

# Matric Suction and Shear Modulus of Unsaturated Compacted Lateritic Soil Subjected to Drying and Wetting

Horn-Da Lin, Cheng-Chun Wang and Johnson H.S. Kung

**Abstract** Compacted lateritic soils used widely in geotechnical engineering in Taiwan are usually under unsaturated condition. Nonetheless, their mechanical behavior is rarely studied. It may be due to complexities in the testing technique especially when comparing with saturated conditions. This study, therefore, attempts to investigate the effects of drying and wetting on the unsaturated compacted soil by self-developed moisture simulation apparatuses. A testing system is also developed to measure the matric suction and shear modulus by integrating bender element, pressure plate, and the filter paper technique. Soil specimens are compacted at different initial water contents including the optimum moisture content (OMC), OMC - 3 % (dry of optimum), and OMC + 3 % (wet of optimum). Then, soil specimens are subjected to different scenarios of drying-wetting paths before measuring the matric suction and shear modulus. The essence of the experimental processes of this study is described below. Conclusions of the test results are also summarized herewith.

**Keywords** Unsaturated soil · Matric suction · Soil-water characteristic curve · Shear modulus · Drying and wetting path

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## 1 Introduction

Residual lateritic soil, mostly in unsaturated condition, is commonly found in western tableland of Taiwan. Due to recent urbanization, lateritic soil has been used in geotechnical constructions such as embankments, dams, and highways. To evaluate the performance of these constructions, the soil properties especially soil stiffness and strength must be known. This paper intends to study the stiffness of the lateritic soil in terms of the shear modulus. This study adopts the bender element test since it provides a fast and simple mean to determine the shear wave velocity.

For an unsaturated soil, matric suction is an important index. The unsaturated lateritic soil is affected by the nature water cycle of wetting and drying due to seasonal rainfall. Drying can increase the matric suction, but it can also cause cracking and shrinkage when the water content is too low. On the other hand, wetting can decrease matric suction then result in soil bearing capacity decrease and shallow-type slope failure in the extreme condition. Therefore, it is worthwhile to study the influence of matric suction on the shear modulus upon drying and wetting. Former studies have showed that matric suction of unsaturated soils is closely related to shear modulus. In particular, by using filter paper method, Wang et al. (2010) showed that the matric suction increased due to drying path. In addition, Yang et al. (2008), Sawangsuriya et al. (2006) investigated the shear modulus of unsaturated soil under wetting path with bender element test and indicated that shear modulus decreased as matric suction decreased. Nevertheless, a comprehensive correlation between the shear modulus and the matric suction due to drying and wetting has not been investigated.

This paper presents a comprehensive experimental study on matric suction and shear modulus of unsaturated a compacted lateritic soil subjected to drying and wetting. In specific, the pressure plate test is used to measure the soil-water characteristic curve of the lateritic soil. Environmental simulation test is adopted to impose predetermined wetting and drying paths on soil samples. Soil specimens of three different initial compaction states are studied including the optimum moisture content (OMC), dry of optimum, and wet of optimum. When drying or wetting process is complete water contents are measured. Then, the bender element and filter paper method are utilized to measure the small-strain shear wave velocities and the matric suction, respectively. The essence of the experimental processes of this study is described below. Highlights of the test results are also discussed herewith.

## 2 Experimental Process

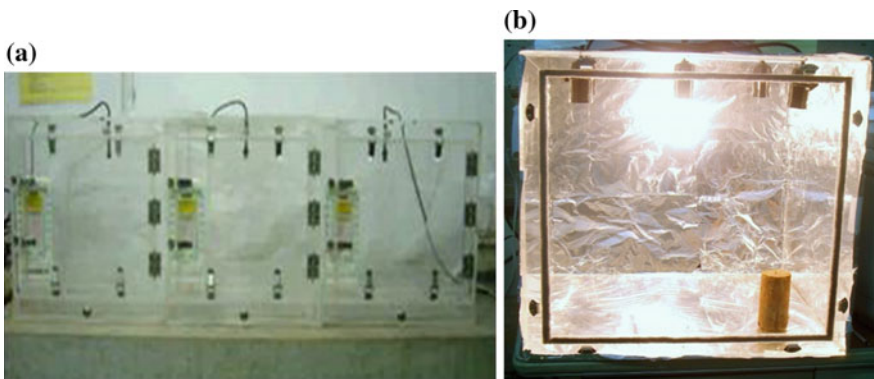
### 2.1 Soil Preparation

The lateritic soil is classified as CL according to Unified Soil Classification System. Its specific gravity, liquid limit, and plastic index are 2.69, 48.6, and 25 %, respectively.

