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On the Physical Meaning of Equivalent Skeleton Void Ratio for Granular Soil with Fines

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Abstract. Recent research on the behavior of silty sand usually involves the use of equivalent skeleton void ratio to characterize its packing density state. The equivalent skeleton void ratio is a modified void ratio by the introduction of a parameter b to account for the participation of fines in the force chains. However, the parameter b is poorly understood. This paper presents an investigation into the physical meaning of the equivalent skeleton void ratio by conducting a series of discrete element method (DEM) simulations on biaxial tests of assemblies of coarse and fine particles. The simulation results reveal that the parameter b is a state variable dependent on confining pressure, packing density and particle gradation and it varies during shearing. It should not be treated as a constant as reported in the literature. It is also found that the distribution pattern of fine particles in the skeleton of the assembly plays a crucial role in the overall macroscopic response. Contraction is principally induced by the movement of fine particles out of the force chains and dilation is generally involved with the migration of fine particles into forces chains. Furthermore, a new expression of the equivalent skeleton void ratio is put forward with the introduction of the parameter d to take into account the absence of large particles from force chains, along with comparisons between this new definition for the equivalent skeleton void ratio and the existing one.

Keywords: Equivalent skeleton void ratio; discrete element method; granular soil; fines
PACS: 45.70.Cc

INTRODUCTION

The shear behavior of silty sands containing a certain amount of fine particles with sizes below 0.074mm in diameter is complex, and diverse or even contradictory views are found in the literature [1]. For some of the experimental studies on silty sand, the critical state soil mechanics (CSSM) theories do not seem to work well. For example, Fig. 1 gives the undrained behaviors of three silty sand samples with the same fines content sheared under different consolidation pressures, reproduced from Yamamuro and Lade [2]. It is noted that these specimens show increasing dilation or decreasing contraction potential with increasing confining pressures, which is contrary to anticipated normal behaviors of clean sands according to CSSM theories and was referred to as reverse behavior [2].

Researchers have attempted to study such reverse behavior within the framework of CSSM as for clean sand. Some of them consider that the malfunction of the CSSM theories in describing these reverse behaviors is attributed to the improper use of the state variable – global void ratio e, which cannot take into account the effect of fine particles in silty sands. In this respect, skeleton void ratio e_s was proposed to assist understanding of shear behaviors of silty sands by treating fine particles entirely as void spaces [3]. However, with the skeleton void ratio as the density parameter, the critical state line (CSL) remains un-unique in e_s - log p' space. Alternatively, equivalent skeleton void ratio e_{se}, as given in Eq. (1), was proposed to describe the packing density state of silty sands, with the fine particles not in force chains being taken as void spaces through the parameter b [4]:

$$e_{se} = \frac{e + (1-b)fc}{1-(1-b)fc} \tag{1}$$

where e is global void ratio; fc is fines content; b refers to the portion of fine particles which are actively involved in force chains. With a specific b value, it was claimed that a unique CSL can be achieved and good correlations are obtained between the equivalent skeleton void ratio and other properties such as steady state shear strength.

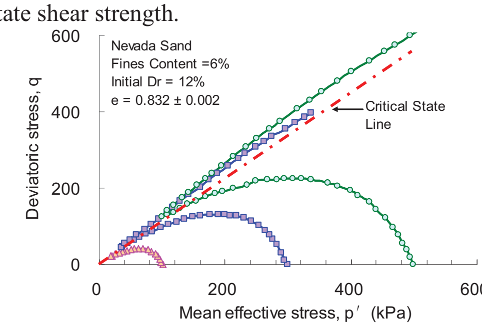

FIGURE 1. Undrained shear behaviors of silty sands at different confining pressures [2].

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While the concept appears to be attractive, the physical meaning of index b in the equivalent skeleton void ratio is not yet well understood. In the literature the parameter b is commonly assumed to be a constant that can be back analyzed from test data or predicted by some empirical expression [4-6]. In the writers' view, the parameter b should vary during the shearing process; in other words it is a state dependent variable.

