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Zhi-qiang LIN
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 20092, China

Jian-gu QIAN
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 20092, China

Zhen-hao SHI
Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 20092, China

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Modeling unimodal/bimodal soil-water retention curves considering the influence of void ratio under capillarity and adsorption

LIN Zhi-qiang[1, 2], QIAN Jian-gu[1, 2], SHI Zhen-hao[1, 2]

1. Department of Geotechnical Engineering, Tongji University, Shanghai 200092, China
2. Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Tongji University, Shanghai 20092, China

Abstract: The constitutive relationship between suction and degree of saturation is of great significance for estimating the shear strength and deformation behavior of unsaturated soils. A unimodal/bimodal soil-water retention curve (SWRC) is proposed considering the effects of various pore structures and the effects of void ratio on capillarity and adsorption. The different mechanisms of water retention through capillarity and adsorption are explicitly distinguished in the proposed model. The relationship between the capillary degree of saturation and suction is described as a specific function related to the characteristics of pore-size distribution, while the adsorptive degree of saturation is modeled considering the effect of capillary condensation explicitly. Subsequently, the decoupling formula of capillary and adsorptive saturation is further put forward. The formula lays a foundation for the model to account for the dependence of capillary part of SWRC on void ratio, which is consistent with the results from micro-scale tests. Eventually, an approach to estimate the shear strength of unsaturated soils with different initial void ratios has been proposed based on the improved SWRC model. The model is verified using data from water retention and direct shear tests reported for various types of soils in the literature.

Keywords: soil-water retention curve; unimodality/bimodality; capillarity; adsorption; void ratio; strength

1 Introduction

The soil-water retention curve (SWRC) is of great value for studying the strength, deformation, and permeability of unsaturated soils[1−2]. The factors, such as mineral composition, pore size distribution, soil structure, sample preparation method, stress history, and stress state, will affect SWRC[3−5]. Among those factors, the influence of the stress state for SWRC is essentially achieved by changing the dry density or void ratio[6].

Gallipoli et al.[7] and Gao et al.[8−9] proposed the SWRC formulas suitable for different void ratios based on the Van Genuchten and Fredlund-Xing models, respectively, considering the correction of parameters by void ratio. Zhou et al.[10] derived the SWRC model considering the effect of dry density based on the incremental relationship between saturation and initial dry density. Based on the capillary model and statistics principles, Zhang et al.[11] obtained a formula that could predict SWRC at any initial void ratio. Both this method and the method in Zhou et al.[10] require two SWRCs with known dry density or void ratio for calibration.

Recent studies have shown that accurate modeling of SWRC in the high suction range requires a clear distinction between the two mechanisms of capillarity and adsorption[12−13] and the responses of the two mechanisms with the change of void ratio are different. Microscopic tests have shown that the initial dry density or void ratio mainly changes the pore size distribution of large pores and has very limited influence on small pores[14−17]. Since the latter type of pores mainly stores adsorptive water, the dependence of SWRC on the void ratio is mainly reflected in the capillary hydraulic-mechanical coupling.

The above models are only suitable for simulating unimodal SWRC. For soils with poor grading, gap grading, and mixing of soil particles with different particle sizes[18−19] or fine-grained soil with dual-pore structure[20]. SWRC tends to show a bimodal structure with an apparent two-stage distribution, and the unimodal SWRC model is no longer applicable.

This study aims to develop an SWRC model suitable for both unimodal and bimodal soils, considering the different effects of void ratio on capillarity and adsorption. According to the characteristics of capillary and adsorbed water, the capillary water is described as a function related to the pore size distribution, and the modeling of adsorbed water explicitly considers the capillary condensation effect. Through decoupling of capillarity and adsorption saturation, the influence of void ratio on SWRC mainly acts on the

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First author: LIN Zhi-qiang, male, born in 1995, PhD candidate, mainly engaged in the study of unsaturated soil mechanics. E-mail: 1710727@tongji.edu.cn
Corresponding author: QIAN Jian-gu. male, born in 1972, PhD, Professor, Doctoral supervisor, mainly engaged in soil mechanics research. E-mail: qianjiangu@tongji.edu.cn

capillary water. Based on the improved model, a prediction method of unsaturated soil strength is proposed, and finally, the model is verified using experimental data.