respectively. The soil specimens were compacted by the Modified Proctor. Prior to the compaction, the soils were air-dried for several days and cleaned by removing large impurities such as roots and vegetation. The target moisture contents of the soil samples were optimum moisture content (OMC),  $OMC - 3\%$  (dry of optimum), and  $OMC + 3\%$  (wet of optimum). The corresponding dry densities were  $1.69$ ,  $1.61$ , and  $1.63 \text{ Mg/m}^3$ , respectively. The required amount of distilled water was sprayed on the air-dried soil and thoroughly mixed with the air-dried soil. The fully mixed soil was put into a plastic bag and stored in the humidity controlled room for about one day to ensure homogeneity. Soil specimens with  $100 \text{ mm}$  diameter and  $120 \text{ mm}$  height were compacted. After compaction, the soil specimens were trimmed to the desired size of  $100 \text{ mm}$  height and  $50 \text{ mm}$  diameter for the testing.

### 2.2 Environmental Simulation Test

The soil specimens were cured with different paths of drying or wetting by the apparatus shown in Fig. 1. The environmental simulation apparatus is shown in Fig. 1a. The apparatus contains three cube boxes. Each box has side dimension of  $45 \text{ cm}$  and was made of acrylic plates of  $0.8 \text{ cm}$  thick. Timer setting sprinklers installed on top are used to create a wetting apparatus that can simulate rainfall infiltration. The calibration test proves that the relative humidity in each box is indeed not affected by the change of relative humidity of outdoor. For drying simulation, a  $60 \text{ W}$  light bulb was installed beneath the ceiling of the box to simulate sunshine drying as shown in Fig. 1b. The drying room is a  $48 \text{ cm}$  cube box made of acrylic plate of  $1 \text{ cm}$  thick. The temperature in the box was controlled approximately at  $37^\circ$ . After the curing processes, the uniformity of the moisture content inside the soil specimen was carefully checked. Figure 2 shows that the



**Fig. 1** Schematic diagram of environmental simulation apparatus. **a** Wetting apparatus. **b** Drying box

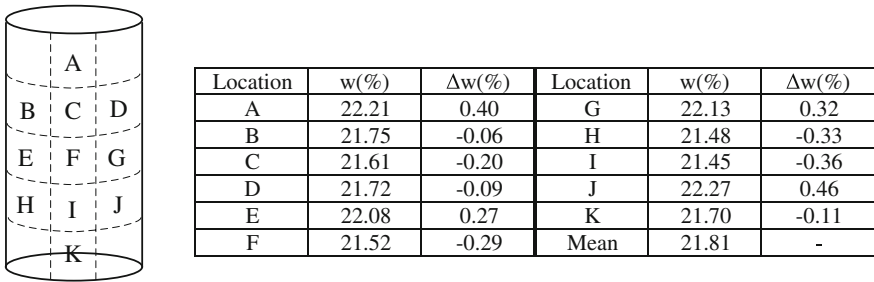


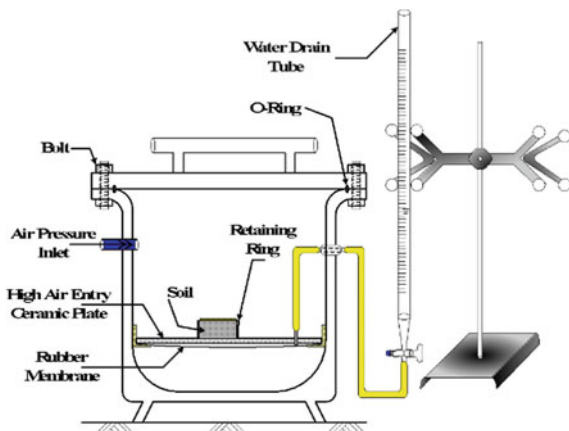
Fig. 2 Moisture content distribution of compacted soil sample after wetting

