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# The Unsaturated Shear Strength of Laterite: Hukou Plateau, Taiwan

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***Abstract*** **-** The engineering properties of saturated soils have been rigorously researched and are well established. On the contrary, unsaturated soils have received less attention due to the expensive equipment, complicated techniques, and tight precision required to conduct tests successfully. Consequently, advancements in understanding the engineering properties of unsaturated soils have been less common. This study combines the traditional cheap direct shear test with the filter paper method to conduct experiments on laterite soils found in Hsinchu, Taiwan, and identify the soil's shear strength and matric suction characteristics. Study results show that the soil's shear strength increases as the unsaturated soil's water content decreases, and higher matric suction is observed. A non-linear relationship defines the relationship between matric suction and shear strength. This study successfully used traditional direct shear tests paired with an improved application of the filter paper method to develop an unsaturated soil shear strength and matric suction relationship.

***Keywords*****:** Unsaturated soils, direct shear test, filter paper method, matric suction

## 1. Introduction

Laterite is a residual soil that has high amounts of montmorillonite and illite. Low shear strength, high pore pressures, high dilatancy potential, and other difficult-to-predict engineering qualities characterize it. The west side of Taiwan is covered by a large area of laterite that is especially prevalent on plateaus. The water table in the plateau can be lower, and the region above is commonly unsaturated. Natural variations in humidity cause soil moisture content in this zone to change continuously, and as a result, the strength and bearing capacity also vary. These fluctuations in soil strength influence slope stability and the maximum bearing capacity of the soil.

According to Chen [1], 99.5% of landslides in Taiwan are shallow and have a failure depth of 1.0 m or less. This phenomenon results from rainfall infiltration into the soil, a rapid shift from dry to moist conditions, and subsequent reduction in soil strength. Inner mountain roads are commonly severed by shallow landslides, a typical disaster resulting from the heavy rains associated with typhoons that annually affect Taiwan [2].

The axial translation technique is commonly used in unsaturated soil tests [3-5]. This technique applied air and water pressures to soil samples in an isolated cell to control matric suction. Thamer Ahmed Mohamed et al. [3] conducted a direct shear test with an axial translation technique for soil in Kuala Lumpur. They found that the failure envelope of unsaturated soil is non-linear due to the non-linear soil water characteristic curve.

The current unsaturated soil test methods allow independent control of matric suction. These tests, paired with the axial translation technique, involve maintaining a confining pressure and changing the air and water pressures applied to the sample to obtain the matric suction of the material. These tests need exact equipment and careful control, and the equipment is also generally costly. Additionally, waiting for air and water pressures to reach equilibrium is time-consuming. As a result, precise unsaturated soil strength experiments are not widely available.

On the other hand, traditional direct shear tests measure the shear strength of soil but provide no data regarding the matric suction. The relationship between matric suction and shear strength cannot be derived. Several researchers have used the soil moisture characteristic curve of the soil to estimate the matric suction of samples tested in direct shear experiments [6]. They assume that the matric suction of the soil does not change during shear failure. In fact, using the moisture content of the soil and the moisture characteristic curve to obtain matric suction may not account for changes in porosity that result during shear failure and the subsequent effect on matric suction.

In this study, the traditional direct shear test is paired with the filter paper method to measure shear strength and estimate matric suction. The application of the filter paper method is adjusted to ensure that changes in porosity resulting from shear failure and associated effects on matric suction are taken into account. Finally, the relationship between the shear strength parameter of laterite and matric suction was discussed.

## 2. Materials and Methods

### 2.1. Materials

Soil samples were collected from the Hukou plateau in Hsinchu, Taiwan. Samples were extracted from a depth of 100 cm from the surface. During sampling, the density and unit weight of the soil were determined using the sand cone method (ASTM D1556-64). Using the Unified Soil Classification System (USCS), the soil was classified as CL, a low plasticity clay. The primary characteristics of the soil are shown in Table 1.

Table 1. Characteristics of the laterite soil sample

| Soil Properties | Value |
|---|---|
| Specific gravity, *Gs* | 2.67 |
| Liquid limit, LL (%) | 38 |
| Plastic limit, PL (%) | 22 |
| Plasticity index, PI (%) | 16 |
| Clay fraction (grain size <2μm), CF (%) | 30.0 |
| Void ratio, *e* | 0.615 |
| Nature water content, $w_n$ (%) | 21.5 |
| Moist unit weight, $r_{wet}$(kN/m$^3$) | 20.14 |
| Dry unit weight,$r_d$(kN/m$^3$) | 16.64 |

### 2.1. The direct shear test experiment

Each soil specimen was remolded and prepared in 60mm diameter and 20mm thickness so that porosity equaled 0.615, matching field conditions. Four samples were formed using static loading for the following moisture contents: 12%, 15%, 19%, 21%, 23%, 25.6%, and saturated, which were labeled w12, w 15, w19, w21, w23, and w25.6 and wsat.