2 Decoupling SWRC model of capillarity and adsorption

The curve form of the bimodal SWRC can be seen as two half-normal distributions, as shown in Fig.1. In order to consider this characteristic, an improved bimodal SWRC formula is proposed to decompose the saturation S_r into the capillary and adsorption sections based on the unimodal model[21−22],

$$S_r = S_r^{cap} + S_r^{ads} \quad (1)$$

where S_r^{cap} and S_r^{ads} represent capillary saturation and adsorption saturation, respectively, as shown in Fig.1.

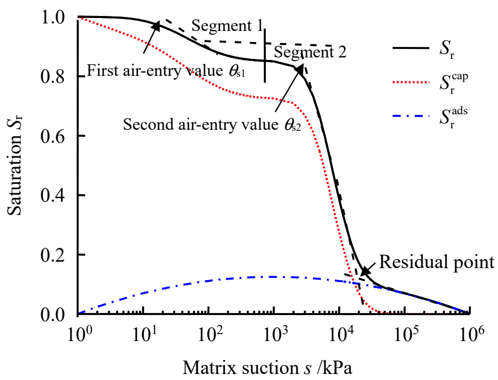

Fig. 1 Bimodal soil-water retention curve

To characterize the two-stage "S" distribution characteristics of the SRWC, the literature[23−24] proposed to model the pore water as two occurrence environments of inter-agglomerates and intra-agglomerates separately. Meanwhile, the model parameters are closely related to the corresponding pore size distribution between inter-agglomerates and intra-agglomerates. In the case of both capillary and adsorption, the capillary water in the pores is related to the pore size distribution[22]:

$$S_r^{cap} = (1-\alpha)A(s) + (\alpha - S_r^{ads})B(s) \quad (2)$$

$$S_r^{ads} = \beta C(s) \quad (3)$$

where s is the matrix suction (kPa); $\alpha = \theta_{S2}/\theta_{S1}$, θ_{S1} is the water content (%) corresponding to the first air-entry value, and θ_{S2} is the water content (%) corresponding to the second air-entry value, as shown in Fig.1; β is a material parameter (dimensionless) that characterizes the changing rate of adsorption saturation in the high suction range; $A(s)$, $B(s)$, and $C(s)$ are all functions of suction, and the parameters corresponding to $A(s)$ and $B(s)$ are related to the pore size distribution characteristics between inter-agglomerates and intra-agglomerates, respectively. Studies have shown that adsorbed water occurs in small pores or intra-agglomerates[25−27]. The first part of the Eq.(2) represents the capillary water content provided by inter-agglomerates, and the second part represents the capillary water content provided by intra-agglomerates, where $(1-\alpha)$ and $(\alpha - S_r^{ads})$ are the capillary saturation when the inter-agglomerates and intra-agglomerates are filled with water, respectively (capillary condensation is not considered at this time).

Based on the unimodal SWRC model of Zhou et al.[22], the function controlling the capillary water is related to the pore size distribution. For the bimodal model, $A(s)$ and $B(s)$ are functions related to the pore size distribution between inter-agglomerates and intra-agglomerates, respectively:

$$A(s) = \left[\frac{1}{2}\operatorname{erfc}\left(\frac{\ln\left(\frac{s}{s_{m1}}\right)}{\sqrt{2}\zeta_1}\right)\right] \quad (4)$$

$$B(s) = \left[\frac{1}{2}\operatorname{erfc}\left(\frac{\ln\left(\frac{s}{s_{m2}}\right)}{\sqrt{2}\zeta_2}\right)\right] \quad (5)$$

where s_m is the suction (kPa) corresponding to the median aperture of the curve, and the subscripts 1 and 2 represent the first and second segments of the curve, respectively; ζ is a dimensionless parameter that characterizes the width of the pore size distribution; erfc( ) is the error function.

