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Critical-state parameters of an unsaturated residual clayey soil from Turkey

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Abstract

This paper deals with the evaluation of the critical-state parameters with respect to the matric suction for saturated and unsaturated undisturbed residual clayey soils from Turkey. In order to conduct the unsaturated triaxial compression testing procedures a conventional triaxial compression apparatus was redesigned. The data for critical-state conditions from these tests are presented with respect to matric suction, based on the critical-state parameters of M, q_o, Γ, λ, which is commonly proposed by many authors. The critical state of the unsaturated samples is compared with that of the saturated samples. This experimental study has demonstrated that matric suction has no influence on parameters of M and λ. The parameters of M and λ are approximately 0.85 and 0.074 respectively for saturated and unsaturated conditions. The relationships between matric suction ($u_a - u_w$) and the intercepts q_o and Γ have been observed as nonlinear, and thus they can be defined as a function of matric suction ($u_a - u_w$). Furthermore, a method is developed to predict the intercepts q_0 according to matric suction for unsaturated clayey soils.
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Keywords: Critical state; Unsaturated soils; Matric suction; Triaxial testing; Residual clay

1. Introduction

The critical-state concept has been proposed as a useful tool for behaviour of the saturated soils by Schofield and Wroth (1968). The critical-state behaviour is described as a state of soil where its volume cannot change under large shear strains. The critical state of saturated soils is expressed through the deviator stress (q), the mean effective stress (p') and the specific volume (v). The critical state is described as three critical-state parameters (M, Γ and λ):

$$q = Mp' \tag{1}$$

$$v = \Gamma - \lambda \ln p' \tag{2}$$

where M is the slope of the critical-state line in $q - p'$ space, Γ is the intercept at $p' = 1$ kPa, and λ is the slope of the critical-state line in $v - \lambda \ln p'$ space.

So far many studies have been conducted on critical state of saturated soils (Schofield and Wroth, 1968; Wood, 1991; Maatouk et al., 1995; Newson, 1998). While the critical-state behaviour of saturated clayey soils is well known, there are still gaps in the knowledge of the critical-state behaviour of unsaturated soils. In recent years, the critical state of unsaturated soils has been given great attention and several models have been proposed to represent the critical state (Toll, 1990; Wang et al., 2002; Toll and Ong, 2003; Chiu and Ng, 2003;

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Tamagnini, 2004; Khalili et al., 2004). However, the these models have been based on limited experimental data, especially for undisturbed samples since the measurement of unsaturated critical-state parameters involves time-consuming, expensive and sophisticated testing procedure (Bishop and Blight, 1963; Fredlund and Rahardjo, 1993; Cui and Delage, 1993; Geisser, 1999; Tekinsoy et al., 2004).

While saturated soils are characterized by water phase in voids in classical soil mechanics, the unsaturated soils are described by the presence of air phase, water phase and air–water interface in voids. It is, therefore, difficult to describe appropriate stress state variables for unsaturated soils. Fredlund and Morgenstern (1977) proposed the stress state for unsaturated soil as the net stress ($\sigma - u_a$) and the matric suction ($u_a - u_w$), where u_a is the pore air pressure and u_w is the pore water pressure. The critical-state concept for unsaturated soils has been developed by using these stress state variables. The physical meaning of matric suction is expressed using the Laplace's equation as follows;

$$(u_a - u_w) = T_s\left(\frac{1}{r_1} + \frac{1}{r_2}\right) \quad (3)$$

where T_s is the surface tension and, r_1 and r_2 are the radii of the water menisci in the unsaturated tests. In unsaturated tests, the matric suction is generally controlled by specific techniques such as axis translation technique and osmotic technique. It is practically adopted to be equal to the difference between pore air pressures and pore water pressures.

In literature, there exist limited researches on critical-state framework for unsaturated soil so far. Most of the existing researches have been conducted on compacted and reconstituted soil samples. However, there are little experimental data on undisturbed soil samples. The experimental results performed on reconstituted soil specimens have indicated that the matric suction does not have an effect on the critical-state lines (CSL). In other words, M and λ, which are critical-state parameters, are not affected by matric suction and can therefore be determined from the saturated critical-state line (Wang et al., 2002). On the other hand, some attempts on compacted soil specimens show the different results. The reason for that is that compacted specimens may have different structure and stress history even if they are prepared at the same conditions. Therefore the same compacted specimens can exhibit different mechanical behaviours (Wheeler and Sivakumar, 1995; Maatouk et al., 1995; Wang et al., 2002).

