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Experimental Study on the Strength Variation of Unsaturated Cohesive Soil in Red Bed with water content

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The shear strength parameter of rock and soil is the basis of engineering design. As the rock-soil environment is ever-changing, geotechnical parameters that are obtained at a certain point of time can represent no other than the geotechnical condition in a specific environment. If engineering design is conducted by using geotechnical shear strength parameters without considering the environmental impact (especially aquatic impact), it may cause serious consequences. To research on the relationship between residual cohesive soil in red bed with water content, we collected cohesive soil from different sites to conduct indoor direct shear tests of undisturbed soil samples from the same field. The remolded cohesive soil samples were prepared for another direct shear test and the unconsolidated and unstrained triaxial test. Meanwhile, the change law of the relation between water content and shear strength of ordinary cohesive soil is compared with our result by curve fitting. Through this method, we obtained the relations between water content and shear strength.

1. Introduction

In the strict sense, the shear strength values provided by survey reports can only reflect the rock and soil conditions in the survey period. However, after decades of domestic and foreign research on the relationship between water content and strength of unsaturated soil, it is found that they have direct relationship with each other, which can be expressed by a relation. The first shear strength relation of unsaturated soil was established by Bishop et al. (1961), according to the Mohr-Coulomb failure criterion.

$$\delta_f = c' + [(\sigma - \mu_a) + \chi(\mu_a - \mu_\omega)]\tan\phi' \quad (1)$$

Where: c' is the effective cohesion; μ_ω is the pore water pressure; $(\mu_a - \mu_\omega)$ is the matric suction; $\emptyset'$ is the effective internal friction angle; x is the parameters related to soil saturation, known as the effective stress parameter of unsaturated soil, whose physical significance is the hydraulic action per unit area. x value is dependent on soil type, saturation, dry-wet cycle, and suction loading path, and ranges between 0 and 1.0, representing dry soil and saturated soil, respectively. In 1978, Fredlund et al. (1987) proposed the shear strength formula of unsaturated soil through bivariate analysis, i.e.

$$T_f = c' + (\sigma - \mu_a)\tan\phi' + (\mu_a - \mu_\omega)\tan\phi^b \quad (2)$$

Where: c' is the effective cohesion; $\emptyset'$ is the internal friction angle associated with the net normal stress variable $(\sigma - \mu_a)$; $\emptyset^b$ is the internal friction angle of the shear strength varying with matric suction $(\mu_a - \mu_\omega)$. In 1992, the Chinese scholar Lu and Zhan (1992) suggested that the unsaturated soil shear strength is composed of three parts: (1) cohesion c'; (2) frictional strength $(\sigma - \mu_a)tan\emptyset$ under the action of external force; (3) the internal friction strength (adsorption strength) τ_a generated by suction. the shear strength of unsaturated soil at any water content can be calculated with water content and matric suction. However, they are seldom applied in actual engineering projects because of the difficulty to measure matric suction. Through the water content and shear strength tests, domestic and foreign scholars obtained the relationship between water content and shear strength. In 2007, Ling and Ying (2007) analyzed the change of unsaturated soil strength with water content, obtaining the relation:

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$$c = c_{50} + k_c(\omega - \omega_{50}) \tag{3}$$

According to the triaxial test,

$$\phi = \phi_{50} + k_\phi(\omega - \omega_{50}) \tag{4}$$

c_{50} is the cohesion when the saturation is 50%, and $\emptyset_{50}$ is the inner friction angle when the saturation is 50%. Koumoto and Houlsby (2001) proposed the relation between sludge moisture content and undrained shear strength.

$$\omega = aS_{ur}^{-b} \tag{5}$$

Where a and b are coefficients, and S_{ur} is the undrained shear strength. Bian et al. (2011) thought that the relationship between total cohesion and water content approaches quadratic curve, and that the relationship between inner friction angle and water content approaches linearity, i.e.

$$\tau = c(\omega) + \sigma\tan\phi(\omega) \tag{6}$$

Where:

$$c(\omega) = a\omega^2 + b\omega + c\phi(\omega) + d\omega + e \tag{7}$$

In 2010, Luo et al. (2010) conducted direct shear test on silt (water content: 2.60% ~ 22.60%), obtaining the relation between water content and shear strength

$$\tau = c + \sigma\tan\phi = A_1 e^{B_1\omega} + \sigma\tan\left(A_2\omega^{B_2}\right) \tag{8}$$

