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Assessment of the unconfined compression strength of unsaturated lateritic soil using the UPV

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Abstract. This study investigates the feasibility of using the results of the UPV (ultrasonic pulse velocity) test to assess the UCS (unconfined compressive strength) of unsaturated soil. A series of laboratory tests was conducted on samples of unsaturated lateritic soils of northern Taiwan. Specifically, the unconfined compressive test was combined with the pressure plate test to obtain the unconfined compressive strength and its matric suction (s) of the samples. Soil samples were first compacted at the designated water content and subsequently subjected to the wetting process for saturation and the following drying process to its target suction using the apparatus developed by the authors. The correlations among the UCS, s and UPV were studied. The test results show that both the UCS and UPV significantly increased with the matric suction regardless of the initial compaction condition, but neither the UCS nor UPV obviously varied when the matric suction was less than the air-entry value. In addition, the UCS approximately linearly increased with increasing UPV. According to the investigation of the test results, simplified methods to estimate the UCS using the UPV or matric suction were established. Furthermore, an empirical formula of the matric suction calculated from the UPV was proposed. From the comparison between the predicted values and the test results, the MAPE values of UCS were 4.52-9.98% and were less than 10%, and the MAPE value of matric suction was 17.3% and in the range of 10-20%. Thus, the established formulas have good forecasting accuracy and may be applied to the stability analysis of the unsaturated soil slope. However, further study is warranted for validation.

Keywords: unsaturated soil; matric suction; unconfined compressive strength; ultrasonic pulse velocity; prediction model

1. Introduction

Basu *et al.* (2015) reported that the geotechnical design and construction, which took place early in a civil engineering project, could significantly contribute to sustainable development by making sustainable choices and setting a precedent for the remainder of the project. In addition, Cho (2016) summarized the topics that geotechnical engineers could make significant contributions to sustainable development. Thus, geotechnical engineering can indeed play an important role in sustainable development. Furthermore, Taiwan is vulnerable to slope-land disasters due to fragile geology conditions and high-frequency earthquakes. Numerous rainfall events during the typhoon season cause serious slope-land disasters, especially landslide and debris flow disasters. These disasters repeatedly occur and often cause serious impacts to mountainous communities. Lately, extreme rainfall occurs more frequently and results in simultaneous disasters with larger magnitude (Tsou *et al.* 2011, Huang 2014, Wu 2014, Shou *et al.* 2018, Lin *et al.* 2019). Recently, the available space for human inhabitancy is very expensive in Taipei City because the population grows. Therefore, Linkou District (Linkou), as shown in Fig. 1, is one of rapidly developing areas for the past decade. Thus, more slope developments are required for rapid urban expansion and increased traffic flow in this area. Linkou District includes tableland, hilly valley and few beaches. The Linkou Tableland is a heavily desiccated terrace with an elevation of 220-250 m. At ground surface, lateritic soil is underlain by flat-lying Pliocene-Pleistocene conglomerates, sandstones, and mudstones. It was formed by strong seasonal weathering effects. The northern part of Linkou District is intruded and covered by andesitic to basaltic rocks which are kin to the Tatun volcanics. The eastern side neighbors and Shanjiao Faults (Teng *et al.* 2001). In fact, detailed investigations of Linkou geological conditions are still limited. It was known that the strength of Linkou lateritic soil can drop significantly when subjected to wetting by water. Therefore, this study was motivated in order to gain better understandings of the lateritic soil of Linkou. Hence, soil properties are important factors for slope stability analysis and sustainable development.

Because the terrace is relatively high, the lateritic soil stratum is often above the groundwater table; thus, it is in

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an unsaturated state for the long-term condition. Because water and air coexist in unsaturated soil pores, the capillary effect induces matric suction via the air-water interface (Fredlund and Morgenstern 1977, Fredlund *et al.* 1978). This suction may vary with the water content change due to rainfall infiltration and affect the behavior of unsaturated soils (Rahardjo *et al.* 2009, Oh and Vanapalli 2011, Ng *et al.* 2016, Kim *et al.* 2017, Tang *et al.* 2017). Thus, for the slope stability analysis of lateritic soils, matric suction should be considered in the evaluation of engineering properties (Lin *et al.* 2010), and the parameters of shear strength for unsaturated soil were used to analyze the slope stability (Zhang *et al.* 2014, Li and Yang 2018, Xu and Yang 2018). In addition, the shear strength of unsaturated soil increased with increasing matric suction (Tang *et al.* 2002, Tekinsoy *et al.* 2004, Nan *et al.* 2011, Hoyos *et al.* 2014). For slope stability application, various strengths may be investigated from different test methods. However, the most commonly used engineering property for strength is the unconfined compressive strength (UCS). Thus, it will be helpful for the analysis of slope stability if the relationship between UCS and matric suction can be established.

Bhange and Nandagawali (2018) indicated that soil is the most complex material in various civil engineering projects. To determine its engineering properties, particularly in the field, the direct methods of destructive tests are commonly used. However, these methods are time-consuming and frequently halt construction activities. Therefore, for quicker and easier assessment, nondestructive methods are used (Bhange and Nandagawali 2018). The ultrasonic pulse velocity (UPV) is a nondestructive testing method and is often used to evaluate the properties of concrete and cement mortar (Breysse 2012, Ercikdi *et al.* 2014, Yilmaz *et al.* 2014, Wang *et al.* 2015, Yilmaz and Ercikdi 2016, Wang and Wang 2017). Because nondestructive testing methods are convenient and easy to operate, some geotechnical researchers have used the UPV method to assess the physical and engineering properties of soil (Yang *et al.* 2008, Weidinger *et al.* 2009, Whalley *et al.* 2011, Yagiz 2011, Asslan and Wuttke 2012, Whalley *et al.* 2012, Byun *et al.* 2013, Hossain *et al.* 2013, Dong and Lu 2016, Bhange and Nandagawali 2018, Vinay *et al.* 2018). Vinay *et al.* (2018) reported that with the increase in water content, the density and ultrasonic pulse velocity increased for compacted clayey soil, and the relationship between the strength and the UPV was also discussed. In addition, Selcuk and Seker (2018) conducted a large-scale regression analysis using experimental data to evaluate the relationship between the California bearing ratio and the UPV.