In the part of adsorbed water, $C(s)$ characterizes the logarithmic linear reduction of saturation with increasing suction when it is close to the dehydrated state[21−22, 28]:

$$C(s) = \left(1 - \frac{\ln s}{\ln s_d}\right) \quad (6)$$

where s_d is the maximum suction (kPa) when the soil is close to an arid state, $s_d = 10^6$ kPa[12].

However, Eq.(6) cannot describe the "capillary condensation" effect of adsorbed water accurately[29]. As the saturation increases, the thickness of the adsorbed water layer reaches a certain critical value, and a liquid bridge is formed spontaneously between the adsorbed water films of the two particles. At this time, the capillary effect is dominant, and the adsorbed water is transformed into capillary water. Existing studies multiply $C(s)$ and $(1-S_r^{cap})$ to ensure that the adsorption saturation is also 0 when the suction is reduced to 0 kPa. This approach is simple and effective[21−22]. However, the above method couples the adsorbed pore water with the capillary pore water. When the capillary water is subjected to volume deformation, it will inevitably affect the adsorption water. Moreover, experiments indicate that different dry densities or void ratios mainly change large pores' distribution but slightly affect small pores[14−17]. The adsorbed water is mainly in small pores, illustrating that it is not sensitive to the mechanical response. This study proposes an improved formula that considers the "capillary condensation" effect,

$$C(s)=\left(1-\frac{\ln s}{\ln s_{\mathrm{d}}}\right)\left(\frac{\ln s}{\ln s_{\mathrm{d}}}\right) \tag{7}$$

As shown in Fig.1, the adsorbed water in the curve presents a peak value and gradually decreases to 0 with the suction decreases using Eq.(7). More importantly, decoupling of the capillary and adsorption parts could be realized using the equation. This characteristic lays a foundation for reasonably considering the dependence of SWRC on soil volume change, which will be discussed in the next section.

3 SWRC model considering void ratio

In order to realize the capillary hydraulic−mechanical coupling, the influence of each parameter in the model on the S_r−s curve form is analyzed first. Figure 2 shows the effect of different values of α (i.e., 0.70, 0.85, 1.00) on the curve shape under the same values of β, ζ_1, ζ_2, s_{m1}, and s_{m2}. As α increases, the platform segment of the curve moves upward. Actually, α characterizes the difference in water content corresponding to the air-entry value of the large and small pores. With the increase of α, the sizes of the two pores gradually approach, which leads to a smaller transition platform of SWRC, and the curve changes to a unimodal shape.

Figure 3 shows the effect of different ζ (ζ_1 = 0.8, ζ_2 = 0.5; ζ_1 = 1.2, ζ_2 = 0.7; ζ_1 = 1.6, ζ_2 = 0.9) on the S_r−s curve form with the same α, β, s_{m1}, and s_{m2}. As ζ increases, the curve rotates around the inflection point[30]. The larger the ζ, the smaller the air-entry value of SWRC, the larger the residual suction, and the larger the width of the corresponding pore size distribution.

Figure 4 shows the effect of different ζ (s_{m1} = 50 kPa, s_{m2} = 5 000 kPa; s_{m1} = 100 kPa, s_{m2} = 8 000 kPa; s_{m1} = 200 kPa, s_{m2} = 11 000 kPa) on the S_r−s curve form with the same α, β, and ζ. As s_m increases, the low suction section of each curve moves to the right as a whole, while the high suction section remains unchanged. This phenomenon is consistent with the experimental data of soil-water characteristics with different void ratios[4].

