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Unsaturated Soil Characteristics of Residual Soil in Indonesia

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Abstract: Unsaturated soil mechanics offers a rigorous framework for analyzing geotechnical problems in which the near-surface strata remain partially saturated for many years. Many slope failures are initiated within these layers, particularly during rainfall stability assessments, and must account for hydraulic mechanical coupling beyond saturated assumptions. This study characterizes the hydraulic behavior of residual soils through the soil–water characteristic curve (SWCC), relating matric suction to water content, as the principal descriptor for incorporating suction effects into strength and deformation analyses. Field observations and laboratory testing were undertaken; matric suction was measured using the filter paper method, and SWCCs were derived to parameterize suction-dependent shear strength for limit-equilibrium evaluation of slopes subjected to infiltration. This work demonstrates how adopting SWCC-based parameters refines the safety factor during transient wetting and clarifies the contribution of suction to apparent cohesion. Although the routine use of unsaturated parameters is not yet a standard practice in Indonesia, the results provide a practical pathway for integrating matric suction into conventional stability calculations and developing context-appropriate guidance. More broadly, these findings reinforce the need to embed unsaturated soil mechanics in slope design and risk assessment, where rainfall-induced failures are of concern.

Keywords: unsaturated soil mechanics; residual soil; matric suction; soil–water characteristic curve (SWCC); rainfall infiltration; slope stability; soil shear strength.

印尼殘積土的非飽和土特徵

摘要：对非饱和土力学概念的认可是扩大该概念在土木工程中应用的全球倡议的一部分。由于边坡破坏经常发生在非饱和土层中，因此岩土工程中的一些问题，例如降雨期间边坡的稳定性分析，需要使用非饱和土力学的概念来研究。非饱和土特性包括水力特性和土力学特性。在本研究中，将研究非饱和土的水力特性，以基质吸力变量相对于土壤含水量变化的变化来表示。这些特征由土壤-水特征曲线（SWCC）描述。本研究旨在探讨饱和土与非饱和土残余土的特性如何。研究方法是通过现场观察和实验室测试进行的。使用滤纸法测量基质吸力。这项研究的结果有望概述非饱和土的特征及其在降雨期间斜坡安全因素分析中的潜在应用。非饱和土特性在边坡稳定性分析中的应用在印度尼西亚尚未成为标准做法。因此，这项研究也有望为降雨期间使用非饱和土参数的标准边坡稳定性分析提供帮助。应用非饱和土力学概念在边坡稳定性分析中的重要性变得更加清晰和显着。

关键词：非饱和土特性、残余土、土抗剪强度.

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1. Introduction

This study is a step toward a wider introduction to unsaturated soil mechanics in Indonesia. This activity includes three main steps: conducting laboratory tests, obtaining a database of unsaturated soil characteristics of residual soil, and its application in practical engineering. Based on the soil characteristic data, correlations between unsaturated soil characteristics and soil properties for local residual soil can be developed. The next stage of the results of this research can be used to develop the application of the unsaturated soil mechanics concept to slope stability analysis.

Slope conditions in Indonesia generally experience landslides on rainy days, whereas they are stable during the dry season. Hilly soils in Indonesia are generally residual soil with a deep groundwater table. Landslides during the rainy season usually occur in unsaturated soil layers, which are located above the groundwater level, as shown in Figure 1. Increasing rain intensity and changing over time can cause slope instability [1].

Problems in the field of geotechnical engineering, such as slope failure in unsaturated soil due to rain, need to be explained using the concept of unsaturated soil mechanics. In the case of soil slope failure in the Cisokan region of West Java [2], a failure area occurred in the unsaturated soil layers.

Slope instability can be caused by alterations in groundwater levels. Several cases of slope failure at several locations in Padalarang, West Java, during the rainy season are shown in Figure 2. In climate conditions where soil wetting and drying frequently occur alternately due to seasonal changes, and slope failure areas are generally located in unsaturated soil layers, this problem is more appropriately analyzed using an unsaturated soil mechanics approach [3,4].