Where A_1, B_1, A_2 and B_2 are constants. The year of 2012 saw Pan and Li (2012) performing triaxial test on expansive soil for special use, obtaining the relation between water content and shear strength

$$c = 258.3276 - 4.4789/\rho + 58.8373\ln\omega \tag{9}$$

$$\phi = 0.7825 + 3.3337\ln\rho + 351.159g/\omega \tag{10}$$

where ρ is the soil density $\rho = a'' + b''\omega^2 + c''\omega$, a'', b'' and c'' are experimental constants related to ρ. In 2006, Li and Miao (2006) used Loess of Malan to analyze the relation between water content and shear strength, arriving at the relation of

$$\tau = c^{1+0.25\lg(\omega/\omega p)} + \tan\phi\sigma^{0.885-0.55\lg(\omega/\omega p)} \tag{11}$$

The red bed cohesive clay is the product of argillaceous sandstone widely spread in the Pearl River Delta, and the thickness can be ten more meters. Its liquidity index ranges from soft plastic to hard, easy to soften with water. This maroon clay is widely used as the bearing stratum of structures. Also, the clay is the major material to reinforce or design soil layers in the foundation pit engineering work and slope engineering work.

2. Factors Affecting Shear Strength of Cohesive Soil

The shear strength of cohesive soil consists of two parts: friction, which is positively proportional to the normal stress, and cohesion between soil particles, which results from cementation and electrostatic attraction between clay particles. The sliding friction between particles and frictional resistance of male & female faces is dependent on factors like soil surface roughness, soil compactness and particle size.

There are many internal factors influencing the cohesion and the internal friction angle, and the mechanism of influence is also complicated. It is divided into two categories: soil structure characteristics (particle size, particle shape, particle connection, etc.) and external environments. There are usually three soil structures: single grain, cellular and flocculent. The structure of soil refers to stratification and fissure. Coarser soil particles mean lower liquid limit and larger internal friction angle; while higher liquid limit means finer soil particles and smaller internal friction angle. For cohesive soil, as the soil particles become coarser, the soil has higher permeability and tends towards dewatering under the shear force, and thus soil particles may rearrange themselves in a way that enlarging the internal friction angle. In addition, the internal friction angle is closely related to void ratio: more denser soil has lower void ratio and larger internal friction angle; while higher void ratio means smaller internal friction angle. The water content and soil density decide the void ratio. The undisturbed cohesive soil is far more reinforced than remolded soil because of the action of flocculent structures. The external environments include disturbance to soil during in-field sampling, transporting and indoor sample preparation, experimental approach, stress, time and temperature.

3. The Relationship between Moisture Content and Shear Strength of Soil in Different Sites

The quick shear test results of 152 samples are: moisture content 15. 7 ~ 59.3, silty clay: C ≈ 2.6 ~ 32.6 kPa. Φ = 0.5 ~ 59.0 º, ω = 22 ± 1%, C = 4.2 ~ 40.1 kPa, φ = 9.6 ~ 19.6 º, and the maximum difference is more than 5 times. Fig. 1 and 2 show the relationship between moisture content and C and φ values, which shows that the relation between water content and shear strength has no significant laws of change. Clay: C ≈ 1.4 ~ 60.5 kPa, Φ = 4.4 ~ 32.9 º, ω = 22 ± 1%, C = 4.2 ~ 71.3 kPa, φ = 9.6 ~ 19.9 º, and the maximum difference is more than 10 times. Silt: C ≈ 2.1 ~ 85.5 kPa, Φ = 4.0 ~ 32.7 º, ω = 22 ± 1%, C = 9.3 ~ 32.5 kPa, φ = 6.7 ~ 22.4 º, and the maximum difference is more than 4 times. The C value decreases markedly with the increase of the water content, while the friction angle decreases with the increase of the water content in a much smaller magnitude. The relationship between moisture content and shear strength of soil has no regularity. Although the soil name, test method and test equipment are the same, the relation between water content and shear strength cannot be represented accurately due to the difference of soil structure, and the influence of factors such as soil structure disturbance and operational impact.