More importantly, it should be noted that in shearing a specimen of mixed soil containing coarse and fine particles, neither the coarse grains nor the fine grains will all participate in the force chains. From this micromechanics perspective, it is necessary to consider the absence of both coarse grains and fine grains from the force chains. Hence, a new parameter d, a mass fraction of the coarse grains in the force chains is introduced into Eq. (1) such that a new definition for equivalent skeleton void ratio is given as:

$$e_{se} = \frac{e + (1-b)fc + (1-d)(1-fc)}{1-(1-b)fc-(1-d)(1-fc)} \qquad (2)$$

where both d and b vary between 0 and 1.

To have a better understanding of the physical meaning of the parameters b and d, a series of numerical simulations have been carried out using the discrete element method (DEM). This paper reports the main results and discussions, which indicate that the new definition for equivalent skeleton void ratio is more rational.

NUMERICAL MODELING

The program PFC^{2D} (Itasca 2005) is used in this investigation to carry out a series of biaxial test simulations in undrained condition. Numerical specimens are composed of idealized particles having two circular constituent particles clumped together (see Fig. 2). Each clumped particle is considered to behave as a rigid body, and the two constituent particles cannot be broken apart. The ratio of the diameter of the constituent particle over the length of the long axis of a clump is defined as the aspect ratio to describe the particle shape, and given to be a value of 0.6 in this study. The size of a clump is described by an equivalent particle diameter – the diameter of a circular particle with the same cross sectional area as the clump.

Four grading curves, as shown in Fig. 2, are considered in this study. The grading curve D is the base grading curve, with the sizes of all particles varying from 0.26 to 0.66 mm. The grading curves A and B respectively contain 10% and 5% particles with their diameters below 0.26 mm, and the minimum particle size is 0.02 mm in diameter. The grading curve C also contains 10% particles with their sizes below 0.26mm, but the minimum particle size is 0.1mm. The linear elastic contact model is employed to describe the contact behavior between particles. The friction behavior at contacts is assumed to observe the Coulomb friction law.

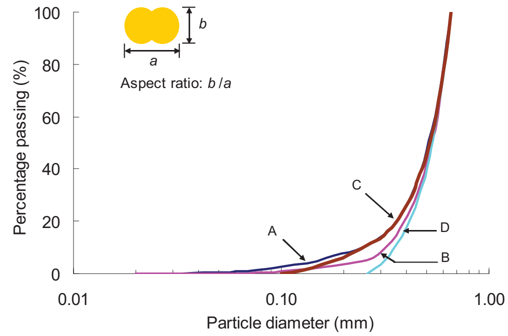

FIGURE 2. Particle shape and particle size distribution in this numerical simulation.

The gravitational deposition is used as the sample preparation method. Undrained shearing is carried out by moving the loading walls with strain-controlled method and at the same time keeping a constant volume for the sample. Damping factor during the shearing test is adopted to be the default value 0.7. Sample information and modeling parameters in this numerical study are listed in Tables 1 and 2.

Table 1 Sample information

Test Name	Grading Curve	Global Void Ratio, e	Particle Number, N	Confining Pressure, p_0 (kPa)
G-1	A	0.2157	9013	1000
G-2	B	0.2175	5212	1000
G-3	D	0.2171	2881	1000
D-4	C	0.2071	5120	200
D-5	C	0.2155	5085	200
D-6	C	0.2249	5041	200
D-7	C	0.2345	5010	200
P-8	A	0.2168	9057	200
P-9	A	0.2172	9013	800
P-10	A	0.2167	9034	1200
P-11	A	0.2171	8885	1800

Table 2 Modeling parameters

Particle Density, ρ	Aspect Ratio, R_a	Inter-particle Friction, μ_s	Wall Friction, μ_w	Normal & Tangential Stiffness, k_n & k_s	Wall Stiffness, k_w
2.65 g/cm^3	0.6	0.5	0.0	10^9 N/m	10^9 N/m

RESULTS AND DISCUSSIONS

Values of b and d at Initial State

Fig. 3 presents b and d values at initial state for cases having different particle gradations, void ratios and confining pressures. It is observed that both b and d show distinct reliance on particle gradation index χ (= D_{10}/d_{50}), global void ration e and confining pressure p_0. Here d_{50} is the mean particle size for fine particles, namely, the particle diameter at 50% in cumulative distribution for fines, and D_{10} is for coarse grains, so χ is in fact a parameter relying on the sand-fines type.

