DOI: 10.5505/2023geoteknik.SS-29

EVALUATION OF MICRO-MECHANICAL SHEAR RESPONSE OF SANDY SOIL IN TERMS OF PARTICLE SHAPE EFFECT

KUMLU ZEMİNİN MİKRO-MEKANİK KESME TEPKİSİNİN DANE ŞEKLİ ETKİSİ AÇISINDAN DEĞERLENDİRİLMESİ

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ÖZET

Bu çalışmada, mikro mekanik parametreler kullanılarak kumlu zeminlerin kayma gerilmesi ve şekil değiştirme davranışı dane şekli etkisi açısından değerlendirilmiştir. Bu kapsamda, ayrık elemanlar sayısal yöntemi ile iki farklı kum numunesi için direkt kesme kutusu deneyi modellenmiştir. Danelerin şekilsel özellikleri görüntü işleme tekniği kullanılarak analizlere yansıtılmıştır. Dane kontaklarının dağılım özellikleri sayısal analizler sonucunda elde edilmiştir. Sonuçlar, dane şeklinin kayma direnci ve hacim değişimi üzerindeki etkilerinin, mikro ölçekli parametrelerde gözlemlenen değişiklikler dikkate alınarak değerlendirilebileceğini göstermiştir.
Anahtar Kelimeler: *Dane şekli, kayma direnci, hacim değişimi, mikro ölçek, ayrık elemanlar yöntemi*

ABSTRACT

In this study, shear stress and strain behavior of sandy soils were evaluated in terms of particle shape effect by using micro-mechanical parameters. In this context, the direct shear box experiment was modeled for two different sand samples using the discrete element numerical method. The shape characteristics of the particles were reflected in the analyses using the image processing technique. The distribution properties of particle contacts were obtained as a result of numerical analysis. The results showed that the effects of particle shape on shear strength and volume change can be evaluated by considering the observed changes in microscale parameters.
Keywords: *Particle shape, shear strength, volume change, micro-scale, discrete element method*

1. INTRODUCTION

Particle shape is the prominent factor affecting the mechanical response of the sandy soils (Cho et al. 2006; Sadrekarimi and Olson 2011; Zhou et al. 2015). The conventional direct shear tests can evidently reveal the effect of particle shape on the stress-strain (i.e., macroscale) response of the soils. However, the mechanism behind this response is still undistinguishable; therefore, the place of particle shape in the mathematical expression of shear strength remains unclear. The discrete element method (DEM) offers an effective way to observe the interaction of the particles at contact level (i.e., microscale) (Danesh et al. 2020; Gong and Liu 2017; Xie et al. 2017). In this way, the evolution of shear strength can be associated with the variation of micro-scale parameters.

The response of granular soils is constituted by the distinct behavior of particles. The particles exhibit various forms of movements such as sliding, rotation, and interlocking depending on the properties of the external loads and boundary conditions (Kandasami and Murthy 2017; Zhao et al. 2015). These movements generally

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occur in a combination in the case of shear, but the geometry of the particles assigns the dominant type of movement (Vangla et al. 2018). The angular particles promote the interlocking mechanism in the sample and so the granular system tends to show dilative response. In addition, due to the energy accumulated at the contact points through interlocking, the system produces higher strength than samples with round particles. On the other hand, the round particles show rotation and the particle frustration is eliminated (Guo and Su 2007; Santamarina and Cho 2004). These responses can be quantified by investigating the orientation of contacts in microscale (Maeda et al. 2010; Seyedi Hosseininia 2012).

Considering all this evidence, combining the shear response with microscale parameters will strengthen the understanding of the effect of particle shape on the shear strength and dilatancy. In this study, the effect of particle shape on the shear response was evaluated in terms of micro-scale perspective using discrete element modeling. For this purpose, two different sand shapes were simulated considering the realistic particle forms through the image processing technique. Conventional direct shear test setup reflected the model to study the shearing response. In this context, the coordination number and anisotropy coefficients were used to associate stress-strain response with the micro-scale properties.

2. DISCRETE ELEMENT MODELING (DEM)

In this study, Particle Flow Code two-dimensional software, PFC2D, (Itasca 2008) was used in the simulation of the direct shear test. The particles of beach sand (S1) and crushed sand (S2) were used to reflect the realistic particle forms. The particle size of the sands is in the range of 2.0 – 3.0 mm and is classified as poorly graded sand (SP) according to the Unified Soil Classification System. Four particles from each sand group were selected to represent the shape feature of the samples. For this purpose, the image of the particles was processed in ImageJ open-source software (Schneider et al. 2012), as shown in Fig. 1.

