A discrete element model for soilbag using PFC

K. Fan, College of Water Conservancy and Hydropower, Hohai University, Nanjing, China
Y.P. Cheng, Civil, Environmental and Geomatic Engineering, University College London, London, UK
Y.H. Wang, Civil, Environmental and Geomatic Engineering, University College London, London, UK
Y.H. Zheng, Civil, Environmental and Geomatic Engineering, University College London, London, UK
S.H. Liu, College of Water Conservancy and Hydropower, Hohai University, Nanjing, China

ABSTRACT
A two-dimensional discrete element model has been developed for the geosynthetic soilbag. The soils filled into the bag was modelled as unbonded particles using the linear contact model, and the flexible bag was modelled as overlapping bonded particles using the linear contact bond model. The micro-parameters of the soils and the bag were determined using biaxial tests and a tensile test data, respectively. To obtain the frictional coefficient between bags in PFC, shear model tests on overlapped bag particles were conducted. The results were also compared with that made of non-overlapping particles. The compressive strength properties of soilbag were studied by biaxial compression model tests on a soilbag. The simulation results were then verified by comparing with the theoretical results.
Keywords: Soilbag, Discrete element method (DEM), PFC, Interface friction, Strength

1. INTRODUCTION

1.1 Publication Quality and Uniformity

Soilbags or more exactly geotextile bags filled with soils or soil-like materials have high compressive strength. Matsuoka and Liu (2003) found that the high compressive strength of soilbags under external loading can be theoretically explained by the increased apparent cohesion that develops because of the tensile force of the wrapped bag, they then applied the soilbags as a new way to reinforce foundations. Until now soilbags have been used to reinforce several hundreds of soft building foundations in Japan and China (Matsuoka and Liu, 2014; Liu., 2017). In those studies, laboratory tests, model tests and field tests were usually used to study the behavior of soilbags and structures constructed with soilbags (Fan et al., 2019; Liu at al., 2019; Ding et al., 2018). However, the tensile force along the wrapped bag is hard to measure experimentally. The key aim of this paper is, therefore, to develop a discrete element method for the soilbag and gain a micromechanical understanding of the behavior of the soilbag.

Recent research has used finite element method to investigate the behavior of granular material wrapped with polyethene bags under vertical compression and cyclic shearing. To effectively address the interfacial discontinuity and the large deformation of soilbags, Ansari et al. (2011) allowed for the consideration of large interfacial slips, surface separation and reclosure in an FE scheme, but they can be better handled with discrete approaches such as the discrete element method (DEM). A 2D discrete element method (DEM) model was developed to study the strength characteristics of soilbags under inclined loads, and a 3D model was also built to investigate the stress states and fabric anisotropies in soilbags (Cheng et al., 2016). In their self-developed models, the bag was modelled as bonded particles, and neighboring bag particles were connected in their normal direction with an elastic spring and a viscous dashpot, but not connected in their tangential direction to model the flexibility of the bag. The reference gap of neighboring bag particles is approximately zero. When the distance increased, a tensile force was generated. This method is appropriate for studying the compression behavior of soilbag. However, bags used in engineering project are always smooth. Therefore, neighboring bag particles with a reference gap of zero used in the model may be not fully appreciated when shear characteristics of the stacked bag are studied, because the gap between the neighboring particles has an inevitable impact to the friction coefficient between bags, which will be explored in this paper.

This paper presents a 2D discrete element model of a soilbag. The bag was modelled as overlapping bonded particles using the linear contact bond model. Shear model tests on bags were conducted to check out the frictional coefficient between bags. Biaxial compression tests on soilbag were conducted to study the strength properties of soilbag, and the results were verified by comparing with the theoretical formulations.

2. NUMERICAL MODELING

The particle flow code, PFC2D, developed by Itasca (Itasca 2018), was used in this study. PFC2D is based on rigid body and soft contact approaches. The soft contact approach allows calculating deformations at the contacts. PFC2D utilizes two successive cycles to compute the forces and displacements of the particles. The motion of each particle is calculated from the resultant contact and body forces acting on the particle using Newton's second law of motion. The contact and body forces are then updated for the resulting motion by applying the force-displacement law. The determination of the micromechanical parameters for the model used in this study are discussed subsequently.