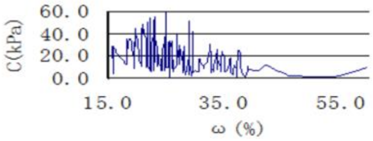

Figure 1: C ~ ω curve

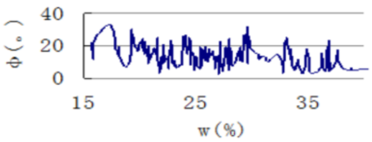

Figure 2: φ ~ ω curve

4. Relationship between Moisture Content and Shear Strength of Residual Cohesive Soil in Red Bed

The sampling drill holes on the site are laid every 2 ~ 4m, totaling 10 holes. The drilling construction projects are numbered ZK01 ~ ZK10. The residual cohesive soil is brown red, whose liquidity index ranges from plastic to hard plastic, easy to soften and disintegrate with water. The rock core occurs in soil. The soil layer is 0.60 ~ 8.10m thick, averaging 4.72m; the buried depth of the layer top is 6.40 ~ 13.60m, and the elevation is 6.32 ~ 13.53m, averaging 11.23m.

In order to obtain good test results, some soil samples were air-dried and saturated. 14 cohesive soil samples underwent saturation analysis, with the water content of 16.1 ~ 31.1% (saturation S = 99%), C ≈ 2.3 ~ 29.3 kPa. Φ = 6.3 ~ 36.6, ω = 20 ± 2 º, C = 2.3 ~ 16.8 kPa, φ = 5.9 ~ 36.6 º, and the maximum difference is more than 6 times. Fig. 1 and 2 are the curves of the relation between water content and C and φ values.

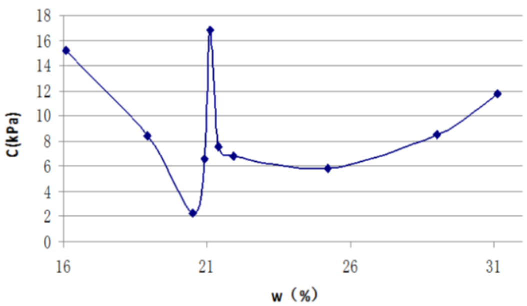

Figure 3: C ~ ω curve

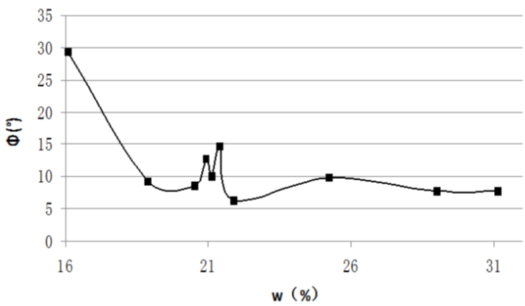

Figure 4: φ ~ ω curve

5. The Relation between Moisture Content and Shear Strength of Remolded Soil Sample in the Red Bed

5.1 Experimental design

In this experiment, the shear strength of remolded soil samples is measured by direct shear, unconsolidated and undrained triaxial test. The relation between shear strength and water content of soil is determined according to the calculated C and φ values of soil samples at different water contents. The compaction test apparatus is used to compact the soil specimens into cylinder. To ensure data optimization, the targeted water content range is 15%-35%. Each water content corresponds to a group of test with 4 samples. Samples in a test group are dried in a dryer, ground into pieces, and sifted through the 0.5mm sieve. They are prepared into discrete soil samples with targeted water content before compaction, so as to maintain the same water content. Undisturbed soil: reddish brown, mixed with grey white clay, plastic, named silty clay

5.2 The experimental procedures for remolded soil samples and interpretation of results

The preparation of soil samples can be shown in the following Fig.:
Collect undisturbed soil, dry it in the dryer for 10h, crush it and sieve the crushed soil particles, weigh the sifted soil, spray water on it, and cure it for a certain time of period. After the curing period, take some soil to dry it for 8h, calculate the actual water content, and prepare soil samples for the compaction test. Results of test and interpretation follow as:

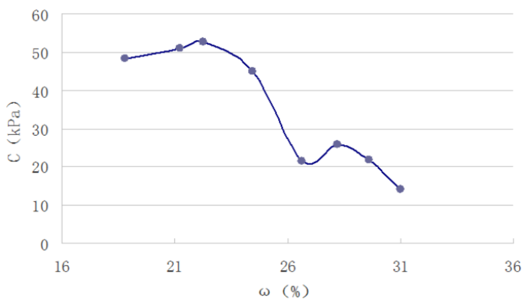

Figure 5: C ~ ω curve

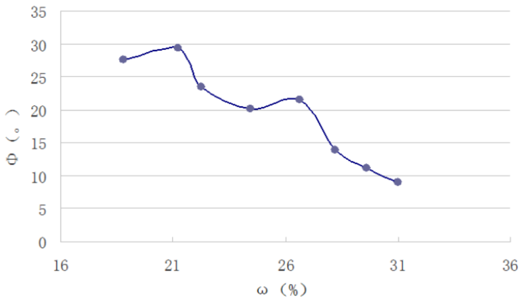

Figure 6: φ ~ ω curve

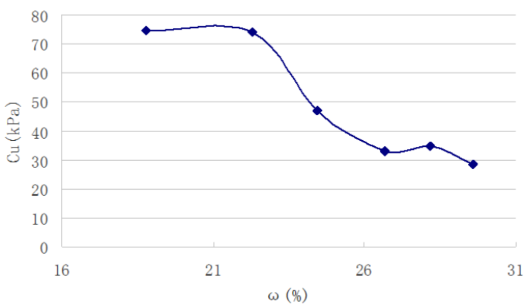

Figure 7: C_u ~ ω curve

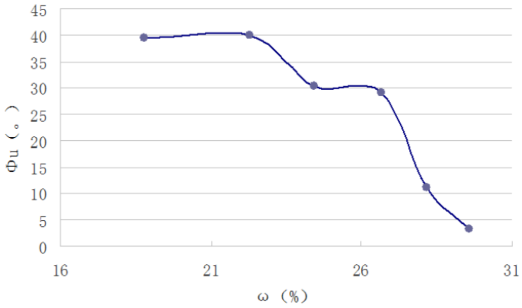

Figure 8: φ_u ~ ω curve

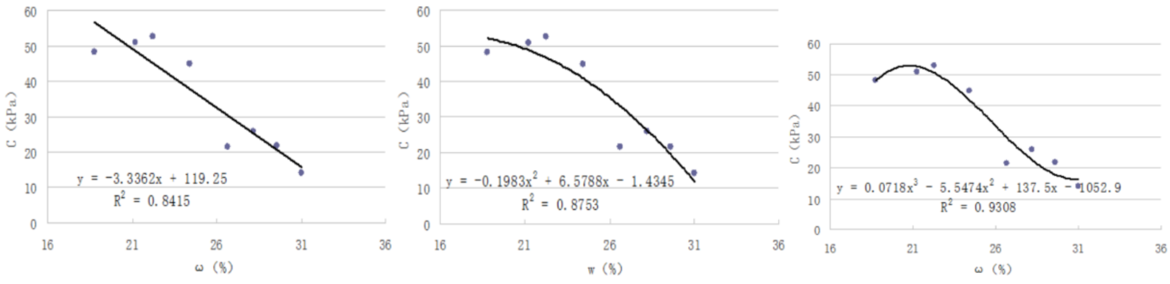

Figure 9: C ~ ω relationship fitting Fig. (linear, quadratic curve, cubic curve fitting)

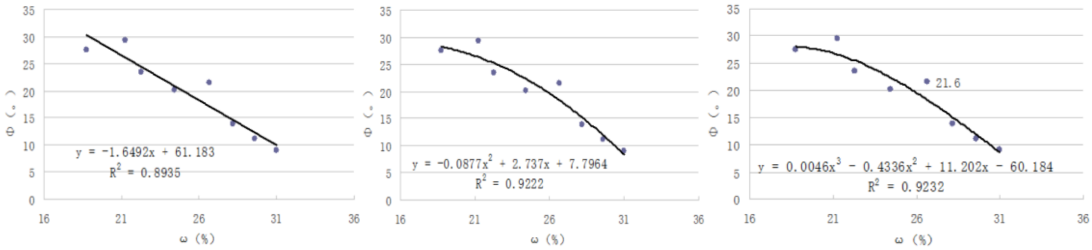

Figure 10: φ ~ ω relationship fitting Fig. (linear fitting, quadratic curve, cubic curve fitting)