Thus, the strength and matric suction for compacted and unsaturated soil can be evaluated by using UPV technology, which will be helpful for the safety assessment and analysis of slope stability. In this study, a series of unconfined compressive strength (UCS) and ultrasonic pulse velocity (UPV) tests for unsaturated soil of Linkuo terrace is performed in different initial compaction conditions. According to the investigation of the test results, simplified methods to estimate the UCS of unsaturated soil by using the UPV or matric suction (s) are proposed. In addition, an empirical formula of matric suction calculated by UPV is established.

2. Testing program

The lateritic soil samples were taken in the Linkou area of northern Taiwan. A series of laboratory tests was performed on samples of the compacted lateritic soil. The degree of saturation of the compacted soil is in the range of 75% to 90% (Wang *et al.* 2010, Yang *et al.* 2012, Lin *et al.* 2017, Lin *et al.* 2018). An unconfined compression test was combined with a pressure plate test to obtain the unconfined compression strength and matric suction of the samples. In addition, the ultrasonic pulse velocity test of samples was conducted. The soil specimens were first compacted at the desired initial water content and subsequently subjected to the designated wetting and drying using the apparatus developed by the authors. As a result, the relationships among the matric suction, unconfined compression strength and UPV can be studied. In this study, the static compaction was used to remold the specimen. This method can satisfactorily use a machine to control the compaction energy and specimen size to reduce tester errors and effectively control the uniformity of the initial condition of the specimen (Lin *et al.* 2017, Lin *et al.* 2018). The basic soil properties, sample preparation, and test procedures are elaborated below.

2.1 Soil properties

The particle-size distribution of the soil was consistent with that of ASTM D452-85, as shown in Fig. 2. The specific gravity and Atterberg limits of the soil were tested in accordance with ASTM D854-83 and ASTM D4318-10, respectively. The specific gravity Gs of the soil was 2.65, the liquid limit LL was 46, the plastic limit PL was 21, and the plastic index was 25. The soil can be classified as CL (clay of low to medium plasticity) according to the Unified Soil Classification System. In addition, X-ray diffraction tests were executed. Fig. 3 illustrates that the main soil minerals were illite (62%), quartz (26.3%), kaolin (6.7%) and chlorite (5%). The proportion of clayey minerals was approximately 73.7%.

Fig. 1 Geological location of the studied Linkuo area (redrawn from Google Map)

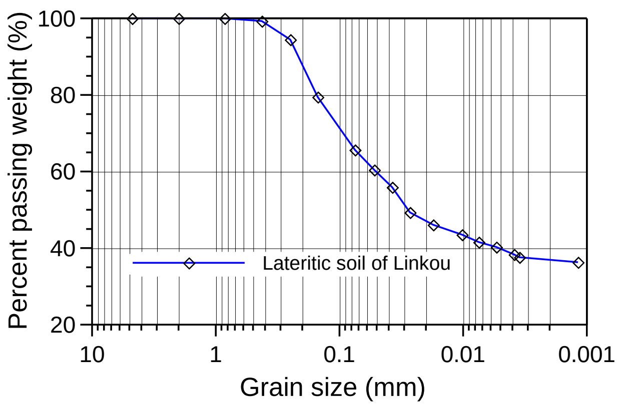


Fig. 2 Grain size distribution curve of Linkuo lateritic soil

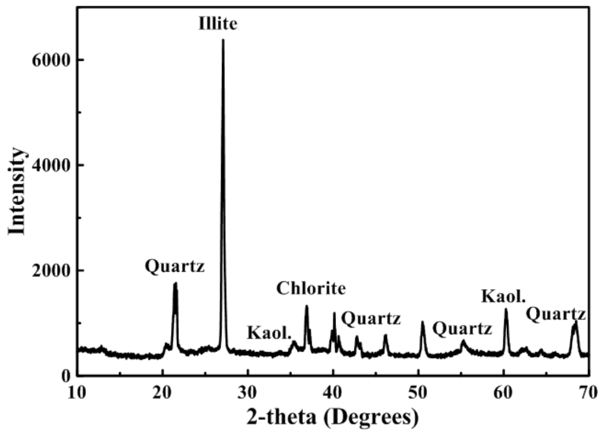


Fig. 3 Results of the X-ray diffraction test

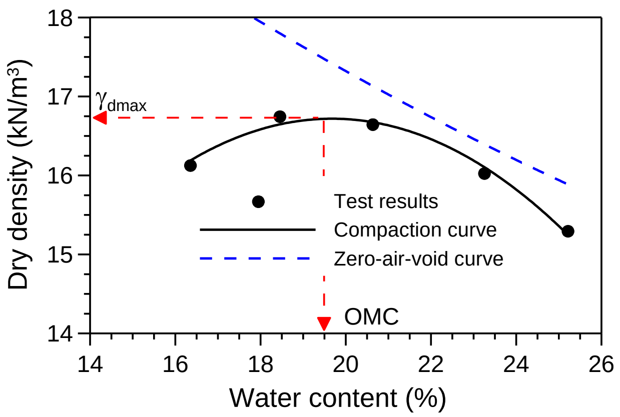


Fig. 4 Compaction curve of Linkuo lateritic soil

2.2 Specimen preparation

To provide reference information for sample preparation, the modified compaction test was conducted according to ASTM D1557-12. The soil was compacted in five layers, and each layer was tamped 25 times. The relationship between the dry density and the moisture content of the soil is shown in Fig. 4. The compaction test results show that the optimum moisture content (OMC) was 19.5%, and the corresponding maximum dry soil unit weight was 16.6 kN/m^3. To include the dry side and wet side, three different initial compaction states were selected

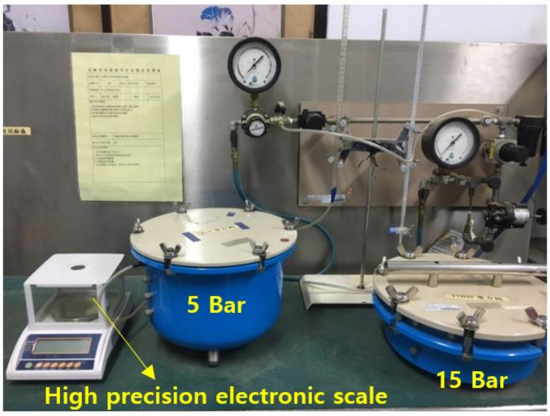


Fig. 5 Pressure plate test apparatus

for the specimen preparation. The water content was controlled at 16.5%, 19.5% and 22.5% to simulate the condition of the dry side, OMC and wet side, respectively. The corresponding dry unit weights were 16.3 kN/m^3, 16.6 kN/m^3, and 16.3 kN/m^3. The soil weight and water content of the remolded specimen were proportioned according to the modified compaction result. The well mixed soil sample was put into a zipper bag for 24 hours to assure homogenization of water content. Then, the soil was placed in the mold and compacted into five layers by static pressure into a remolded specimen with a diameter of 5 cm and a height of 10 cm.