2.1 Infilled-soil

The biaxial sample used to determine the micro-mechanical parameters of the soils filled into the bag, had a width of 0.1 m and height of 0.2 m. Particles with diameters ranging from 1.6 to 4 mm were generated at a porosity of 0.16. The particle size distribution followed a fractal distribution curve with a fractal dimension of 1.3. The input parameters presented in Table 1 were used to perform the biaxial test as outlined in PFC2D manual (Itasca 2018). The deviatoric stress (σ_1-σ_2)/2 versus axial strain is shown in Fig.1. These plots were obtained at four confining pressures: 25, 50, 75 kPa and 100kPa. Fig. 2 shows the large dilation of the sample, indicating the dense behavior of the granular material. The shear strengths of the specimens were taken from the final values of the deviatoric stresses. The s–t plot of the test is shown in Fig. 3, and the friction angle of the assembly was calculated using Equation (1).
From the s–t plot, the friction angle of the sand is calculated as:

$$\frac{s}{t} = \sin\varphi = 0.273;\ \varphi = 15.84; \qquad [1]$$

Table 1. DEM input parameters.

	Soil particle	Bag particle	Bag particle-soil particle	Bag particle -wall	Soil particle -wall
k_n(N/m/m)	1e8	1e7	1e8	1e8	1e8
k_n/k_s	1	1	1	1	1
μ	0.2	0	0	0	0
ρ(kg/m3)	2160	2160	—	—	—

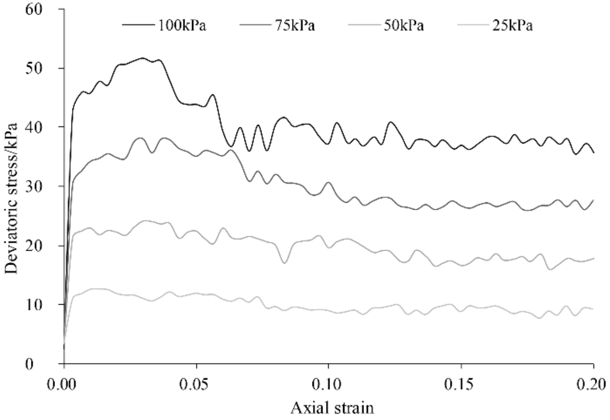
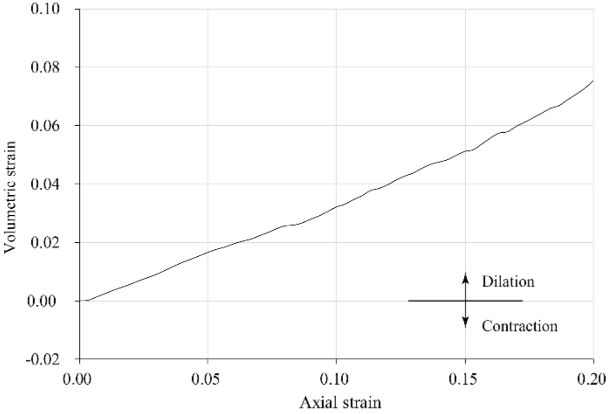


Figure 1. Deviatoric stress versus axial strain from biaxial test simulations

(a) Devialtoric stress



(b) Volumetric strain

Figure 2. Volumetric strain versus axial strain from biaxial test simulations at the confining pressure of 50kPa

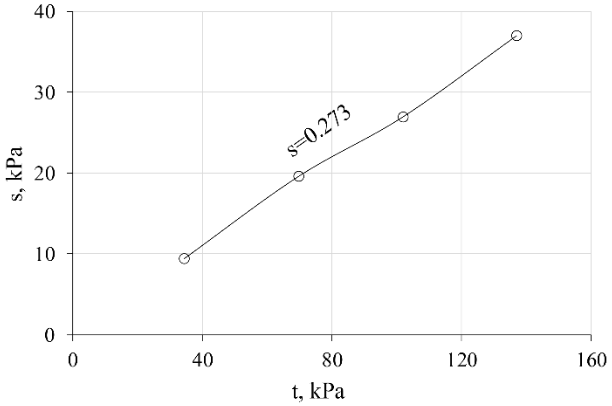


Figure 3. s versus t plot

2.2 Bag

The bag was modelled using overlapping bonded particles of 0.2 mm in diameter in the DEM model. The property of the bag was characterized by its tensile strength, and the tensile strength was determined by the contact bond forces between the bag particles. Here the tensile strength of 400N/m was selected, and a strength property of bag with a linear stress-strain relationship was selected, as shown in Fig.4.