1.1 State of The Art Unsaturated Soil Mechanics

The differences between the concepts of unsaturated and saturated soil mechanics are illustrated in Fig. 3. In unsaturated soil mechanics, the phases of soil are not only water and soil but also air and the interface between air and water. In unsaturated soil, there is a variable matric suction stress condition in addition to the net normal stress condition. An important characteristic of unsaturated soil is its condition when it has negative pore water pressure [3, 5].

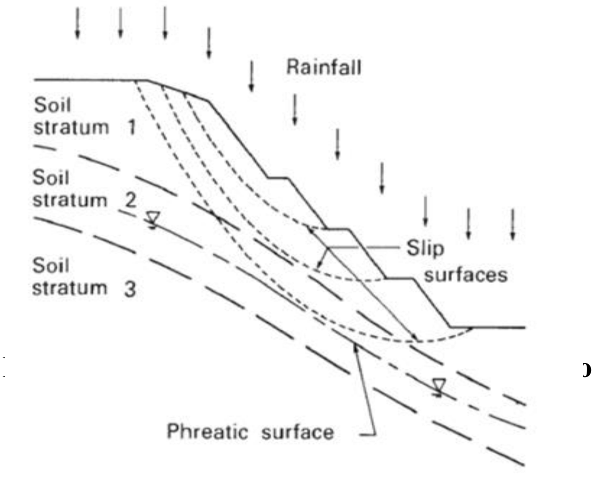

Figure 2. The landslides due to rain in West Java, Indonesia [2]

The soil layer above the groundwater level had negative pore water pressure and was categorized as an unsaturated soil layer. When it rains, there is a change in the pore water pressure in the unsaturated soil relative to the pore air pressure. The change in pore water pressure u_w, to pore air pressure u_a, is expressed as the matric suction. The higher the matric suction, the greater the shear strength of the soil. The higher the shear strength of the soil, the greater the strength or stability of unsaturated soil slopes. Research and attention regarding the concept of unsaturated soil mechanics have been carried out in several previous studies [4–11]. This research is a further step in the development and dissemination of unsaturated soil mechanics in the field of practical engineering.

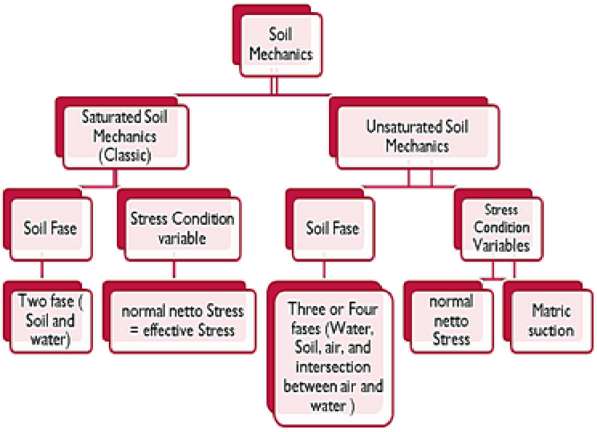

Figure 3. State of The Arts Unsaturated Soil Mechanics (Developed by the authors)

1.2 The Objectives of Research

The lack of data regarding the characteristic parameters of unsaturated soils in Indonesia is one of the reasons for this study. This study aims to identify the characteristics of saturated unsaturated soil by determining the soil-water characteristic curve and the mechanical properties of the soil by determining the shear strength parameters of unsaturated soil for residual soil.

Currently, there is no database regarding the unsaturated soil characteristics of residual soils in Indonesia. In Indonesia, unsaturated soil shear strength parameters still have limited data for each type of residual soil. Determining the shear strength parameter of unsaturated soil ϕ^b is currently still based on assumptions and correlations made based on residual soil data from other countries. Laboratory tests are required to determine the parameter ϕ^b through triaxial tests of unsaturated soil. This research is a means of fulfilling the need for a database of unsaturated soil characteristics through the shape of the soil-water characteristic curve (SWCC), saturated permeability, permeability function, and a database of unsaturated soil shear strength parameters for residual soil. In this study, the results emphasize the SWCC shape of the residual soil sample.