2.3 Matric suction measurement

The pressure plate test was used to obtain the Soil-Water Characteristic Curve (SWCC). In this study, two pressure plate extractors of 5 bar and 15 bar from Soilmoisture Equipment Corp. were used, as shown in Fig. 5. The test procedures of the pressure plate are specified in ASTM D3152-72. The SWCC results were used to control the matric suction of the specimens for the unsaturated unconfined compression and UPV test. More details are described in Section 2.4.

The soil samples were compacted at three different initial water contents: OMC-3%, OMC, and OMC+3%. The tests of OMC-3% and OMC+3% are denoted as DRY and WET for easy reference. The samples were saturated following ASTM D2435-80. In essence, the sample was subjected to a 2.5 kPa normal stress and put into the odometer that is filled with pure water for 2 to 3 days. The sample is then considered saturated. Then, ten stages of matric suction were applied to the soil sample: 1, 10, 20, 40, 100, 200, 400, 800, 1000 and 1400 kPa. The test results are shown in Fig. 6. The test results were regressed using the function suggested by Fredlund and Xing (1994). The SWCC results of three initial compaction conditions are in the range of the SWCC results reported by Vanapalli *et al.* (1999).

Fig. 6 shows the test results. In general, the SWCCs had similar trends for all three sets of the tests. The volumetric water content decreased when the suction increased, despite the initial compaction condition. However, the initial volumetric water contents slightly varied. The OMC was

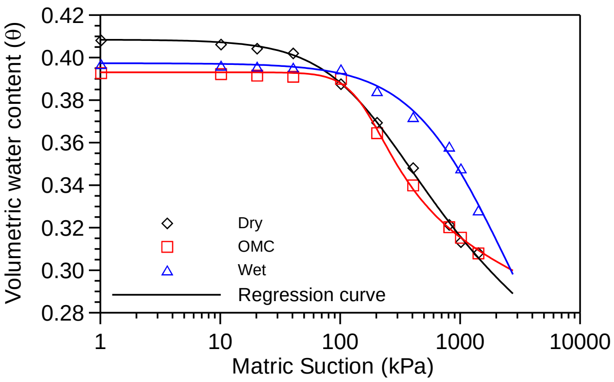
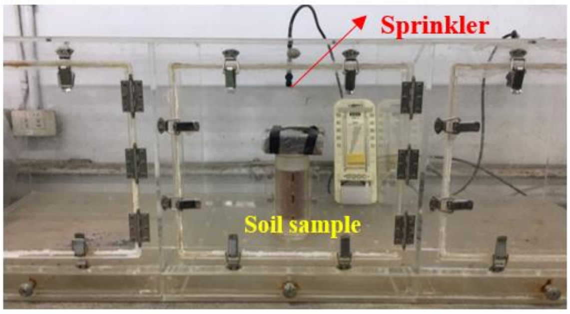
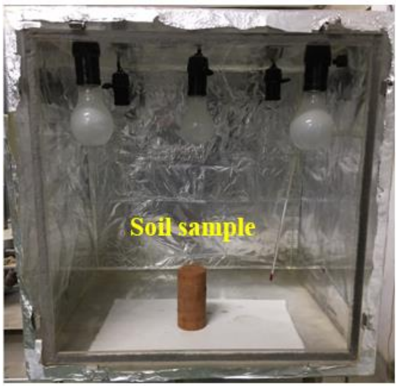


Fig. 6 SWCCs for different compaction conditions



(a) Wetting



(b) Drying

Fig. 7 Wetting and drying apparatus

the densest and exhibited the smallest initial water content, as expected. Lin *et al.* (2018) found that the dry side sample adsorbed more water upon the saturation process due to its flocculated soil structure, which resulted in higher initial water content than the wet side. The measured changes in water content before and after the saturation of the sample were 6.3%, 5.3%, and 4.3% for the dry side, OMC, and wet side, respectively. Fig. 6 also shows the air-entry values of three test sets. The wet side had a slightly larger air-entry value (106 kPa) than the OMC (100 kPa). The dry side had the lowest air-entry value (67 kPa). The wet side sample exhibited better water retention ability due to its dispersed structure. In general, the range and differential tendency of the air-entry value are identical to the test results of our previous study (Lin *et al.* 2018).

2.4 Unsaturated unconfined compression test

An integrated procedure was developed by the authors to conduct the unsaturated unconfined compression test (Lin *et al.* 2018). The test procedure included the following main steps: (1) prepare the soil specimens at different initial compaction conditions of OMC-3%, OMC, and OMC+3%; (2) determine the desired water content according to the target matric suction using the SWCCs in Fig. 6; (3) cure the soil specimens to the desired water content using the wetting and drying apparatus in Fig. 7; and (4) conduct the unsaturated unconfined compression test. Some important highlights are reiterated below.

The matric suctions applied to the specimen were 100, 300, 600, 900, 1200 and 1400 kPa. The SWCCs (Fig. 6) were used to obtain the desired water content according to the target matric suction. Soil samples were prepared following the same procedure as that for the pressure plate test to obtain the designated matric suction. In addition, the filter paper method (ASTM D 5298-94) was used to double check the matric suction. The results appear fairly reasonable (Yang *et al.* 2008, Yang *et al.* 2012, Lin *et al.* 2016).

The wetting and drying apparatus developed by the authors is shown in Fig. 7. The apparatus has been satisfactorily used to cure soil samples to the desired water content with good uniformity (Wang *et al.* 2010, Lin *et al.* 2015, Lin *et al.* 2016, Lin *et al.* 2018). To check the uniformity of the moisture distribution of a cured sample eleven measurements of water content of different portions of a specimen was conducted. The results repeatedly show that the variation in water content within a sample, was less than 0.5% (Wang *et al.* 2010). The wetting process proceeded using the timer-controlled sprinklers installed at the top of the wetting chamber. A light bulb was installed under the ceiling of the drying box to dry the sample at approximately 32°C to impose uniform evaporation of the soil specimen. After the soil specimen was cured to the target matric suction, the unconfined compression test (UC test) was conducted according to the test procedure specified by ASTM D2166-13. The strain rate was 1.0%/min in this study.

