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Indirect and Direct Consideration of Microstructure in a Constitutive Model

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Abstract

It is important to describe and quantify microstructure when modelling microstructure-related behaviour of soils. There are indirect and direct methods to consider microstructure in modelling. Indirect methods only consider the impact of microstructure on soil behaviour. Whilst direct methods focus on geometric and structural features of microstructure such as pore size distribution (PSD). This paper presents two examples of indirect and direct consideration of microstructure in a constitutive model. The indirect method considers the microstructural impact through effective degree of saturation and the direct method adopts the pore size distribution as microstructure index. The performance of each approach is evaluated based on experimental results and it is found that both have good performance in studying the hydro-mechanical behaviour of soils while the direct method can provide more information of microstructure.

Keywords: microstructure; pore size distribution; constitutive model; hydro-mechanical model

1 Introduction

It is widely acknowledged that microstructure has a significant impact on the hydro-mechanical behaviour of soils [1–5]. To describe and quantify microstructure in a model, there are indirect methods and direct methods. Indirect methods focus on the effect of microstructure on soil behaviour but ignore the exact microstructural features. Direct methods attach more importance to the detailed microstructural features such as pore shape, pore size and pore size distribution (PSD).

Two modelling examples of both indirect and direct methods is presented in this paper and are compared with experimental results. For the indirect method, the effective degree of saturation is adopted as a microstructural index because it is defined to neglect the residual degree of saturation stored in intra-aggregate pores (micropores) [6–8]. For the direct method, PSD is selected to represent microstructure due to its direct description of pore sizes and their volumes which are highly related to volume change behaviour of soils. The other reason to choose PSD is that the water content can be directly obtained from it. This gives the model the potential in predicting hydraulic behaviour such as soil-water characteristic curve (SWCC) [9, 10]. PSD and its interaction with stress-strain behaviour are considered in the model through a PSD-dependent effective stress [3]. The Glasgow Coupled Model (GCM) [11] is adopted as the hydro-mechanical framework for both methods.

Both methods have their own merits and deficiencies. The indirect method requires only one parameter to represent microstructure. However, this method fails to consider the evolution of microstructure because the residual degree of saturation is assumed to be constant and not impacted by changes to the microstructure. The direct method assumes soil pores are cylindrical and evolution of PSD is solely related to the change of void ratio. Direct methods will typically require more parameters to represent microstructure and can make the model much more complex. However, direct methods give the possibility of studying microstructural-hydro-mechanical coupled behaviour within a unified framework and can be applied to predicting the evolution of microstructure and SWCCs.

2 Comparison between an indirect method and a direct method

In GCM, the effective stress σ^* is an important factor that affects the hydro-mechanical behaviour of soils, which is defined as [12]:

$$\sigma^{*} = \bar{\sigma} + \chi \cdot s \tag{1}$$

where $\bar{\sigma}$ is the net mean stress, s is the suction and χ is the Bishop's effective stress coefficient. The most significant difference between the indirect method and the direct method lies in the definition of χ. For the indirect method, χ is replaced by the effective degree of saturation S_{e} where the residual degree of saturation S_{res} represents the water within disconnected micropores [6]:

$$\chi = S_{\mathrm{e}} = \frac{S_{\mathrm{r}} - S_{\mathrm{res}}}{1 - S_{\mathrm{res}}} \tag{2}$$

while S_{res} can be considered as a microstructural index (related to micropores), it cannot provide detailed information about microstructure (such as pore size, pore volume) and it is assumed to be unchanged during loading. Therefore, the evolution of microstructure is not considered in this indirect method.

For the direct method, the pore size distribution (PSD) is used to represent microstructure and χ is defined by a PSD-dependent equation [3]:

$$\chi = \frac{\delta e_{\mathrm{w1}}}{\delta e} \tag{3}$$

where δe_{w1} is the change of water ratio and δe is the change of void ratio, both of which can be determined from two PSDs. Based on this definition, the effect of microstructure on effective stress (hydro-mechanical behaviour) can be considered. Since this χ is PSD-dependent and PSD evolves during loading, the evolution of PSD must be considered in the model. Fitting PSD with two log-normal distributions [13] and the shape of PSD can be determined by fitting parameters a_i, μ_i and ψ_i, as defined below:

$$f(r) = \sum_{i=1}^{2} \frac{a_i}{\sqrt{2\pi}\psi_i r} \exp\left(-\frac{(\ln(r) - \mu_i)^2}{2\psi_i^2}\right) \tag{4}$$

Assuming the evolution of PSD is linear to the change of void ratio Δe, then the evolution of PSD can be determined by fitting parameters K_1^i, K_2^i and K_3^i:

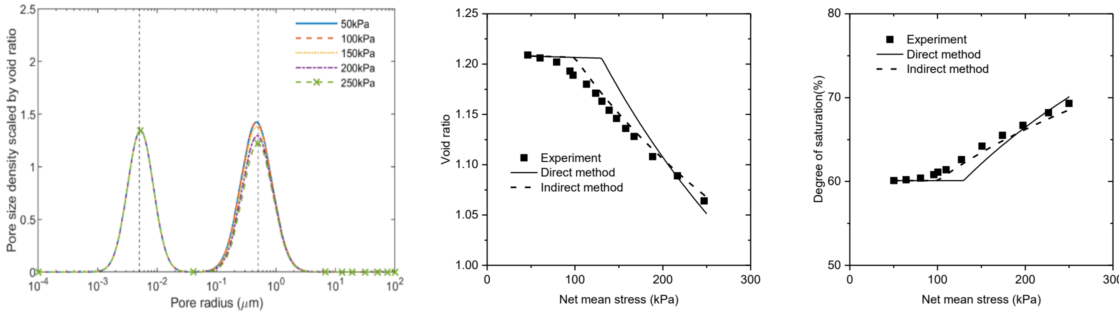
$$[\Delta a_i \quad \Delta \mu_i \quad \Delta \psi_i] = [K_1^i \quad K_2^i \quad K_3^i] \cdot \Delta e \tag{5}$$

3 Comparison in model performance for both direct and indirect methods

Two examples have been given in this section to compare the performance of both direct and indirect methods in predicting the hydro-mechanical behaviour of soils under different loading conditions.