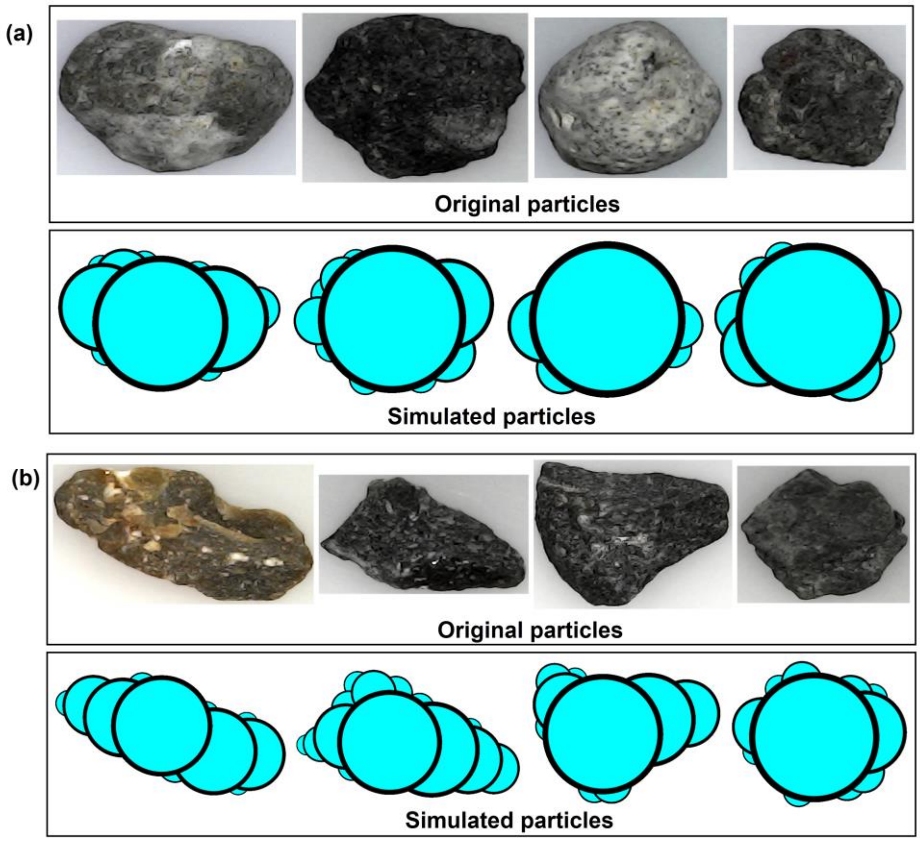

Fig. 1 Original and simulated particles for (a) S1 and (b) S2 sands

To quantify the shape feature of the S1 and S2 sands, the roundness (R) parameter suggested by (Cox 1927) was used as shown in the following definition.

$$R = \frac{4\pi A}{P^2} \quad (1)$$

where A is the area and P is the perimeter of the particle. The roundness parameter takes values between 0 and 1. As a result, the average roundness for S1 and S2 sands was measured as 0.728 and 0.665, respectively. It can be observed that S1 particles have higher roundness than S2 particles.

In the DEM model, the shear response is controlled by the contact models between sand particles. Table 1 presents the contact properties used in this study. A Hertz-Mindlin contact model was utilized as adopted by many prior studies (Grabowski et al. 2020; Lu et al. 2019; Taghizadeh et al. 2017). Direct shear analyses were performed by simulating a box with 100 mm (Width) $\times$ 30 mm (Height) size in PFC2D. The samples were prepared for the densest sample conditions. For this purpose, the interparticle friction coefficient was set to 0.01 at the sample generation state. In the simulations, the normal stress was arranged to 55 kPa through servo-control mechanism. After a mechanical equilibrium was achieved in the model, the shear test was launched by forcing the bottom half of the box with a low constant velocity of 0.01 m/s. The test was stopped when the shear strain was reached to 10%. Shear stress was obtained by dividing the total contact forces applied to the side walls by the width of the shear box. Fig. 2 shows the sample states at the initial and end of the analysis.

Table 1 Contact parameters for DEM simulation

Parameter	Value
Particle density (kg/m^3)	2650
Shear modulus (Pa)	8.0×10^9
Poisson's ratio	0.12
Friction coefficient	0.35