A shear displacement rate of 0.514 mm/min was applied to the specimen. The normal stress was set to 15, 22, 36, and 50 kPa. The sample was first preloaded to induce subsidence. Once the majority of subsidence had occurred, the horizontal shear force was applied. The shear box was wrapped with a plastic film during the experiment to decrease the soil's water content changes.

### 2.2. The calibration of the Whatman No. 42 filter paper

The filter paper method [7] had been approved that the moisture content of the filter paper at equilibrium is related to soil matric suction. The ash-free quantitative Whatman No. 42 filter paper disks were calibrated and used in this study. The calibration measurement was established using a pressure plate apparatus [8] which has a 15-bar operation pressure and uses a drying process.

The calibration curve for the Whatman No.42 filter paper is shown in figure 1. In figure 1, the water content at the breakpoint is approximately 51.6%; the bilinear regression curve [9] can be expressed as follows:

$$\text{Log Suction} = 5.051-0.062w_{fp} \quad (1)$$

$$\text{Log Sustion} = 2.525-0.013w_{fp} \quad (2)$$

Where w*fp* is the calibrated water content of the filter paper.

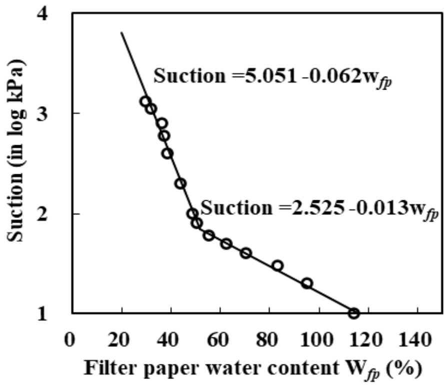


Fig. 1: Calibration curve of the Whatman No. 42 filter paper

### 2.3. Soil matric suction measurement

Soil matric suction was measured using the contact filter paper method. After completion of the direct shear test, three filter papers were placed along the failure plane of the specimen. The central filter paper was a Whatman No. 42 paper used to measure matric suction. Once the filter papers were placed correctly between the stacked sample pieces, the bundle was wrapped using insulation tape, set within a glass container, and closed using the insulation tape.

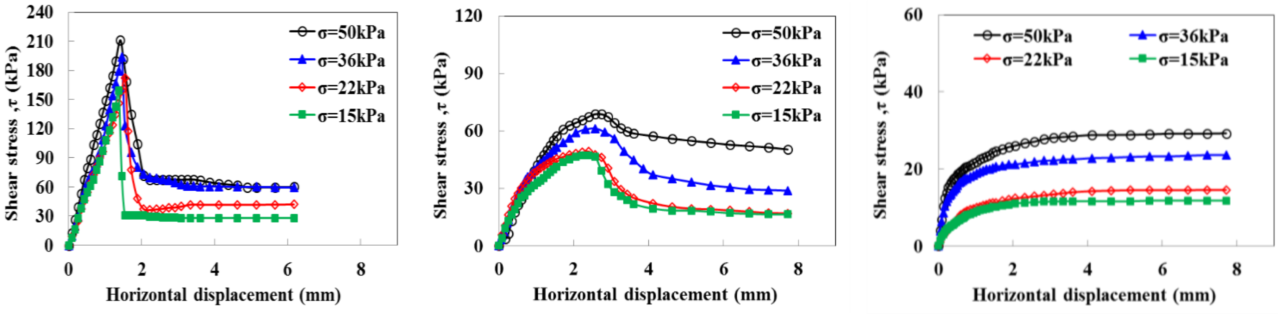
The temperature significantly affects matric suction measurements, and the following methodology was used: The glass container was placed in a styrofoam container and again sealed with insulation tape. Put the styrofoam box in a controlled 22.5$^0$C temperature cabinet for equilibrium.

After 14 days, the central filter paper was extracted from the specimen, and the water content of the filter paper was measured. The established calibration equations were then used to estimate the matric suction.

