A state dependent constitutive model for unsaturated soil-steel interfaces considering bonding effect

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Abstract. The frictional behaviours between unsaturated soils and structure are controlled mainly by the complex phenomena that develop within a thin soil layer close to the contact area. The constitutive model for soil-structure interfaces (SSI) must be established to predict the performance of related soil-structure systems accurately. Multi-stage suction-controlled ring shear (RS) tests with three different upper annular platens were carried out on an equal number of statically compacted samples of Shanghai clay under controlled suction states for a given net normal stress. A state dependent constitutive model for unsaturated soil-structure interfaces based on critical state concept considering bonding effect was proposed. In all stress conditions, the tested and predicted results for smooth interface and rough interface are well matched.

1 Introduction

The frictional behaviours between unsaturated soils and structure are controlled mainly by the complex phenomena that develop within a thin soil layer close to the contact area [1]. Once the localized thin zone of failure has developed, then constitutive models of soil mass behaviour cannot meet the requirements, the constitutive model for soil-structure interfaces (SSI) must be established to predict the performance of related soil-structure systems accurately.

Summarizing the latest experimental results of unsaturated soil-continuum interfaces (e.g., [1-5]), one can find some new characteristics for unsaturated soil interfaces. As suction increased for a given net normal stress, maximum shear stress increased (but was always less than soil mass strength), residual shear stress was generally unchanged, strain softening behavior became significant and the amount of dilatancy increased. In addition, Khoury and Miller (2012) concluded that hydraulic hysteresis can significantly influence the mechanical response of soil-structure interfaces (e.g., shear strength of after drying-wetting path was greater than that after only drying path). Three examples of features of behavior that require adequate modelling for a typical unsaturated interfacial constitutive model are: (a) the nonlinear influence of matric suction on critical shear stress (i.e., residual strength) of interfaces; (b) the mechanical response of unsaturated soil interfaces in stress-controlled and suction-controlled shearing conditions; and (c) the irreversible volume behavior induced by the evolution of soil fabric involving inter-particle or particle-structure capillary bonding.

2 Suction-controlled ring shear tests on unsaturated soil-steel interfaces

2.1 Testing apparatus

Figure 1 shows a schematic diagram of the suction-controlled ring shear test (RST) device that are used for testing the residual strength and large deformation behaviours of an unsaturated soil-structure interface. The RST device consists of (1) main cell with rotational shear system; (2) data acquisition and process control (DA/PC) system; and (3) PCP-15U suction control panel based on the axis-translation technique.

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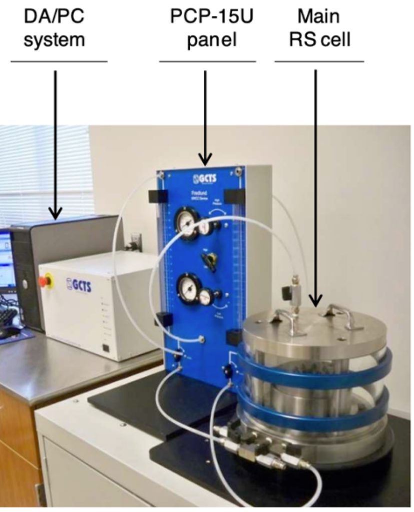


Fig. 1. Schematic diagram of the suction-controlled ring shear apparatus [6]

Three kinds of upper annular platen were applied to interstage the behaviours of unsaturated soils and interface (see Fig. 2). All the platens have an outer diameter of 152.4mm and an internal diameter of 96.5 mm, which are the same dimensions of the specimen surface. Note that the upper annular platen with a single, sintered rough surfaced bronze stone (shown in Fig. 2 (a)) can induce the 3mm failure surface so that the platen can be used to study the behaviours of soils, while other two (see Fig. 2b and 2c) were used to study the behaviours of interface with different roughness.