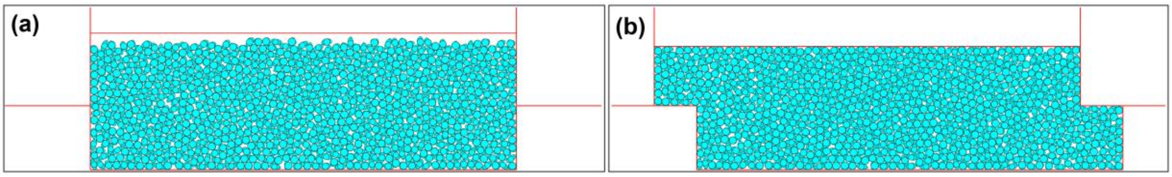

Fig. 2 Sample state for (a) initial and (b) end of analysis

3. SIMULATION RESULTS

The macroscale response of the samples was investigated using stress-strain plots. Fig. 3 shows the variation of stress ratio (τ/σ) and volumetric strain (ε_v) plots with respect to shear strain (γ). It is noted that the shear strain corresponds to the ratio of shear displacement to the width of shear box (i.e., 100 mm). In volume change response, the expansion is considered to be positive. It is shown that the angular S2 sample led to a higher shear strength than the round S1 sample. In addition, the dilative volume change is more pronounced in S2. The reason behind this effect was revealed by investigating the variation of micro-scale parameters with respect to the particle shape.

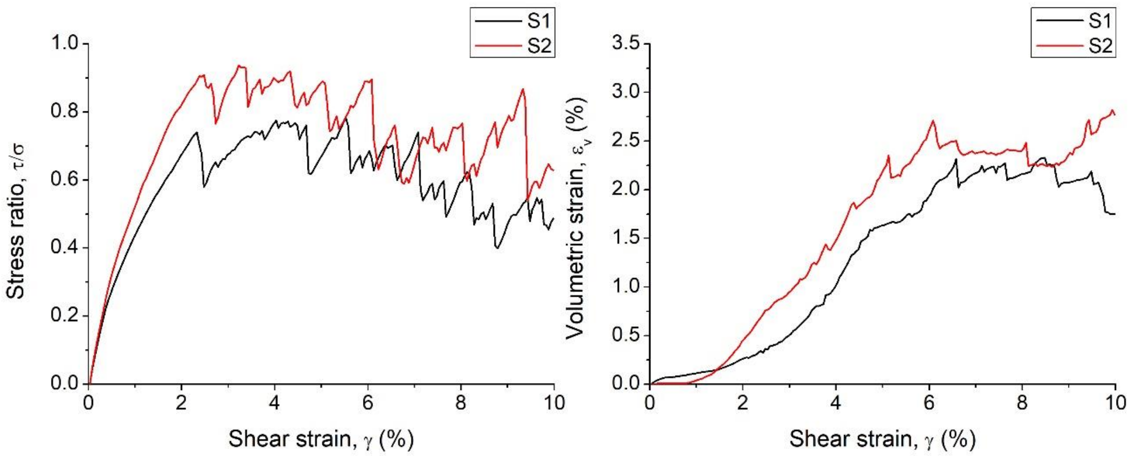

Fig. 3 Variation of shear stress and volumetric strain with respect to shear strain

The overall strength in granular media is formed by the sum of the force accumulated at each contact. The distribution of contacts therefore provides valuable information to clarify the context of the shear response. The contact distribution property of the samples can be quantified with coordination number parameter (*Z*). The coordination number simply describes the average number of contacts a particle makes with surrounding particles, and it is calculated with the following expression.

$$Z = 2N_c/N_p \tag{2}$$

where N_c is contact number and N_p is the particle number. Fig. 4 shows the variation of *Z* during the shear test.

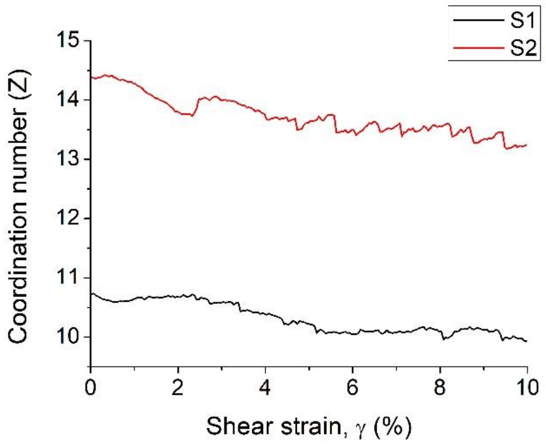

Fig. 4 Variation of coordination number with shear strain

S2 angular particles produced a higher coordination number than S1 particles. It shows that the angular particles tend to create more contact than the round particles. This increases the possibility of interlocking in angular sand samples during the shear (Nie et al. 2020). Therefore, the S2 sample led to higher shear strength than S1. In addition, Z values steadily decrease with shear strain. This is because the sample experiences a volume increase (i.e., dilatation) as observed in Fig. 3 and so the number of contacts decreases with the shear strain.

The orientation of the contacts is another important point in understanding the microstructure of the granular system. Fig. 5 presents the probability distribution function (PDF) of the contact normal for the initial (i.e., 0 mm) and residual state (i.e., 10 mm) of the shear tests. The plots were produced with an interval of 10°.

