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Modelling the water retention behaviour of anisotropic soils

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Abstract

Water retention curve (WRC) is an important parameter for unsaturated soils. It is greatly affected by the anisotropy of pore structure, as supported by experimental results in the literature. So far, however, the mechanism and theoretical modelling of anisotropy effects have not been investigated. These two issues were explored in this study based on two-dimensional analysis. Soil pores were approximated as a series of ellipses for simplicity. According to experimental results in the literature, the pores of anisotropic specimen are more elongated than those of isotropic specimen on average. The elongated pore has a higher water retention ability than the round pore when they have the same area. As a consequence, the water retention ability of anisotropic specimen is higher than that of isotropic specimen. On the basis of this mechanism, a new WRC model was proposed for isotropic and anisotropic soils by considering the influence of pore shape. To verify the new model, it was applied to simulate the WRCs of three soils with isotropic and anisotropic pore structures. Measured and calculated results were well matched with the coefficient of determination (R^2) in the range of 0.89 to 0.99 and the root-mean-square error (RMSE) ranging from 0.009 to 0.073. It is convincingly demonstrated that the new model is able to capture the influence of anisotropy on WRC.

Key words

Unsaturated soil; water retention; anisotropy; pore shape

1. Introduction

Soil properties are often anisotropic (i.e. direction-dependent) for different reasons such as geological deposition and anisotropic stress history. The influence of anisotropy on the stiffness, strength and permeability has been extensively investigated by previous researchers. In the literature, however, there are limited studies of anisotropy effects on the water retention curve (WRC). This curve is an important hydrological parameter for seepage analysis used in the agricultural, hydrological, environmental and geotechnical areas related to the vadose zone (Lamorski et al., 2017; Ng and Pang, 2000; Sakai et al., 2015; Tan et al., 2016; Walczak et al., 2006; Zhou et al., 2020; Ng et al., 2020). Sivakumar et al. (2010) prepared two types of specimens with the same density through isotropic and anisotropic compression. At a given suction, the anisotropic specimen has a higher degree of saturation than the isotropic one. Tse (2007) investigated the influence of stress-induced anisotropy on the water retention behaviour of a completely decomposed granite. Three specimens were prepared using the same method and then controlled to the same mean net stress (i.e. the difference between total stress and pore air pressure) but different stress ratios (i.e. the ratio of deviator stress and mean net stress). For both intact and compacted specimens, the equilibrium degree of saturation at a given suction at a larger stress ratio is higher than that at a lower stress ratio. Similar observation was reported by Habasimbi and Nishimura (2018) through a series of tests on unsaturated clay. The above results consistently suggest that anisotropy would alter the water retention curve of unsaturated soils. Up to now, however, there is no theoretical investigation on the WRC of anisotropic soils. Further studies are required to understand the mechanism of anisotropy effects and to model

WRC of anisotropic soils.

In this study, a new water retention model for anisotropic soils was developed. The influence of anisotropy on the pore shape and hence the WRC was incorporated. The model was verified using experimental results reported in the literature.

2. Mathematical formulations

2.1. Influence of anisotropy on the pore shape and water retention curve

WRC of unsaturated soils is mainly governed by its pore characteristics, such as the pore orientation, pore shape, pore size distribution and pore connectivity. Among these four factors, the first two are directly affected by soil anisotropy. The pore orientation does not affect the WRC, which is a scalar variable, as confirmed by the experimental results of Priono et al. (2017). Hence, the present study focuses on the influence of pore shape on the basis of two-dimensional analysis for simplicity. Soil pores are approximated as a series of ellipses, based on the results of experimental studies and discrete element method (DEM) simulations in the literature (Chow et al., 2019; Gao et al., 2020; Kang et al., 2014). For each ellipse, two parameters are required to describe the area and shape independently. The area is denoted by A (unit: cm^2), while the shape is characterized by the elongation ratio (E) (unit: cm cm^{-1}) defined as follows (Chow et al., 2019):

$$\mathrm{E} = \frac{L_{min}}{L_{maj}} \tag{1}$$

where L_{min} and L_{maj} are the lengths (unit: cm) of the minor and major principal axis, respectively. According to this definition, E falls in the range of 0 to 1. When E approaches 0, the pore is very elongated. When E is equal to 1, the pore becomes perfectly round. By using these two independent variables (i.e. A and E), $L_{\min}$ and L_{maj} can be determined:

