Discrete element analysis of direct shear test on bonded sand

Mingjing Jiang\textsuperscript{i)}, Yiru Chen\textsuperscript{ii)} and Guowen Lu\textsuperscript{iii)}

\textsuperscript{i)} Professor, Department of Civil Engineering, Tianjin University, No.135 Yaguan Road, Tianjin 300350, China.
\textsuperscript{ii)} M.S. Student, Department of Civil Engineering, Tianjin University, No.135 Yaguan Road, Tianjin 300350, China.
\textsuperscript{iii)} Ph.D Student, Department of Civil Engineering, Tianjin University, No.135 Yaguan Road, Tianjin 300350, China.

ABSTRACT

This paper presents a three-dimensional (3D) numerical simulation of bonded sand in direct shear tests using the distinct element method (DEM), by employing a 3D contact model for bonded sand considering the size of bond. Firstly, series of direct shear tests with different vertical pressure were simulated by DEM. Then, the macroscopic characteristics of sample were analyzed along with sand sample without cementation. Finally, the bonding effect on the mechanical response of sand were studied, and the bond breakage information were studied within the shear band. The results show that the bonded sand demonstrates higher peak and residual stress as well as dilatant behavior due to cementation, and intensive bond breakage and high local void ratio are found inside the shear band.

Keywords: bonded sand, strain localization, direct shear test, distinct element method

1 INTRODUCTION

Sand formed in natural environment has certain structures, and inter-particle bonding has significance effects on mechanical response of sand, which cannot be ignored in engineering design. As a result, cementation, fabric, density and stress history together determine the macroscopic behaviour during deformation, and the characteristics are completely different from remoulded sand (Cuccovillo and Coop, 1990 and 1997). And studies on bonded sand are mainly based on laboratory tests and numerical simulations (Airey, 1993; Wang and Leung, 2008; Jiang et al, 2011). Direct shear test (DST) as an efficient and widely used experimental method can measure the mechanical properties of soil samples in a relatively easy way (Jewell and Wroth, 1987; Azadi, 2017). Because of the design of the apparatus, non-uniform deformation will occur in the shear plane and a shear band will finally be formed. However, the microscopic information is unable to be captured in the laboratory. Especially strain localization which is associated with the evolution of bond degradation should be paid closer attention (Leroueil and Vaughan, 1990; Wang and Leung, 2008; Jiang et al, 2011).

The distinct element method (DEM), firstly developed by Cundall and Strack (1979), is an effective tool to capture both macroscopic and microscopic information on the tested sample, and can provide insights behind the deformation pattern. Numerous experimental tests have been simulated by DEM (Thornton and Zhang, 2003; Wang and Leung, 2008; Jiang et al, 2011 and 2013; Shen et al, 2016). And a serie of numerical simulations performed on sand with and without cementation showed good agreement with laboratory results and were capable of simulating strain localization with its underlying mechanism explored well.

Jiang et al. (2016) have developed a 3D contact model for bonded granular material and implemented it into a commercial software PFC3D to simulate various laboratory tests. It has been proven to be a high-efficient model for bonded granular and hence is employed in this study to analyse the bonding effects on mechanical response.

2 CONTACT MODEL AND SIMULATION SCHEME

2.1 Contact model

A reasonable bond contact model is the key to simulate the mechanical properties of cemented sand by using DEM. This model incorporates the complete interactions in the normal, tangential, rolling and torsional directions. The mechanical responses of this model are illustrated in Figure 1. Furthermore, it can take the effect of bond size on bond strength and stiffness into account by employing a size-dependent bond failure criterion based on experimental studies, and has already been employed into simulation of iso-compression and triaxial tests of bonded sand. The details of this model are referred to the work by Shen and Jiang (2016), where $F_n$, $F_s$, $M_r$ and $M_t$ are the...
normal contact force, tangential contact force, moment and torque respectively; $K_n$, $K_s$, $K_r$ and $K_t$ are the normal, tangential, rolling and twisting stiffnesses respectively; $u_n$, $u_s$, $\theta_r$ and $\theta_t$ are the normal displacement, tangential displacement, relative rolling rotation and twisting rotation respectively.

Fig. 1. Mechanical responses of the contact model (a) normal direction, (b) tangential direction, (c) rolling direction, and (d) twisting direction (Jiang, 2019).

2.2 Simulation scheme

The numerical specimen is composed of spheres with the diameter ranging from 0.11mm to 0.36mm. Its grain size distribution is shown in Figure 2, and the uniformity coefficient $C_u=1.34$. An assembly of 40,000 spheres with density of 2655kg/m$^3$ was firstly generated by Under-Compaction Method (Jiang et al, 2003) with initial void ratio 0.84. The parameters used in simulation are same as the work by Jiang et al. (2018), i.e. the modulus of the particle material $E=100$MPa, inter-particle friction $\mu=0.5$, critical damping coefficient 0.7.

Then the sample was first one-dimensionally (1D) consolidated under a vertical stress of 12.5kPa, and then bonds were formed at all contacts by directly endowing these contacts with the mechanical behavior governed by the bond contact model mentioned above. Note that the relevant parameters of particles in this study were same as the work by Jiang et al. (2018) for comparison. The parameters used in this paper were determined on the basis of the 3D aluminum spheres experimental results, and the parameters of bond were adopted from Lu (2018), which are listed in Table 1.

