Main features of two simple bond contact models for bonded granulates: PFC model and Jiang model

Caractéristiques principales de deux simple modèles de contacts pour matériaux cimentés : le modèle de PFC et de Jiang

Mingjing Jiang, ISSMGE member, Haibin Yan
Department of Geotechnical Engineering, Faculty of Civil Engineering, Tongji University, Shanghai, China, 200092

ABSTRACT

This paper presents a numerical investigation on the main features of these two bond contact models by using the Distinct Element Method (DEM). The DEM study shows that: (1) PFC model can be described by the physical model in Jiang model, in which a rigid bond element is introduced into both tangential and normal models. (2) Their peak strength at a single contact is identical in tension, but different in tangential direction. (3) Their bonded samples demonstrate strain-softening and shear-dilatancy in biaxial compression tests, which cohesions increase with the increasing of bond strength. However, in contrary to PFC samples, the peak frictional angle of Jiang samples increases with the increasing of bond strength which is in good agreement with the experimental data.

RÉSUMÉ

Cet article présents un étude numérique sur les caractéristiques des deux modèles de contacts cimentés utilisés dans la Méthode des éléments discrets. Les résultats sont les suivants : 1) le modèle de PFC peut être inclus dans le modèle de Jiang constitué par un élément rigide sois pour la direction tangentielle sois pour la direction normale. 2) la résistance maximum est la même pour les deux modèles en direction normale (tension), mais différent en direction tangentielle. 3) les échantillons numériques soumis à compression bi axiale sont caractérisés par un comportement de strain-softening et dilatance. L'angle de frottement maximum obtenu par le modèle de Jiang, au contraire du modèle PFC, augmente quand la résistance du contact cimenté est augmentée. Ce comportement numérique reproduit les données expérimentales.

Keywords : Bond contact model, PFC model, Jiang model, mechanical behaviour, distinct element method

1 INTRODUCTION

It is known in the geotechnical community that most natural soils (sands) in situ are micro-structured soils. An important feature of such soils is the availability of interparticle bonds at particle contacts, which behavior plays an important role in natural soil mechanics. It is difficult to investigate the bonding effect by experiment, mainly because quantitative data on all bonds within the samples is still unavailable in geo-laboratory.

An effective and convenient approach to examine the effect of bonds is to carry out numerical tests on bonded materials by using the discrete element method (DEM). DEM is a numerical method which simulates the mechanical behavior of an assembly of arbitrarily shaped discrete bodies. The classical contact model proposed by Cundall and Strack (1979) for dry granulates consists of two parts: a normal and a tangential contact model. The physical models of the two parts are shown in Figure 1. They both include a spring maintaining an elastic relation between contact force and relative displacement, and a dashpot dissipating energy. The normal model includes a divider, so that the contact can not transfer tension force, while the tangential model includes a slider to provide the contact a shear resistance controlled by the Mohr–Coulomb criterion.

Based on the classical contact model for dry granulates, Jiang et al (2002, 2005, 2007) proposed a simple bond contact model (namely Jiang model hereafter) for bonded granulates in their DEM code NS2D to investigate the mechanical behavior of naturally micro-structured soils. There is also a simple bond contact model in the DEM commercial software PFC2D developed by Itasca Consulting Group, Inc. (2004), namely PFC model in this paper, which aim was initially to generate clusters of particles in Distinct Element Method (DEM) analyses so that the internal frictional angle of DEM material can be increased to that of real sands.

In order to investigate the difference between the two models, this paper presents an investigation on the main features of these two bond contact models. In the paper, first, the main features of the two models were introduced. Second, Jiang model was incorporated into PFC2D. Then, the PFC2D was used to simulate compression, tension and shear tests on two disks in contact which are controlled by the two bond contact models respectively. Finally, the PFC2D was used to perform biaxial tests on loose bonded granulates.