$$L_{min} = E^{0.5}(A/\pi)^{0.5} \tag{2}$$

$$L_{maj} = E^{-0.5}(A/\pi)^{0.5} \tag{3}$$

The value of $L_{\min}$ and L_{maj} would affect the water retention curve of this pore. There is a critical value of suction s_{cri} (unit: kPa), below which the pore is fully saturated and above which the pore is not able to retain water. The value of s_{cri} is calculated using the following equation (Ng and Menzies, 2007):

$$s_{cri} = \frac{2T_s}{L_{min}} + \frac{2T_s}{L_{maj}} \tag{4}$$

where T_s is the surface tension coefficient (unit: mN cm^{-1}) of air-water interfaces. Substituting equations (2) and (3) into (4),

$$s_{cri} = \frac{2T_s}{(A/\pi)^{0.5}}(E^{0.5} + E^{-0.5}) \tag{5}$$

According to equation (5), s_{cri} of a pore is governed by not only its area but also its elongation ratio. At a given area, s_{cri} is larger when the pore is more elongated (i.e. a smaller E). Recently, Gao et al. (2020) investigated the characteristic of pore shape of a clay through quantitative Scanning Electron Microscopy (SEM) analysis. They found that E of most pores falls in a small range with a dominant value at each state. This dominant value is used here to characterize the pore shape of a soil specimen. This simplification could keep the formulations simple and minimize the number of model parameters. The dominant values of E under isotropic and anisotropic states are denoted by E_{iso} and E_{ani}, respectively. Hence, the values of s_{cri} at isotropic state (s_{cri}^{iso}) and anisotropic state (s_{cri}^{ani}) can be calculated using equation (5):

$$s_{cri}^{iso} = \frac{2T_s}{(A/\pi)^{0.5}}\left({E_{iso}}^{0.5} + {E_{iso}}^{-0.5}\right) \tag{6}$$

$$s_{cri}^{ani} = \frac{2T_s}{(A/\pi)^{0.5}}\left({E_{ani}}^{0.5} + {E_{ani}}^{-0.5}\right) \tag{7}$$

To investigate the influence of anisotropy, isotropic state can be considered as a reference. The value of s_{cri}^{ani} is normalized by s_{cri}^{iso} and defined as β. By assuming that soil anisotropy does not alter A, equations (6) and (7) suggest that

$$\beta = \frac{{E_{ani}}^{0.5}+{E_{ani}}^{-0.5}}{{E_{iso}}^{0.5}+{E_{iso}}^{-0.5}} \tag{8}$$

Equation (8) suggests that β is governed by E at isotropic and anisotropic states. Some researchers investigated the influence of anisotropy on E of porous materials. Oda et al. (1985) carried out a series of biaxial compression tests on photoelastic disks. They found that the pores became more elongated during the shearing process (i.e. a reduction of E due to the stress-induced anisotropy). Chow et al. (2019) studied the pore structure of kaolin clay under one-dimensional compression. They found that soil pores became more elongated during the anisotropic one-dimensional compression. Similar observations were reported by Gao et al. (2020) through a series of triaxial compression tests on clay. The above results consistently imply that the anisotropic specimen would have a smaller dominant E and hence a higher equilibrium water content at a given suction than the isotropic one.

2.2. Modelling the water retention behaviour of anisotropic soils

Many water retention models have been reported in the literature and most of them are able to capture the WRCs of isotropic soils. This note uses the model of van Genuchten (1980) as an example:

$$S_r = \left(1 + \left(\frac{s}{m_3}\right)^{m_2}\right)^{-m_1} \tag{9}$$

where S_r is the degree of saturation [-]; s is the suction (unit: kPa); m_1, m_2 and m_3 are soil parameters. Parameters m_1 and m_2 are dimensionless and m_3 has a unit of kPa. When an isotropic specimen becomes anisotropic, its pores would become more elongated (i.e. a smaller E), as discussed above. The scaling factor β in equation (8) can be applied to describe anisotropy effects on the s_{cri} of all pores. Then, equation (9) is revised as follows:

$$S_r = \left(1 + \left(\frac{s}{m_{3-\text{iso}}}\frac{1}{\beta}\right)^{m_2}\right)^{-m_1} \tag{10}$$