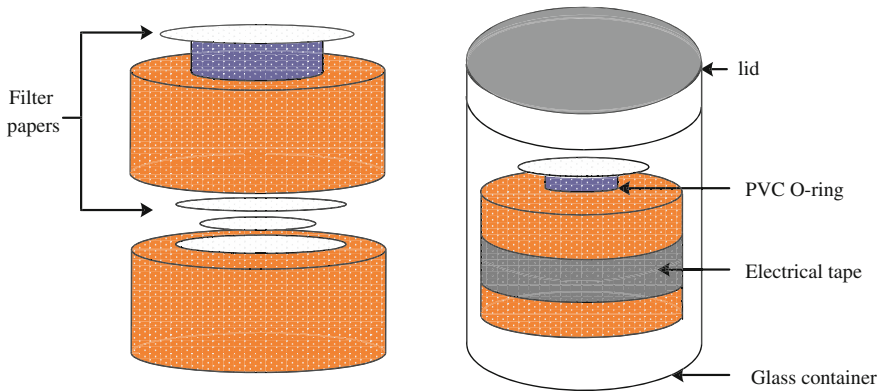
difference in moisture content after wetting, between the measured values and the mean value is less than 0.46 %. Extensive calibration tests have proven that the wetting and drying apparatuses can successfully impose desired wetting and drying paths onto the soil specimen with excellent moisture homogeneity (Wang et al. 2010; Yang et al. 2008).

### 2.3 Matric Suction Measurement (Pressure Plate Test and Filter Paper Test)

Pressure plate test in this study follows the ASTM D3152-72 standard (ASTM 2000). The specimen pre-saturated by oedometer was placed in the pressure chamber (5 or 15-bar) for testing. A schematic diagram of the pressure plate test was shown in Fig. 3. Afterwards, target air pressures were applied. For each stage of air pressure, if the difference in the specimen weight measured between two days was within 0.05 g the sample was deemed in equilibrium. The moisture content was

Fig. 3 Schematic diagram of pressure plate test apparatus





**Fig. 4** Filter paper method for measuring soil suction

recorded. The soil-water characteristic curve (SWCC) can be constructed by correlating various stages of air pressure and moisture content values (ASTM 2000).

In this study, the filter paper method was also conducted according to ASTM D 5298-94 (2000), Wen (2007). Figure 4 illustrates the test setup for suction measurement. The soil specimens were cut into two layers. A stack of three filter papers was placed at the center of the two specimens. Then, the specimen was put into a glass container for about 7–10 days for equilibrium. The moisture content change of the central filter paper was measured by an electronic balance with 0.0001 g accuracy. It was then converted to equivalent matric suction values by the calibration curves (Yang et al. 2008).

### 2.4 Bender Element Test

When the moisture content of the soil specimen reached a preassigned state, the shear wave velocity was measured using the bender element. Particularly, the bender elements were placed in two ends of the specimens through striated notches, as shown in Fig. 5a. Its thickness, width and height are 1, 12, and 10 mm, respectively. One bender element functions as the shear wave transmitter and the other acts as the receiver. To facilitate the test under suction controlled condition, one of the bender elements needs to be installed into the triaxial base plate with high air entry disk, as shown in Fig. 5b. Figure 6 shows the integrated testing system of the bender element test. A sine pulse was generated by a EGC-3236A with 10 MHz and  $\pm 10$  V function generator. Signals were displayed on a high definition oscilloscope. The high definition oscilloscope is a Nicolet Type Pico ADC212/100 with a definition of 12 bit in each channel and a maximum sampling rate of 100 MS/s. The travel time of the shear wave was used to compute the shear wave velocity  $V_s$ . Finally, the shear modulus  $G_{max}$  can be calculated according to equation:  $G_{max} = \rho V_s^2$ .