2 TWO BOND MODELS

2.1 *Jiang model*

Jiang et al. (2002, 2005, 2007) proposed a simple bond contact model for bonded granulates by introducing a rigid-plastic bond element into the classical normal and tangential contact model, respectively, as illustrated in Figure 1. This bond element has its peak strength R, with its behavior defined in terms of external force F and displacement as follows

$$u = 0 \text{, if } F < R \text{ ; the bond is intact} \quad (1a)$$
$$u = \infty \text{, if } F \geq R \text{ ; the bond is broken and } F = 0 \quad (1b)$$

As shown in Fig. 1, the normal and tangential components of the model are similar in their principle. Note that a rigid bond element is set to be in parallel with a slider in the tangential contact model to produce shear resistance. The physical model for bonds in Fig. 1 will reduce to the classical contact model for dry granulates proposed by Cundall and Strack (1979) when the bond elements are broken or excluded. The mechanical performance of the normal (tangential) bond contact model can be expressed in terms of normal (tangential) relative displacement u_n (u_s) and contact force F_n (F_s). The normal

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-582

(tangential) model is mainly characterized by a constant stiffness parameter K_n (K_s) (in N/m in a 2-D system) and a normal (tangential) bonding strength R_{nb} (R_{tb}) (in N).

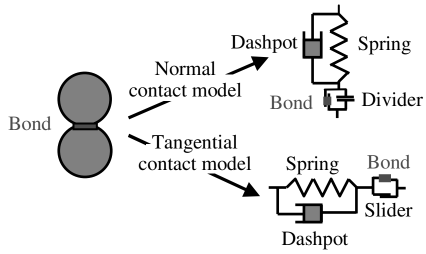


Figure 1. Simple bond contact model proposed by Jiang et al (2002).

2.2 *PFC2D model*

In PFC2D, a contact model consists of three parts: a stiffness model, a slip model, and a bonding model. The stiffness model reflects an elastic behavior of the contact. The slip model provides the contact a shear resistance controlled by the Mohr–Coulomb criterion. The bonding model provides the contact a tension or shear resistance before failure. The readers can refer to a manual on PFC2D for more details. This PFC bond model seems similar to Jiang model. But they are different on many aspects, as will be shown in next sections.

3 MAIN MECHANICAL PERFORMANCE OF TWO BOND MODELS

In this study, Jiang model was firstly incorporated into PFC2D and a series of compression, tension and shear tests, plotted in Fig. 2, were carried out by using the PFC2D on two disks in contact which are controlled by the two bond contact models respectively. In the tests, first, create two disks in contact but without overlap and generate a bond at the contact which is controlled by the two bond contact models respectively. Second, let the two disks reach an equilibrium state. Finally, fix one disk and move the other at a constant velocity. Note that no rotation was allowed for the two disks during the tests. Table 1 provides the material parameters used in the contact tests.

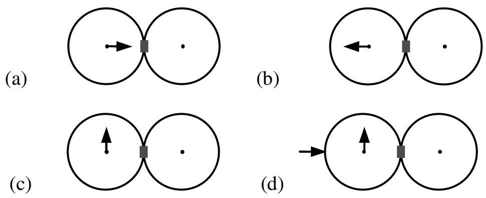


Figure 2. Tests on two particles in bonded contact: (a) compression test; (b) tension test; (c) shearing test; (d) combined loading test.

Table 1. Material parameters used in DEM analysis of single contact tests

Density of particles (kg/m3)	2,600
Normal spring stiffness (N/m)	1.5×10^7
Tangential spring stiffness (N/m)	1.0×10^7
Normal bond strength (N)	500
Tangential bond strength (N)	500
Interparticle coefficient of friction	0.5
Local damping coefficient	0.7
Viscous damping coefficient (normal and shear)	0.7

Figure 3 presents mechanical performances of two bond models obtained in DEM compression, tension and shear tests on bonded contacts. Fig. 3 shows that the two models are linearly elastic in compression, and elasto-brittle-plastic in both tension and shear. In addition, there is no difference between the two models in compression and tension tests. This shows PFC model can be described physically by the physical model in Fig. 1, in which a rigid bond element is introduced into both tangential and normal models. However, Fig. 3 shows the peak shear strength in Jiang model is larger than that in PFC model. This feature can be further clarified by the combined loading test illustrated in Fig. 2(d), in which the same friction coefficient but different normal forces were used.