## 3. Results and Discussion

### 3.1. Shear stress and displacement

Figure 2 shows typical results of the direct shear tests on the unsaturated soil samples with different water contents. For low soil moisture contents, a brittle stress behavior was observed. For example, as shear stress was applied to the w12 specimen, a nearly linear relationship defined the shear stress and strain curve. However, after a small peak, the specimen failed, and the strength of the specimen rapidly decreased. This brittle behavior steadily transitioned into a plastic behavior as the moisture content of the specimens was increased. Once the water content exceeded 23%, peaks in the stress curve were no longer observed. Instead, a constant strength was obtained as the maximum shear stress was neared. This phenomenon was observed for all normal load values.



(a) w12 (b) w21 (c) wsat

Fig. 2: Typical direct shear test results on laterite soil specimens.

Figure 3 shows the relationship between soil moisture content and shear strength. It is known that as moisture content increases, shear strength decreases. When the soil is dry, the soil has a tight structure, and the soil particles are strongly bonded. In this situation, the frictional resistance to sliding within the soil is considerable, slipping does not readily occur, and soil shear strength is high. The increase in moisture content causes the clay molecules to absorb more water and increases the thickness of the adsorbed water layer on the surface of the clay molecules. At this time, when slippage occurs between clay particles, the frictional resistance between particles decreases, and the overall shear resistance of the soil also decreases. This reduction in strength demonstrates the difference in the shear strength associated with dry and saturated soil and the significant influence moisture content has on the shear strength of soils.

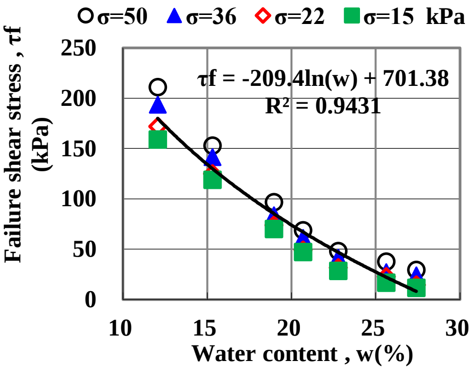


Fig. 3: Relationship between soil moisture content and mean shear strength.

### 3.2. Soil shear strength parameters *C*' and *ϕ*'

Direct shear tests can identify the failure envelope using a linear soil model. The friction angle ϕ and cohesion c were computed from each model. Results are shown in figure 4 and 5. Soils with lower moisture content had a larger friction angle. For example, at a water content of 12%, the apparent internal friction angle exceeded 56 degrees. This increase in friction angle is a result of the soil dilatancy effect. The apparent internal friction angle of the saturated specimen was 28 degrees. A relationship between the soil's apparent internal friction angle and the moister content can be described by the regression formula (3):

$$\phi = 478.31*w-0.867 \tag{3}$$

Where w is the water content of the soil.

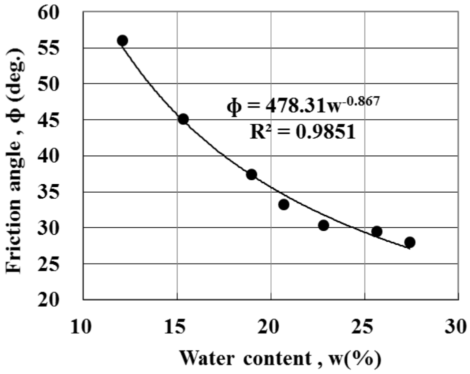


Fig. 4: Soil friction angle and moisture content.

From Figure 5, it is clear that as moisture content increases, cohesion decreases. The cohesion strength of the saturated specimen may be near 0 kPa. The regression formula describing soil cohesion and moisture content is shown below.

$$c = 571.35-174.1*\ln(w) \tag{4}$$

Where w is the water content of the soil.

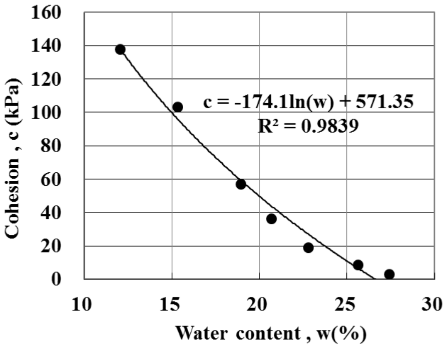


Fig. 5: Soil cohesion and moisture content.