2.5 Ultrasonic pulse velocity test

The UPV test followed ASTM D2845. The surface area of the specimen under each transducer was sufficiently planar such that a feeler gauge of 0.001 in. (0.025 mm) thick would not pass under a straightedge on the surface. The two opposite surfaces on which the transducers were placed were parallel to each other within 0.005 in./in. (0.1 mm/20 mm) of lateral dimension. The specimen preparation procedure of the UPV test was identical to that of the unsaturated unconfined compression test.

In this study, the type of H-2845 for V-Meter Mark III Ultrasonic System was used to measure the UPV. The apparatus was developed by the company of Humboldt James, as shown in Fig. 8. The accuracy was approximately 0.1 μs, and a frequency of 54 kHz was selected to estimate the velocity of the compression wave. The UPV can be calculated by Eq. (1).

$$V_p = \frac{L}{t} \tag{1}$$

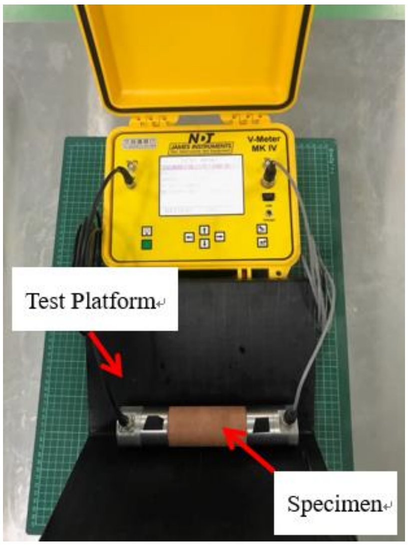


Fig. 8 Ultrasonic test

where V_p, L and t are the ultrasonic pulse velocity, distance of wave propagation and travel time, respectively. In general, the distance of wave propagation is equal to the length of the specimen.

3. Experimental results

3.1 Effect of matric suction on the unconfined compressive strength

Three different initial compaction conditions (OMC-3%, OMC, OMC+3%) were studied. Fig. 9 illustrates the UCS results of three sets of samples of different initial compaction conditions. In addition to the matric suction of 100-1400 kPa, the soil samples compacted at three different initial conditions and saturated by the wetting process are also included in Fig. 9 as the reference results of zero matric suction. The test results show that the UCS significantly increased with matric suction regardless of the initial compaction condition. All of the relationships between the stress and strain of the unsaturated soil specimens exhibited peak and post-peak behavior. The tendency of the test results was similar to that of our previous study (Lin *et al.* 2018). The test results of UCS are summarized in Table 1.

Fig. 10 shows the relationship between UCS and matric suction for different initial compaction conditions. The UCS was minimal when the sample was wetted to zero matric suction and increased when the sample was dried due to the increase in matric suction. This phenomenon is consistent with the findings of Vilar (2006). In addition, Vilar (2006) concluded that the relationship of the unsaturated soil strength and the matric suction was approximately linear at low suction; however, when the matric suction was larger than a certain value, the increase in strength became mild. Nevertheless, this issue warrants further study. It was found that the variation of UCS was not obvious when the matric suction within the air-entry value. In this study, the air-entry value was 67 kPa, 100 kPa and 106 kPa for the DRY set, OMC set and WET set, respectively. Thus, the air-entry

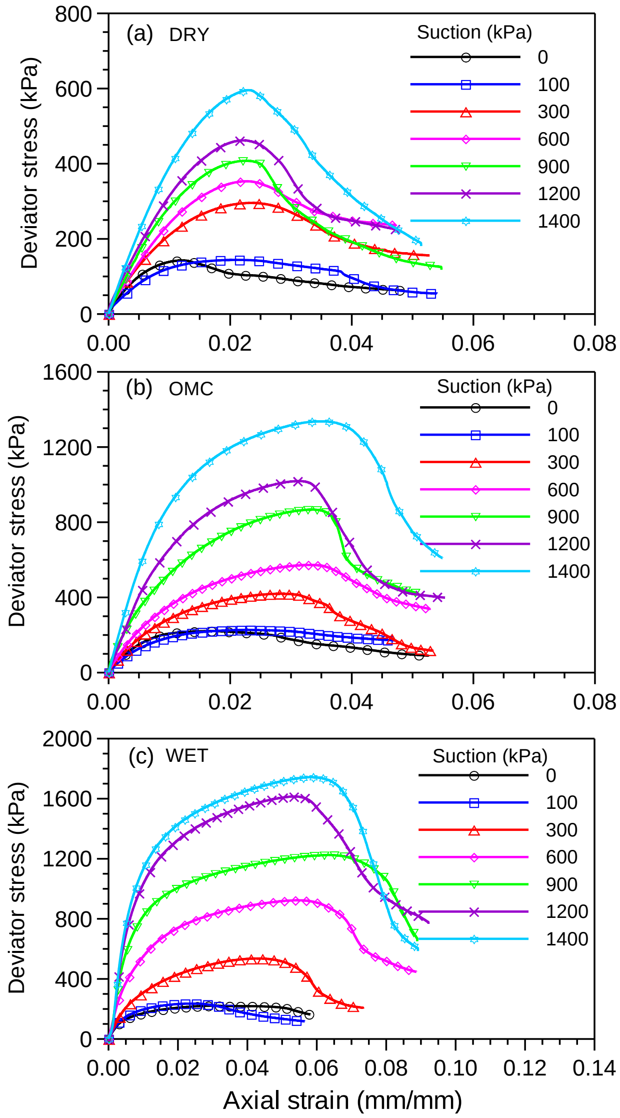


Fig. 9 Results of the unconfined compression strength test

value was distributed in a narrow range for three different initial compaction conditions. Furthermore, the UCS was in an approximately linearly increasing relation to the matric suction when the matric suction was larger than the air-entry value up to 1400 kPa, as shown in Fig. 10. This trend is consistent with the finding of Chae *et al.* (2010).

