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Effect of particle elongation on shearing behavior of soil

Zeng-Le Ren[1,2], Yi Pik Cheng[1], Xiaomin Xu[2] & Nuo Duan[3]

[1] *Department of Civil, Environmental and Geomatic Engineering, Chadwick Building, University College London, Gower Street, London WC1E 6BT, United Kingdom*

[2] *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, UK, CB2 1PZ, United Kingdom*

[3] *Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, UK, CB2 1PZ, United Kingdom*

1 INTRODUCTION

Both experimental studies (Cho et al. 2006, Cavarretta et al. 2010, Altuhafi & Coop 2011) and numerical studies (Coetzee 2016, Nie et al. 2019) showed that particle shape plays a significant role in influencing the most fundamental mechanical behavior of granular materials. Measurements, such as morphology (or form), roundness and surface texture (or roughness), were commonly used to characterize shape of soil particles. Form is the first scale property which describes the global shape of a particle (Sneed & Folk 1958); roundness is the second scale order property which reflects the sharpness or angularity of corners; surface texture or surface roughness, the third scale, is generally regarded as too small to influence the overall shape.

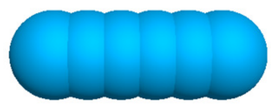
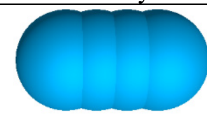
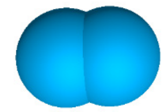
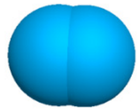
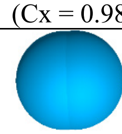
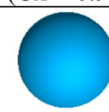
The discrete element method (DEM) could be used to model particle shape factors. It provides the possibility to explore how and to what extent one of specific shape factors affects soil behavior. A comprehensive study on DEM models with different particle shapes will lead to a better understanding of soil behavior. The numerical modelling in this study was conducted with Particle Flow Code (*PFC3D*) version 5.0, Itasca (2014). In this paper, the elongation effect of particle shape on shear behavior of soil particles based on numerical direct shear tests is presented.

2 DESIGN AND ANALYSIS

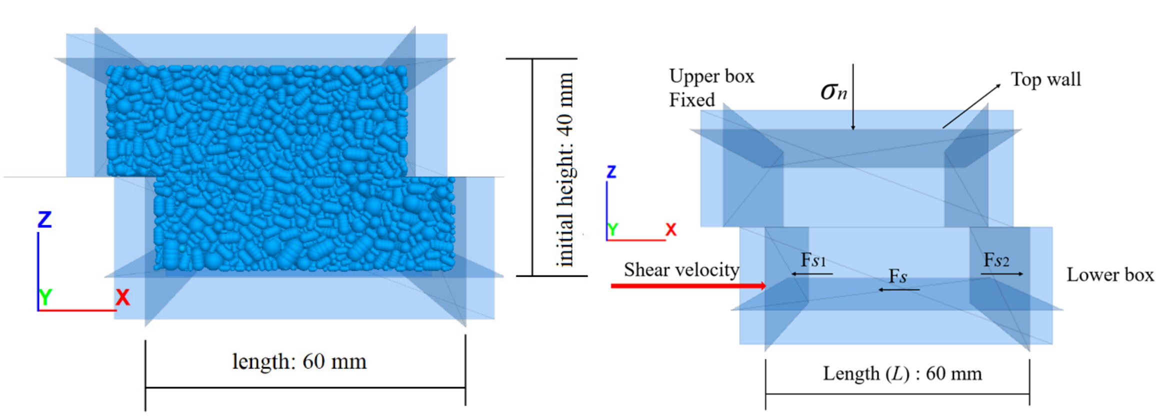
e soil particles were categorized by their shapes as elongated, convex or round, according to the elongation index (suggested by Blott & Pye 2008), convexity index (suggested by Yang & Luo 2015) and roundness index (Wadell 1932). In order to study the elongation effect of particle shape on shearing behavior of soil individually, both convexity index and roundness index of particle shape should be kept constant. The quantification of elongation index is relevant to the length of the three representative axes: the longest axis with the length L, the medium axis with the length I and the shortest axis with the length S, whereas the convexity index and roundness are relevant to particle volume and particle radius, respectively. Table 1 shows the different ranges of elongated shapes used in this study to investigate elongation effect on soil shearing behavior. To avoid the effects of convexity and roundness, the radius of the spheres making up an element shape are identical, therefore the roundness equals to 1.0. Besides, spheres in each element shape were generated as adjacently as possible to keep the convexity of the element shape similar.