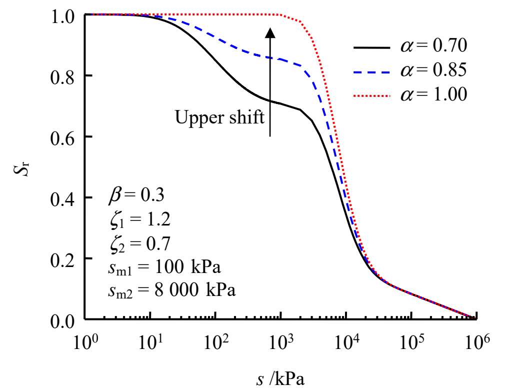

Fig. 2 Effects of α on the shape of SWRC

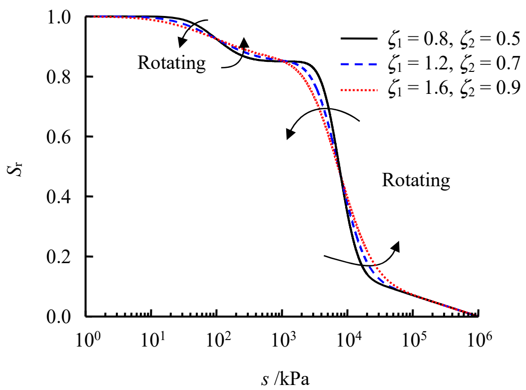

Fig. 3 Effects of ζ on the shape of SWRC

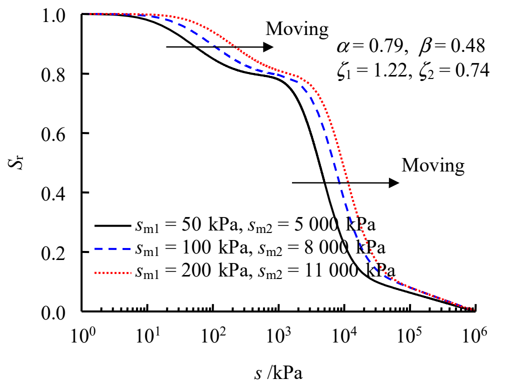

Fig. 4 Effects of s_{m1} and s_{m2} on the shape of SWRC

As can be seen from Figs. 2−4, the above parameters are related to the pore structure of soil and are insensitive to the high suction part of the water retention curve. In the proposed model, the parameters only affect the capillary water part of the low suction part.

Figure 5 shows the effect of different β (i.e., 0.10, 0.30, 0.50) on the S_r−s curve form with the same α, ζ, and s_m. As β increases, the high suction section of the curve moves to the upper right, that is, the saturation becomes higher with the same suction. In fact, β represents the changing rate of adsorption saturation when it is close to the maximum suction. The larger the β, the larger the slope of SWRC.

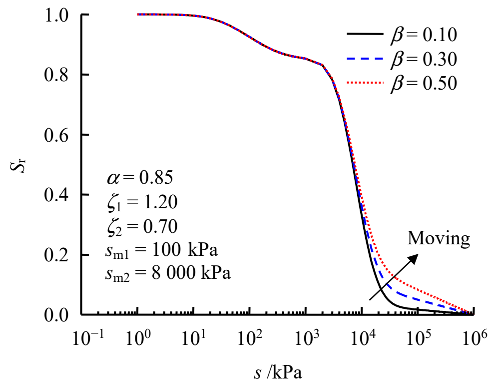

Fig. 5 Effects of β on the shape of SWRC

The law revealed by the above parametric analysis is consistent with the physical meaning it represents. α, ζ, and s_m control the capillary water part, β controls the adsorbed water part, and s_m is the key parameter to realize the capillary hydraulic-mechanical coupling. Actually, s_{m1} is the suction corresponding to the median pore size of segment 1 in the curve, and s_{m2} is the suction corresponding to the median pore size of segment 2 in the curve. The median pore size changes with the change of the void ratio, and therefore the focus is the influence of the void ratio on s_m. Based on the practices of Gallipoli et al.[7] and Gao et al.[8−9], e^k is introduced to modify s_{m1} and s_{m2} to consider the influence of different void ratios on SWRC:

$$s_{m1} = \frac{s_{m1}^0}{e^k} \tag{8}$$

$$s_{m2} = \frac{s_{m2}^0}{e^k} \tag{9}$$

where s_m^0 is the reference suction value when the void ratio $e = 1$; k is the material parameter; and the subscripts 1 and 2 represent the first and second segments of curve.