The effects of the initial compaction condition on the UCS are also shown in Fig. 10. Under identical matric suction, the DRY set had the lowest strength because the dry side sample adsorbed more water upon the wetting process to saturation as explained in Section 2.3, where SWCCs were presented. In general, the trend of the strength results is consistent with the results of the SWCCs. Therefore, the wetting and drying processes significantly affect the soil retention behavior and unsaturated soil strength. Lin *et al.* (2018) and Yang *et al.* (2004) have reported similar findings. Additionally, the slope of the UCS vs. matric suction line increased with increasing initial compaction water content. However, Chae *et al.* (2010) indicated that the variation in slope for the relationship

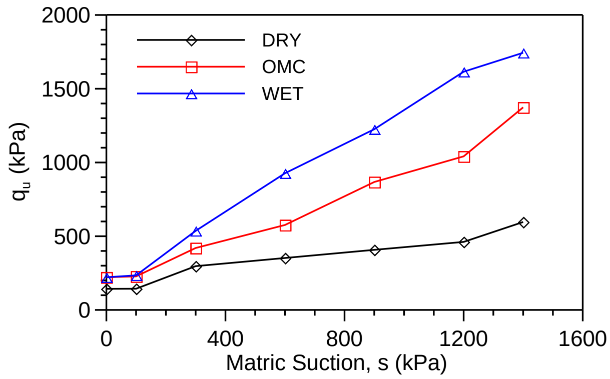


Fig. 10 UCS versus matric suction

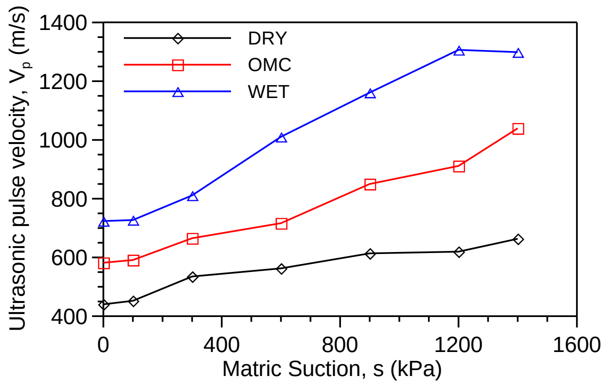


Fig. 11 UPV versus matric suction

Table 1 Results of the UCS and UPV tests

Matric suction	Initial compaction condition								
	DRY			OMC			WET		
	ω(%)	q_u(kPa)	V_p(m/s)	ω(%)	q_u(kPa)	V_p(m/s)	ω(%)	q_u(kPa)	V_p(m/s)
0	25.97	142.8	440.5	24.39	221.3	582.1	24.84	221.7	724.0
100	24.68	144.2	452.3	24.19	227.6	591.3	24.66	234.4	727.5
300	22.38	296.9	534.9	21.41	420.4	665.4	23.44	535.8	811.1
600	21.36	352.0	562.6	20.25	575.8	716.5	22.35	926.8	1010.6
900	20.63	407.8	614.0	19.67	867.6	850.1	21.43	1225.7	1161.3
1200	20.14	461.6	619.7	19.38	1041.2	911.5	20.83	1615.5	1306.4
1400	19.68	595.8	663.6	19.07	1373.6	1039.8	20.47	1743.8	1298.7

Table 2 Coefficient values of the prediction model

	AEV(kPa)	q_{u0}(kPa)	V_{p0}(m/s)	m	m_{avg}	n	α
DRY	67	142.8	440.5	1.797		0.326	5.387
OMC	100	221.3	582.1	2.494	2.420	0.818	3.026
WET	106	221.7	724.0	2.478		1.243	1.985

between the UCS and the matric suction was not significant for the silty soils of Japan. Thus, the characteristics of the increment of the UCS vs. matric suction may depend on many factors such as the soil type, compaction method, and initial water content.

3.2 Effect of matric suction on the ultrasonic pulse velocity

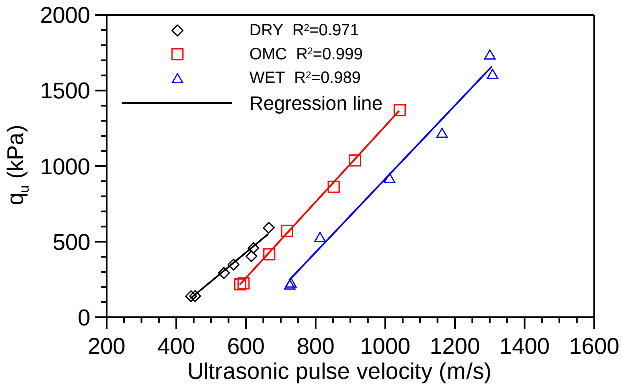


Fig. 12 Relationship between UCS and UPV

The ultrasonic pulse velocity (UPV) test is one of the most popular nondestructive techniques to assess the mechanical properties of concrete or rock materials. Weidinger *et al.* (2009) demonstrated that dynamic elastic moduli such as Young's modulus and the shear modulus for compacted soil could be determined by the UPV test. In addition, Galán-Marín *et al.* (2013) indicated that the UPV results correlated well with the mechanical properties of stabilized soils. Furthermore, the nondestructive UPV test provides effective results to determine the properties of the compacted soil and clayey soils (Bhange and Nandagawali 2018, Vinay *et al.* 2018). Although the behavior of unsaturated soil has been discussed by former researchers, the UPV test has seldom been used to evaluate the properties of unsaturated soil. Therefore, the feasibility of assessing unsaturated soil properties with the nondestructive technique is worth studying.

The relationship between UPV and matric suction for different initial compaction conditions is shown in Fig. 11. In any initial compaction condition, the test results show that the UPV appreciably increased with matric suction. Similarly, the variation in the UPV was not significant when the matric suction was less than the air-entry value, but the UPV rapidly and linearly increased after the matric suction exceeded the air-entry value up to 1400 kPa, as shown in Fig. 11. The effects of the initial compaction condition on the UPV are also observed in Fig. 11. Under identical matric suction, the DRY set had the lowest UPV, and the WET set had a larger UPV than the OMC set. This tendency is consistent with the UCS test results. The UPV test results are summarized in Table 1.

3.3 Relationship between UCS and UPV

The UPV test is often used to calculate the UCS of concrete or rock (Mahure *et al.* 2011, Yagiz 2011, Wang *et al.* 2014, Wang *et al.* 2015). In addition, previous studies reported that the UCS of cemented soil can be estimated by applying a UPV test (Ercikdi *et al.* 2014, Yilmaz *et al.* 2014, Yilmaz and Erikdi 2016). Whalley *et al.* (2012) found that the shear wave velocity was related to the void ratio, matric potential and net stress with a function of four fitted parameters for unsaturated soil. Thus, the UCS can be evaluated based on the UPV test results.