As shown by Fig. 3(a), b values decrease with increasing χ. In general, a larger size ratio between large particles and fine particles suggests that fine particles may be more easily trapped in voids due to a more substantial size disparity. Particularly, increasing fines content increases the size ratio between large particles and fine particles. That is to say, fine particles are more likely to be confined in voids, due to a more significant size disparity at a higher fines content. It is therefore believed that there will be more fine particles to be trapped in voids formed by large particles, when increasing fines content. This is the reason why b values reduce with increasing χ. However, d values do not seem to vary notably with χ. Following this observation, it can be inferred that increasing fines content have little influence on the presence of coarse grains in the solid skeleton.

Fig. 3(b) shows that values of b and d decrease with initial global void ratios. On the basis of this observation, one is able to reach a conclusion that decreasing initial global void ratios not only causes the decrease of void spaces as the direct response, but also promotes the participation degrees of both fine and large particles in force chains. In such a manner, the stiffness of the skeleton is to be enhanced with decreasing void ratio. From this perspective, particles in a granular specimen packed in dense state are desired to be better arranged, and more particles are anticipated to be present in force chains.

Fig. 3(c) reveals that both b and d values rise with the increase of confining pressure in low pressure region, indicating that increasing confining pressure makes more fine and large particles move into force chains. However, further increase of confining pressure does not seem to have exerted a substantial effect upon the role of small particles in the skeleton, since b values are almost kept unvaried when p_0 is over 800kPa, while d values decrease, signifying that increasing confining pressure at high pressure region may push some large particles out of the skeleton.

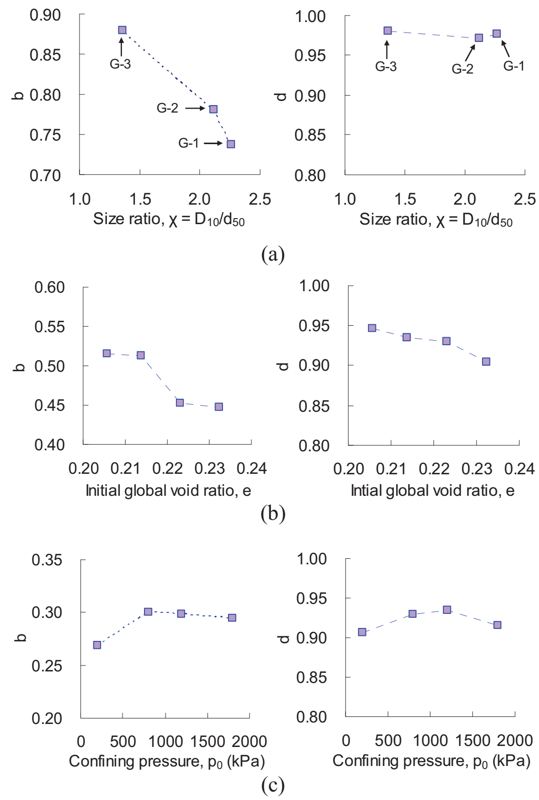

FIGURE 3. Values of b and d at initial state for samples with: (a) different particle gradations; (b) different void ratios; (c) different confining pressures.

Evolutions of b and d during Shearing

Fig. 4 presents the macroscopic shear behaviors of granular specimens having different particle gradations. It is observed that G-1, the specimen having the highest content of fine particles, exhibits pure contraction behaviors. The specimen G-3, the specimen with base grading curve, shows the most dilative behaviors. It is evident that contractiveness increases with increasing content of fine particles.