For specimen generation, the soil sample (take EI = 1.0 as an example) was initially prepared randomly by generating 15,664 spheres particles with diameters ranging from 0.52 mm to 5.6 mm (following particle size distribution of Fujian standard sand but scaled up by 7 times). The sand was modelled as unbounded particles with the linear contact model in a box of size 60 mm (Length) × 60 mm (Width) × 40 mm (Height) with rigid frictionless walls. Sample preparation at the densest state was used in this paper. The specimen is enclosed by 10 rigid boundaries, including the top, the bottom, two at the front, two at the back, two at the left, and two at the right of the specimen. In order to prepare a dense specimen, the initial value of porosity and inter-particle friction are set to 0.15 and 0.0, respectively. Once the DEM assembly has been generated, a numerical servo-control mechanism was activated to compress the specimen to reach a 4.5 kPa isotropic stress state, and the inter-particle friction were changed to 0.2 before compressing the specimen to reach a 5.0 kPa isotropic stress state.

Table 1. Particle shape with different elongation index values used in this study.

Elongation Index (EI) Effect Convexity (Cx) = 0.96 ~1.0 Roundness (R) = 1.0	 EI = 0.35 (Cx = 0.96)	 EI = 0.53 (Cx = 0.98)	 EI = 0.7 (Cx = 0.98)
	 EI = 0.8 (Cx = 0.99)	 EI = 0.95 (Cx = 0.99)	 EI = 1.0 (Cx = 1.0)

Prior to shearing, specimen was consolidated to the target stress (σ_n) of 30 kPa. During shearing, the lower section of the box was moved horizontally at a velocity of 1 mm/s. The servo-mechanism for Z direction was turned on, while the servo-mechanism for X and Y direction were turned off. Therefore, the top platen was allowed to move vertically, while the lateral boundaries were restrained from moving vertically. The inter-particle friction was kept constant value of 0.2, and the friction between particle and wall was 0. Other parameters for the DEM simulations such as the effective modulus of 40 MPa, the damping value is 0.7, and the ratio of normal stiffness to shear stiffness of 1.2 were chosen for the soil particles. For each stage, the standard of the equilibrium state was the maximum contact force ratio reaching 0.001. The horizontal displacement was measured by recording the movement of bottom walls. The vertical displacement was measured by recording the movement of the top wall. Figure 1a shows the illustration of sample (EI = 0.53) at the end of shearing. Figure 1b shows the illustration of the calculation of shear force. The shear force F_s is the summation of shear forces acting on the left-side wall (F_{s1}) and the right-side wall of the lower box (F_{s2}). The length and width of the shear box are L and W, respectively. If the box is sheared at a velocity of v, then at any time t, the contacted shearing area of the shear band incorporating the shear displacement is W (L-vt). Then the shear stress (τ_s) could be calculated as: $\tau_s = \frac{Fs}{W(L-vt)}$. The shearing was stopped when reaching 10 mm shearing displacement.



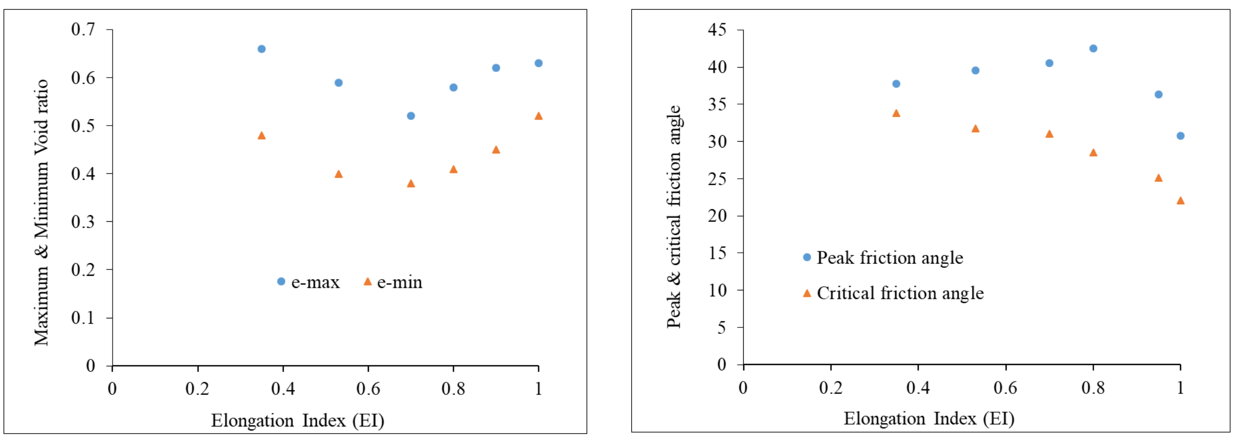
(a) (b)

Figure 1. The 3D DEM direct shear test model: (a) element shape EI = 0.53 at the end of shearing state; (b) calculation of shear stress.