Because there are similar relationships for UCS vs.

suction and UPV vs. suction, the UCS should be related to the UPV. Therefore, the UCS can be estimated by the UPV if the relationship between UCS and UPV is established. Fig. 12 shows the relationship between UCS and UPV for all specimens regardless of the initial compaction condition. As shown in Fig. 12, the correction coefficient R^2 for linear regression was between 0.971 and 0.999; thus, the UCS approximately linearly increased with increasing UPV. This trend is similar to the results of cemented paste backfill soil, concrete and rock (Mahure *et al.* 2011, Yagiz 2011, Wang *et al.* 2014, Yilmaz *et al.* 2014, Wang *et al.* 2015, Yilmaz and Ercikdi 2016). In addition, the linear increasing lines are approximately parallel for different initial compaction conditions.

4. Development of empirical models

4.1 Relationship between UCS and UPV

According to the test results, the relationship between UCS and UPV can be expressed as a linear increasing function, as shown in Fig. 13. Thus, the UCS can be expressed as Eq. (2).

$$q_u = q_{u0} + m(V_p - V_{p0}) \tag{2}$$

where q_u is the unconfined compressive strength (UCS); q_{u0} is the initial UCS at zero matric suction, that is, the UCS of the saturated condition; V_p is the ultrasonic pulse velocity (UPV); V_{p0} is the initial UPV at zero matric suction, that is, the UPV of the saturated condition; and m is the slope value of the relationship between UCS and UPV. In this study, the m value was 1.797, 2.494 and 2.478 for the DRY set, OMC set and WET set, respectively. The model coefficients are shown in Table 2. The parameter of the DRY set is slightly different from the other two sets mainly due to more water adsorption during the wetting process as has been explain in Section 2.3.

However, test results (Fig.12) show that three linear lines are approximately parallel to each other. Thus, it may be possible to develop a single linear relationship to represent three set results if the incremental values are used. The outcome is quite promising as shown in Fig. 14. Thereby, the increase in UCS, Δq_u, can be expressed in Eq. (3). Thus, all of the UCS values of different condition specimens can be determined by Eq. (3). In this study, the linear coefficient is defined as m_{avg} and its value was approximately 2.420 for all of the test results. However, whether it is applicable to other types of soil requires further study.

$$\begin{aligned}\Delta q_u &= q_u - q_{u0} \\ &= m_{avg} \times \Delta V_p \\ &= m_{avg}(V_p - V_{p0})\end{aligned} \tag{3}$$

4.2 Relationship between UCS and matric suction (s)

In this study, the variation of UCS is not obvious when the matric suction (s) is within the air-entry value (AEV). Thus, the UCS can be assumed as a constant and close to

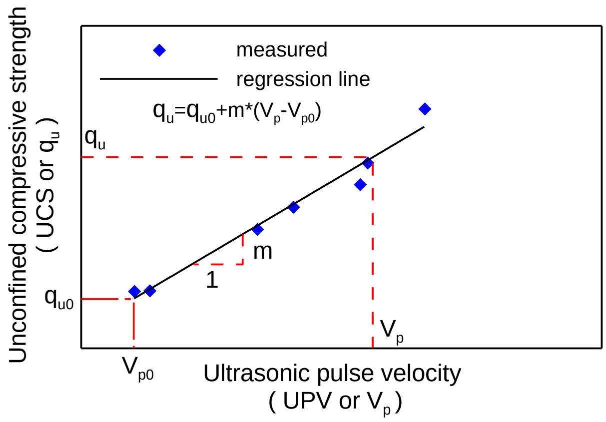


Fig. 13 Characteristics of the UCS versus UPV

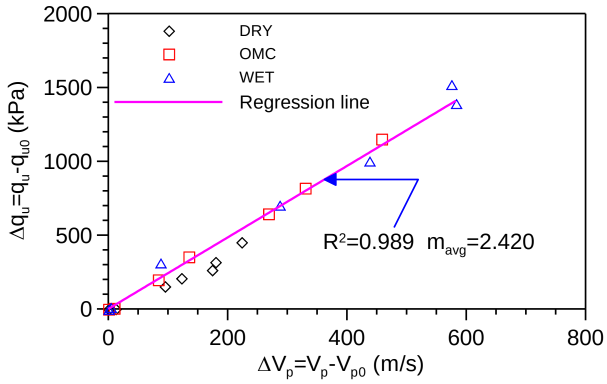


Fig. 14 Relationship between the increase in UCS and the variation in UPV

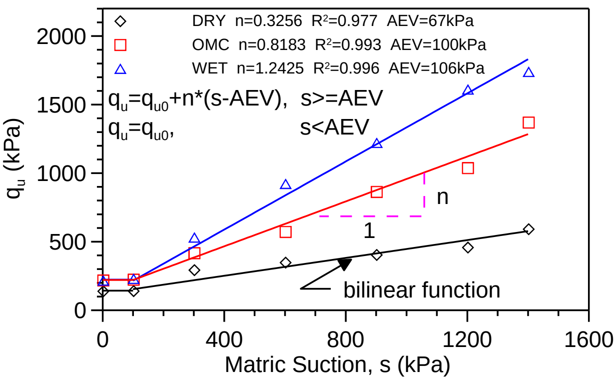


Fig. 15 Relationship between UCS and matric suction

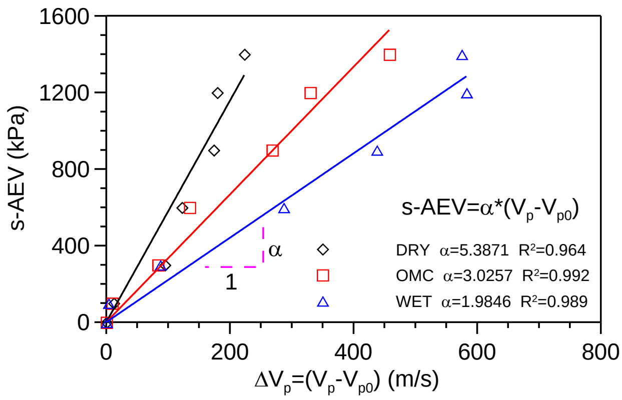


Fig. 16 Relationship between the increase in matric suction and the variation in UPV

the UCS in saturated condition. However, the UCS is in an approximately linear increasing relation with the matric suction when the matric suction is larger than the air-entry value up to 1400 kPa, as shown in Fig. 10. Thus, the UCS can be estimated by a bilinear function of Eq. (4) as shown in Fig. 15. In particular, it is a horizontal line when the matric suction does not exceed the air-entry value.

$$q_u = q_{u0} \quad \text{when} \quad s < AEV$$
$$q_u = q_{u0} + n \times (s - AEV) \quad \text{when} \quad s \geq AEV \tag{4}$$

where s is the matric suction, AEV is the air-entry value, n is the slope value of the relationship between the UCS and the matric suction. In this study, the n value was 0.326, 0.818 and 1.243 for the DRY set, OMC set and WET set, respectively. The model coefficients are shown in Table 2.