Equation (10) is the newly derived WRC model for unsaturated soils. Compared with equation (9), the new model is applicable for both isotropic and anisotropic soils. There are four model parameters (i.e. m_1, m_2, $m_{3\text{-iso}}$ and β) in the new model. Note that parameter β represents anisotropic effects on the pore shape and water retention curve through equations (8) and (10), respectively. It takes the same value in these two equations, because equation (10) is derived based on equations (8) and (9). The value is equal to 1 for isotropic soils and larger than 1 for anisotropic soils. In addition, parameters m_1, m_2 and $m_{3\text{-iso}}$ are assumed to be independent of soil anisotropy. WRCs at both isotropic and anisotropic states are required to calibrate these two parameters. In this study, the calibration is conducted using MATLAB with two steps. First of all, equation (10) is applied to fit a WRC of isotropic specimen. The values of parameters m_1, m_2 and $m_{3\text{-iso}}$ are determined when the coefficient of determination (R^2) is the highest. After that, the equation is applied to fit a WRC of anisotropic specimen to calibrate parameter β."

3. Model verification

To evaluate capability of the new model, it was applied to simulate the WRCs of three soils tested by some previous researchers. These soils and their values of model parameters are summarized in Table I.

Sivakumar et al. (2010) investigated the water retention behaviour of kaolin clay. Two different methods were used to prepare soil specimens, including isotropic compaction and anisotropic one-dimensional compaction. By using each method, a slightly compacted specimen (void ratio = 1.19) and a heavily compacted specimen (void ratio = 0.99) were prepared. Figure 1 shows the WRCs of these four specimens with different densities and degrees of anisotropy. Experimental results in this figure were obtained from Tests IS(A), ID(A), IS(B) and ID (B) in Sivakumar et al. (2010). The computed results by the new model are also included in this figure for comparison. It is clear that the anisotropic specimen could retain more water than the isotropic specimen at a given suction, at both slightly and heavily compacted conditions. This trend was well captured by the proposed model. The coefficient of determination (R^2) is larger than 0.98 and the root-mean-square error (RMSE, [-], dimensionless here) is below 0.018 for all cases, as summarized in Table I. In addition, note that the value of β is 1.61 and 1.20 for slightly and heavily compacted specimens, respectively. The difference is likely attributed to the distribution of pore elongation ratios. Through DEM simulations, Sufian et al. (2019) found that pores in looser specimens were more sensitive to anisotropic stress compression than those in denser specimens. This implies that the influence of anisotropy on E and hence the WRC was more significant (see equations (8) and (10)) in looser specimens than that in denser specimens.

Figure 2 shows the measured and computed WRCs of a completely decomposed granite from Hong Kong. The experimental results were reported by Tse (2007). Three different specimens were subjected to the same mean net stress of 80 kPa but different stress ratios of 0, 0.75 and 1.2. After equilibrium, each specimen was dried for measuring the WRC. The results illustrate that for the equilibrium water content at a given suction, its value at a higher stress ratio (i.e. more anisotropic) is higher than that at a lower stress ratio. More importantly, the influence of stress-induced anisotropy was well captured by the new model, with R^2 larger than 0.90 and RMSE below 0.073. As expected, the value of β is larger when the stress ratio is higher (see Table I). This is because the pores are more elongated due to anisotropic stress condition.

Habasimbi and Nishimura (2018) investigated the influence of stress ratio on the WRC of a silt from Japan. One specimen was tested at isotropic stress condition, while the other one was tested at one-dimensional stress condition. Their tests were fitted using the proposed model. Experimental results in Figure 3 are corresponding to the drying WRC at a net stress of 100 kPa reported by Habasimbi and Nishimura (2018). The measured and computed results are well matched, as shown in this figure. The values of R^2 are larger than 0.89 and the values of RMSE are below 0.011.

The results shown in Figures 1 through 3 clearly demonstrate that the new model is able to well capture the water retention behaviour of isotropic and anisotropic soils. The model capability is closely related to the considerations of pore shape in equations (8) and (10). The proposed WRC model can be applied in seepage analysis for different purpose. Slope hydrology and its influence on the stability is taken as one example here. The stress condition of soils in a slope is often anisotropic and heterogeneous, depending on many factors such as the slope geometry and soil property. Consequently, soils in the slope could have different anisotropic pore structures and hence WRCs. Moreover, the degree of anisotropy may evolve under the action of external loading. For instance, there are many construction activities near slopes in densely populated and hilly cities like Hong Kong. In such cases, the proposed model could be used to improve the seepage analysis. It should be pointed out that, however, evolving anisotropy and its influence on the parameter β in equation (10) are complicated. More theoretical and experimental studies are necessary prior to the practical implementation and application of the proposed modelling approach.