### 3.3. Volume change

In the test procedure, the vertical displacement was recorded at each stage, and the data was used to calculate the void ratio variation. The specimen water content cannot be measured in the consolidated and shear failure stage. Nevertheless, at the end of the shear stage, the specimen was weighted to calculate soil water content. Figure 6 is the void ratio variation in the direct shear test. The void ratio value was changed to trim at the consolidation stage. At the failure stage, the void ratio value was more significant than the initial value when the soil water content was smaller. However, the void ratio value was smaller than the initial value when the soil water content was greater than 23%. At the stage of the end of the test, the change in the void ratio was more severe. This phenomenon can be attributed to the shear dilation effect of the soil; the volume dilation of the dry soil during a shearing failure is significant, resulting in a decrease in the void ratio.

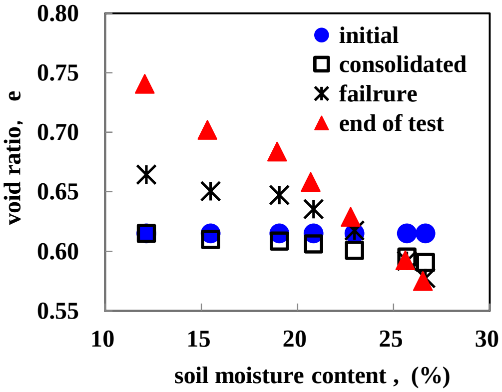


Fig. 6: The void ratio variation during the direct shear test.

### 3.4. The results of matric suction measurements using the filter paper method

From the discussion in Figure 6, we know that the void ratio of the soil is different from the initial stage when the filter paper test. This study employed calibration curves defined by equations (1) and (2) to calibrate the soil matric suction. Figure 7 shows the relationship between the calibrated soil matric suction and soil moisture content. Experiment results show that matric suction was higher for lower soil moisture contents. Additionally, soil matric suction from high soil moisture content could be unreliable. The ASTM specifications suggest applying calibration formulas for suction values ranging between 10 kPa and 100 Mpa. An accurate measurement of the amount of water absorbed by the filter paper at high moisture contents and corresponding matric suction values is difficult to obtain.

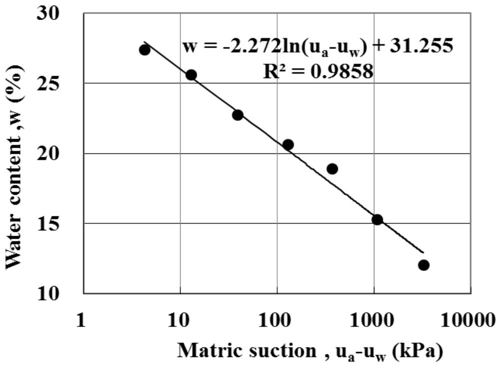


Fig. 7: Soil matric suction and moisture content.

Regarding matric suction and direct shear test results, the effect of matric suction on soil shear strength is illustrated in figure 8. The figure shows that the apparent friction angle also increases as matric suction increases. A positive non-linear relationship describes the effect of matric suction on shear strength. These results demonstrate that matric suction contributes significantly to the shear strength of soils.

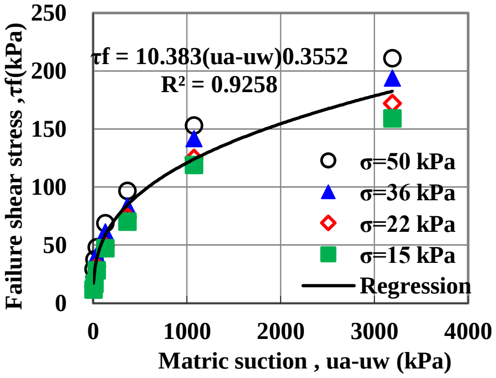


Fig. 8: A non-linear relationship between Soil matric suction and shear stress.

The relationship between soil apparent friction angle and matric suction is shown in figure 9. The figure shows that as matric suction increases, the apparent friction angle increases. The model that defines the relationship between friction angle and matric suction is shown below:

$$\phi = 22.257*(u_a-\underline{u}_w)^{0.1011} \tag{5}$$

Where $u_a-\underline{u}_w$ is the soil matric suction.

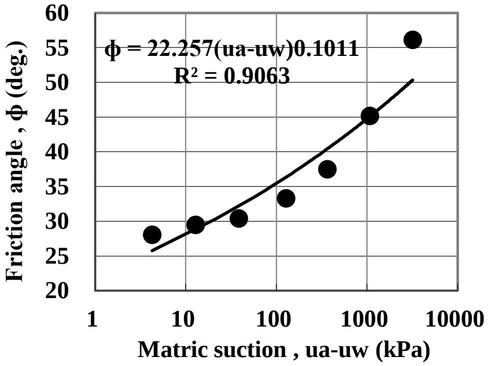


Fig. 9: Soil friction angle and matric suction.