4.3 Relationship between matric suction (s) and UPV

As shown in Fig. 16, the differences between matric suction (s) and air-entry value (AEV) were close to a linear increment with the changes in UPV. Thus, the matric suction s can be calculated by UPV as expressed in Eq. (5).

$$s = AEV + \alpha \times (V_p - V_{p0}) \tag{5}$$

where α is the slope value of the relationship between $(s - AEV)$ and $(V_p - V_{p0})$. In this study, the α value was 5.387, 3.026 and 1.985 for the DRY set, OMC set and WET set, respectively. The model coefficients are shown in Table 2.

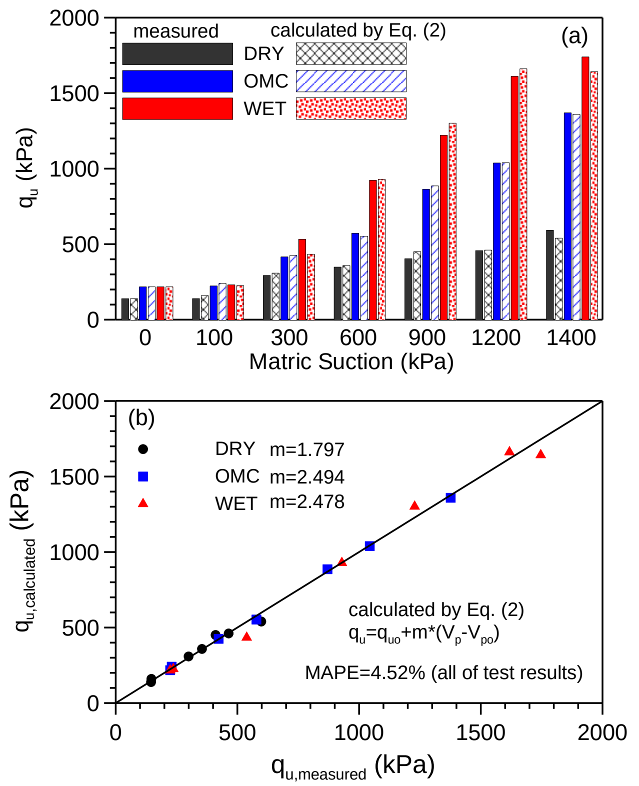


Fig. 17 Comparison of the test results and those calculated by the empirical formula (Eq. (1)) in this study

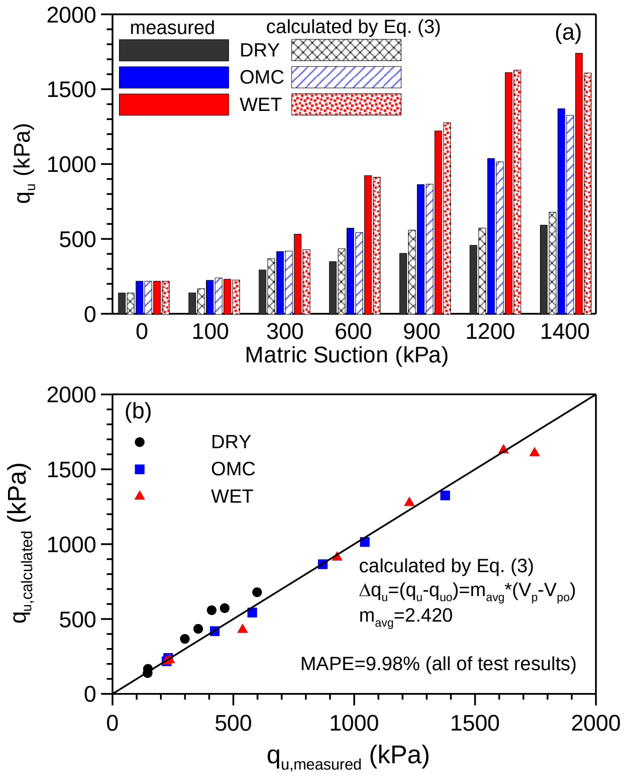


Fig. 18 Comparison of the test results and those calculated by the empirical formula (Eq. (2)) in this study

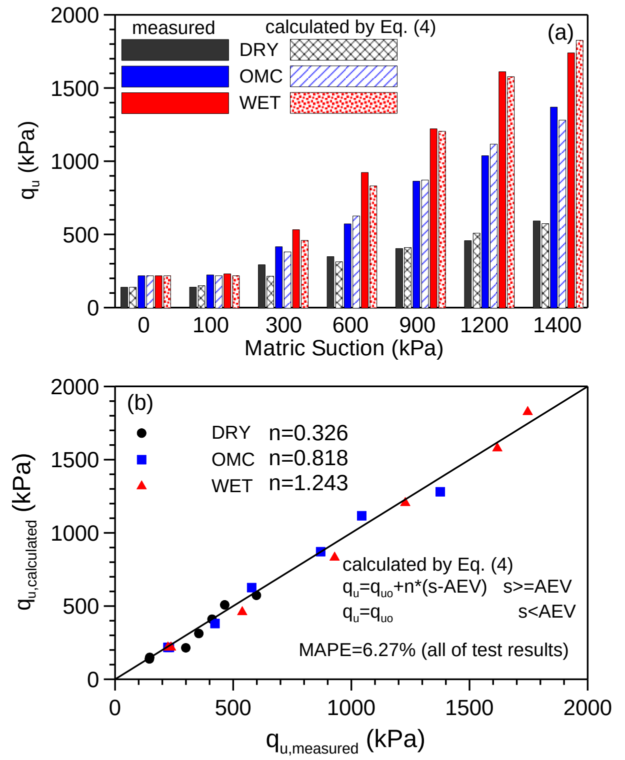


Fig. 19 Comparison of the test results and those calculated by the empirical formula (Eq. (3)) in this study