2. Research Method

This study uses an empirical and experimental methodology. The data were collected from both field observations and laboratory tests, followed by a numerical analysis to determine the characteristics of unsaturated soil for residual soil. Laboratory tests to obtain unsaturated soil characteristics were performed based on the results of the soil-water characteristic curve (SWCC) using the matric suction determination method based on standard ASTM filter paper (D5298-94). Laboratory tests to determine soil shear strength parameters such as cohesion and effective friction angle ϕ' and ϕ^b (shear angle when variable matric suction was included) were conducted through triaxial tests for unsaturated soils based on ASTM D4767.

2.1. Location

Samples were taken from locations in West Java Province in Indonesia. In this study, the sample was taken from Padalarang district, Bandung Regency, as shown in Figure 4. Padalarang has hilly areas or slopes that are often found, especially in public road areas that are at risk of landslides. Slopes in West Java are generally unsaturated residual soils, and landslides are often found during heavy rain. The coordinates of the location are 6˚47'12.54” S latitude and 107˚26'22.45"E Longitude, exactly in Cijengkol Village.

Figure 4. 4 Location where soil sample was taken (Developed by the authors)

2.2. Sampling Method

Data collection techniques were conducted through observations and investigations in the field and laboratory. Laboratory tests include the physical properties of the soil to obtain soil parameters, such as the plasticity index (PI), bulk density, and specific gravity. The shear strength of unsaturated soil is determined through triaxial testing of unsaturated soil, which considers the presence of matric suction, where the effective cohesion (c'), effective shear angle (φ'), and shear angle due to changes in matric suction (φ^b) are obtained. In this study the Soil water characteristics curve (SWCC) was formed from collected data of residual soil sample about 22 data points. The data points were then plotted to determine the relationship between the matric suction and gravimetric water content, volumetric water content, and degree of saturation.

2.3. Unsaturated Soil Characteristics

The important characteristics of unsaturated soil are described by the soil water characteristic curve (SWCC). The SWCC describes the water content in the soil against variations in matric suction, which is a constitutive curve for changes in the volume of unsaturated soil. Soil testing to obtain the SWCC form of residual soil was performed by Rahardjo et al..[12] using the tempe cell test equipment and pressure plate test, and its correlation with the soil shear strength parameters. The SWCC also represents the permeability variation curve against the suction value of unsaturated soil [3]. Perera et al. [7] carried out research on the determination of SWCC based on soil properties, such as grain size distribution (GSD) and property index (PI). The relationship function of the SWCC GSD and PI parameters is given in his research based on statistical analysis to produce SWCC nonplastic and plastic soils. The resulting SWCC can be used to predict SWCC indirectly based on soil properties.

2.3.1. The Measurement of Matric Suction

The filter paper method was used to measure the total suction and matric suction indirectly. The filter paper functioned as a sensor. The working principle is based on the assumption that the filter paper reaches a balance according to the suction power of the soil. Balance was achieved when the fluid shifted from the soil to the filter paper. The water content of the filter paper was measured to determine the water vapor pressure has been obtained. The water content of the filter paper is closely related to the suction value given by the calibration curve from McQueen and Miller (1968a) in [3].

The method of measuring the matric suction with filter paper was based on the ASTM standard (D5298-94). The filter paper used met the specifications according to the ASTM standard E833. Whatman No. 42 filter paper was used. Figure 6 shows the calibration curve obtained using Whatman No. 42 filter paper from several previous studies.

The filter paper method can be applied to more varied matric suction values (from several kilopascals to hundreds of kilopascals) (Fawcett and Coliis-Goerge 1967; Mcqueen and Miller 1968a in [3]. When the filter paper was placed in direct contact with the soil sample, it was assumed that moisture flowed from the soil to the filter paper until equilibrium was reached. The water content of the filter paper was measured. The water content measurement results were then calibrated using a calibration curve to obtain the matric suction value of the filter paper, which was associated with the matric suction value of the soil.