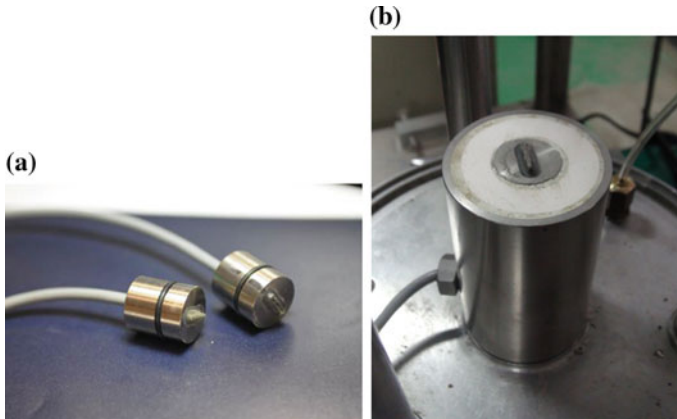


Fig. 5 Pictures of bender elements. **a** Bender element. **b** Bender element integrated with ceramic disk

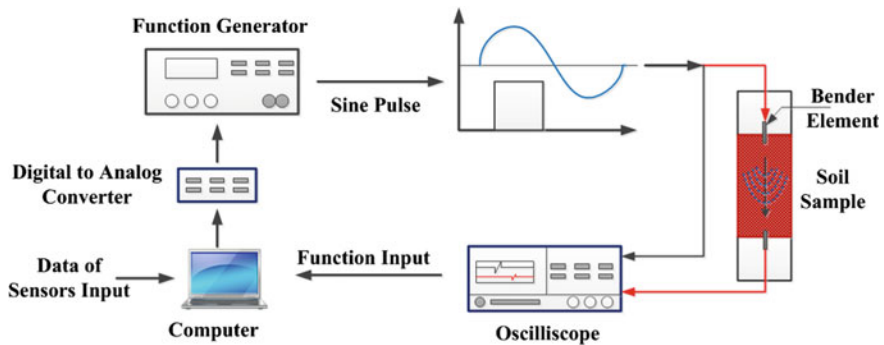


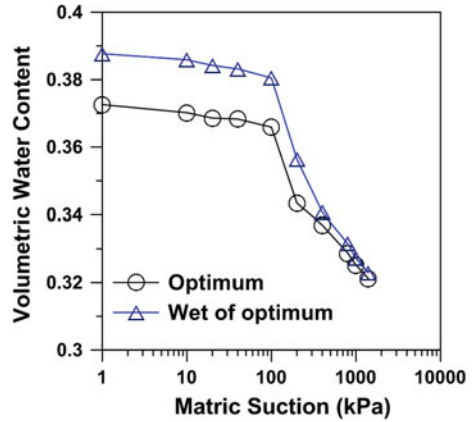
Fig. 6 Bender element testing system for measuring shear modulus

### 3 Test Result and Discussion

#### 3.1 Unsaturated Soil Characteristic Curve

Figure 7 shows the SWCCs of two sets of soil samples with initial compaction water contents of OMC and OMC + 3 %. The water retention ability is better for optimum samples as expected. The test result indicated that the air entry value of the optimum soil specimen is slightly higher than that of the wet of optimum soil specimen. Besides, pore water dissipated easier when the air pressure increases for the wet of optimum soil specimen.

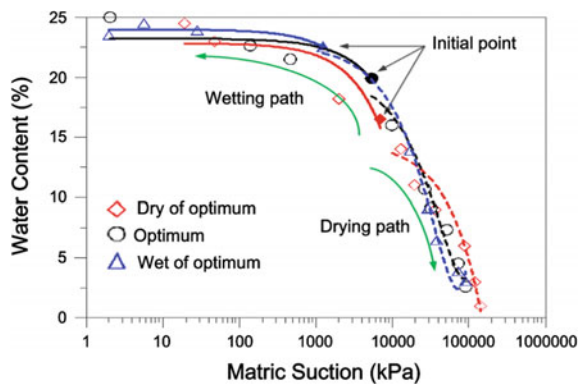
Fig. 7 SWCCs test results



### 3.2 Influence on Matric Suction Under Different Wetting and Drying Paths

All three sets of test results are plotted together in Fig. 8 to demonstrate the general trend of influence of the initial compaction state. The test results show that matric suction decreases and water content increases when soils are subjected to wetting. Matric suction decreases with increasing water content. The change in matric suction is much less significant upon wetting despite of the initial compaction condition. When wetting continues and reach the equilibrium water content all three sets of test results converge together. This implies that suction behavior is no longer influenced by the initial compaction state because soils are almost fully saturated under this circumstance. On the other hand, drying test results shows that the matric suction increases much more significantly and rapidly than that of wetting. The effect is the least for optimum samples as would be expected.