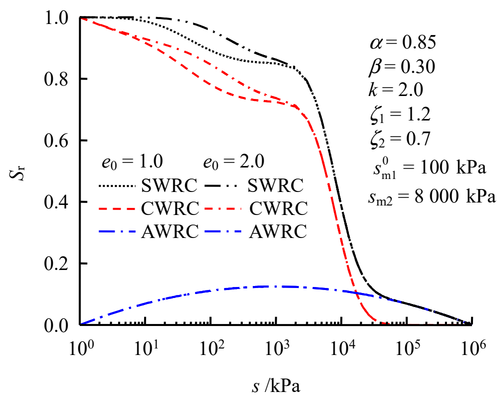

Fig. 6 Effects of void ratio on the shape of SWRC for fined-grained soil with dual-porosity

For fine-grained soils with dual-pore structure[20], the formation of two peak values is related to the dual-pore structure (the pores in the inter-agglomerates or intra-agglomerates). The pores in the intra-agglomerates are slightly affected by the void ratio, and e^k only affects s_{m1}, as shown in Fig.6. For coarse particle mixtures, the pore sizes corresponding to the two peak values are both larger, and e^k can affect s_{m1} and s_{m2}, as shown in Fig.7. From Figs. 6 and 7, different initial void ratios only change the capillary saturation but do not affect the adsorption saturation. The improved model reasonably considers the dependence of SWRC on the soil void ratio.

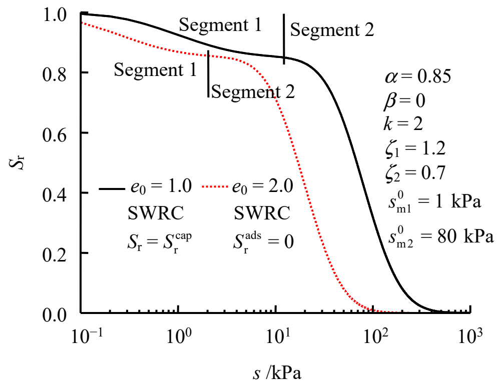

Fig. 7 Effects of void ratio on the shape of SWRC for coarse mixtures

From Eqs. (1)−(3) and (7)−(9), the SWRC curve, capillary-water retention curve (CWRC), and adsorption-water retention curve (AWRC) can be obtained.

$$\left.\begin{aligned} &\text{SWRC}: S_r = (1-\alpha)A(s) + \alpha B(s) + \beta C(s)[1 - B(s)] \\ &\text{CWRC}: S_r^{cap} = (1-\alpha)A(s) + [\alpha - \beta C(s)]B(s) \\ &\text{AWRC}: S_r^{ads} = \beta C(s) \end{aligned}\right\} \tag{10}$$

When α = 1, the model is degenerated into a unimodal mode.

4 Model verification

To verify the validity of the model, water retention data of soil with different unimodal/bimodal characteristics are selected from the existing references. Vanapalli et al.[5, 31] conducted soil-water characteristics tests on silty clay under different vertical pressures, and the corresponding void ratios for vertical pressures of 25, 100, and 200 kPa were 0.59, 0.50, and 0.44, respectively. Lee et al.[32] conducted a soil-water characteristic test on silt. The void ratios of 0.56, 0.51, 0.48, and 0.45 correspond to vertical pressures of 0, 100, 200, and 300 kPa, respectively. The improved unimodal SWRC model was used to simulate the test results, as shown in Figs. 8 and 9.