The climatic conditions, parent materials, topography and drainage are the main factors controlling residual soils. This type of soils are formed from the weathering of rocks and deposited on the same place. The residual soils are exposed to strong evaporation. On the other hand they are subjected to have negative pore water pressures known as matric suction. As unsaturated soils are wetted or dried, changes occur in the volume and shear strength as a result of variation of matric suction. The reduction in bearing capacity and the resilient modulus of soils is also associated with the decrease in the matric suction. Thus, residual soils have been of interest to unsaturated soil mechanics in recent decades.

In this paper, it is aimed at examining the critical-state parameters of an undisturbed residual clayey soil from Diyarbakır region in the south-east of Turkey. For this reason, the consolidated drained triaxial compression tests have been carried out both under unsaturated and saturated conditions. In the unsaturated tests, the axis translation technique has been applied in order to control the matric suction. Pore water volume changes were measured by means of volume change transducer connected to water compartment under the high air entry ceramic disc. Since the experimental data of critical state on undisturbed soils are fairly limited, an undisturbed residual soil which has a particular concern for unsaturated soil mechanics is studied in this research. This study presents the findings of an exploratory experimental investigation into the critical-state lines for an unsaturated residual soil corresponding to different soil suctions.

2. Materials and method

2.1. Sampling procedure and soil properties

The samples employed in this study were obtained from residual soil in quite large areas south of Diyarbakır city in Turkey. In this region, semi-arid climatic conditions exist and strong summer evaporation results in desiccation. Existing clay formation is underlined by thick basalt layer and has changing depth between 1 m–9 m. Therefore, the clay is residual and formed by alteration of basalt and basaltic tuff (Taşkıran and Kayadelen, 2005). Soil contains numerous fissures and some are normally visible. By X-ray diffraction analysis, the clay minerals are found as smectite and chlorite. Non-clay minerals include quartz, calcite and feldspat. Since the existing soil deposit is homogeneous and contains no gravel or larger particles, the undisturbed samples were taken from drilling boreholes with Shelby (thin-walled metal) tubes of a diameter of

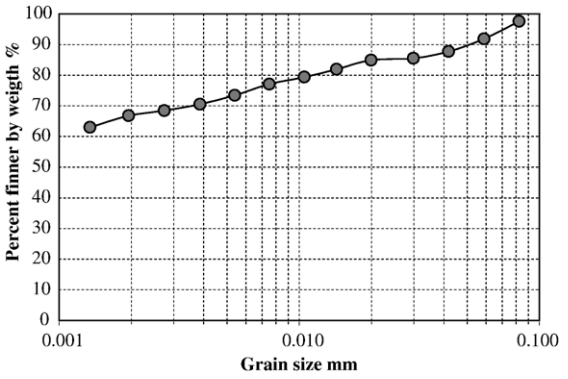


Fig. 1. Particle size distribution curve.

82 mm, a thickness of 2 mm and a length of 950 mm in accordance with ASTM-1587. The soil formation is stiff at the top of the profile and becomes softer with increasing depth due to capillary water rising from the aquifer in the basalt layer. Therefore, a pilot borehole was drilled to examine the whole soil sequence. All samples were taken from the same depth of 2.5 m where the total depth of soil layer was approximately 4.20 m. Specimens 50 mm diameter and 100 mm high were prepared for triaxial tests by trimming procedure.

The grain size-distribution is shown in Fig. 1. The soil consists of 5% sand and 95% silt and clay. Liquid limit (w_L), plastic limit (w_p), volumetric shrinkage limit (w_{vs}) and plasticity index (I_p) are found to be 77, 32, 10 and 45%, respectively. The soil is classified as CH according to the Unified Classification System. The representative geotechnical properties are summarized in Table 1.

2.2. Testing equipment

In order to evaluate the stress–strain behaviour of unsaturated soils, the triaxial compression and direct shear tests are performed on unsaturated samples with various degree of saturation or matric suction. The matric suction is generally controlled by using the axis translation technique (Alonso et al., 1990; Fredlund and Rahardjo, 1993; Gan and Fredlund, 1996; Aversa and Nicotera, 2002). In the application of this technique, the air pressure greater than atmospheric pressure is applied to a soil specimen in order to raise the pore water pressure to a positive value so that the cavitation risk of water in the measuring system is prevented (Fredlund and Rahardjo, 1993). In the current study, the triaxial compression test apparatus was modified to determine the critical-state parameters of unsaturated soils (Fig. 2).