3.1 Unsaturated isotropic loading for Speswhite kaolin

The result of modelling by both indirect and direct methods is presented in Fig.1(a), (b) and (c) for an isotropic loading path for Speswhite kaolin from net mean stress of 50kPa to 250kPa [7]. Compared with experimental results [14, 15], both methods can give a satisfactory result in reproducing the stress-strain behaviour of soils. It should be noted that PSD data has been assumed based on information available in the literature thereby limiting its fidelity. The direct method can also predict the evolution of PSD that it evolves with the compression of macropores and so gives the advantage of allowing the representation of microstructure evolution during loading and hydraulic behaviour such as SWCC.

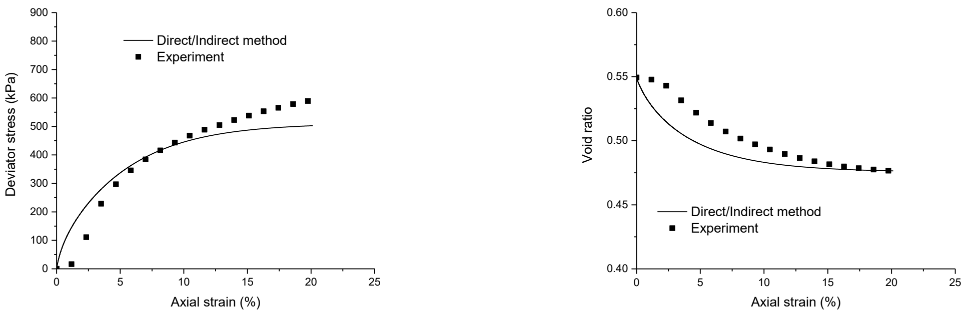


(a) PSD evolution from direct method (b) p_{net}-e (c) $p_{\text{net}} - S_{\text{r}}$

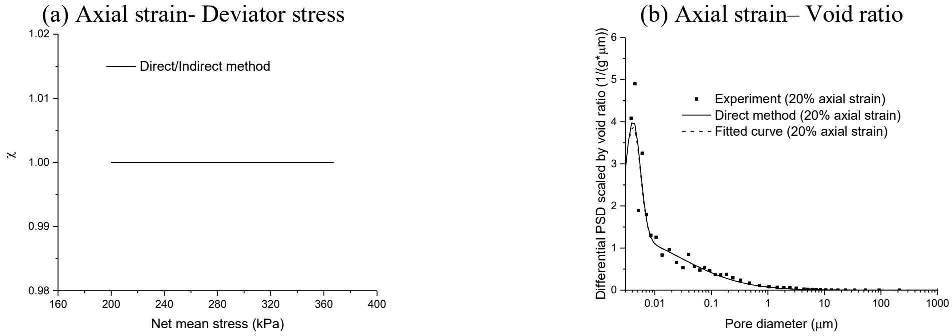
Fig.1 Comparison among indirect method, direct method and experimental results for Speswhite kaolin

3.2 Saturated shearing for Dundee silt

Both indirect and direct methods are used to reproduce the hydro-mechanical behaviour of Dundee silt in a triaxial test. The sample of Dundee silt was prepared at an initial water content of 15% and a dry density of 1.62 Mg/m^3. The sample was then saturated and consolidated before shearing under a constant confining stress of 200 kPa. Both indirect and direct methods are used to reproduce the hydro-mechanical behaviour of Dundee silt in this triaxial test. As shown in Fig.2(a) and (b), the results provided by both methods are identical to each other. This is because the suction is always zero during saturated shearing and the effective stress is invariably the same for both methods. Both methods present a good performance in predicting the change of deviator stress and void ratio during shearing. The Bishop's effective stress coefficient χ remains 1 for both methods (see Fig.2(c)). For the direct method, the model also successfully reproduces the PSD at 20% axial strain while the indirect method cannot give more information about the microstructure.



(a) Axial strain- Deviator stress (b) Axial strain– Void ratio



(c) Net mean stress- Biship's effective stress coefficient (d) Comparison among experimental PSD, fitted PSD and predicted PSD from the direct method

Fig.2 Comparison among indirect method, direct method and experimental results for Dundee silt

4 Conclusions

Comparison between an indirect method and a direct method of considering microstructure in constitutive modelling of hydro-mechanical behaviour of soils is presented in this paper. The modelling performance is validated based on experimental results of Speswhite kaolin and Dundee silt. Both methods can give a satisfactory result in predicting the hydro-mechanical behaviour of two different soils. The direct method is able to provide more details of the microstructure (pore size distribution and its evolution) and is of higher potential in studying the microstructure-induced behaviour of soils.

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