INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

DEM Modelling of crushed stone material - emphasis on the grain size distribution and porosity

Daeyoung Lee
Senior Researcher, Korea Institue of Construction Technology, Ilsan, Korea
Namkak Cho
Graduate Student of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada
Chungsik Yoo
Professor, Sungkyunkwan University, Suwon, Korea

Keywords: DEM, Crushed stone, PFC2D, Modelling, Porosity, Large scale direct shear test

ABSTRACT

In this study, a coarse material mainly containing crushed stones was modelled using PFC^{2D} a commercially available code based on a DEM(Distinct Element Method)code. The results obtained using the DEM code showed that an irregular grain shape, GSD(Grain Size Distribution) and porosity of coarse material could be modelled successfully. Using the modelled assembly, a large-scale direct shear test was simulated results showed very good agreement with the laboratory test results.
The current modeling approach can be applied to other coarse materials having various GSD and porosity. Using such modelling, prediction of the strength characteristics of coarse material at field scale would be possible.

1 INTRODUCTION

Granular material comprising crushed stone, gravels, and sandy soil has long been used as a basic construction material In geotechnical engineering, granular material has been used in diverse application such as foundations for structures, fill material in soil and rockfill dams, as a substitute for soft soil, and for reinforcing soft soil. Recently, due to dwindling supply of natural aggregates , interest in soil improvement using crushed stone has been increasing. Therefore, studies on the geotechnical strength and deformation characteristics of crushed stone are required for their use in construction. It is known that the strength and deformation characteristics of granular soil are influenced by its maximum grain size, void ratio, and grain size distribution, which are obtained by laboratory testing. However, when applying laboratory-derived strength and deformation characteristics of these materials to design and construction, in situ variability and scale effects make these laboratory-derived characteristics poor estimators of field conditions. In order to solve such a problems, large scale direct shear test or large-scale triaxial cell tests have been carried out, but these do not overcome limitations of laboratory testing. Recently, a number of modeling approaches using a DEM code with discontinuity elements representing granular material model have been presented. This method has the advantages of considering the interlocking effect, grain size distribution and void ratio, which better characterise granular particles.
In this study, in order to model the strength characteristics of crushed stone used in stone column and granular piles, a DEM(Distinctive Element Method) code was used considering the grain size distribution and void ratio of the granular materials, and the results were compared with those obtained from the large-scale direct shear test on crushed stone. This modelling method provided an estimate of the strength characteristics of granular materials, which previously required laboratory and in situ testing.

2 TEST MATERIAL AND DEM (DISTINCT EMEMENT METHOD) MODELING

2.1 Test material

The test material used in this study was crushed stone with a grain size ranging from 5 to 10mm. To examine the basic properties of the material, specific gravity, water absorption, sieve analysis and large-scale direct shear tests were conducted. Table 1 shows the values of specific gravity, water absorption ratio, unit weight, friction angle and Unified Soil Classification obtained.

Table 1: Physical properties

Specific gravity, Gs	Absorption ratio, %	Unit weight γ, (t/m^3)	Fricion angle φ, (°)	USCS
2.29	1.0	1.64	54	GP

2.2 DEM Code

The DEM code used in this study is the Particle Flow Code (PFC^{2D}) developed by "ITASCA Consulting Group." for commercial use and widely used for many research projects since it's first distribution in 1995. Using PFC a rock or granular materials can be modelled as an assemblage of circular disks confined by planar walls. This method simulates the mechanical behavior of a collection of non-uniform-sized circular rigid particlesin contact. The rigid particles interact only at the soft contacts, which possess finite normal and shear stiffness. Specific bonding strengths also can be given at each contact for the modelling of bonded material such as rocks, while no bonding is required for unbonded materials such as sands or gravels. Each particle is assumed to be rigid. The assumption of particle rigidity is reasonable when movements along interfaces account for most of the deformation in a material. The deformation of a packed-particle assembly, or a granular assembly such as sand, is described well by this assumption, because the deformation results primarily from the sliding and rotation of the particles as rigid bodies and the opening and interlocking at interfaces — not from individual particle deformation. In addition to circular particles, the PFC model also includes "wall elements." Walls allow one to apply velocity boundary conditions to the assemblies of balls for the purposes of compaction and confinementThis wall element is also frequently used to apply external loading on the particle assembly by the user specifying the same velocity on the wall. However, walls only can interact between the disks and the wall, with no interaction at on wall-to-wall contacts. The detailed constitutive laws at the particle contacts and the laws of motion are not addressed here, but are addressed elsewhere[1-6]

2.3 Modelling of crushed stone

2.3.1 Modelling of grains

In the modelling of granular material using the DEM analogue, researchers often have used circular disk elements, as described above. Use the circular disk elements has the advantages for saving computation time, but it has not been successful in considering the effect of grain shape. Jensen et al (1999), Thomas and Bray (1999), Guo and Morgen(2004) all indicated that circular disk elements are not adequate to model geometry-dependent particles such as irregularly shaped grains, because this element is not appropriate for considering interlocking effects, rolling resistance, and it ultimately might result in low strength predictions and less dilation.