Figure 4 provides the shear strength envelopes in the two models obtained in DEM tests on bonded contacts. Fig. 4 shows that PFC model presents a tangential strength of bond independent of normal contact force, while the strength in Jiang model increases with normal contact force. The shear strength in Jiang model is larger than that in PFC model under the same condition.

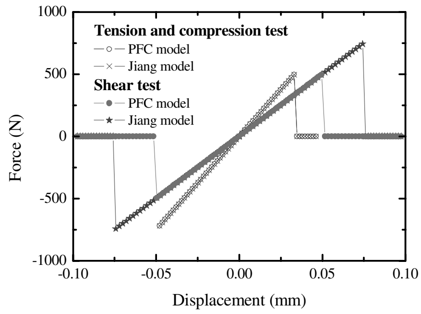


Figure 3. Mechanical performances of two bond models obtained in DEM tests on a single bonded contact

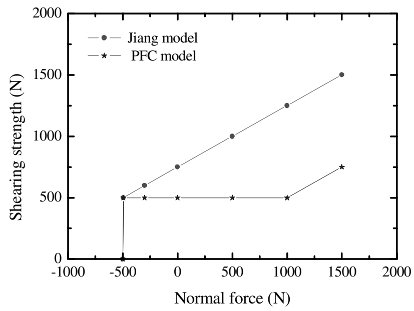


Figure 4. Shear strength envelopes in two models obtained in DEM tests on bonded contacts

4 BIAXIAL TESTS ON BONDED GRANULATES

The PFC2D was used to simulate a total of 25 biaxial tests on bonded granulates, including 20 tests on bonded granulates controlled by the two bond contact models respectively and 5 tests on unbonded granulates.

4.1 *DEM specimen*

A material of a particle size distribution used by Jiang et al (2002), with ten types of particles, was used to form biaxial compression test sample. The sample has a width of 800 mm and a height of 1,680 mm. The planar void ratio of sample is 0.27, which is very loose here. The total number of sand particles in the sample is 24,000. In order to simulate the membrane boundary used in geo-lab, a flexible side boundary consists of bonded particles was used in the DEM simulation of biaxial compression test. The material parameters of sand particles and membrane particles used in DEM simulations are summarized in Table 2. The top and bottom boundaries are rigid walls with the same normal and tangential contact stiffness as the sand particles. In addition, the coefficient of friction between wall and particle is set to zero.

The multi-layer under-compaction method proposed by Jiang et al (2003) was used to generate samples. During the generation process, all of the boundaries are walls. The generation procedure is summarized as follows.

(1) Multi-layer. The sample is constituted of five horizontal layers, and each layer contains 4800 particles distributed randomly in an area with the width of 800 mm and the height of 437 mm, corresponding to a planar void ratio of 0.65. These

particles are then statically compacted to a targeted planar void ratio by moving downward the top wall at a constant and large speed, 5.0 m/s here, while the lateral and bottom walls being fixed. The coefficient of friction at inter-particle contacts is set to 1.0 during the generation process so that the sample can keep a very loose state.

(2) Under-compaction. In order to get a homogenous sample and to ensure that all the layers achieve a final average planar void ratio e_p^f =0.27, the bottom layer, 1, must be compacted at a planar void ratio $e_p^{(1)}$ larger than e_p^f (namely under-compaction). Similarly, the compaction of the second layer, 2, ensures that the layers 1 and 2 have an average planar void ratio $e_p^{(1+2)}$ larger than e_p^f . This step is repeated until the final layer, n, which is compacted directly to achieve $e_p^{(1+2+\cdots+n)}$ = e_p^f . The distribution of $e_p^{(1)}$, $e_p^{(1+2)}$, …, $e_p^{(1+2+\cdots+n)}$ has to be determined by trial and error, and it satisfies $e_p^{(1)} > e_p^{(1+2)} >$ ... $> e_p^{(1+2+\cdots+n)} = e_p^f$. Here the optimum values are: $e_p^{(1)}$ = 0.29, $e_p^{(1+2)}$ = 0.288, $e_p^{(1+2+3)}$ = 0.285, $e_p^{(1+2+3+4)}$ = 0.28, $e_p^{(1+2+3+4+5)} = e_p^f = 0.27$.