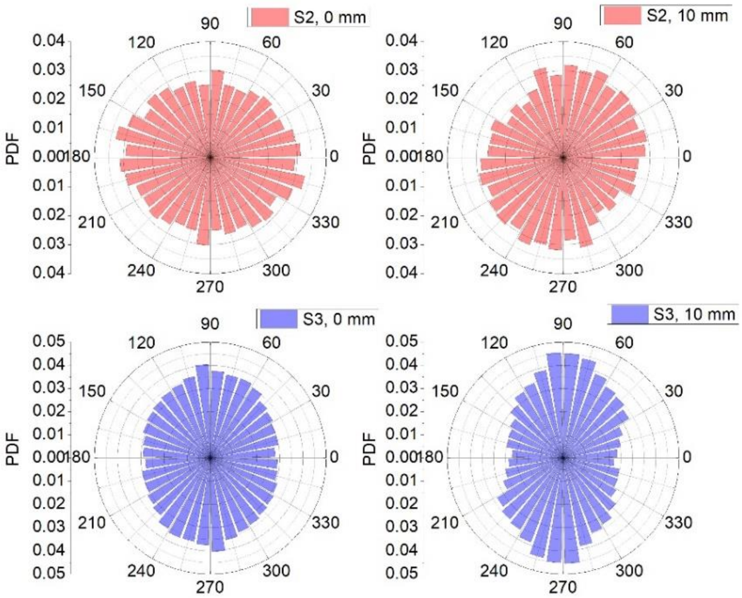

Fig. 5 Orientation of contact normal for S1 and S2 sands

In Fig. 5, it can be observed from rose diagrams that the contacts have an isotropic distribution at initial state of the test. With increasing shear strain, the contact distribution becomes anisotropic. Moreover, the plots show that S2 angular particles lead to more anisotropic distribution than S1 round particles. In order to present the variation of anisotropy with a parameter, second-order Fourier series approximation proposed by (Bathurst and Rothenburg 1990) was used. In this approach, the anisotropy for contact normal, contact normal force, and contact shear force is denoted by a_c, a_n, and a_s coefficients. These coefficients take values between 0 and 1. As the level of anisotropy increases, the coefficients approach 1. Fig. 6 shows the variation of anisotropy coefficients with respect to the shear strain.

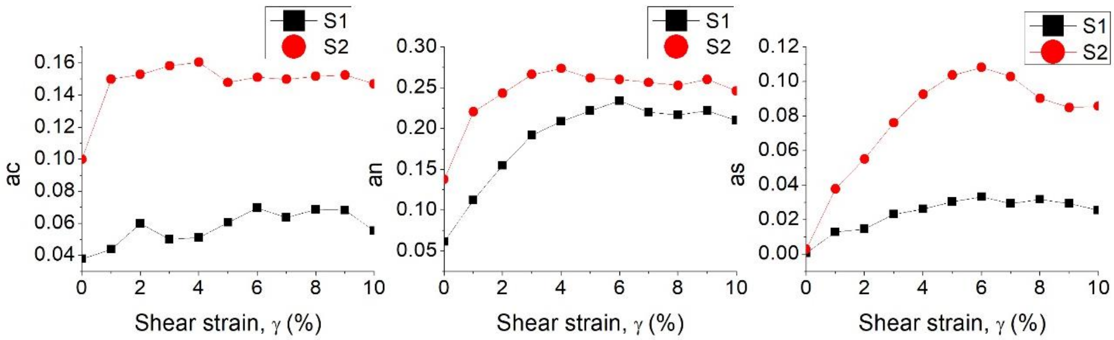

Fig. 6 Variation of anisotropy coefficients with shear strain

The angular S2 sand produces higher anisotropy coefficients. It is seen that the anisotropy coefficients first increase with shear strain and then follow a plateau. This behavior is similar to the variation of shear stress presented in Fig. 3. In particular, the force anisotropies (i.e., a_n, and a_s) demonstrate more similar trends as the shear stress-strain plots. Based on this evidence, it can be stated that the macro-scale shear response can be evaluated by investigating the micro-scale parameters. In future studies, more comprehensive mathematical definitions for shear strength can be produced using micro-scale parameters.

4. CONCLUSION

In this study, the shear behavior of sandy soils was evaluated using the discrete element method in terms of particle shape effects. Micro-mechanical parameters were used to understand the shear stress and strain responses of the samples. Overall, it was concluded that the strength and dilatation increase with the angularity of the particles. The interlocking mechanism is more pronounced in S2 angular particles, as angular particles produce a greater number of contacts than round particles. This leads to the increase of shear strength and dilatation in the angular sand samples. Shear stress-strain plots have similar trends with the variation of anisotropy coefficients. This shows that the definition of shear strength can be updated by taking into account the effect of particle shape using anisotropy coefficients.

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