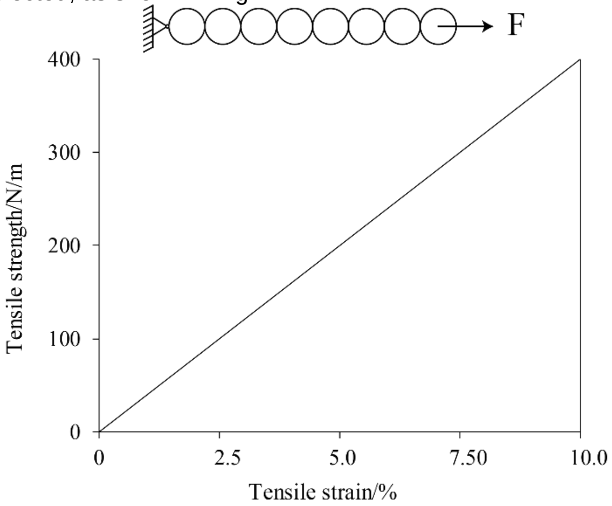
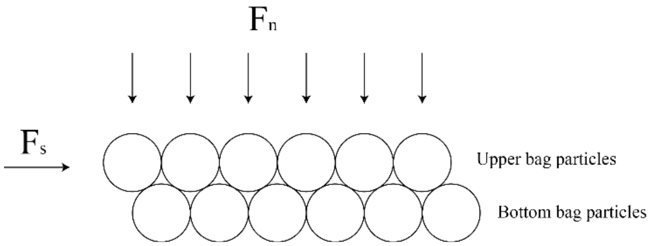


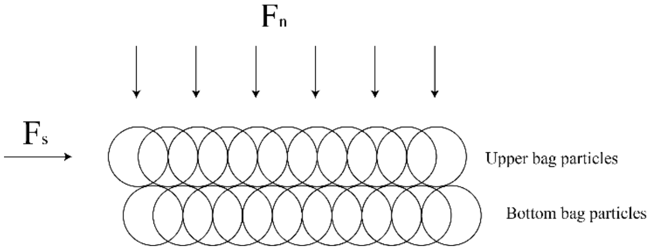
Figure 4. Numerical result of tensile model tests

3. INTERFACE FRICTION OF BAGS

The stability of retaining structures constructed with soilbags is closely related to the interlayer friction of soilbags which is influenced by the friction coefficient of bags. In previous studies, the bag was always modelled as bonded particles, and the neighboring bag particles are connected in their normal direction with the reference gap of zero. This will cause a large gap between the neighboring bag particles, which will make the upper bag particles embedded in the gap when the two soilbags are arranged vertically, as shown in Fig 5(a). Overlapping particles, therefore, were used in the model to reduce the size of the gap, the size of the overlap equals to the radius of a particle, as shown in Fig.5(b). To validate the effectiveness of this method, the friction model tests on non-overlapping particles and overlapping particles were conducted. In the friction tests, the position of bottom bag particles is fixed. A constant normal force F_n was loaded on the upper bag particles, a side thrust forces F_s was then loaded on the left side of the upper bag particles.



a) Un-overlapping bag particles (rgap=0)



b) Overlapping bag particles (rgap=0.2mm)

Figure 5. Friction tests on un-overlapping and overlapping bag particles

Fig.6 shows the relationship between the peak force of F_s and normal force F_n in the friction model tests. It can be seen that the relationships both for un-overlapping particles and overlapping particles are linear. Because the surface for both particles is not smooth, both friction coefficients are bigger than the input parameter of 0.2. However, as a result of a relatively smooth surface, the friction coefficient of overlapping particles is smaller than that of un-overlapping particles, and we believe that using overlapping particles in the model will be more appreciate compare with the un-overlapping particles when the shear characteristics of stacked soilbags are studied in the future.

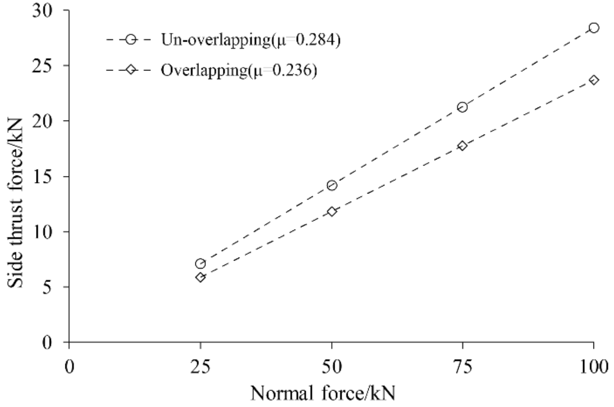


Figure 6. Relationship between the peak force of F_s and normal force F_n in friction model tests.