Table 2. Material and membrane parameters used in DEM simulations of biaxial tests

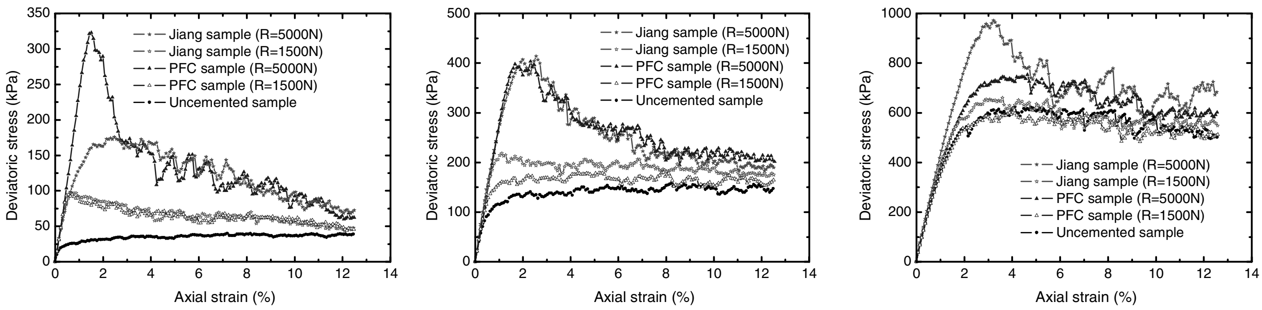
Local damping coefficient	0.5
Density of particles (kg/m3)	2,600
Normal spring stiffness (N/m)	7.5×10^7 in tests; 7.5×10^9 in specimen generation
Tangential spring stiffness (N/m)	5.0×10^7 in tests; 5.0×10^9 in specimen generation
Normal contact stiffness between sand and membrane (M in short) (N/m)	3.75×10^6
Diameter of M particles (mm)	2.0
Density of M particles (kg/m3)	1,000
Normal bond strength for M particles (N)	1.0×10^{100}
Shear bond strength for M particles (N)	1.0×10^{100}
Normal contact stiffness for M particles (N/m)	3.75×10^6

The interparticle coefficient of friction is set to 0.5 after the generation of sample. The sample is then consolidated under a small vertical pressure of 12.5 kPa with the side boundary fixed. After that, all the contacts between sand particles are bonded with Jiang model or PFC model in different samples, namely Jiang sample and PFC sample, respectively. For simplicity, the normal and tangential bond strengths of all the bonds were set to the same value. Then the membrane particles are used to replace the side walls, and the sample is subjected to an isotropic constant confining pressure to a stable state. Finally, the sample is under the constant confining pressure with the top wall moving downwards and the bottom wall moving upwards at a constant velocity of 6.0% per minute. Some comparative tests under different loading rate were performed to evaluate if the loading rate could influence the test results. However, no significant difference was found in preliminary study.

A series of numerical biaxial compression tests have been performed with different bond strength (0, 1500, 5000 N) and under different confining pressure (50, 100, 200, 400, 800 kPa).

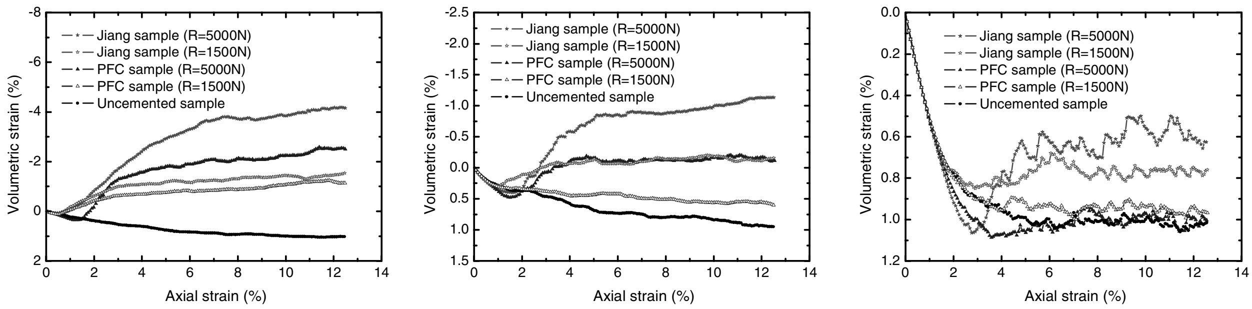
4.2 *Mechanical response of bonded granulate specimen*