The apparatus has ability to control and measure the pore air and pore water pressure in the soil specimen independently by using axis translation technique. The pore water pressures (u_w) was controlled through a saturated ceramic disc with a high air entry value. For that purpose, a ceramic disc with air entry value of 500 kPa was sealed using epoxy resin along its periphery to the pedestal of the triaxial cell. The constant pore air pressure was applied to the upper surface of the specimen. Pore-water pressure was allowed to drain and maintained at atmospheric condition through the ceramic base plate. In this way the matric suction was able to be at a constant value. For unsaturated soils, the total volume change equals to the sum of the water and air volume changes. The overall volume and pore-water-volume changes of the soil specimen are generally measured owing to the difficulties in measuring air-volume changes. The difference between the overall and pore water volume change gives the air volume change (Fredlund and Rahardjo, 1993). The water content variation was measured by means of the volume change transducer connected to water compartment below the high-air entry ceramic disc in this work. The grooves inside the water compartment run as water channels for flushing air bubbles accumulated due to diffusion. The volume change transducer

Table 1
Geotechnical parameters of soil

w_L %	w_P %	I_p %	w_{vs} %	S and %	Silt+ clay %	A_c	γ_d kN/m^3	Soil type
77	32	45	10	5	95	0.79	14.81	CH



Fig. 2. Triaxial compression test equipment for unsaturated soils: (1) triaxial cell; (2) volume change transducer for pore-water and total volume change; (3) diffused air volume indicator; (4) constant pressure device; (5) vertical displacement transducer; (6) pore-water pressure transducer; (7) data logger.

allows continuous electrical monitoring of volume change of pore water with 0.01 cm^3 sensitivity. Another volume change transducer was connected between the constant pressure device and triaxial cell to measure overall volume change of soil specimens (Fig. 2). The soil specimens were enclosed in two rubber membranes with two slotted aluminium sheets separated by layer silicon grease between the membranes. In this way, air which is diffused into cell water through the rubber membrane was eliminated (Alonso et al., 1990). The air bubbles, accumulated in the water compartment due to diffusion, were periodically removed by flushing. So, the diffused air volume change was measured by using diffused air volume indicator (DAVI) proposed by Fredlund and Rahardjo (1993) and the measurement of pore-water volume change was corrected.

The experimental setup is shown in detail in Fig. 2. The system arrangement includes a triaxial cell, a pressure–volume controller, plumbing arrangements and data acquisition system. The system enables computer-controlled stress or strain rate testing and can give real-time graphical outputs.

2.3. Testing program

Although the soil specimens were taken from the same place, some of the physical properties (e.g. unit weight) may change during the sampling. Therefore, the soil specimens with identical physical properties were selected among all samples for testing. The undisturbed soil specimens with a diameter of 50 mm and height of 100 mm were employed in both saturated and unsaturated triaxial compression tests. Fifteen undisturbed specimens were used in tests. Three undisturbed specimens for saturated soil specimens and twelve undisturbed specimens for unsaturated soil specimens were used in the consolidated drained triaxial compression tests. The matric suction was in the range of 50–400 kPa. This range is adequate in practice since engineers are generally concerned with the performance of geotechnical structures in the relatively low suction range of 0–500 kPa.

2.3.1. Consolidated drained triaxial compression tests under saturated condition

The saturated stress–strain behaviours of soil specimens were determined by means of conventional triaxial compression test apparatus. The saturated triaxial compression tests were carried out under consolidated and drained condition. Prior the tests, the soil specimens were saturated until a value of pore pressure coefficient (B_w) exceeding 0.95. For this purpose, the cell pressure and saturation water pressure (back pressure) were applied and then increased gradually. A difference of 10 kPa between cell pressure and back pressure was maintained so that accidental swelling of the specimen resulting from a high pressure or consolidation of the specimen due to high cell pressure is prevented. At the end of the saturation process, the soil specimens were consolidated under a confining pressure (σ_3). Then, they were sheared at a strain rate of 0.004%/min as long as pore water was allowed to drain out.