Figure 10 shows the relationship between soil cohesion and matric suction. As soil matric suction increases, soil cohesion also increases. As soil moisture nears saturation, the water absorbed within the clay molecules increases in thickness and builds outward from the surface of the clay molecule. Slip between clay particles occurs. At the same time, the matric suction is low, which causes the soil cohesion to drop. Cohesion increases with increases in soil matric suction. From the experimental results, a regression equation describing the relationship between soil cohesion and matric suction is developed and shown below:

$$c = 2.0131*(u_a-u_w)^{0.5567} \tag{6}$$

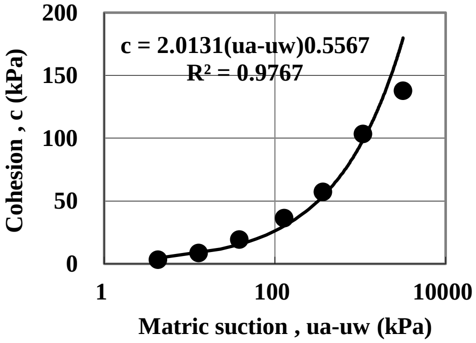


Fig. 10: Soil cohesion and matric suction.

## 4. Conclusion

Laterite's strength characteristics are critical for ensuring the safety and success of engineering projects. In particular, foundation, short pile, and slope stability designs depend on a thorough understanding of strength characteristics and are influenced by the unsaturated strength of the soil. By combining traditional direct shear tests with an improved application of the filter paper method, a series of tests were conducted on the soil by varying the soil moisture content. The results are listed below:

(1) Increases in shear stress applied to dry laterite caused a steady rise in strain until a peak shear strength was reached, at which brittle failure occurred and shear strength rapidly diminished. As moisture content was increased, the peak strength became less apparent, and the specimen became more plasticity in strain.
(2) Soil matric suction increased as soil moisture content decreased; consequently, the soil's cohesion and friction angle increased. Soil matric suction had a positive effect on soil strength.
(3) Using a traditional direct shear test paired with an improved application of the filter paper method, unsaturated soil shear strength measurements, and experiment results appear consistent with the literature. This method is relatively cheap, quick, and easy to implement and may be successfully applied to further unsaturated soil shear strength measurements. Results from such studies will be of significant use to engineering applications.

## References

[1] R. H. Chen and C. N. Liu, “Study of rain-induced slope failure in a lateritic terrace,” *Proceeding of the National Science Council*, Republic of China.1993, Part A: Physical Science and Engineering, Vol. 17, No. 6, pp. 403-409.

[2] S. R. Yang, “Probability of road interruption due to landslides under different rainfall return periods using remote sensing techniques,” *Journal of Performance of Constructed Facilities*, Vol. 30, No. 1, C4015002, 2016.

[3] T. A. Mohamed, F. H. Ali, S. Hashim and B. B. K. Huat, “Relationship between shear strength and soil water characteristic curve of an unsaturated granitic residual soil,” *American Journal of Environmental Sciences*, Vol. 2, No. 4, pp. 142-145, 2006.

[4] S. Nam, M. Gutierrez, P. Diplas and J. Petrie, “Determination of the shear strength of unsaturated soils using the multistage direct shear test,” *Engineering Geology*, Vol. 122, pp. 277-280, 2011.

[5] L. R. Hoyos, C. L. Velosa and A. J. Puppala, “A novel suction-controlled ring shear testing apparatus for unsaturated soils,” *2010 GeoShanghai International Conference-Experimental and Applied Modeling of Unsaturated Soils*, 2010. Geotechnical Special Publication. American Society of Civil Engineers, Shanghai, China, pp. 32-39.

[6] F. Q. Bai and S. H. Liu, “Measurement of the shear strength of an expansive soil by combining a filter paper method and direct shear tests,” *Geotechnical Testing Journal*, Vol. 35, No. 3, pp. 451-459, 2012.

[7] D. G. Fredlund and H. Rahardjo, *Soil Mechanics for Unsaturated Soils*, John Wiley & Sons, New York, USA, 1993.

[8] A. P. Hamblin, “Filter paper method for routine measurement of field water potential,” *Journal of Hydrology*, 53, pp. 355-360, 1981.

[9] R. Bulut and W.K. Wray, “Free energy of water-suction-in filter papers,” *Geotechnical Testing Journal*, 28(4), pp. 355-364, 2005.