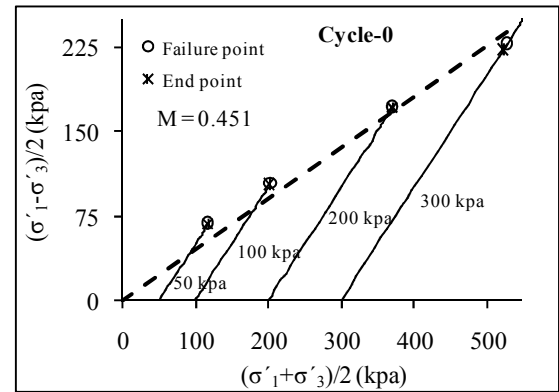

Figure 9. Volumetric strain versus axial strain of 2nd drying-wetting cycle.

Figure 10. Volumetric strain versus axial strain of 4th drying-wetting cycle.

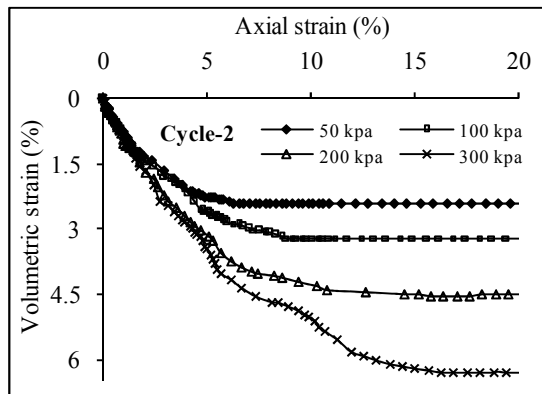*Figure 11. Volumetric strain versus axial strain of 8th drying-wetting cycle.*

Figure 12. Effective stress paths of initial soil samples.
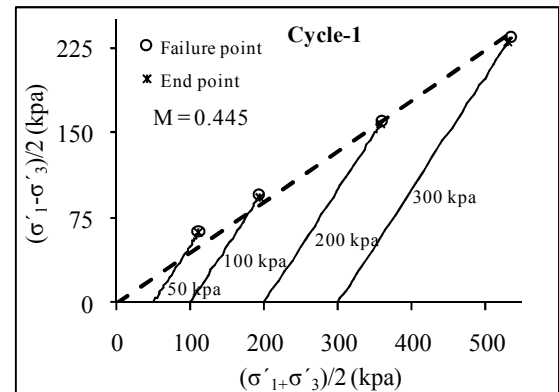

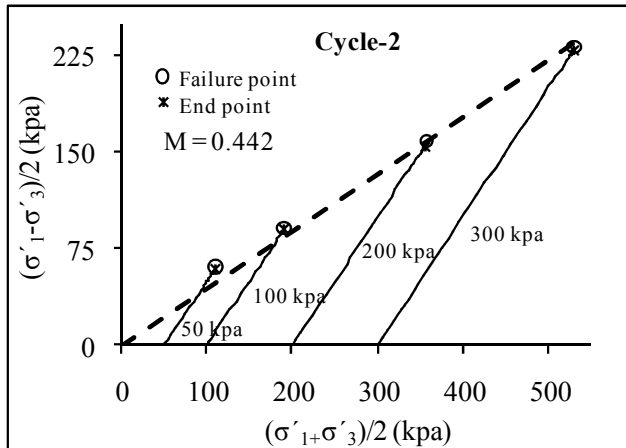*Figure 13. Effective stress paths of 1st drying-wetting soil samples.*

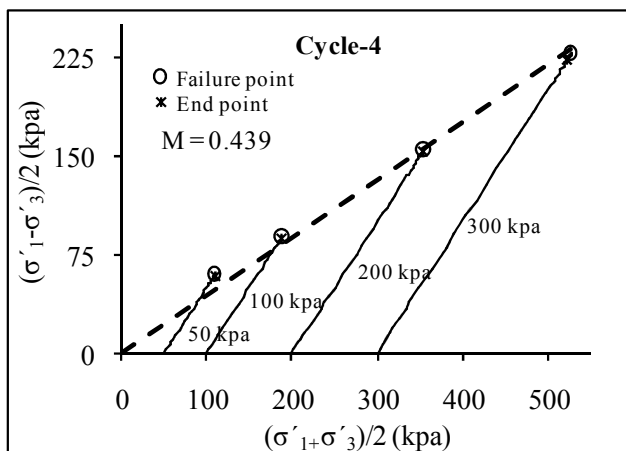*Figure 14. Effective stress paths of 2nd drying-wetting soil samples.*