One of the solutions to overcome this limitation is to introduce a clump concept. In clump assemblies, circular particles are grouped, with infinite bond strength assigned to maintain particle stiffness and have them act like single particles. The size of clump can be decided by specifying the zone, so if the particle center is positioned within the zone, the particle is joined to the clump. Figure 1 illustrates the way a clump is created for simulating irregular grain shape.

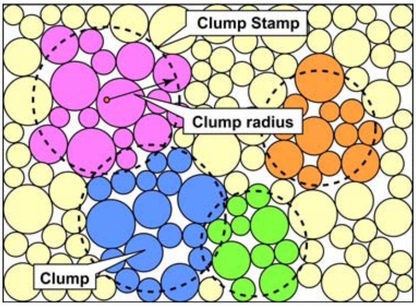


Figure 1 : Illustration of irregular grain generation using clump logic

2.3.2 Generating grain size distribution and application of porosity

For coarse-grained materials such as gravels and rockfill material, their particle size distribution is obtained using laboratory sieve analysis. The percent finer than each sieve is obtained by measuring the mass of material retained on each sieve

In the PFC analysis, the particles were generated and densely packed with a low porosity. Doing this insured the particles were in conact and reduced floaters (i.e. particles having no contact with adjacent particles). This procedure is similar to the laboratory compaction test, except that the porosity is fixed in the analysis. The initial porosity for packing was set to 0.16 by default. If one uses a high porosity for initial packing, particle contacts would significantly be reduced, giving a false responses when the material is loaded. To avoid this, the initial packing was set to a default porosity, and particles were deleted one by one until the specified porosity was reached. This procedure may change the GSD slightly, but only to a minor degree.

Figure 2 shows a modeled assembly with an applied porosity of 0.23 and Figure 3 compares the modelled GSD with the measured laboratory GSD. The difference in the GSD is attributed to the effect of the application of porosity.

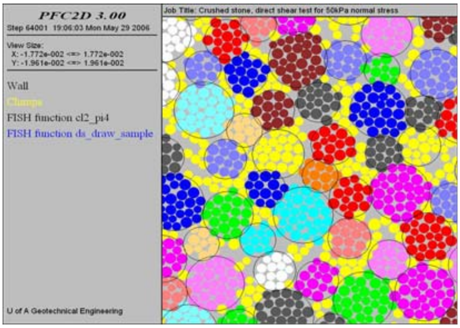


Figure 2 : Simulation sample model after applying the GSD and aporosity of 0.23

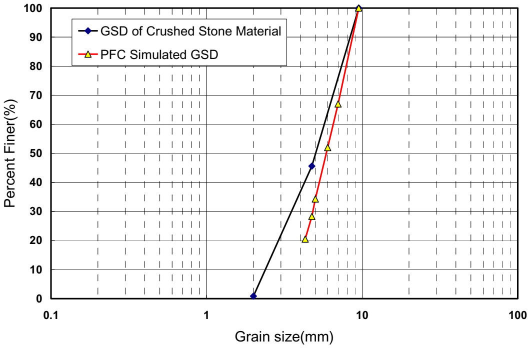


Figure 3 : Comparison of GSD between modelled and laboratory GSDs

2.3.3 Modelling of Direct shear testing

Using the generated specimen illustrated above direct shear testing was modelled. It is more desirable to choose a sample dimension the same as the actual laboratory sample dimension (500 X 250 X 500mm) but since modelling was based on a 2D analysis only and moreover, applying the same dimension to the PFC simulated sample would require a lot of particles and huge computation time for both GSD generation and shearing, the simulated sample dimension was down-scaled to 200mm in width, 100mm in height with unit thickness in the out-of-plane direction.

The initial micro parameters of this sample are given in Table 2. In this study, the minimum grain size was limited 1.0mm and the grain radius ratio was set to 2.0. Using this grain size, a total of 13,700 grains were generated at the default minimum porosity 0.16.

Table 2 : Micro parameters for sample generation

Microparameter	γ_c , (kg/cm^3)	E_c ,(GPa)	k_n / k_s	μ	$R_{\min}$,(mm)	$R_{\max} / R_{\min}$	Porosity
Value	2,639	5.0	5.0	1.0	0.5	2.0	0.16

Figure 4 illustrates the modelled direct shear testing scheme. The upper half of the shear box was modelled using two fixed walls on both the left and right sides. The velocities of these walls were kept at zero during the simulation. Normal stresses were activated by adjusting the top wall (id=2) velocity. This velocity adjustment servo algorithm is the same as Potyondi & Cundall(2004) adapted for simulating biaxial testing of brittle rock. The lower half of the shear box was modelled a three segment single wall, with shearing activated by moving this wall to the right. During the simulation, shear stresses and normal stresses were calculated from the forces applied to each wall and displacements were obtained by tracing the wall displacement.