After bonds were endowing, the sample was consolidated under vertical stress $\sigma_v$ of 50kPa, 100kPa, 200kPa, respectively, then it was sheared in a quasi-static condition by horizontally moving the upper and lower sections of the box in opposite directions at a speed rate of 1%/min. DST was carried under constant $\sigma_v$ applied through the top and bottom walls by a servo control algorithm during shearing. And to better measure the responses of sample, two measure spheres were created based on trials according to the work by Jiang et al. (2018).

Table 1. Simulation parameters of bond (Lu, 2018).

<table>
<thead>
<tr>
<th>Items</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent modulus $E$ (MPa)</td>
<td>200</td>
</tr>
<tr>
<td>Critical bonding ratio</td>
<td>0.3</td>
</tr>
<tr>
<td>Modulus reduction factor</td>
<td>0.2</td>
</tr>
<tr>
<td>Stiffness ratio</td>
<td>1.5</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>4</td>
</tr>
<tr>
<td>Compressive strength (MPa)</td>
<td>140</td>
</tr>
</tbody>
</table>

3 DEM SIMULATION RESULTS AND DISCUSSION

3.1 Stress–strain relationships, volumetric change

Figures 4 and 5 provide the stress-strain curves and void ratio evolution of sand without and with cementations. Here, shear strain is defined as shear displacement divided by sample length. The results show that the simulations can capture the main mechanical behaviors of cemented sand, such as the strength enhancement, strain softening and volumetric dilation, which were shown in both experimental tests and numerical simulations.

Previous researches have revealed that the dilatancy mainly occurs in the shear band and investigation on the properties of the shear band can help explain the shear behavior of the whole sample (Wang and Leung, 2008; Jiang et al, 2013 and 2018). The void ratio within the shear band, as in Measure sphere 2, experiences obvious change which indicates the highly non-uniform deformation in the shear band. However, the void ratio increases notably when the peak stress is exceeded, whereas it of pure sand changes a little. And the void ratios experience much bigger changes than in the bonded sand samples.

Fig. 3. (a) Measure spheres and applied vertical stress (Jiang et al, 2018), (b) numerical assembly.
Fig. 4. Stress-strain curves of (a) sand (Jiang, 2018), (b) bonded sand.

Fig. 5. The evolution of void ratio in (a) sand (Jiang, 2018), (b) bonded sand.

3.2 Micro characteristics

To further study the bonding effects on the mechanical responses, a box shape zone in the centre of sample was chosen to represent the shear band as shown in Figure 3. This zone is larger enough to contain all the particles in the shear band and eliminate possible boundary effects as well. All contacts within it were used in the analysis of the shear band below.

It has been widely accepted that the shear band in cemented granular materials is associated with bond breakage (Leroueil and Vaughan, 1990; Wang and Leung, 2008; Jiang et al, 2011). As shown in Figure 6, bond breakage ratio has almost same trend in all cases, whereas more bonds are broken in the shear band zone. Higher vertical pressure leads to higher ratio of broken bond numbers and higher peak stress. It should be noted that though \( \sigma_v \) can suppress the extent of dilatancy while bond promotes it, and \( \sigma_v \) suppressive effect plays as a more dominant factor.

The relationship between stress shared by bonds and particles was drawn in Figure 7 to quantify the strength shared by bonds with bond breakages accumulating. Deviatoric stress \( q \) is defined as:

\[
q = \sqrt{\frac{1}{3} (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}
\]  

where \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are the major, medium and minor principal stresses, respectively.

The results show that the bonding is strong, and stress is mostly shared by bonds regardless of \( \sigma_v \), so the peak and residual stresses are higher than pure sand. And when bonds start to break as shear strain increases, the stress shared by particles begins to increase a little. And because a higher \( \sigma_v \) leads to a higher bond breakage ratio, the percentage of stress shared by particles decreases as \( \sigma_v \) increases. So the deviatoric stress is mainly contributed by bonds and bond degradation leads to stress softening.

To better understand the effect of bond degradation on soil yield and strain localization, the evolution of the shear stress, void ratio and the bonds breakage ratio during DST were studied. Here bonds breakage ratio \( \eta \) (Jiang et al, 2011) is defined as followed:

\[
\eta = \frac{(N_1 - N_2)}{N} \left( \frac{\varepsilon_1 - \varepsilon_2}{\varepsilon_1 - \varepsilon_2} \right)
\]  

where \( N \) is the total number of bonds at the beginning and \( N_1 \) and \( N_2 \) stand for the number of intact bonds at strain \( \varepsilon_1 \) and \( \varepsilon_2 \), respectively.

Here only sample under \( \sigma_v =100kPa \) was selected for analysis. As shown in Figure 8, most bonds remain...
intact until it reaches point A, which can be defined as a yielding point. At the same time, the volumetric behavior changes from contractive to dilative. Then, bonds breakage rate starts to raise sharply until the peak stress (point B) is reached and passed a little, then both bonds breakage rate and shear stress drop significantly with shear strain increasing. Finally, although both the shear stress and void ratio remains approximately constant (point C), and bond breakage continues to occur at a small but non-negligible rate.

4 CONCLUSIONS

A series of DSTs on bonded sand at different vertical stresses were carried using DEM, and comparisons were made between pure and bonded sands. The feasibility of the microscopic contact model is verified and the effects of bonding were studied at macro and micro scales. The main conclusions are (1) bonding has great effects on the stress and volumetric behaviors of sand, and especially the bond breakages are more concentrated in the shear band; (2) within the shear band, the evolutions of void ratio and bond breakage experience obvious change, which should be investigated further in the future.

ACKNOWLEDGEMENTS

The research was financially supported by the National Nature Science Foundation of China with Grant Nos.51639008, 51890911.

REFERENCES