Figure 15. Effective stress paths of 4th drying-wetting soil samples.
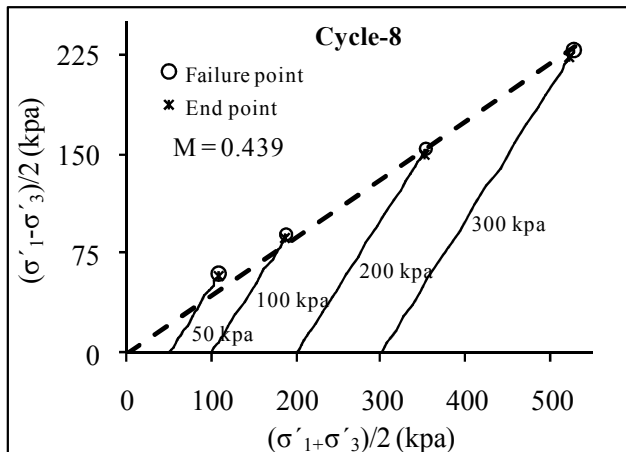

Figure 16. Effective stress paths of 8th drying-wetting soil samples.

The deviatory stress and initial stiffness of saturated soils increase and the volume of soils becomes contractive as the net normal stress increases. The increase in the net normal stress may force soil particles to close pack arrangement (volume contraction) during shearing.

This volume contraction makes the sample denser, eventually the shear resistance and the initial stiffness increase. But the deviatory stress and initial stiffness of saturated soils

decrease with increasing drying-wetting cycle numbers. The slope of the critical state line also decreases with increasing cycle numbers.

The saturated strength parameters (c_d and φ_d) of the drying-wetting cycles specimens are determined by the classical Mohr-Coulomb approach which are given in table 2. The failure envelope of the drying-wetting cycles is shown in Fig. 17. The cohesion (c_d) and internal friction angle (φ_d) decrease with increasing cycle number (N) but the attenuation rate of φ_d is less than c_d (Fig. 17). The variations of c_d and φ_d with respect to drying-wetting cycles can be calculated using exponential function and the obtained results are fitted well with the measured c_d and φ_d data (Fig. 18).

Table 2. Saturated shear strength parameters of drying-wetting cycles.

Shear strength parameters	Drying-wetting cycle numbers (N)				
	0	1	2	4	8
Cohesion c_d	19.35	16.6	15.5	15	15
Friction angle φ_d	24.95	24.25	23.97	23.8	23.78

Figure 17. Mohr-Coulomb failure envelop of different drying-wetting cycles.

Figure 18. Variation of c_d and φ_d with respect to drying-wetting cycles.

The variations of saturated shear strength under different net normal stress and drying-wetting cycles are given in table 3 and found that the saturated shear strength increases with increasing net normal stress. It can also be seen that at same net normal stress, the shear strength decreases with increasing drying-wetting cycles.

Table 3. τ_{sat} *with different wetting-drying cycles and net normal stress.*

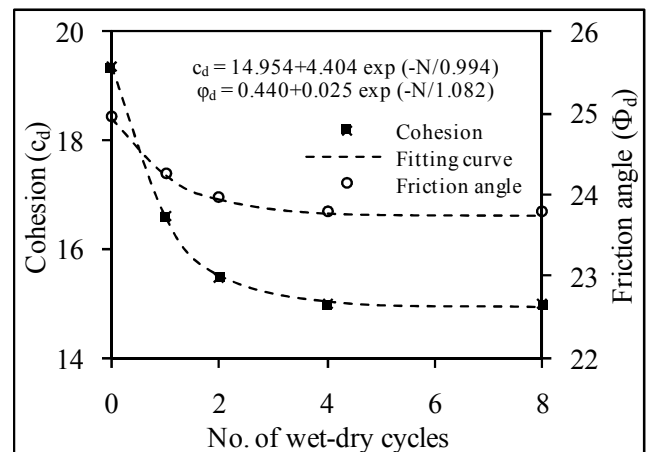| (σ-μ_a)/kpa	τ_{sat} (kpa) with dry-wet cycles				
	0	1	2	4	8
50	42.6	39.1	37.7	37.05	37
100	65.85	61.6	59.9	59.1	59
200	112.4	106.6	104.3	103.2	103
300	158.9	151.6	148.7	147.3	147

The attenuation rate (%) of saturated shear strength with respect to drying-wetting cycles is calculated using following equation-

$$\Delta_\tau = \frac{|\tau_i - \tau_0|}{\tau_0} \times 100\% \qquad (1)$$

Where, Δ_τ is the attenuation rate (%), τ_0 & τ_i are the saturated shear strength of initial and after different drying-wetting cycles respectively.