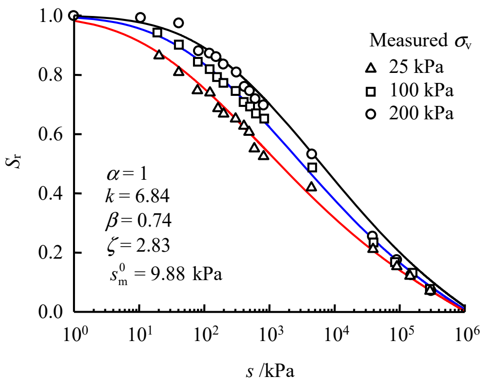

Fig. 8 SWRCs of silty clay under different stresses

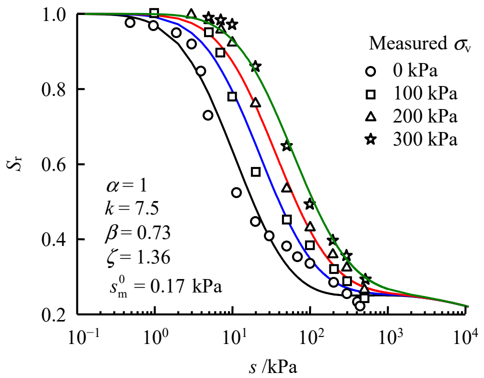

Fig. 9 SWRCs of silt under different stresses

The SWRCs of silty clay and silt in Figs. 8 and 9 show unimodal characteristics. Using the soil-water test results of silty clay under a vertical stress σ_v of 25 kPa (initial void ratio of 0.59) calibrates the parameters to obtain $\beta = 0.74$, $\zeta = 2.83$, $s_m^0 = 9.88$ kPa, and $k = 6.84$. As the curve is a unimodal shape, $\alpha = 1$. Soil-water test results are used as calibration parameters when the vertical pressure of silty soil is 0 (initial void ratio of 0.56). Similarly, $\beta = 0.73$, $\zeta = 1.36$, $s_m^0 = 0.17$ kPa, and $k = 7.5$ are obtained.

The calibrated parameters are used to simulate the SWRC under other vertical stresses, and the results show that the improved model is suitable for simulating the water retention response of the unimodal fine-grained soil. In addition, with only one set of parameters ($\alpha = 1$), the dependence of SWRC on soil void ratio has also been reasonably described.

Cai et al.[33] used axis translation technique, filter paper method, and salt solution vapor equilibrium method to measure the water retention capacity of three different suction sections of Guilin lateritic clay. They pointed out that the dual-pore structure of the Guilin lateritic clay compacted sample results in the bimodal character of the water retention curve.

Figure 10 shows that the pore size distribution for the inter-agglomerates is significantly affected by volume change and void ratio for fine-grained soils with aggregate structure, which is reflected in the low suction section for different initial void ratios with different water retention curves. On the contrary, the pore size distribution for intra-agglomerates is less affected by the void ratio, and the water retention curves under different void ratios in the high suction section almost overlap. The model can accurately simulate the bimodal water retention characteristics of fine-grained soils with different void ratios.

Li et al.[34–35] conducted a series of coarse-grained mixtures (SM gravel, GW-GM sand) on soil-water characteristics under low suction using axis translation technique. Due to the different particle sizes of the mixture, SWRCs present bimodal characteristics, as shown in Figs. 11 and 12. Meanwhile, the coarse-grained soil hardly contains adsorbed water, and the capillary saturation is equal to the total saturation, $\beta = 0$. Comparative analysis shows that the improved model can better simulate the bimodal characteristics of the water retention curve of coarse-grained soil.