4. Summary and Conclusion

In this study, anisotropy effects on the WRC were investigated based on two-dimensional analysis. The pores of unsaturated soils are approximated as a series of ellipses for simplicity. Compared to isotropic specimen, the pores of anisotropic specimen are more elongated and therefore have a higher equilibrium water content at a given suction. On the basis of this mechanism, a new water retention model was proposed for anisotropic soils. A new variable, which is a function of the dominant elongation ratio, was newly added in the model of van Genuchten (1980) for incorporating anisotropy effects.

The new model was verified by using experimental results of three different soils. For each soil, the WRCs of both isotropic and anisotropic specimens were determined by previous researchers. The measured and computed results are well matched, with R^2 in the range of 0.89

to 0.99 and RMSE ranging from 0.009 to 0.073.

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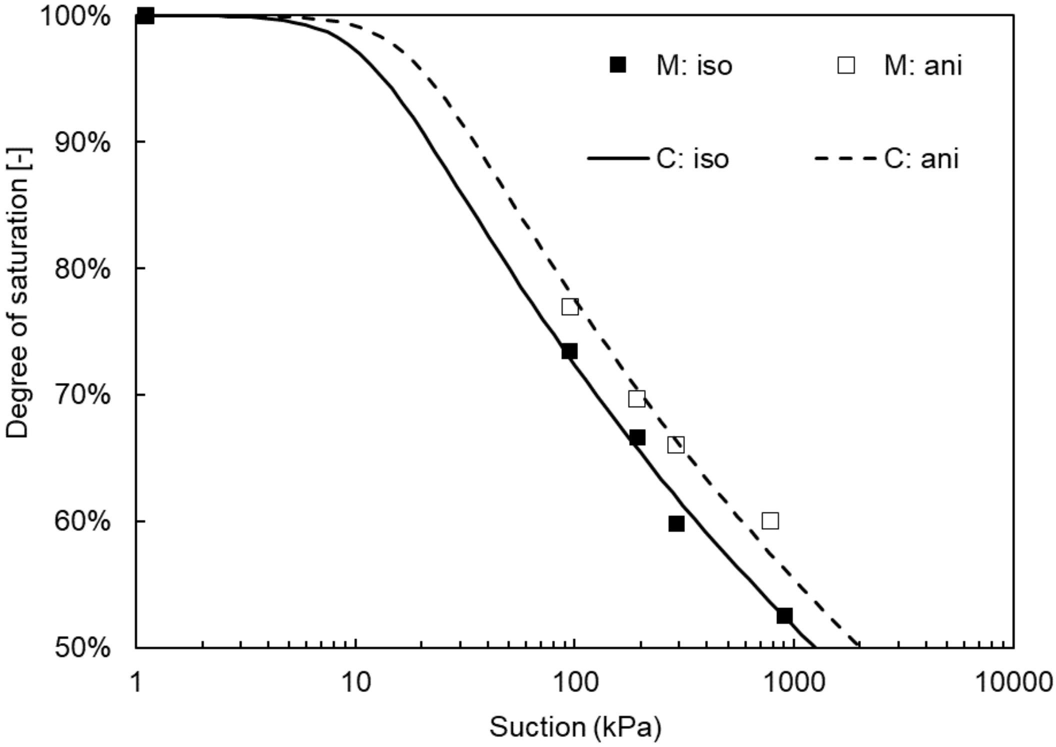
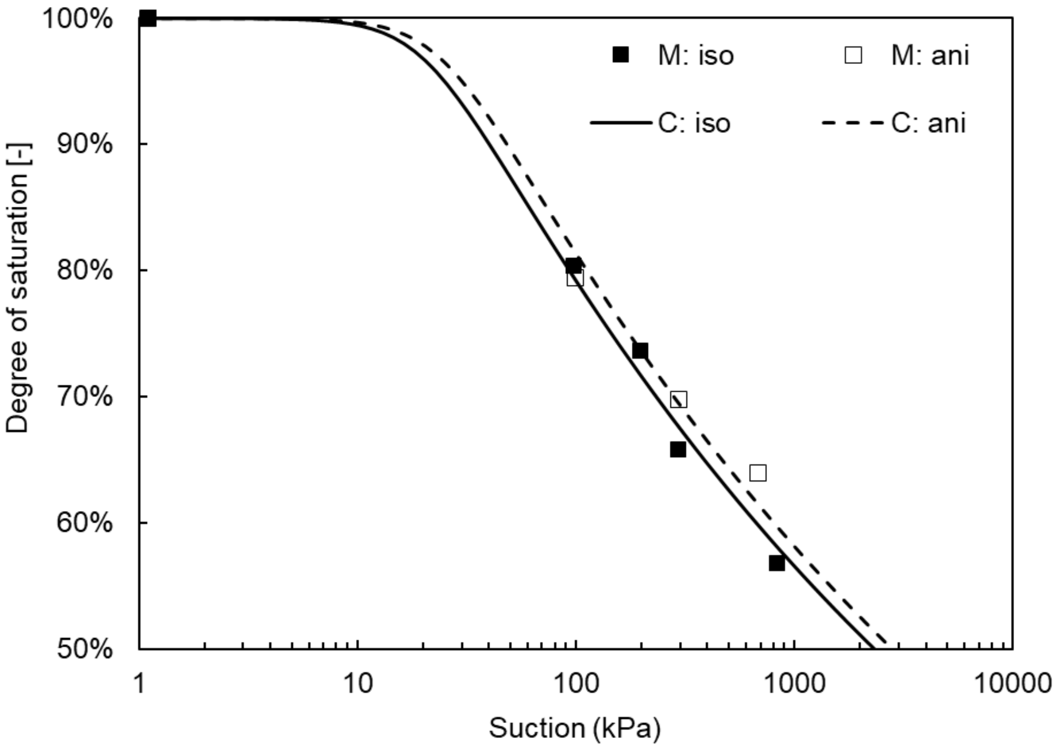
List of figures