2.3.2. Consolidated drained triaxial compression tests under unsaturated condition

For the unsaturated triaxial tests, a total of 12 undisturbed soil specimens were used. Following setting up in the modified triaxial cell, each sample was saturated in order to reduce the initial matric suction of a soil sample to 0 kPa. The saturation procedure is the same as the saturated test. After the saturation process, a known magnitude of the air pressure was applied to the top surface of the specimen in accordance with axis translation technique as described by Fredlund and Rahardjo (1993). So, the soil specimens were desaturated by removing the pore water from the specimen to obtain certain matric suction value. After matric suction equilibrium, the specimens were consolidated under a prescribed confining pressure (σ_3). The overall volume change of the specimen was continuously monitored by using volume change transducer connected between the triaxial cell and constant pressure device. The volume of water flowing out of specimen was observed by means of another volume change transducer. It was assumed that the consolidation reached an equilibrium condition as there is no longer a tendency for the overall volume change and the flow of water from the specimen.

Upon obtaining a stress and matric suction equalization under any applied pressure (i.e., σ_3, u_a and u_w), the soil specimens were sheared at a strain rate of 0.004%/min. This strain rate is sufficiently slow to ensure fully drained conditions during shearing. The overall volume and water volume changes were measured during the shearing. Yet, water volume changes have errors due to diffused air volume into the water compartment below the base plate. Therefore, the air bubbles accumulated in the water compartment were periodically removed by flushing to measure the diffused air volume by DAVI. The flushing was performed by applying a water pressure from the constant pressure device to water compartment so that the air bubbles were forced to enter into the DAVI. The details of measurement of diffused air volume are given by Fredlund and Rahardjo (1993). The water volume

changes were corrected by subtracting the air volume from the pore water volume.

3. Results and discussion

Several researchers have proposed p′, q and v as the critical-state variables for the unsaturated soils (Wang et al., 2002; Toll and Ong, 2003). In the current study, mean effective stress, $p' = (\sigma_1 + 2\sigma_3)/3 - u_a$, deviator stress, $q = \sigma_1 - \sigma_3$, and specific volume, $v = 1 + e$, are measured at critical state for each matric suction, $(u_a - u_w)$, based on net confining pressure, $(\sigma_3 - u_a)$, for saturated and unsaturated consolidated drained triaxial tests, and are tabulated in Table 2. The deviator stress versus axial strain relationship and the variations of volumetric strain with axial strain during loading were measured for samples under various net confining pressures and they can be obtained from Kayadelen et al. (in press).

The critical-state lines (CSLs) for saturated and unsaturated soils are shown in $q - p'$ and $v - p'$ spaces in Figs. 3 and 4, respectively. As seen from these figures, the unsaturated critical-state lines are found to be approximately parallel to the saturated line for each matric suction in $q - p'$ space as stated by many studies (Maatouk et al., 1995; Khalili and Khabbaz, 1998; Wang et al., 2002). M is 0.825–0.866 for unsaturated states and 0.879 for saturated state (Table 3). The nearly same trend exists regardless of saturated and unsaturated states. As expected and seen from Table 3, when the matric suction is increased, the intercept q_0 increases. Since the undisturbed specimens were slightly over-consolidated residual clay, the saturated line does not go through the origin (Fig. 3). Thus, the one critical-state line in $q - p'$ space for the saturated and unsaturated soil

Table 2
List of test series

$u_a - u_w$ kPa	$\sigma_3 - u_a$ kPa	q kPa	p′ kPa	e_{cr}	ε_{cr} %	S_r %
0	25	40	38	1.070	5.35	100
	100	139	146	0.948	10.12	100
	150	195	215	0.898	10.05	100
50	50	118	89	1.029	11.85	93.63
	150	222	224	0.960	12.20	94.34
	200	297	299	0.939	13.70	94.93
100	70	156	122	1.039	17.44	91.02
	150	249	233	1.003	18.28	91.94
	200	315	305	0.970	18.60	92.61
200	100	282	194	1.031	13.25	81.24
	150	313	254	1.008	16.64	82.21
	200	388	329	0.990	17.60	82.71
400	100	369	223	1.035	16.17	74.39
	200	454	351	1.010	16.82	75.18
	300	546	482	0.979	16.72	75.53