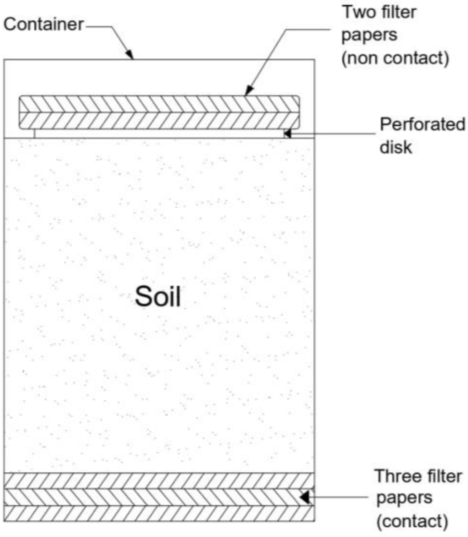

Figure 5. Concept of matric suction measurement with filter paper [3]

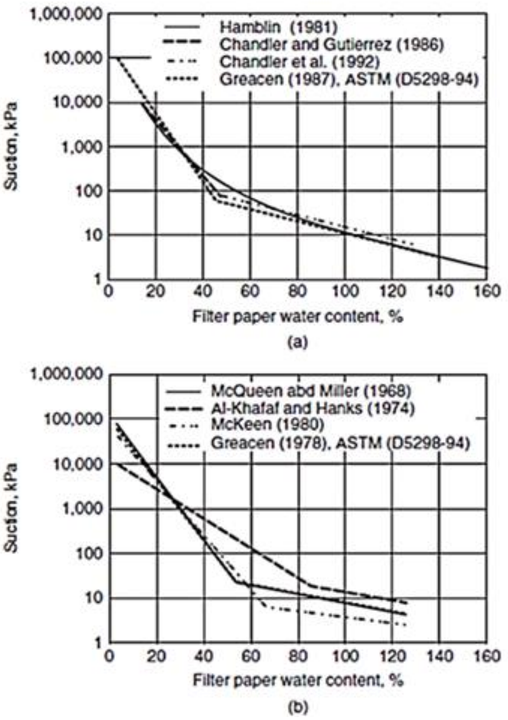

Figure 6 Calibration curve for measurement results using Whatman filter paper No. 42 (a) and Schleicher and Schuell filter paper No. 589(b) [3]

Figure 6 shows the calibration curve measured using Whatman filter paper no.42 in several previous studies. The figure shows that the curve of Whatman filter paper no. 42 was consistent in terms of its absorption capacity. It can be observed from the resulting curve that it is almost the same. However, Schleicher and Schuell no. filter paper. 589, the resulting curve exhibits a wider variation.

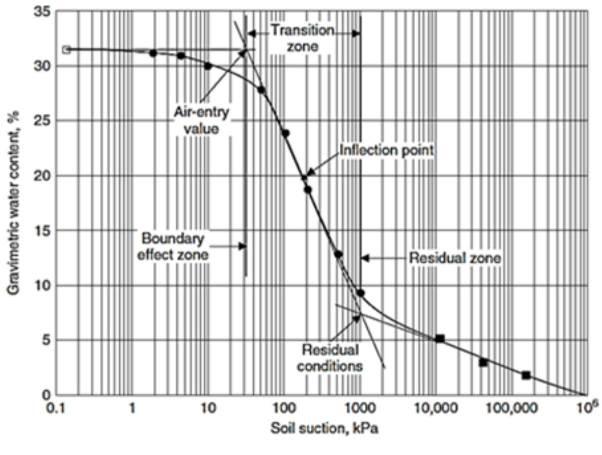

Figure 7. Form of SWCC results and its important points of curve [3]

Soil water characteristics curve (SWCC) describes variations in water content relative to variations in matric suction [3, 13]. SWCC is one of the components of the constitutive curve of volume change in unsaturated soil. The results of the analysis produced an SWCC form, as shown in Figure 7. The key importance of the transition point is the air entry value (aev) and the residual value. The ev point is a reference value for the matric suction for the triaxial testing of unsaturated soil. Several studies on SWCC have been conducted by several researchers [14-17].