3 RESULTS AND DISCUSSION

Figure 2 presents the numerical results obtained from direct shear tests on *PFC* models with various elongated particle shapes under vertical stress of 30 kPa. Both the convexity and roundness are constant. Figure 2a shows the elongation effect on initial maximum and minimum void ratio. It was observed that, both the maximum and minimum void ratio decrease to reach minimum values for EI = 0.7, then present an increasing trend with an increase of EI values. Similar trend was reported by Cecile (2010) numerically. It seems that particles with some angularity tend to reach a denser initial state first. However, too elongated particles reduce the ability to move or rotate, leading to an expected larger void ratio.

Figure 2b shows the elongation effect on shear peak and critical friction angle. When the EI value ranges from 0.35 to 0.8, the peak friction angle shows an increasing trend with an increase of EI value. When the EI value ranges from 0.8 to 1.0, the peak friction angle shows a decreasing trend with the particles becoming not elongated. However, the critical friction angle decreases with an increase of EI value. The trend for critical friction angle of various elongated particles agrees with the available experimental data reported (Cavarretta et al. 2010, Yang & Luo 2015, Altuhafi et al. 2016). However, only the peak friction angle for particles with EI values ranging from 0.8 to 1.0, the numerical results agree with the reported experimental results. The reason is that current particle shape experimental studies may only regard the typical EI value for sand is ranging from 0.7 to 0.98. They do not consider too elongated particles like the EI value ranges from 0.3 to 0.6. That means there is a transition point when considering the effect of EI on particle shear behavior.



(a) (b)

Figure 2. Particle Elongation (EI) effect on soil behavior: (a) initial maximum and minimum void ratio; (b) shear peak and critical friction angle – EI relationship.

4 CONCLUSIONS

In this paper, a method to prepare samples using *PFC3D*, considering elongation, convexity and roundness based on numerical direct shear tests was proposed. It would provide the possibility to investigate the contribution of one of specific shape factors to the shearing behavior of soil.

It shows that for the range of EI values studied and for the samples under the same normal stress level, particles with some angularity are denser than that of spherical particles, however, too elongated particles present a larger void ratio. For shearing behavior, a transition point exists in investigating the elongation effect on peak friction angle of soil, while the critical friction angle of sand particles decreases linearly with an increase of elongation index value.

REFERENCES

Altuhafi, F.N. & Coop, M.R. 2011. Changes to particle characteristics associated with the compression of sands. *Géotechnique*, 61 (6), pp. 459-471.

Altuhafi, F.N., Coop, M.R. & V.N. Georgiannou. 2016. Effect of particle shape on the mechanical behavior of natural sands. *J. Geotech. Geoenviron. Eng*. 142 (12): 04016071.

Blott, S.J. & Pye, K. 2008. Particle shape: a review and new methods of characterization and classification. *Sedimentology*, 55, 31– 63.

Cavarretta, I., Coop, M.R. & O'Sullivan, C. 2010. The influence of particle characteristics on the behaviour of coarse grained soils*.* *Géotechnique* 60, No. 6, 413–423.

Coetzee, C.J. 2016. Calibration of the discrete element method and the effect of particle shape. *Powder Technol*., 297, 50-70.

Cho, G.C., Dodds, J. & Santamarina, J.C. 2006. Particle shape effects on packing density, stiffness, and strength: natural and crushed sands. *J. Geotech. Environ. Engng* ASCE 132, No. 5, 591–602.

Itasca Consulting Group, Inc. 2014. *PFC3D – Particle Flow Code in 3 Dimensions, Ver. 5.0.* Minneapolis: Itasca.

Nie, Z.H., Zhu, Y.G. & Gong, J. 2019. Investigating the effects of Fourier-based particle shape on the shear behaviors of rockfill material via DEM. *Granular Matter*, 21:22, https://doi.org/10.1007/s10035-019-0875-9.

Nouguier-Lehon, C. 2010. Effect of the grain elongation on the behaviour of granular materials in biaxial compression. *Computes Rendus Mecanique* **338**, 587–595.

Sneed, E.D., & Folk, R.L. 1958. Pebbles in the lower Colorado River, Texas a study in particle morphogenesis. *The Journal of Geology*, 66(2), 114-150.

Wadell, H. 1932. Volume, shape, and roundness of rock particles. *The Journal of Geology*, 40(5), 443-451.

Yang, J. & Luo, X.D. 2015. Exploring the relationship between critical state and particle shape for granular materials. *J. Mech. Phys. Solids*. **84**, 196–213.