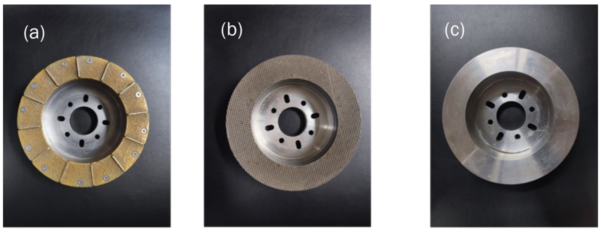


Fig. 2. Three kinds of upper annular platen: (a) upper annular platen with a single, sintered rough-surfaced bronze stone; (b) rough upper annular platen; (c) smooth upper annular platen.

2.2 Test materials

The soil samples used for the test are located in Block 58-01, Zhangjiang Central District, Pudong New Area [north to Haike Road (planned width 24m) and Chuanyang River, south to Zhongke Road (planned width 32m), west to Zhuowen Road (planned width 24m)), east to Sunjiazhai River (planned river course) and Yuren Road (planned width 16m)]. The depth of the soil sample is about 20 meters in the fifth layer of Shanghai soft soil, containing mica and organic matter, partially interbedded with thin layers of silts and powdery lumps, etc., and belong to the typical gray clay. The basic properties of the tested Shanghai grey clay are shown in the Table 1.

Table 1. Basic properties of the tested Shanghai Grey clay

Parameter	Unit	Value
Specific gravity, G_s	-	2.74
Saturated density of gravity, γ_{sat}	kN/m^3	17.2-17.8
Liquid limit, w_L	%	43.6
Plastic limit, w_p	%	24
Plasticity index, I_P	%	19.5
Initial water content, w_0	%	38.6-46.2
Initial void ratio, e_0	-	1.087-1.297
Permeability, k_{20}	m/s	2.33E-07

Figure 2 showed the soil water characteristic curves (SWCC) with different initial void ratios, which depicts the relationship between the gravimetric water content and matrix suction. The SWCC tests in this study were carried out via the WP4C from Tongji university.

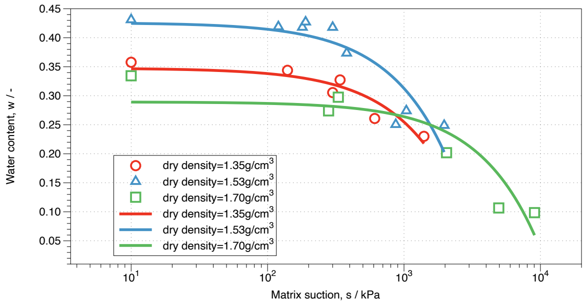


Fig. 3. Soil water characteristic curves (SWCC) of the remoulded Shanghai grey clay with different initial void ratios.

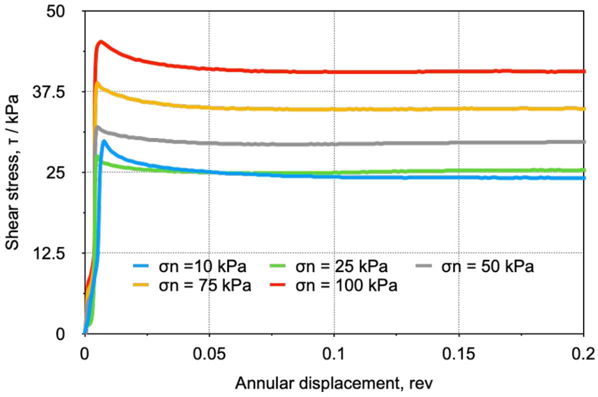
2.3 Sample preparation and test procedure

After the soil samples were taken, they shall be dried by natural air and crushed, and then passed through a 2mm sieve, and then mixed with water to a certain initial moisture content, and then the sample with specific initial dry density and void ratio shall be obtained by compaction. The ring-shaped specimens confined in the lower annular platen are compacted to specific height by static compaction method. To reduce the friction between the ring wall and the specimen, internal surface of the lower annular platen was lubricated. And place the wet filter papers on top of each ceramic disk to ensure continuity between the pore-water in the sample and water in the ceramic disks.