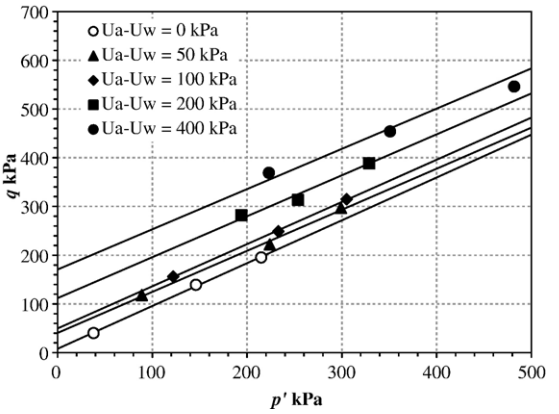


Fig. 3. Critical-state lines in $q - p'$ space.

can be considered depending on the matric suction as follows:

$$q = Mp' + q_0 \tag{4}$$

where q_o is the final intercept of the CSL with the q axis. λ is 0.074–0.076 for unsaturated states and 0.074 for saturated state. The one critical-state line in $v - \lambda \ln p'$ space for the saturated and unsaturated soil can be considered depending on the matric suction as defined in Eq. (2).

It is found from this study that the critical-state parameters M and λ for unsaturated soils are independent of matric suction and can be determined from the saturated critical-state line. However, the intercepts q_o and Γ are dependent on matric suction (Figs. 5 and 6). These findings agree with experimental results reported by Alonso et al. (1990), Wheeler and Sivakumar (1995),

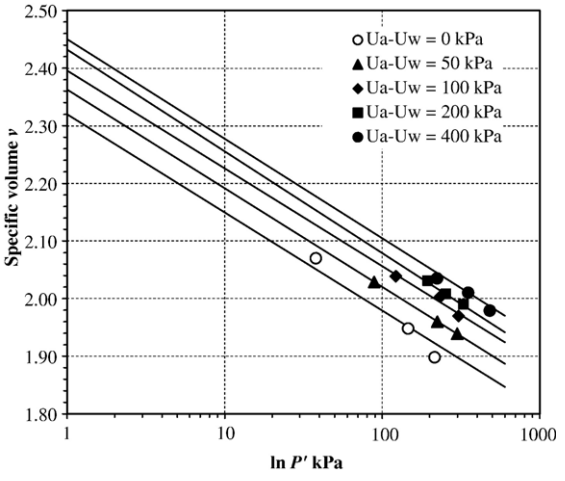


Fig. 4. Critical-state lines in $v - \ln p'$ space.

Table 3
The critical-state parameters for each matric suction

u_a-u_w kPa	λ kPa	Γ	M	q_0 kPa
0	0.074	2.320	0.879	7.72
50	0.074	2.363	0.843	40.44
100	0.074	2.386	0.866	49.43
200	0.076	2.432	0.840	112.02
400	0.075	2.450	0.825	170.75

Adams and Wulfsohn (1997), Rampino et al. (1998), and Wang et al. (2002). In the previous studies, the compacted and reconstituted specimens were employed. The current study in which the undisturbed soil specimens were employed reveals that the parameters (M and λ) of undisturbed specimens are independent of matric suction as for the parameters of compacted and reconstituted specimens.

The relations between matric suction (u_a-u_w) and the intercepts q_o and Γ are attempted in this study and they have been obtained as follows:

$$q_0 = -0.0006(u_a - u_w)^2 + 0.655(u_a - u_w) \quad \text{with } R^2 = 0.984 \tag{5}$$

$$\Gamma = -10^{-6}(u_a - u_w)^2 + 0.0008(u_a - u_w) + 2.32 \quad \text{with } R^2 = 0.997. \tag{6}$$

Figs. 5 and 6 indicate that as (u_a-u_w) increases, the intercepts q_o and Γ increase nonlinearly. These parameters sharply rise up to the matric suction of 100 kPa. However, they appear to increase with the decreasing rate beyond the matric suction of 100 kPa.