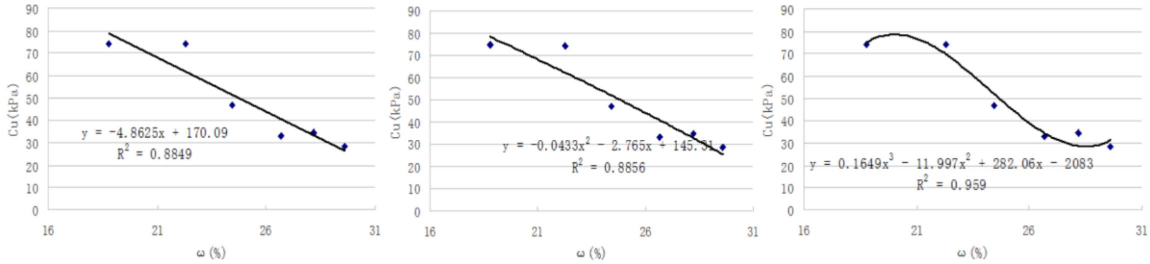

Figure 11: C_u ~ ω relationship fitting Fig. (linear, quadratic curve, cubic curve fitting)

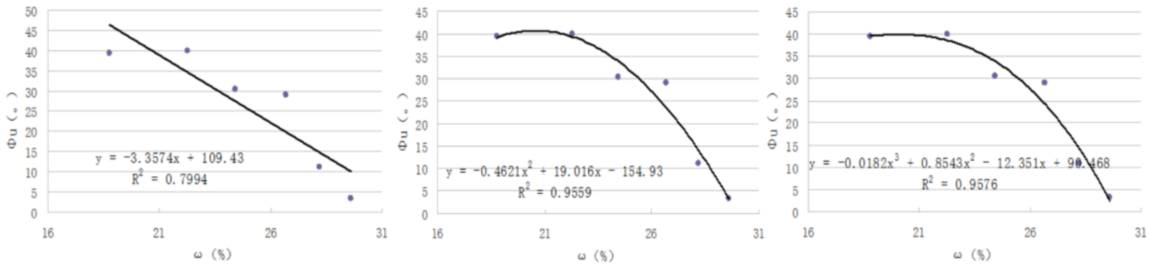

Figure 12: $φ_u$ ~ ω relationship fitting Fig. (linear fitting, quadratic curve, cubic curve fitting)

In Fig. 5, the C ~ ω relationship curve is "S" type, and can be divided into three stages. In the first stage, the water content changes while the cohesion is basically unchanged; in the second stage, as the water content increases, the cohesion slumps. In the third stage, the water content increases, and the cohesive force continues decreasing, but with a lower rate of descend. The water content of the soil samples increases from 18.77% to 31.00%, and the cohesion decreases by 34.10KPa, from 48.11KPa to 14.01KPa, at the descend rate of 70.9%.

In Fig. 6, φ ~ ω relationship curve is "S" type, and can be divided into three stages. The first stage is the opposite to the counterpart in Fig. 5; in the second stage, φdecreases at a slow rate; in the third rate, the rate of descend becomes higher. The water content of the soil samples increases from 18.77% to 31%, and the internal friction angle decreases by 18.5 °, from 27.5 ° to 9.0 °, at the descend rate of 67.3%.

In Fig. 7, C_u ~ ω curve is "S" type, and can be divided into three stages. In the first stage, the water content changes, while the cohesion is basically unchanged; in the second stage, as the water content increases, the cohesion slumps. In the third stage, the water content increases, and the cohesive force continues decreasing, but with a lower rate of descend. The water content of the soil samples increases from 18.77% to 29.59%, and the cohesion decreases by 45.95KPa, from 74.45KPa to 28.50KPa, at the descend rate of 61.7%.