List of tables



(a)



(b)

Figure 1. Comparisons between measured (M) (Sivakumar et al., 2010) and computed (C) water retention curves of kaolin clay specimens isotopically (iso) and anisotropically (ani) compacted: (a) void ratio = 1.19; (b) void ratio = 0.99

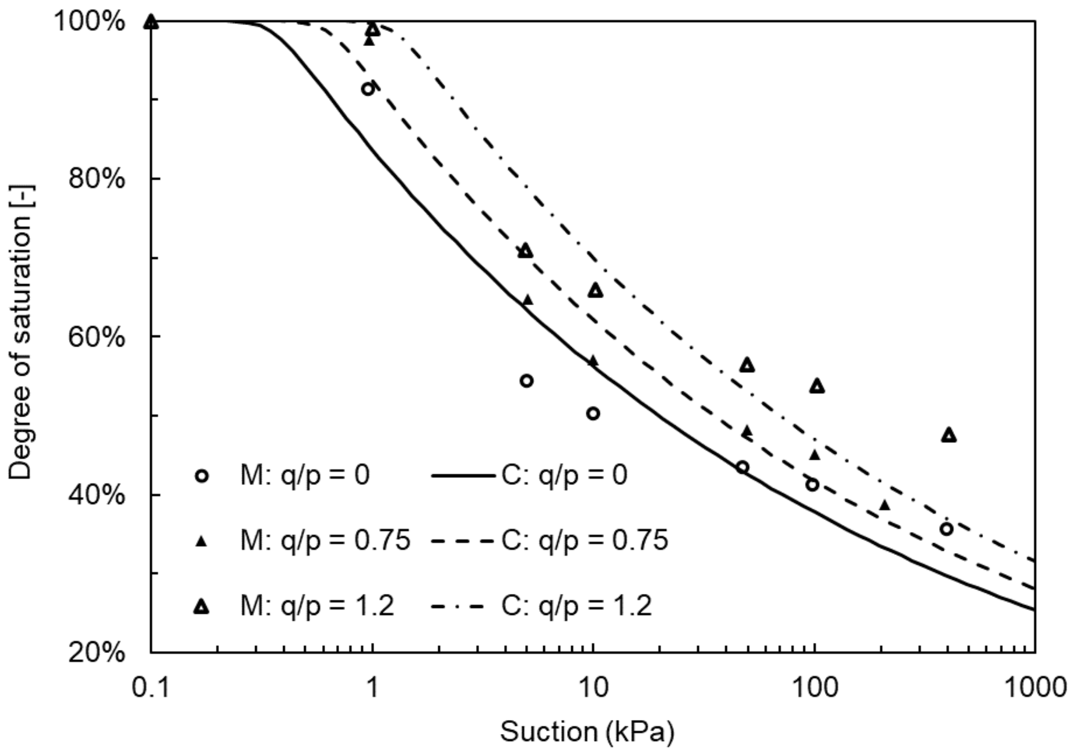


Figure 2. Water retention curves of a completely decomposed granite tested by Tse (2007) at the same mean net stress but different stress ratios (deviator stress divided by the mean net stress)