Figures 5 and 6 provide the numerical results obtained from biaxial compression tests on these two kinds of ideal bonded sands under the confining pressures of 50, 200 and 800 kPa. For reference, the responses of unbonded samples are also presented. Figs. 5 and 6 show that the bonded samples demonstrate strain-softening and shear-dilatancy, which is enhanced by the increasing of bond strength. The brittle stress-strain response and dilative volumetric response of the Jiang sample are distinct at any value of the confining pressure, while the similar response can be found under low confining pressure in the PFC sample but vanishes with the increasing confining pressure. In comparison to the unbonded sample of the same void ratio, Figs. 5 and 6 show that cementation alters the stress-strain response from the strain-hardening to the strain-softening and the volumetric response from contraction to dilation. Cementation leads to an increased peak deviatoric stress, and shear banding. The numerical results, especially the results from the Jiangsample, are in good agreement with the experimental data obtained by Wang and Leung (2008). Figure 7 presents the peak and residual strength envelops of the bonded samples with different bond strength, respectively. The strength envelops of unbonded sample are also presented for reference.



(a) (b) (c)

Figure 5. Stress-strain response of bonded sands with different bond strength under different confining pressure in DEM simulations: (a) σ_3 =50kPa; (b) σ_3 =200kPa; (c) σ_3 =800kPa.



(a) (b) (c)

Figure 6. Volumetric response of bonded sands under different confining pressure in DEM simulations: (a) σ_3 =50kPa; (b) σ_3 =200kPa; (c) σ_3 =800kPa.

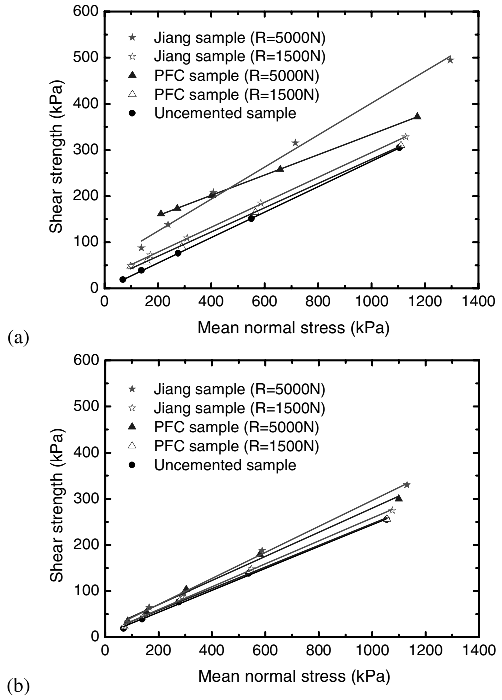


Figure 7. Strength envelops of bonded sands with different bond strength: (a) peak strength; (b) residual strength.

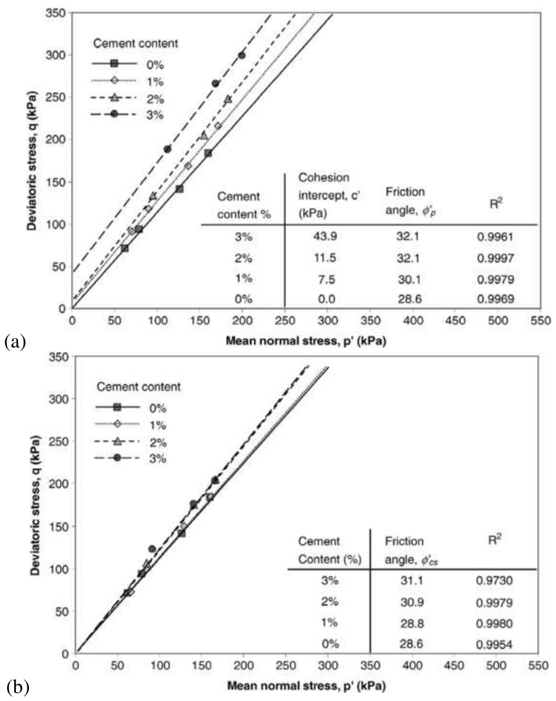


Figure 8. Strength envelope of cemented sand with different cement content obtained experimentally by Wang and Leung (2008): (a) peak-state strength; (b) residual strength.