In Fig. 8, $φ_u$ ~ ω relationship curve is "S" type, and can be divided into three stages. In the first stage, the water content changes, while the cohesion is basically unchanged; in the second stage, as the water content increases, the cohesion slumps. In the third stage, the water content increases, and the cohesive force continues decreasing, but with a lower rate of descend. The water content of the soil samples increases from 18.77% to 29.59%, and the internal friction angle decreases by 31.0 °, from 34.41 ° to 3.41 ° at the descend rate of 90.0%.

The curves obtained in the experiment are fitted separately with linear equation and fitting equations (curves9, 10, 11and 12). [R^2] narrowly exceeds 80% in the linear fitting equation, higher than 85% in the quadratic curve fitting equation, and higher than 90% in the cubic fitting equation. The fitting effect of $\varphi_u \sim \omega$ relation curve is the best, reaching 96%.

6. Conclusion

6.1 for undisturbed soil: the cohesive force C value decreases significantly with the increase of water content; the friction angle φ also decreases with the increase of water content, but at a much smaller magnitude. Due to the ever-changing and complex rock-soil parameters, and the multiple factors influencing shear strength, the shear strength of the same cohesive soil type in different sites changes with on-site water contents, making it difficult to form correlation curves.
6.2 For undisturbed soil in the same field: even the same cohesive soil type can hardly form the correlation curve between its shear strength and water content, limited by the differences in soil structure and mineral composition.
6.3 for the shear strength test of the remolded soil in the red bed: since the soil structures like particle size, mineral composition and porosity are basically uniform with even distribution, the factors influencing shear strength are relatively small in amount. Accordingly, the shear strength decreases with the increase of water content no matter in the direct shear test or in the triaxial test (UU), showing the relation curve of “S” shape. The cubic fitting result in the triaxial test is the optimal. The relations between moisture content and shear strength in a certain interval are obtained:

$$\tau = C(\omega) + \sigma \tan \varphi(\omega) \tag{12}$$

$$C（\omega）= 0.165\omega^3 - 12.0\omega^2 - 282.06\mathrm{x} - 2083 \tag{13}$$

$$\varphi（\omega）= -0.0185\,\omega^3 + 0.854\,\omega^2 - 12.351\,\mathrm{x} + 90.468 \tag{14}$$

References

Bian J.M., Wang B.T., 2011, Research on Influence of Water Contents on the Shear Strength Behavior of Unsaturated Soils, Chinese Journal of Underground Space and Engineering, 7(1), 17-18.

Bishop A.Ω., Alpan I., Blight G.E., 1961, Factors Controlling the shear-strength of partly saturated Cohesive soils, ASCE ConferenCe on Shear of Cohesive Soils, Boulder, CO: University of Colorado, 503-532.

Fredlund D.G., Morgenstern N.R, Ωidger R.A., 1987, The shear strength of unsaturated soils, Canadian GeoeChniCal Journal 15(3): 313-321.

Koumoto T., Houlsby G.T., 2001, Theory and practice of the fall Cone test, GéoteChnique, 51(8): 701-712, DOI: 10.1680/geot.51.8.701.40475.

Li B.X., Miao T.D., 2006, Research on water sensitivity of loess shear strength, Chinese Journal of Rock Mechanics and Engineering, 25(5), 1007.

Ling H., Ying Z.Z., 2007, Variation of Unsaturated soil strength with water contens, Chinese Journal of Rock Mechanics and Engineering, 26(7): 1499-1503, DOI: 10.3321/j.issn:1000-6915.2007.07.026.

Lu Z.J., Zhan H.M., 1992, Shear strength and Swelling pressure of unsaturated soil, Chinese Journal of Geotechnical Engineering, 14(3), 2-4.

Luo J., Wang G.Y., Bo K., 2010, Experimental Study on Influence of Water Content on Silt Strength, Subgrade Engineering, 148(1), 116-117.

Pan X., Li Y.H., 2012, Study on the parameters of swelling soil moisture content and shear strength, Sichuan Building Science, 38(6): 135-137, DOI: 10.3969/j.issn.1008-1933.2012.06.036.