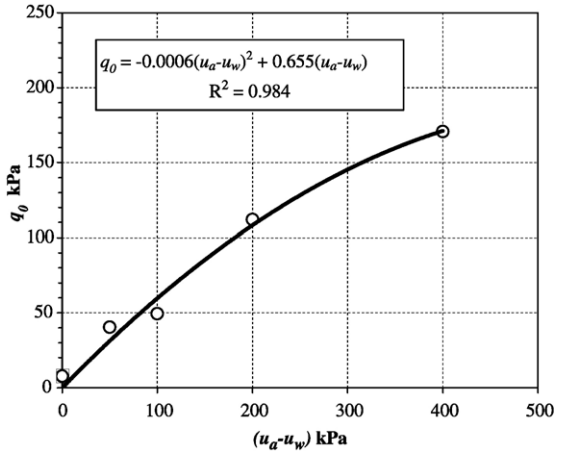


Fig. 5. Relation between the intercept q_0 and matric suction (u_a-u_w).

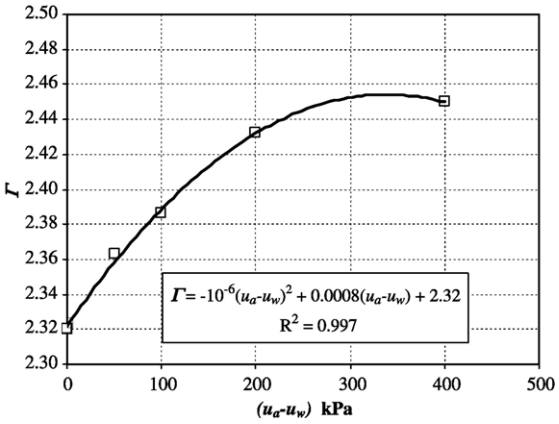


Fig. 6. Relation between the intercept Γ and matric suction (u_a-u_w).

3.1. A method for prediction of critical-state lines of unsaturated soils

Several investigators have proposed the models for estimation of contribution of matric suction to the shear strength. This contribution is called suction strength and generally associated with soil water characteristic curve (SWCC) (Fredlund and Rahardjo, 1993; Vanapalli et al., 1996; Oberg and Sallfors, 1997; Khalili and Khabbaz, 1998; Tekinsoy et al., 2004). Tekinsoy et al. (2004) developed an equation for suction strength by assuming that there is a logarithmic relationship between the matric suction and suction strength as follows:

$$\tau_{us} = \tan\phi'[(u_a - u_w)_b + P_{at}]\ln\left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right]. \tag{7}$$

Where τ_{us} is the contribution of the matric suction to the shear strength (suction strength), ϕ' is the angle of shear strength at peak state, (u_a-u_w) is the matric suction, $(u_a-u_w)_b$ is the air entry value of soils, P_{at} is atmospheric pressure. This equation is considered as part of the total apparent cohesion of unsaturated soils and thus total apparent cohesion is written as follows:

$$c_{total} = c' + \tan\phi'[(u_a - u_w)_b + P_{at}]\ln\left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right]. \tag{8}$$

Where c' is the apparent cohesion obtained from the saturated condition, c_{total} is total apparent cohesion obtained from unsaturated condition based on different matric suction.

Eq. (8) was developed for the intercept of the shear strength envelope with respect to peak state. In this

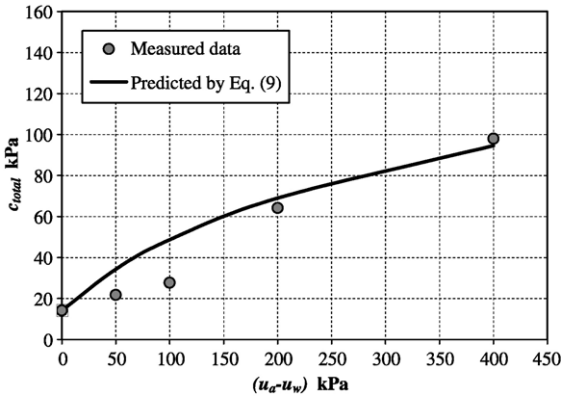


Fig. 7. Comparison of measured total cohesion for critical state with those predicted from Eq. (9).

study, Eq. (8) was modified in terms of the critical-state parameters and developed for predicting the critical-state lines for different matric suction. The angle of shear strength (ϕ') in Eq. (8) is obtained from the peak state of stress strain relationship. As the critical angle of shear strength ϕ'_{cr} is replaced with ϕ' in Eq. (8), the contribution of matric suction to the shear strength at critical state is obtained and total apparent cohesion for the critical state under different matric suction values is written as follows:

$$c_{\text{total}} = c' + \tan\phi'_{cr}[(u_a - u_w)_b + P_{at}]\ln\left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right] \quad (9)$$

where ϕ'_{cr} is the angle of shear strength at critical state. On the other hand, the relationship between the