2.3.2. Fitting Equation of Soil Water Characteristic Curve (SWCC)

The soil water characteristic curve was obtained from the best-fit equation using several fitting equations. This equation includes variables related to air penetration and soil desaturation speeds. The SWCC equation can be adjusted for soil drying and wetting [3]. Fredlund and Xing [6] in [3] proposed the following SWCC equation:

$$w(\psi) = C(\psi).w_s / \{\ln[e + (\psi/a_f)^{n_f}]\}^{m_f} \quad (1)$$

$$C(\psi) = 1 - \ln(1 + \psi/\psi_r)/\ln[1 + (10^6/\psi_r)] \quad (2)$$

Where:
w (ψ) = water content as a function of suction, ψ
C (ψ) = correction factor to adjust SWCC to 106 kPa at 0% water content
af = fitting parameter indicating the curved point
nf = fitting parameter related to desaturation speed
mf = fitting parameter related to the curvature near the residual condition.

Suction at 0 % water content has the same value for all porous materials, which is 106 kPa, and this value has been studied in various types of soil (Croney and Coleman, 1961) [3]. This value has also been supported by thermodynamic influences (Richards 1965) [3]. Fitting was performed using Solver in Microsoft Excel by iterating the parameters obtained from the fitting equation, and the coefficient of determination (R^2) value was close to 1. The R^2 value represents the fit of the curve to the data. The R^2 value was obtained using Eq. (3), eq. (4) and eq. (5).

$$SSE = \sum(y_{data} - y_{fit})^2 \quad (3)$$

$$SST = \sum(y_{data} - \overline{y_{data}})^2 \quad (4)$$

$$R^2 = 1 - SSE/SST \quad (5)$$

Where:
SSE = Sum squared error
SST = Total of Variations

2.3.3. Shear Strength Measurement of Unsaturated Soil

The soil shear strength in the laboratory was measured using triaxial test equipment [19-22]. For unsaturated soils, a different test procedure was required because it was necessary to regulate the pore air pressure and pore water pressure to determine the amount of matric suction when the test was carried out. The working concept of an unsaturated soil triaxial tool is illustrated in Fig. 8 [19].

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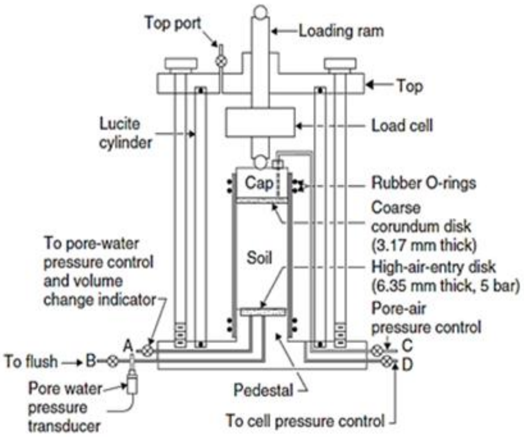

Figure 8. Work principle of the triaxial test for unsaturated soil [3]

Triaxial tests were performed on saturated and unsaturated soils to determine the shear strength parameter conditions (cohesion, φ', $φ^b$). The triaxial test is flexible in its procedure. In the testing of unsaturated soil, the high air-entry disk must be saturated. Setting the difference between the pore air pressure and pore water pressure is required for this triaxial test. Determining the air entry value (aev) is the basis of this procedure. Several previous studies have been conducted to determine the unsaturated soil strength parameters, [18-19]. Currently, in Indonesia, the residual soil properties are still limited to the physical and mechanical properties of saturated soil conditions [23].