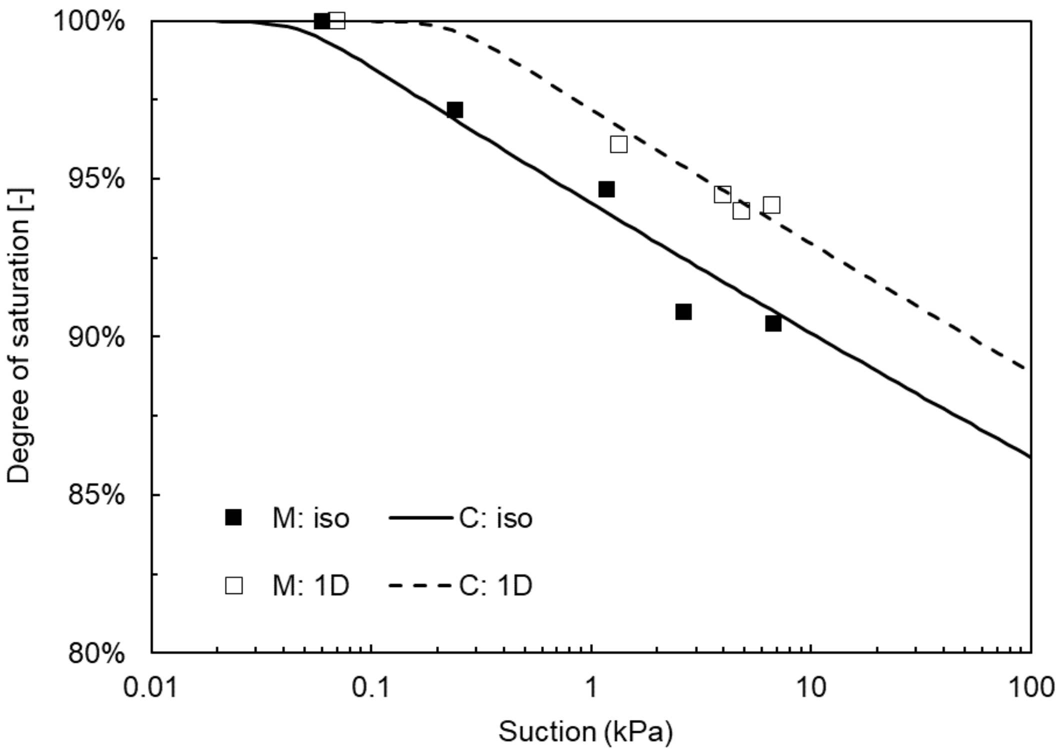


Figure 3. Water retention curves of a silt from Japan at isotropic (iso) and one-dimensional (1D) stress conditions (test data from Habasimbi and Nishimura (2018))

Table I. Summary of model parameters and their values for various soils

Soil specimen		Soil parameters				Goodness of fit	
		m_1	m_2	m_{3-iso} (kPa)	β	R^2	RMSE [-]
Kaolin clay (Sivakumar et al., 2010)	Isotopically compacted with specific volume of 2.19	0.048	2.99	10.96	1.00	0.99	0.016
	One-dimensionally compacted with void ratio of 1.19				1.61	0.99	0.014
	Isotopically compacted specific volume of 1.99			20.45	1.00	0.99	0.015
	One-dimensionally compacted with void ratio of 0.99				1.20	0.98	0.018
Completely decomposed granite from Hong Kong (Tse, 2007)	Stress ratio = 0	0.022	7.99	0.36	1.00	0.95	0.073
	Stress ratio = 0.75				1.78	0.97	0.039
	Stress ratio = 1.2				3.54	0.90	0.066
Silt from Japan (Habasimbi and Nishimura, 2018)	Isotropic stress	0.004	4.82	0.05	1.00	0.95	0.011
	One-dimensional stress				4.94	0.89	0.009