Fig. 8 Water content versus matric suction



### 3.3 Influence of Wetting and Drying on Shear Modulus and Matrix Suction

Figure 9 shows the relationship between matric suction and shear modulus of unsaturated soil under drying and wetting paths. It is observed that the variation in the shear modulus is highly correlated to the change in the matric suction. For example, in the wetting path, the moisture content increases with reduction in the matric suction. As a result, shear modulus also decreases. On the other hand, in the drying path, the moisture content decreases quickly with sudden increase in the matric suction. This phenomenon leads to sudden increase in the shear modulus. Apparently, variations in both shear modulus and matric suction are more pronounced in the drying path than those in the wetting path.

A regression analysis is used to establish the correlation equations between shear modulus and matric suction, as shown in Table 1. The coefficient of determination ( $R^2$ ) values range from 0.89 to 0.99. It indicates that the shear modulus and the matric suction are highly correlated. In other words, it is feasible to evaluate the shear modulus by means of the matric suction. Moreover, the regression analysis is conducted between the shear modulus and the water content. It is found that the

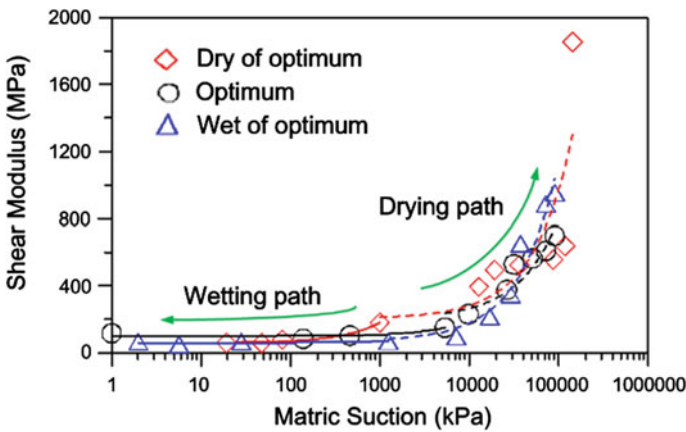


Fig. 9 Shear modulus versus matric suction

Table 1 Regression analysis results of matric suction and shear modulus

Initial state	Drying path		Wetting path	
	Regression equation	$R^2$	Regression equation	$R^2$
Dry of optimum	$G_{max} = 0.1192\psi + 60.3530$	0.98	$G_{max} = 0.0095\psi + 232.7399$	0.89
OMC	$G_{max} = 0.0113\psi + 90.2226$	0.94	$G_{max} = 0.0128\psi + 87.1897$	0.95
Wet of optimum	$G_{max} = 0.0102\psi + 57.6420$	0.97	$G_{max} = 0.0102\psi + 42.2416$	0.99

Note  $\psi$  = matric suction (kPa);  $G_{max}$  = shear modulus (MPa)



shear modulus has higher correlation with the matric suction than the water content (Wang et al. 2010). Therefore, the matric suction is a good index to estimate the shear modulus in engineering applications.

## 4 Conclusions

In this study, the lateritic soil was tested to study the influence of the matric suction upon wetting and drying path. The environmental simulation apparatus filter paper method and bender element test were successfully integrated. The pressure plate test was also used to measure the SWCC curve. Soil samples were compacted at optimum moisture content, dry of optimum, and wet of optimum. They are then cured with different paths of drying or wetting using the environmental simulation apparatus. After wetting or drying, the specimens were tested to determine the shear wave velocity using the bender element, and then, the filter paper method was used to measure the matric suction.

The SWCC results show that the water retention ability is better for optimum samples as expected, and the air entry value is slightly higher than that of the wet of optimum samples. Test results also indicate that upon wetting soil's shear modulus and matric suction decrease as water content increases. On the other hand, the shear modulus and matric suction increase with water content decrease upon drying. Comparison of test results of drying and wetting indicate that the influence on matric suction and shear modulus is path dependent and more pronounced due to drying. The regression analysis showed that the coefficient of determination ( $R^2$ ) between shear modulus and matric suction ranges from 0.89 to 0.99. The above findings suggest that the matric suction is a key index parameter when predicting the shear modulus of unsaturated lateritic soils.

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