3. Results and Discussions

The soil property tests resulted in soil parameter values, such as specific gravity, liquid limit, plastic limit, plasticity index, optimum water content, saturated water content, and mineral content, as presented in Table 1.

In this research, the initial stage of investigation is to find a soil–water relationship curve, known as the soil-water characteristic curve (SWCC). This curve is a characteristic form of unsaturated soil, which is the relationship between the soil water content and matric suction. Matric suction is an important variable that differentiates between the saturated and unsaturated soil conditions.

Table 1. Soil properties of residual soil sample

Properties		Unit
Specific Gravity (Gs)	2.65	
Volume weight	13.5	kN/m^3
Silt content	91.70	%
Clay content	7.05	%
Liquid limit	54.01	%
Plastic limit	40.06	%
Plasticity Index (PI)	13.09	%
Soil Classification Based on USCS	MH	
Optimum water content	52.5	%
Maximum Dry volume weight	10.95	kN/m^3
Saturated water content	65.4	%

Based on Table 1, the residual soil sample has a plasticity index (IP) in the medium category of 13.9 % and a specific gravity of 13.5 kN/m3 with the soil classified as clayey silt. Saturated water content was achieved at a water content of 65.4%. The soil permeability coefficient was found to be 3.66 × 10-8 m/s and can be categorized as a type of silt with a clay content of 7.05%.

3.1. Soil Water Characteristic Curve (SWCC) for Drying Condition

Drying SWCC is performed after the soil undergoes a saturation process and dries until it reaches a certain water content. The matric suction was measured indirectly using filter paper with a procedure based on ASTM D6836-02, with modifications. The SWCC was developed based on the results of indirect matric suction measurements using filter paper. The water content of the filter paper was converted into a matric suction value by using the calibration curve of Leong et al. (2002) in [3].

The SWCC for residual soil in this study is reviewed based on the relationship between matric suction and gravimetric water content, volumetric water content, and degree of saturation. The relationship between the gravimetric water content and volumetric water content is also shown under dimensionless and normalized conditions. The soil water content (w_s) value was expressed as the gravimetric water content in the SWCC. The SWCC measurement results, which describe the relationship between the matric suction and gravimetric water content of the residual soil, are presented in Figure 9.

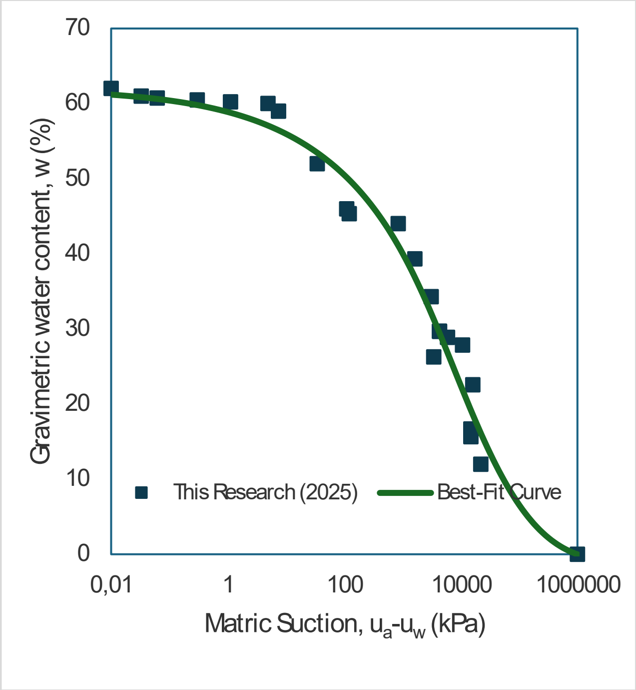

Figure 9. Plot of matric suction value data against gravimetric water content, w (Developed by the authors)

The plot results are data points that show the relationship between the gravimetric water content of the soil and matric suction. To obtain a curved shape, fittings are required to describe the matric suction value at any point. Using the equations based on Fredlund and Xing [5] in the form of Eq. (1) and eq. (2), the fitting calculations for SWCC for the gravimetric water content parameters were determined. The results of the SWCC fitting calculations for the gravimetric water content parameters are presented in Table 2.