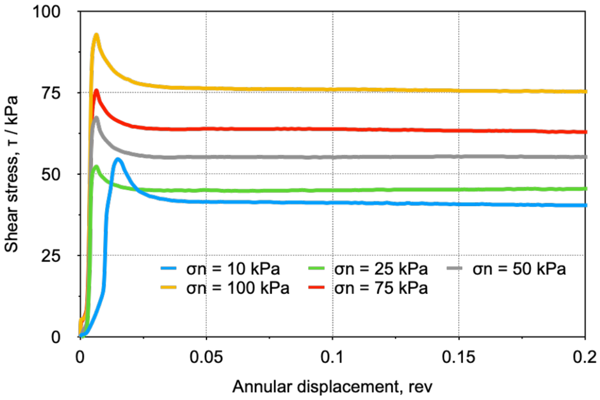
When assembling completely the RS device, all the drainage lines are filled with deaired water to flush the whole system. And then, setting the flushing and volume water indicator of the suction control panel to an appropriate position. A sitting load was applied to ensure the contact between the upper annular platen and the sample. Then, an initial normal stress σ_n 10 kPa greater than the corresponding matrix suction value were attained by applying monotonical loading. The soil should be consolidated at least 24 hours under this condition and then increasing the pore-air pressure by compressed air in the main cell. When the process of suction equalization finished (it may take about 120 h to 168 h), the net normal stress (σ_n-u_a) of 10 kPa can be obtained. Finally, after consolidation and suction equalization, the 6 multi-stage suction-controlled RS tests with three different upper annular platens were carried out on an equal number of statically compacted samples of Shanghai clay under controlled suction states, s= 50 and 100 kPa and for net normal stress, σ_n-u_a = 10, 25, 50, 75 and 100 kPa. During this process, the shearing rate remained at 0.0087 rev/min.

3 Test results and discussion

(a) Smooth interface, s=50 kPa



(b) Rough interface, s=50 kPa



(c) Soil, s=50 kPa

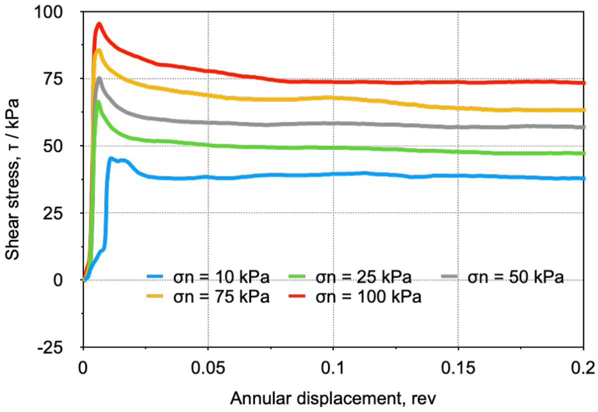
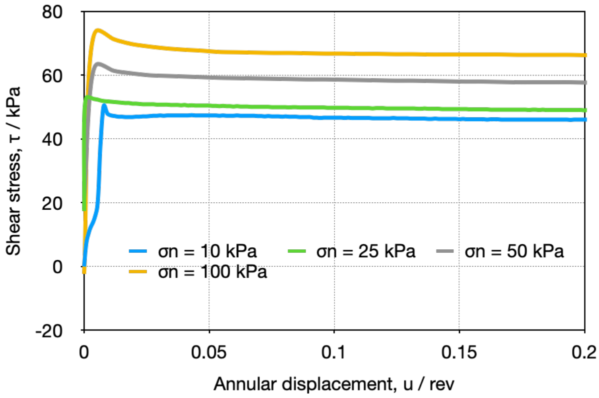
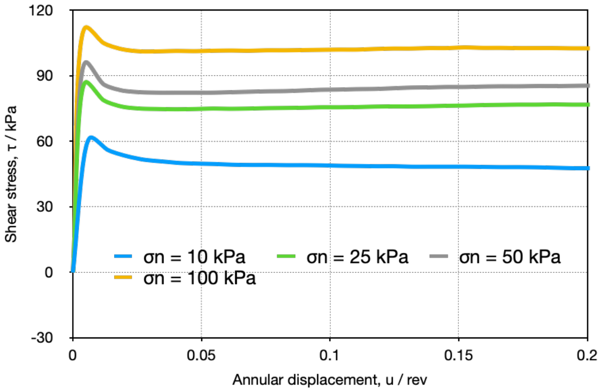