5. Comparison between prediction and test results

Lewis (1982) suggested that the MAPE (the mean absolute percentage error) value can be used to determine

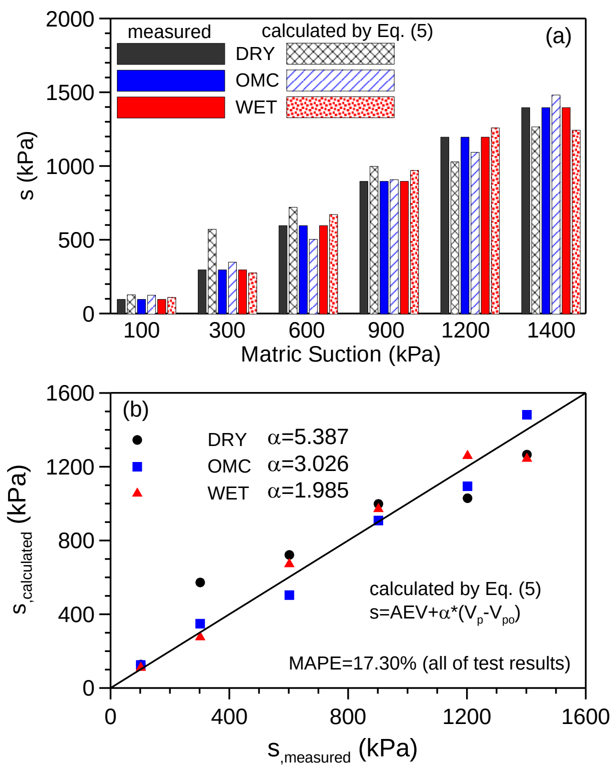


Fig. 20 Comparison of the test results and those calculated by the empirical formula (Eq. (4)) in this study

the accuracy. It is defined as the difference between the evaluated value of model and the measured result of test, as shown in Eq. (6). When the MAPE value is less than 10%, it indicates an excellent agreement; when the MAPE value is in the range of 10-20%, it indicates a good agreement; when the MAPE value is in the range of 20-50%, it indicates a reasonable agreement; when the MAPE value is greater than 50%, it indicates a poor agreement.

$$MAPE = \frac{1}{k}\sum_{i=1}^{k}\left|\frac{y_i - \widehat{y}_i}{y_i}\right| \tag{6}$$

where y_i= measured value, $\widehat{y}_i$= model analysis value, and k= number of analytic data.

5.1 Unconfined compressive strength (UCS)

Fig. 17 shows the comparison between the UCS calculated values and the measured results for different matric suctions at different initial compaction conditions analyzed by Eq. (2) proposed in this study. The result shows that the predicted analysis values derived from the UPV were notably similar to the test results, as shown in Fig. 17(a). In addition, the MAPE value was 4.52% and less than 10%. Therefore, the UCS prediction model established in this study has an excellent predictive ability, as shown in Fig. 17(b). Furthermore, the UCS calculated by Eq. (3) was consistent with the test results when the slope value of the relationship between UCS and UPV was considered constant, as shown in Fig. 18(a). The MAPE value in Fig. 18(b) was 9.98% and was slightly lower than 10%, which indicates an excellent to good consistency. It is worth noting that the individual slope value (m) was used in different compacted conditions when using Eq. (2); thus, its accuracy is higher than the overall slope value (m_{avg}) in Eq. (3). Additionally, the UCS calculated values from Eq. (4), which is derived from the matric suction, were similar to the test results, as shown in Fig. 19(a). The MAPE value was 6.27% and was lower than 10%. Thus, the UCS prediction model also has excellent accuracy, as shown in Fig. 19(b).

In brief, the above examination further confirms the reasonability between the prediction and the UCS test results. Therefore, the three empirical formulas (Eqs. (2)-(4)) derived from UPV and matric suction in this study provide an excellent predictive ability.

5.2 Matric suction(s)

Fig. 20 shows the comparison between the matric suction estimated values and the test results in different initial compaction conditions analyzed by Eq. (5). The results show that the predicted values derived from the UPV were similar to the test results, as shown in Fig. 20(a). The MAPE value was 17.30%, which is between 10% and 20%. Thus, the matric suction empirical formula deduced in this study has a good predictive ability, as shown in Fig. 20(b).

6. Conclusions

1. The unconfined compressive strength (UCS) significantly increased with matric suction regardless of the initial compaction condition. The variation in UCS was not obvious when the matric suction was less than the air-entry value. In particular, the UCS approximately linearly increased with the matric suction when the matric suction was larger than the air-entry value up to 1400 kPa. Additionally, the DRY set had the lowest n value of the slope of the correlation between UCS and matric suction, the WET set had the highest n value, and the n value of the OMC set was in the middle.
2. The test results show that the UPV appreciably increased with the matric suction. The variation of UPV was not significant when the matric suction was similar to the air-entry value, but the UPV rapidly and linearly increased when the matric suction exceeded the air-entry value up to 1400 kPa. Under identical matric suction conditions, the DRY set had the lowest UPV, and the WET set had a larger UPV than the OMC set. This tendency was consistent with the results of the UCS test.
3. The UCS exhibited an approximately linear relationship with increasing UPV. This trend was similar to the results of the cemented paste backfill soil, concrete and rock. The slope m value of the relationship between UCS and UPV for different initial compaction conditions was between 1.80 and 2.49. Furthermore, the linearly increasing lines were approximately parallel for different initial compaction conditions.
4. Methods to estimate the unconfined compressive strength (UCS) of Linkuo lateritic unsaturated soil by using the ultrasonic pulse velocity (UPV) or matric suction (s)

were proposed in this study. In addition, a simplified empirical formula to calculate the matric suction by using the UPV was established. The comparisons between measured results and predicted values, the MAPE values of UCS were within 4.52-9.98% and were less than 10%. Furthermore, the MAPE value of matric suction was 17.3% and in the range of 10% to 20%. Thus, the established formulas have a good forecasting accuracy and may be applied to geotechnical problems such as the stability analysis of the unsaturated soil slope. However, further study is warranted for validation.

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