The variations of saturated shear strength attenuation rate (%) under different net normal stress and drying-wetting cycles are given in table 4. For example, at 50 kpa confining pressure, the attenuation rate is 8.22%, 11.50%, 13.03%, 13.15% for 1, 2, 4 and 8 cycles respectively. The attenuation rate from cycle 0→1, 1→2, 2→4 and 4→8 are about 8.22%, 2.78%, 1.53% and 0.12% respectively. It is stated that the attenuation rate is more pronounced in the first cycle and decreases with subsequent cycles and finally reaches to a constant state after 4 cycles. The attenuation rate also decreases with increasing net normal stress. This reduction of shear strength with drying-wetting cycles might be due to the changes of particle arrangement and the grain size distribution, decrease of pore volume and void ratio or due to the formation of micro-cracks and fissures.

Table 4. τ_{sat} *attenuation rate (%) with different wetting-drying cycles and net normal stress.*

(σ-μ_a)/kpa	τ_{sat} attenuation rate (%)			
	Δ_{c-1}	Δ_{c-2}	Δ_{c-4}	Δ_{c-8}
50	8.22	11.5	13.03	13.15
100	6.45	9.04	10.25	10.4
200	5.12	7.17	8.14	8.32
300	4.56	6.39	7.27	7.46

Based on regression analysis, a mathematical function is proposed to obtain the best fitting saturated shear strength attenuation rate with drying-wetting cycle samples. The mathematical equation is-

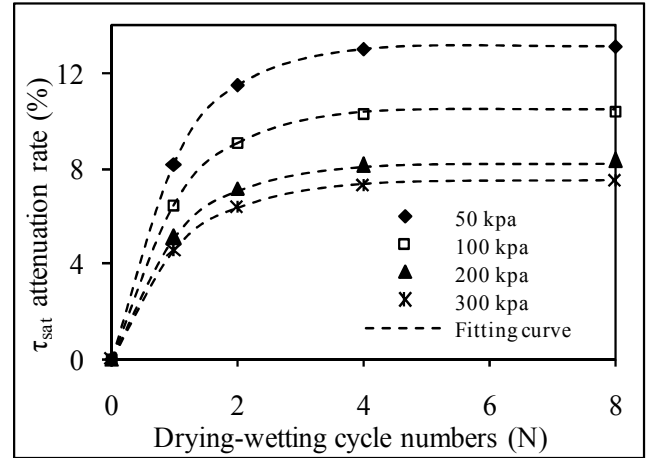$$\Delta_\tau = J_0 - \frac{J_0}{\left(1 + \frac{N}{J_1}\right)^{J_2}} \qquad (2)$$

Where, Δ_t is saturated shear strength attenuation rate, N is the drying-wetting cycle number and J_0, J_1 & J_2 are fitting parameters. The variations of fitting parameters (J_0, J_1 & J_2) with respect to different net normal stress (σ-μ_a) can be calculated by the following equations-

$$J_0 = 7.2128 + 10.7652 \exp[-0.012(\sigma-\mu_a)] \qquad (3)$$

$$J_1 = -2.5494 - 5.36 \exp[0.0066(\sigma-\mu_a)] \qquad (4)$$

$$J_2 = -2.1357 - 5.1727 \exp[0.0065(\sigma-\mu_a)] \qquad (5)$$

Using the above mathematical function, the predicted attenuation rate of saturated shear strength with respect to different drying-wetting cycles and net normal stresses are fitted well with the calculated data (Fig. 19). The correlation coefficients are more than 99%, indicating that the proposed mathematical function can describe the attenuation rate of drying-wetting cycle samples saturated shear strength.

Figure 19. *Fitting curves of τ_{sat} attenuation rate (%) under drying-wetting cycles.*

4. Conclusion

In this study, the effects of multiple drying-wetting cycles on saturated shear strength of undisturbed residual soil are investigated using a series of consolidated drained triaxial tests. The stress-strain curves for the drying-wetting cycle samples appear to be strain-hardening. The deviatory stress and initial stiffness of saturated soils increase with increasing net normal stress but decrease with increasing drying-wetting cycle numbers. The axial strains to attain maximum deviator stress for these drying-wetting samples show higher values range from 14.57-18.94% which is a reflection of highly plastic nature of the soil. The slope of the critical state line decreases with increasing cycle numbers. The cohesion (c_d) and internal friction angle (φ_d) decrease with increasing cycle number (N) but the attenuation rate of φ_d is less than c_d. The variations of c_d and φ_d with respect to drying-wetting cycles can be expressed by exponential function. The saturated shear strength of residual soil decreases with increasing number of cycles. The effect is more significant for the first cycle and decreases with subsequent cycles and finally reaches to a constant state after 4 cycles. The attenuation rate of shear strength due to drying-wetting cycles is also analyzed. Furthermore, a mathematical function is proposed in this paper which can describe the saturated shear strength attenuation rate of drying-wetting cycle samples. Such studies are useful to understand the possible changes in shear strength behavior of residual soil that are subject to periodic drying and wetting from climatic variations and may provide the reference to the future geotechnical engineers and disaster

reduction professionals to build up engineering structures safely and economically.

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