Fig. 4 Relationship between shear stress and annular displacement at suction = 50 kPa: (a) smooth interface ;(b) rough interface and (c) Soil

(a) Smooth interface, s=100 kPa



(b) Rough interface, s=100 kPa



(c) Soil, s=100 kPa

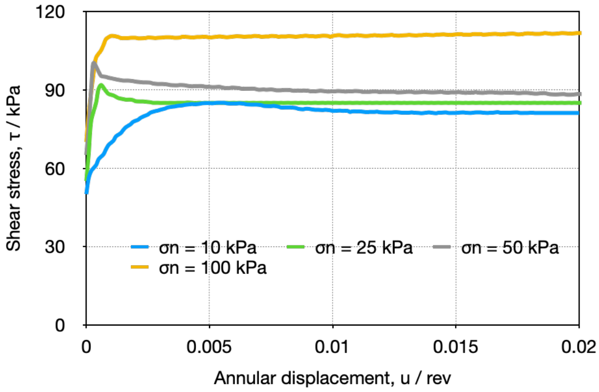


Fig. 5 Relationship between shear stress and annular displacement at suction = 100 kPa : (a) smooth interface ;(b) rough interface and (c) Soil

Figure 4 and Figure 5 show the shear stress-annular displacement at suction = 50kPa and 100kPa, respectively. Results showed that at a low stress level, the residual strength of the soil is the highest while the residual strength of the smooth interface is the lowest. With the increase of the stress level, the strength of the rough interface gradually approaches the strength of the soil and tends to exceed the strength of the soil. It is interesting that the stress- and suction-dependent interface friction angles are higher than that of clays only, which can be explained by the fact that clay asperities face higher interlocking forces when sheared against rough steel asperities. Besides, from Fig. 6, the the effect of suction on peak shear strength of the soil-structure interface was nonlinear while on the post-strength was not negligible either.

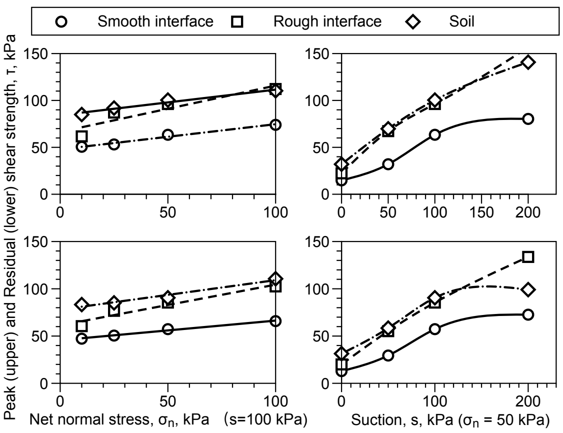


Fig. 6 Stress- and suction- dependent failure envelope

4 Constitutive model

4.1 Constitutive model for unsaturated interfaces

The effective normal stress σ_n' is expressed by:

$$\sigma_n' = \sigma_n + S_e s \tag{1}$$

where σ_n is net normal stress, equal to $\sigma_n^{total} - u_a$; σ_n^{total} is total normal stress and u_a is the pore air pressure; s is the matric suction, equal to $u_a - u_w$, and u_w is the pore water pressure; S_e is the effective degree of saturation, which is defined as:

$$S_e = \frac{S_r - S_r^{res}}{S_r^0 - S_r^{res}} \tag{2}$$

where S_r^{res} the residual degree of saturation and S_r^0 is the degree of saturation at zero suction.