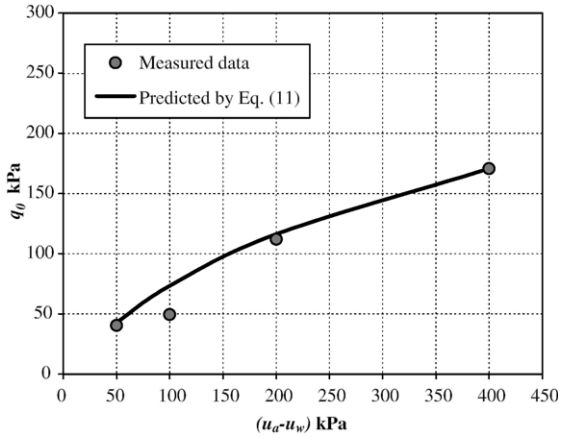


Fig. 8. Comparison of measured contribution of matric suction by the present study to intercept of CSL with those predicted from Eq. (11).

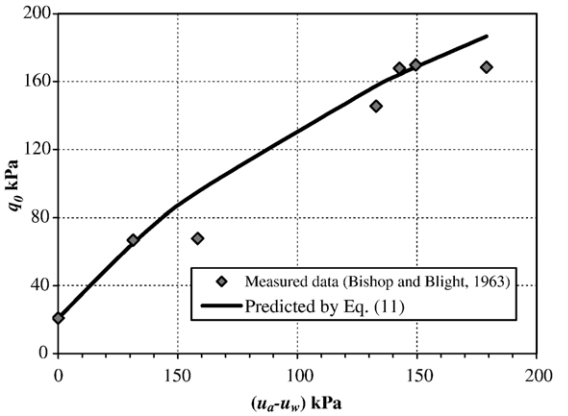


Fig. 9. Comparison of measured contribution of matric suction to intercept of CSL by Bishop and Blight (1963) with those predicted from Eq. (11).

apparent cohesion and intercept q_o of CSL is given as follows:

$$q_o = \frac{6\cos\phi'_{cr}}{3 - \sin\phi'_{cr}} c_{\text{total}}. \quad (10)$$

Substituting Eq. (9) into Eq. (10), the intercept of CSL of unsaturated soils having any matric suction is determined as follows:

$$q_o = \frac{6\cos\phi'_{cr}}{3 - \sin\phi'_{cr}}\left[c' + \tan\phi'_{cr}[(u_a - u_w)_b + P_{at}]\ln\left[\frac{(u_a - u_w) + P_{at}}{P_{at}}\right]\right]. \quad (11)$$

Consequently, Eq. (11) states that as the critical-state parameters of a saturated soil and its air entry value are

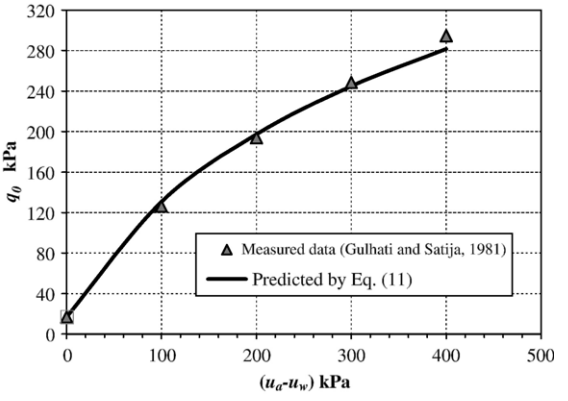


Fig. 10. Comparison of measured contribution of matric suction to intercept of CSL by Gulhati and Satija (1981) with those predicted from Eq. (11).

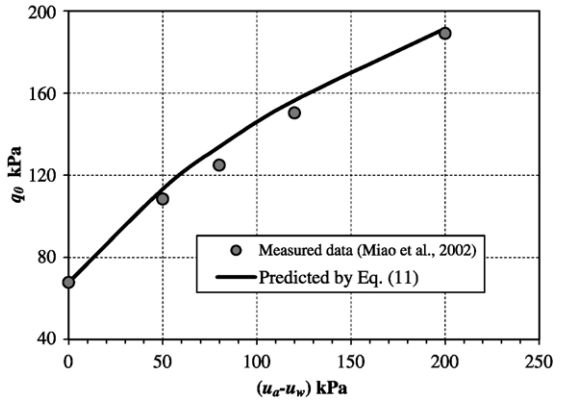


Fig. 11. Comparison of measured contribution of matric suction to intercept of CSL by Miao et al. (2002) with those predicted from Eq. (11).

known, the contribution of matric suction to the intercept of CSL for different matric suction can be predicted.