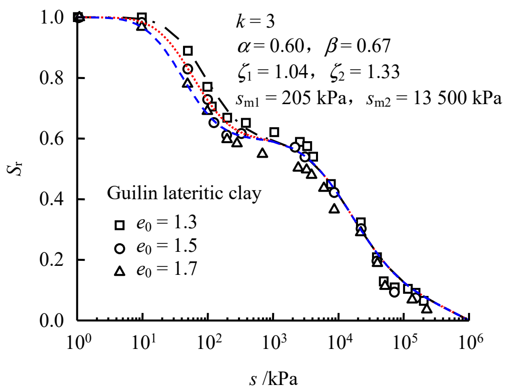

Fig. 10 SWRCs of Guilin lateritic clay[33] with different void ratios

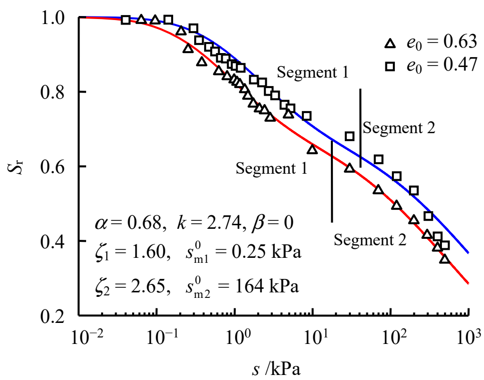

Fig. 11 SWRCs of SM-gravel[34] with different void ratios

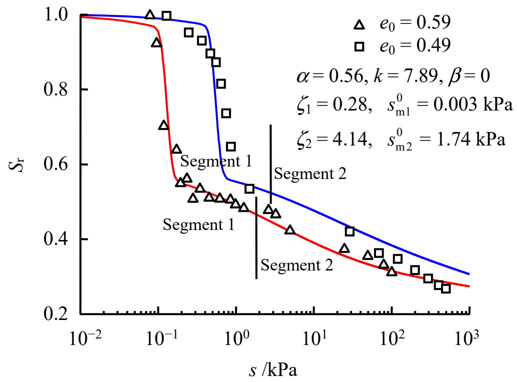

Fig. 12 SWRCs of GW-GM with sand[35] with different void ratios

5 Strength prediction equation based on improved SWRC

An important application of SWRC is to predict the engineering properties of unsaturated soils. In order to reflect the application value of the improved model, this section proposes a method based on the improved SWRC model to predict the strength of unsaturated soils with different initial void ratios.

Bishop[36] proposed the most classic unsaturated soil effective stress σ'_{ij} equation:

$$\sigma'_{ij} = \sigma_{ij} - u_a\delta_{ij} + S_r s\delta_{ij} \quad (11)$$

where σ_{ij} is the total stress tensor; u_a is the pore air pressure; and δ_{ij} is the Kronecker symbol.

For shear failure along a given failure plane, the ultimate shear stress can be estimated by combining the above effective stress and the classic Mohr-Coulomb criterion:

$$\tau = (\sigma_n - u_a + S_r s)\tan\varphi' + c' \quad (12)$$

where σ_n and τ are the total normal stress and shear stress acting on the shear surface, respectively; c' and φ' are the effective cohesion and the effective internal friction angle, respectively.

This approach overestimates the suction effect and ignores the existence of adsorption suction[12, 22, 37], resulting in the predicted strength often greater than the actual strength, especially for fine-grained soils under low saturation condition. Actually, only capillary action has the main influence on soil strength[22, 38–39]. They are replacing the total saturation S_r with the capillary saturation S_r^{cap} to distinguish the effects of two different effects:

$$\tau = (\sigma_n - u_a + S_r^{cap} s)\tan\varphi' + c' \quad (13)$$

Substituting the modified SWRC model considering the void ratio into Eq.(13), the strength prediction result considering the influence of the void ratio can be obtained.

Vanapalli et al.[5, 31] conducted direct shear tests on silty clay in different dry and wet conditions. Figure 13 shows the prediction results of the water retention curve of silty clay with different initial void ratios. The selected model parameters are from the calibration results of Fig.8. Figure 13 indicates that the part of adsorbed water is not affected by the void ratio.