Fig. 7 shows that the peak and residual strength of the two bonded samples is larger than that of the unbonded sample. Their cohesions increase with the increasing bond strength. However, their frictional angles vary in different ways. The peak frictional angle of Jiang samples increases with the increasing of bond strength, while PFC samples decrease with the bond strength. In contrast, their residual frictional angles increase with the increasing of bond strength. The varied enhancement of friction angle of the Jiang sample follows a general trend: It increases with increasing bond strength but is suppressed by confinement. This trend is in good agreement with the experimental data in Fig. 8 obtained by Wang and Leung (2008).

5 CONCLUSIONS

There are two simple bond contact models for bonded granulates, in which bond rolling resistance is not taken into account, proposed by Itasca Consulting Group, Inc. (2004) in PFC2D and by Jiang et al (2002) in their NS2D respectively. The initial aim of the former model was to generate clusters of particles in Distinct Element Method (DEM) analyses, while the latter to investigate the mechanical behavior of naturally-microstructured soils. This paper presents an investigation on the main features of these two bond contact models. The DEM study shows that:

(1) The two models show linear elastic behavior in compression, and elasto-brittle-plastic behavior in both tension and shear directions. Both the models reduces to the classical contact laws for dry granulates after bonds are broken. Such behaviors can be described physically by the physical model in Jiang model, in which a rigid bond element is introduced into both tangential and normal models.

(2) The peak strength at the contact is the same in tension direction, but different in tangential direction in the two models. The tangential strength of bonds in Itasca model is independent of normal contact force, while it is assumed to be dependent on normal force in Jiang model. The shear strength in Jiang model is larger than that in PFC model under the same condition.

(3) Their bonded samples demonstrate strain-softening and shear-dilatancy in biaxial compression tests. The peak and residual strength of the two bonded samples is larger than that of the unbonded sample, which cohesions increase with the increasing of bond strength. The peak frictional angle of Jiang samples increases with the increasing of bond strength, while PFC samples decrease with the bond strength. In contrast, their residual frictional angles increase with the increasing of bond strength. The varied enhancement of friction angle of the Jiang sample is in good agreement with the experimental data obtained by Wang and Leung (2008).

ACKNOWLEDGEMENTS

The financial support from NSFC project with grant No. 50679057, Pujiang Talents Project with grant No. 06PJ14088, Shanghai, China, and Fund for Chinese Researchers Returning from Overseas with grant No. 2007-1108 are greatly appreciated.

REFERENCES

Cundall, P. A. and Strack, O. D. L. (1979), A discrete numerical model for granular assemblies, Geotechnique, 29, 47-65

Itasca Consulting Group, Inc. (2004), PFD2D- Particle Flow Code in 2 Dimensions, Version 3.1, User's Manual. Minneapolis: Itasca.

Jiang, M.J., Leroueil, S., and Konrad, J.M. (2002), DEM study of micro structured soil. 55th CSCE-ASCE conference, Hamilton, Ontario, Canada, 313-320

Jiang, M.J., Leroueil, S., and Konrad, J.M. (2005), Yielding of micro-structured geomaterial by Distinct Element Method analysis. Journal of Engineering Mechanics, ASCE, 131(11), 1209-1213

Jiang, M.J., Yu, H-S and Leroueil, S. (2007), A simple and efficient approach to capturing bonding effect in naturally-microstructured sands by Discrete Element Method. Int. J. Num. Meth. Eng., 69, 1158-1193.

Jiang, M. J., Konrad, J. M., and Leroueil, S. (2003), An efficient technique for generating homogeneous specimens for DEM studies. Computers and Geotechnics, 30(7): 579–597.

Wang, Y. H., and Leung, S. C. (2008), Characterization of Cemented Sand by Experimental and Numerical Investigations. Journal of Geotechnical and Geoenvironmental Engineering (ASCE), 134(7): 992–1004.