Define the state parameter by the ratio between the current void ratio, e, of unsaturated soils and the critical void ratio, e_{cs}, at same mean effective stress as follows:

$$\psi = \frac{e}{e_{cs}} \tag{3}$$

where

$$e_{cs} = h(\xi)\left[\Gamma - \lambda \ln\left(\frac{\sigma_n'}{p_{\text{ref}}}\right)\right] \tag{4a}$$

$$h(\xi) = 1 + a \cdot \left[\frac{1 - S_e^{\frac{1}{4}}}{0.45e}\right]^b \tag{4b}$$

In every Eq. (4b), the effective degree of saturation S_e can be obtained by a void-ratio-dependent soil water characteristic curve (SWCC) [7]:

$$S_e(s, e) = \left[1 + \{\beta \exp(k_p e)\ s\}^n\right]^{-m} \tag{5}$$

where β, k_p, m and n are SWCC parameters.

For extremely small strains (less than 10^{-6}), interface behavior is predominantly elastic. An incremental constitutive equation is

$$\mathrm{d}\boldsymbol{\sigma}' = \boldsymbol{D}^{e}\mathrm{d}\boldsymbol{\varepsilon}^{e} \tag{6}$$

where $\boldsymbol{D}^e$ is a second-order elastic constitutive matrix.

$$\boldsymbol{D}^{e} = \begin{bmatrix} D_t^e T & 0 \\ 0 & D_{t0}\dfrac{1+e}{e}\left[\left(\dfrac{\sigma_n'}{p_{\text{ref}}}\right)^2 + R\left(\dfrac{\tau}{p_{\text{ref}}}\right)^2\right]^{0.5} \end{bmatrix} \tag{7}$$

where D_{t0} and T are two dimensionless elastic parameters decided by the inherent property of the interface.

As shown in Fig. 7, the yield surface of the proposed interface model is formulated in the plane of effective normal stress (σ_n') and shear stress (τ) to describes the plastic deformation caused by a change of stress ratio, and takes the following form:

$$f = \tau - \eta\sigma_n' = 0 \tag{8}$$

where η, the yield stress ratio, is a hardening parameter, which indicates the yield function opening.

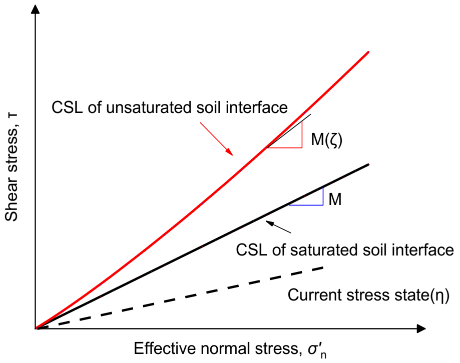


Fig. 7 Yield surface in the $\boldsymbol{\sigma_n'} - \boldsymbol{\tau}$ plane

The hardening relationship linking change in stress ratio with state parameter and bonding variable, assumes that the unsaturated soils within the contact zone are constantly endeavoring to reach the stress ratio $\eta = M$, which can be attained at infinite strain.

$$K_p = h_0 D_t^e\left[\frac{M}{\eta}\psi^{-n^b} - 1\right] \tag{9}$$

And a state-dependent flow rule is adopted

$$d = A\left(\psi^{n^d} - \frac{\eta}{M}\right) \tag{10}$$

where n^d is a parameter related to phase transformation and A is the dilatancy coefficient