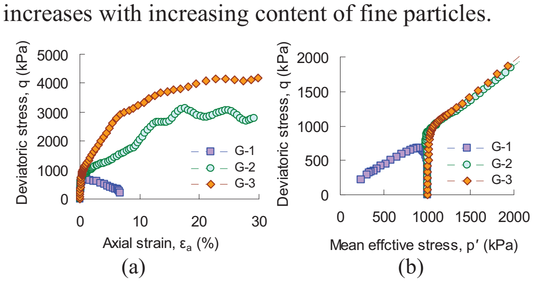

FIGURE 4. Shear behaviors of granular specimens having different particle gradations: (a) q vs. ε_a; (b) q vs. p'.

Also, Fig. 5 gives the evolutions of b and d values in the shearing process, to improve the understanding of macroscopic shear behavior of these specimens from a microscopic perspective. It is seen that b values are different for different particle gradations, but d values almost coincide with each other in shearing and approximate to 1.0. This suggests that the macroscopic shear responses of these granular specimens are firmly related to the variations of b, namely, the movement of fine particles. For example, the liquefied specimen G-1 demonstrates a pure decrease in b values during the whole shearing stage, referring to that fine particles are continuously removed from force chains and the loss of supporting effect from small particles induces liquefaction. The decrease of b values for other two samples signifies temporary contractive behaviors with fine particles moving out of force chains, and the increase of b values indicates dilative responses with fine particles migrating into force chains.

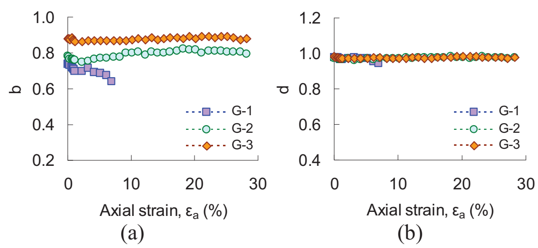

FIGURE 5. Evolutions of b and d during shearing for cases with different particle gradations: (a) b vs. ε_a; (b) d vs. ε_a.

Equivalent skeleton void ratio

Fig. 6 shows a comparison between the current definition and the new definition for equivalent skeleton void ratio. It is seen that the value estimated from the current definition is distinctly smaller than the new one, due to that the absence of coarse grains from the skeleton is not considered in the current definition. It is to be pointed out that it is sufficiently rational to use global void ratio to describe the shear behavior of clean sands since participation degree of coarse grains is high and almost will not vary in shearing as revealed in this study, but this does not mean that the traditional e_{se} is the best density index.

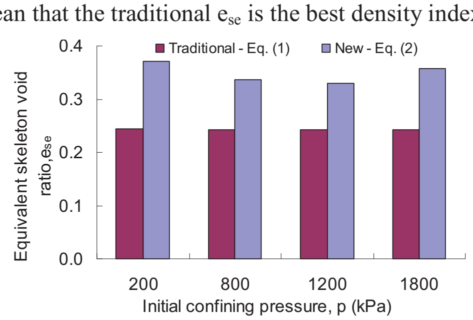

FIGURE 6. Comparison of equivalent skeleton void ratios at initial state for samples with different confining pressures.

CONCLUDING REMARKS

In this paper, results of a series of DEM simulations on the biaxial shear behavior of granular specimens having different particle gradations, void ratios and confining pressures are presented. Particularly, the physical meaning of parameter b in the equivalent skeleton void ratio is assessed. A new definition is put forward which takes into account both fine and coarse particles in the force chains by introducing two parameters b and d. It is revealed that both b and d are state-dependent parameters relying on the initial states including void ratio and confining pressure. They are also found to depend on the particle gradation property. The value of b varies during the shearing process, implying the movement of fine particles in the force chains and therefore the alteration of the microstructure.

While the simulations were conducted under the 2D condition, the findings are found to be consistent in principle with those from the 3D simulations, which will be presented elsewhere in detail.

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