The air entry value of the residual soil used in the current study, which is obtained from the SWCC from the pressure plate test, is determined as 40 kPa. The parameters of the volumetric content at saturation (θ_s) and volumetric content at residual state (θ_r) were approximately determined as 58.1% and 5.4%, respectively. The c' and ϕ'_{cr} are found as 14.14 kPa and 19.6°, respectively. Eq. (11) is tested with the test results of the current study. Fig. 7 shows the comparison of measured total apparent cohesions for critical state with those predicted from Eq. (9). As can be seen from Fig. 7, measured total apparent cohesions for critical state are compatible with those predicted from Eq. (9). Fig. 8 indicates the predicted and measured q_0 of CSL versus matric suction. It appears that there is a good agreement between the predicted and measured values. This comparison reveals that Eq. (11) gives reasonable results, and can be properly used for the prediction of intercept of CSL of an unsaturated soil. The Eq. (11) is also compared with the data obtained from the previous experimental studies by Bishop and Blight (1963), Gulhati and Satija (1981) and Miao et al. (2002) in order to test the validity of the model developed. As far as Figs. 9, 10 and 11 are concerned, a good agreement between experimental and predicted results has been observed.

4. Conclusion

In this study, the critical-state parameters for unsaturated residual samples from the Diyarbakir, Turkey for both saturated and unsaturated states were experimentally examined and determined. For that purpose the conventional triaxial test apparatus was modified and fully controlled by means of computer. The matric suction was controlled by using axis translation technique. The test results have shown that the critical-state lines for the unsaturated soil specimens with respect to different matric suction or different degree of saturation are parallel to each other and they are also parallel to those for the saturated soil specimens. In other words, the matric suction does not have an effect on the critical-state parameters (M and λ). The parameters of M and λ of the residual soil used in this work have a constant value of approximately 0.85 and 0.074 for both saturated and unsaturated states, respectively. It has also been observed that the variations of intercepts q_o and Γ with the matric suction are nonlinear and therefore they can be defined as a function of matric suction $(u_a - u_w)$. A new method for the prediction of intercept q_0 for unsaturated soils has also been proposed. The validity of the proposed method is tested from the experimental results obtained from both the current study and other publications. The comparison between the results of the proposed model and the experimental results reveals that the proposed model satisfactorily agrees with the experimental data and appears to be a reasonable and usable method.

Nomenclature

q	Deviator stress
p	Mean stress
p'	Mean effective stress
v	Specific volume
M	Slope of the projection of the critical-state line in $q-p'$ space
Γ	Critical-state intercept for volumetric plane at $p'=1$ kPa
λ	Slope of the projection of the critical-state line in $v-\lambda \ln p$ space
q_0	Final intercept of the critical-state line with q axis
u_a	Pore air pressure
u_w	Pore water pressure
$(p-u_a)$	Net mean stress
(σ_3-u_a)	Net confining pressure
(u_a-u_w)	Matric suction
$(u_a-u_w)_b$	Air entry value
T_s	Surface tension
r_1, r_2	Radius of the water meniscus
e_{cr}	Void ratio at critical state
ε_{cr}	Strain at critical state
τ_{us}	Suction strength
c'	Apparent cohesion from the saturated condition
c_{total}	Total apparent cohesion
ϕ'	Angle of shear strength at peak state
ϕ'_{cr}	Angle of shear strength at critical state
θ_s	Volumetric water content at saturation

θ_r	Volumetric water content at residual state
S_r	Degree of saturation
P_{at}	Atmospheric pressure
w_L	Liquid limit
w_P	Plastic limit
I_p	Plasticity index
w_{vs}	Volumetric shrinkage limit
A_c	Activity
γ_d	Dry unit weight
B_w	Pore pressure coefficient
CH	Highly plastic clay
CSL	Critical State Line
SWCC	Soil Water Characteristic Curve

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