4. COMPRESSION STRENGTH PROPERTIES OF SOILBAG

4.1 Theoretical strength of soilbag

First, the 2D strength formula of the soilbag derived by Matsuoka et al. (2003) was reviewed. Fig.7 shows a soilbag subjected to external principal stresses σ_1 and σ_2 in a two-dimensional manner. Under the actions of σ_1 and σ_2, the soilbag usually tends to be flat, accompanied by the extension of the total perimeter of the bag. As a result, a tensile force T is produced along with the bag, which in turn produces additional stress on the soil particles inside the bag. The components of the additional stress are expressed as

$$\sigma_{01}=2T/(B\times 1); \quad \sigma_{03}=2T/(H\times 1); \tag{2}$$

where B and H are the width and height of the soilbag, respectively. Thus, the stresses acting on the soil wrapped in the bag are the combined result of the externally applied stresses and the produced stresses by the bag tensile force T. At failure, the following equation holds:

$$\sigma_1+2T/B=\mathrm{K}_\mathrm{p}(\sigma_2+2T/H) \tag{3}$$

where $\mathrm{K}_\mathrm{p}=(1+\tan\varphi)/(1-\tan\varphi)$ and φ is the internal angle of friction of the wrapped soil.

By comparing Eq. (3) with the strength expression of $\sigma_1 = \mathrm{K_p}\sigma_2 + 2c\sqrt{\mathrm{K_p}}$ for a cohesive-frictional material, the following expression of the apparent cohesion, *c*, of the soilbag resulting from the bag tension T is obtained.

$$\sigma_T = \frac{T}{B\sqrt{K_\mathrm{p}}}\left(\frac{B}{H}\mathrm{K}_p\text{-}1\right) \qquad [4]$$

Thus, soilbag can be taken as a cohesive-frictional material with an apparent cohesion *c* as expressed in Eq. (4) and the same internal friction angle as that of the material contained in the bag.

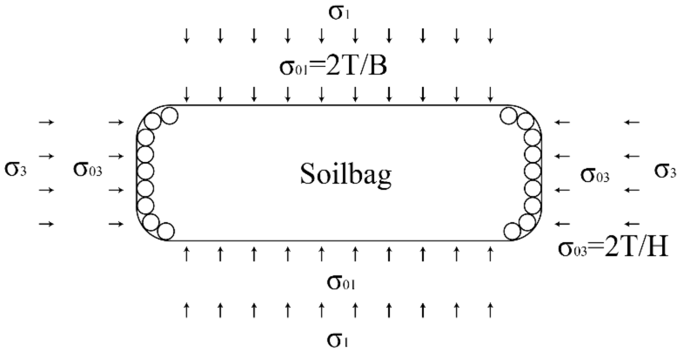


Figure 7. Stresses acting on particles inside soilbag

4.2 Numerical results of biaxial tests on soilbag

Fig. 8 gives the numerically simulated stress-strain relations of soilbag at 50kPa. The failure of the specimens under the confining stresses σ_2 results from the breakage of the bags, accompanying with the rapid decrease of the deviatoric stress. The shear strengths of the specimens were taken as the deviatoric stresses at the bag broken points. The shear strengths of the specimens were taken from the peak values of the deviatoric stresses during shearing.

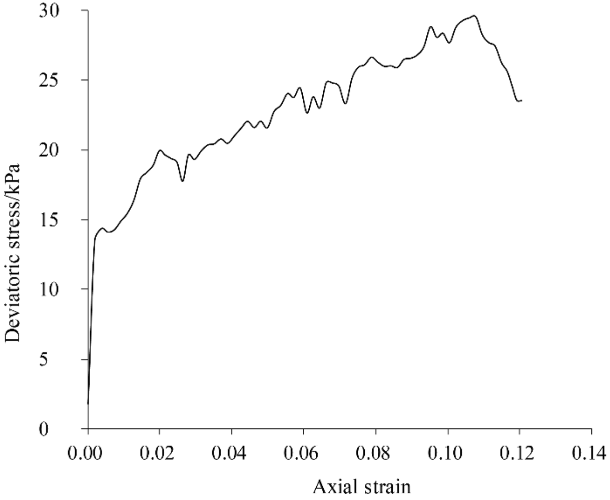


Figure 8. Deviatoric stress versus axial strain of soilbag at the confining pressure of 50kPa

Fig.9 shows the results of the biaxial model tests on soilbag and the theoretical strength of soilbag. It can be seen the model results are in good agreement with the theoretical results. The reason for the little different is that the induced tensile force T along the bag is assumed to be uniform in the theoretical strength of soilbag, it is not, however, uniform in a real soilbag as well as in this model, as shown in Fig.10.