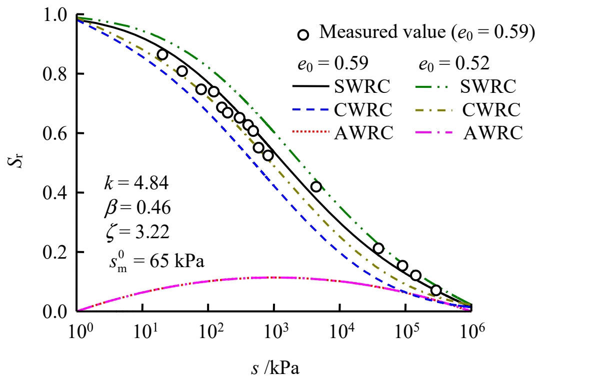

Fig. 13 SWRC, CWRC and AWRC of silty clay with different void ratios

Figure 14 shows the comparison of the shear strength and the predicted value of the silty clay when the initial void ratio is 0.59. The total saturation and capillary saturation are used to predict. Figure 14 indicates that the prediction result using capillary saturation S_r^{cap} is better than the result using total saturation S_r that over-estimates the actual strength of the soil.

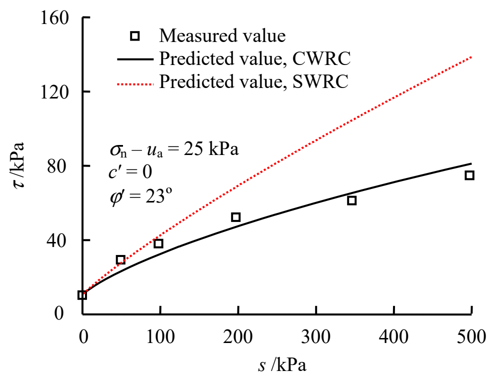

Fig. 14 Comparison between the measured and predicted strength of silty clay (e_0 = 0.59)

Figure 15 shows the shear strength from direct shear tests and prediction results of silty clay with different initial void ratios. In addition to the distinction between capillary water and adsorbed water, these comparisons also indicate that it is necessary to consider the capillary hydraulic–mechanical coupling effect in the SWRC model to accurately estimate the shear strength of unsaturated soils under different degrees of compaction.

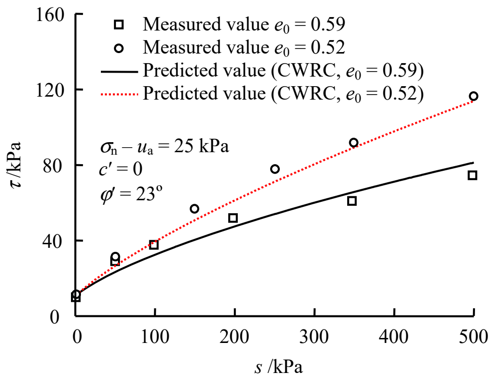

Fig. 15 Comparison between the measured and predicted strength of silty clay with different void ratios

6 Conclusions

This paper proposes an improved SWRC model. Compared with the existing model, the improved model takes into account the dual-pore structure, that is, the influence of the two-segment distribution of the curve on the water retention characteristics of capillary water. It is suitable for the simulation of the shape of unimodal or bimodal curves. Meanwhile, it clearly distinguishes the different effects of the void ratio on capillarity and adsorption.

Considering the different water retention mechanisms of capillarity and adsorption effects, the improved model decomposes saturation into the capillarity and adsorption parts. The capillary water retention characteristics are described with a function related to the pore size distribution. The adsorbed water part explicitly considers the capillary condensation effect and realizes the decoupling of capillary and adsorption saturation. The latter lays the foundation for proposing SWRC that considers the influence of the void ratio, that is, the change of the void ratio only changes the structure of the macro-pores and then only affects the water retention behavior of the capillarity part.

The proposed SWRC model is validated with experimental data. The results show that the model can reasonably describe the water retention behavior of SWRC soils with unimodal or bimodal shapes for different void ratios and the capillary hydraulic–mechanical coupling characteristics. Based on the improved SWRC model, a method of using capillary saturation to predict the strength of unsaturated soil is proposed. The comparison with the test results presents that the proposed strength equation can better describe the suction enhancement behavior of unsaturated soils with different void ratios.

For fine-grained soils with bimodal SWRC, the soil-water characteristics and shear strength for different void ratios are studied. After relevant tests are carried out in the future, the method in this paper can be further applied.

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