Table 2. The Fitting parameter of SWCC in gravimetric water content

Fitting Parameter	
a_f	300000
m_f	6.2
n_f	0.30
ψ_r	3000
Std. Dev/RSME	3.88
R^2	0.9549

The value of the coefficient of correlation (R^2) was determined using Equation (5) to be 0.9549. An R^2 value close to 1 indicates that the relationship curve matches the data variables used in the laboratory test results.

The volumetric water content was obtained from the conversion of gravimetric water content values, w.Gs, into the void ratio, e, based on the shrinkage curve. The shrinkage curve was obtained by measuring the volume and mass of the soil samples under saturated-to-dry conditions. The void ratio and water content of dry soil can be determined from this measurement. The properties of unsaturated soil, such as the air penetration value, AEV, and residual water content, can also be determined from the shrinkage curve. This will be useful for determining the shrinkage condition as a form of change in stress in the soil matric suction or negative pore water pressure [3].

The volumetric water content (Θ_w) is the ratio of the volume of water in the soil to its total volume. The volumetric water content is commonly used in agricultural science. Determination of the volumetric water content is needed in soil that experiences large changes in volume when matric suction occurs. The results of the SWCC measurements of the volumetric water content parameters are presented in Figure 10.

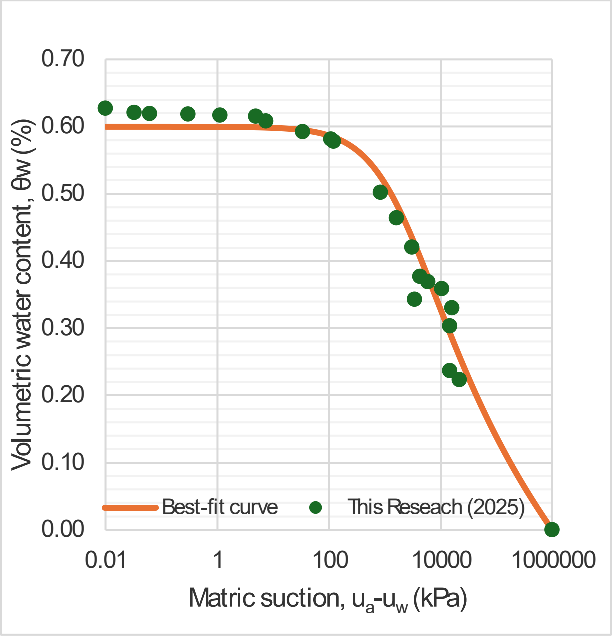

Figure 10. Plot of matric suction value data against volumetric water content, Θ_w (Developed by the authors)

The fitting parameter calculations for SWCC for the volumetric water content parameters were determined. The results of the SWCC fitting for this volumetric water content parameter are listed in Table 3.

Table 3. The fitting parameter of SWCC in volumetric water content

Fitting Parameter	
a_f	300
m_f	0.4
n_f	0.5
ψ_r	1500
Std. Dev/RSME	0.03
R^2	0.9797

The degree of saturation was obtained from the conversion of gravimetric water content values, w.Gs, into the void ratio, e, based on the shrinkage curve. The SWCC measurement results in terms of the saturation degree parameters are shown in Fig. 11. The results of the SWCC fitting for this degree of saturation parameter are shown in Table 4.