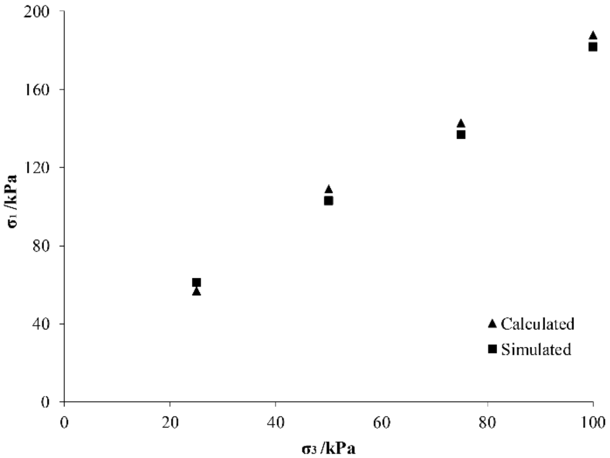


Figure 9. Results of the biaxial model tests on soilbag and the theoretical strength of soilbag

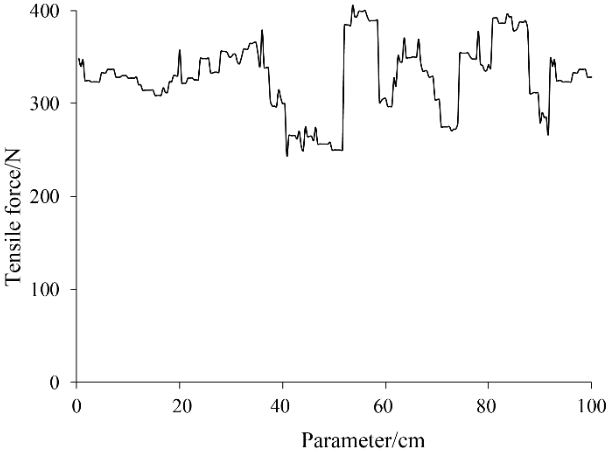


Figure 10. Distributions of the tensile forces around the circumferences of the bag at the confining pressure of 50kPa

5. COMPRESSION STRENGTH PROPERTIES OF SOILBAG

An improved discrete element model has been developed for soilbag. The bag was modelled as overlapped bonded particles using the linear contact bond model, and the soil was modelled as unbonded particles using the linear contact model. The model for soilbag has been evaluated using simulations of biaxial experiments and comparing with available data. Additionally, the interface friction coefficient of bags was also verified. Further DEM work based on this model will concentrate on studying the shear strength and deformation of stacked soilbags.

ACKNOWLEDGEMENTS

This work was supported by the China Scholarship Council (No. 201806710071). These supports are gratefully acknowledged.

REFERENCES

Ansari, Y., Merifield, R., Yamamoto, H., & Sheng, D. (2011). Numerical analysis of soilbags under compression and cyclic shear. *Computers and Geotechnics*, 38(5): 659-668.
Cheng, H., Yamamoto, H., & Thoeni, K. (2016). Numerical study on stress states and fabric anisotropies in soilbags using the DEM. *Computers and Geotechnics*, 76: 170-183.
Ding, G. Y., Wu, J. L., Wang, J., Fu, H. T., & Liu, F. Y. (2018). Experimental study on vibration reduction by using soilbag cushions under traffic loads. *Geosynthetics International,* 25(3): 322-333.
Fan, K., Liu, S. H., Cheng, Y. P., & Wang, Y. (2019). Sliding stability analysis of a retaining wall constructed by soilbags. *Géotechnique Letters*, 9(3): 211-217.
Itasca Consulting Group, Inc. (Itasca). (2018). *Particle flow code in two dimensions (PFC2D)*, Itasca, Minneapolis.

Matsuoka, H. and Liu S.H. (2003) New earth reinforcement method by soilbags (" Donow"). *Soils and Foundations,* 43(6): 173-188.

Matsuoka, H. and Liu, S. H. (2014). *A new earth reinforcement method using soilbags*. CRC Press, London, UK:.

Liu, S. H. (2017). *Principle and application of soilbags*. Science Press, Nanjing, China.

Liu, S. H., Jia, F., Shen, C. M., and Weng, L. P. (2018). Strength characteristics of soilbags under inclined loads. *Geotextiles and Geomembranes*, 46(1): 1-10.

Liu, S., Fan, K., & Xu, S. (2019). Field study of a retaining wall constructed with clay-filled soilbags. *Geotextiles and Geomembranes,* 47(1), 87-94.