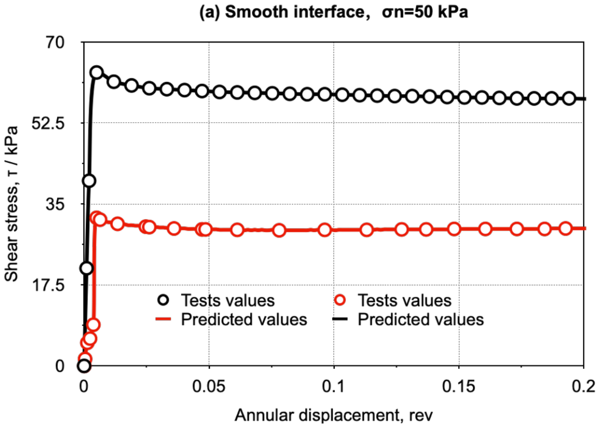
4.2 Application of the constitutive model to the unsaturated soil-steel interface test results

Figure 8 showed the tested and predicted shear behaviour at a given net stress of 50 kPa with different suction of 50 and 100 kPa. In all stress conditions, the tested and predicted results for smooth interface and rough interface are well matched. This implies that the model is able to well capture the influence of net stress on the interface shear behaviour. It can be seen from the tested results that when suction increases from 50 to 100 kPa, the peak shear strength increases whereas the increase in the critical state shear strength is much smaller. Not that the generalization into complete tensorial space is ambiguous since the results are from ring shear.

The presence of meniscus water explains why the value of void ratio during virgin loading of unsaturated soil is always greater than that under saturated conditions for the same soil at the same effective stress. And their ratio e/e_s is a unique function of the bonding variable, ξ, which is the basis on which the presented model applies. That is, the proposed model is not conceptually applicable to dry soils. The experimental validation would require further experimental data from the suction-controlled shear test programme conducted on unsaturated Shanghai clay interface. However, the extension to the case of unsaturated clay should not present any conceptual difficulty due to the proposal of the unified state parameter.

Table 4 Required parameters for simulation of the behavior of unsaturated Shanghai- steel interfaces

Parameters	Smooth interface	Rough interface
D_{t0}	0.64	0.64
T	1.34	1.54
M	0.83	1.21
Γ	0.114	0.122
λ	1.21	1.05
a	5.23	5.23
b	1.34	1.34
A_0	0.2	0.2
A_1	0.24	0.12
n^d	3.45	1.65
h_0	1.2	1.4
n^b	0.02	0.02
m	1.978	1.978
k_p	2.67	2.67
β	1.40E-4	1.40E-4



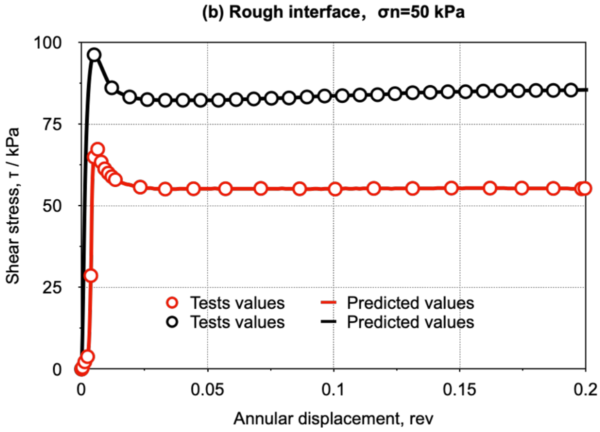


Fig. 8 A comparison of tests results with model predictions for unsaturated interface at a net normal stress of 50 kPa: (a) smooth interface; and (b) rough interface

5 Conclusions

The effect of suction on peak shear strength of the soil-structure interface was nonlinear while on the post-strength was not negligible. With the increase of the stress level, the strength of the rough interface gradually approaches the strength of the soil and tends to exceed the strength of the soil. The effect of roughness on the shear behaviours of unsaturated soil interface is significant. A state dependent constitutive model for unsaturated soil-structure interfaces based on critical state concept considering bonding effect was proposed. In all stress conditions, the tested and predicted results for smooth interface and rough interface are well matched.

6 Acknowledgements

Authors are thankful to Prof. Nasser Khalili of University of New South for his instructive discussions. The authors are also grateful for the support provided by the National Natural Science Foundation of China (Grant 42272310 and 41972274) for this research work.

7 Reference

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