$$S = w. Gs/e \tag{6}$$

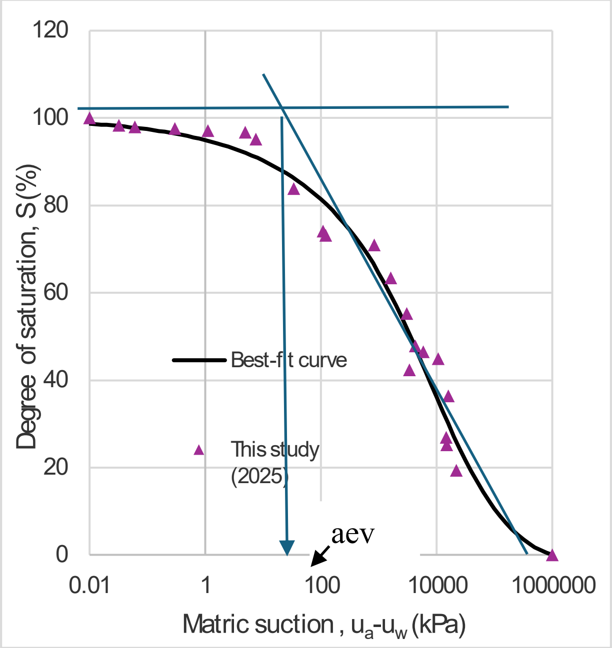

Figure 11. Plot of matric suction value data against Degree of saturation (Developed by the authors)

Table 4. The fitting parameter of SWCC in Degree of saturation

Fitting Parameter	
a_f	300000
m_f	6.20
n_f	0.30
ψ_r	3000
Std. Dev/RSME	4.79
R^2	0.9785

The results of the SWCC fitting of the degree of saturation curve show the air penetration value (aev). The air penetration value represents the matric suction value when the soil starts to experience desaturation as the soil dries out. This indicates that air begins to replace water in the largest soil pores. This air penetration value is related to the failure envelope of the extended Mohr-Coulomb circle for unsaturated soils in triaxial test results. If the matric suction segment is smaller than the air penetration value, then we used the ϕ' value as an angle that expresses the increase in shear strength due to an increase in matric suction. If the segment of the matric suction value is greater than the air penetration value, then we used the ϕ^b value as an angle that expresses the increase in shear strength due to increasing matric suction [3, 13].

The air entry value is affected by the grain size, grain-size distribution, and number of voids. The smaller the granules, the higher the air entry value and the smaller the permeability value [8, 12]. The air entry value was obtained at a matric suction of 70 kPa. The results of determining the air entry (penetration) values are shown in Figure 11. After obtaining the air entry value (aev) for the residual soil sample based on its SWCC, the matric suction value was adjusted in the triaxial unsaturated soil test. The matric suction value provided in the test must exceed that of aev. The soil shear strength parameter ϕ^b can be determined using the extended Mohr–Coulomb failure envelope method by applying a certain matric suction.

4. Conclusion

Drying soil–water characteristic curves (SWCCs) derived from disturbed residual soil exhibit excellent goodness-of-fit across alternative state variables gravimetric water content, volumetric water content, and degree of saturation with coefficients of determination (R^2) of 0.9549, 0.9797, and 0.9785, respectively. These values indicate a strong, internally consistent relationship between the matric suction and moisture state.

The air entry value (AEV), estimated from the fitted SWCC in terms of the degree of saturation, occurs at a matric suction of approximately 70 kPa. The AEV provides an appropriate reference suction for configuring and interpreting unsaturated triaxial tests on the same residual soil.

The results expand the empirical database for residual soils under unsaturated conditions and establish a defensible basis for the subsequent determination of suction-dependent shear strength parameters and their incorporation into stability analysis.

Declarations

Author Contributions

Conceptualization, S.K., I.W.S., E.M.; methodology, S.K. and E.M.; software, E.M.; validation, I.W.S., S.K., and E.M.; formal analysis, E.M.; investigation, E.M.; resources, E.M., I.W.S., S.K.; data curation, E.M.; writing—original draft preparation, E.M.; writing—review and editing, E.M.; visualization, E.M.; supervision, I.W.S. and S.K.; project administration, E.M.; funding acquisition, I.W.S. and S.K. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available upon request from the corresponding authors.

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No funding information was available for this study.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this manuscript. In addition, ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies, have been completely observed by the authors.

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