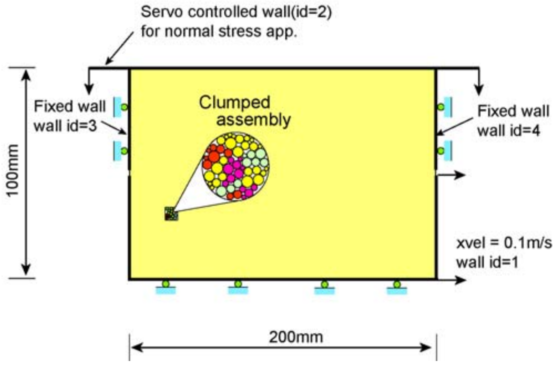


Figure 4 : Direct Shear testing scheme

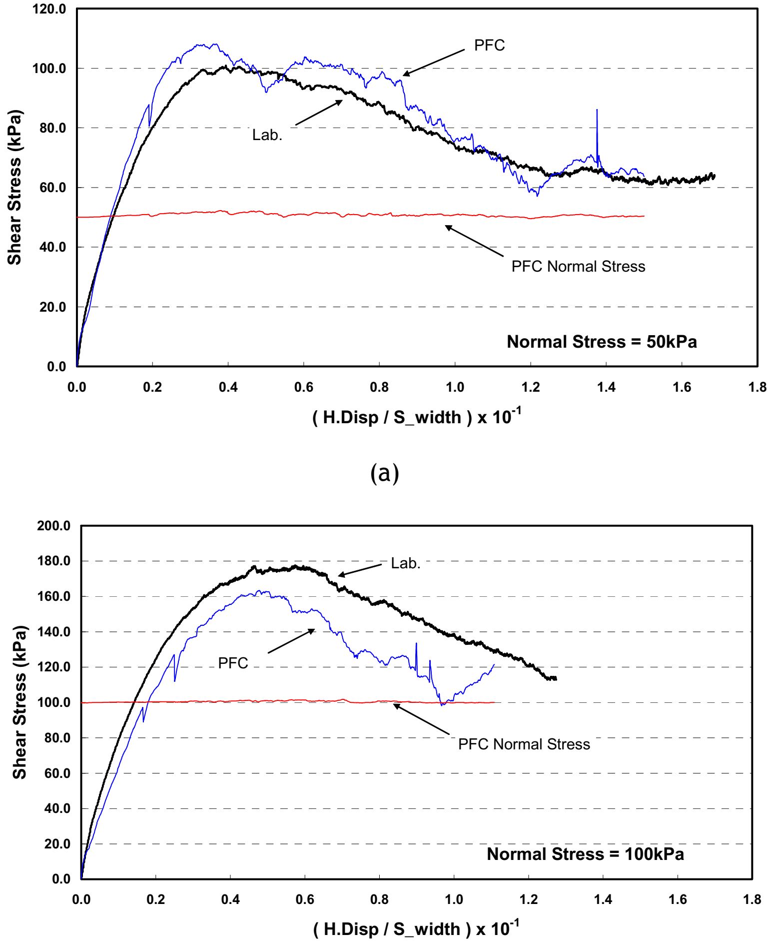
3 RESULTS AND DISSCUSION

3.1 Shear Behaviour of crushed stone

Figure 5 compares the relationships between the shear stress and resulting horizontal displacement for the model and the laboratory tests on crushed stone with a maximum size of 10mm. As the sample dimension in the analysis was not the same as the actual sample, direct comparison of the displacements is not appropriate. For comparison purpose, the horizontal and vertical displacements were normalized relative to the width and height of specimen, respectively. In Figure 5, it can be seen that the vertical stress modelled in PFC is maintained relatively constant throughout, indicating that the servo algorithm for the wall element functioned well.

The model and actual shear stress versus horizontal displacement relationships are well matched at a relatively low normal stress(50kPa), but a little difference at high normal stress(100kPa). The internal friction angle calculated for the model was less than the laboratory result by approximately 10 degrees, as shown in Figure 6, although the intercepts on the vertical axis are different. The cause is thought to be the adoption of a larger minimum particle size to reduce the computation time, which would have reduced the interlocking between particles, in turn reducing the internal friction angle of the material.

In addition, particle leakage from the upper half of the shear box with incresing horizontal displacement may have locally reduced the normal stress and resulting shear strength. In Figure 5, there is a point where the shear stress reduced sharply before reaching the yield point. The reason for this is also thought to be due to localised strength reduction through particle leakage. This might be corrected in future work by extending the side wall to prevent particle leakage.



(a)

(b)

Figure 5 : Comparison of shear stress and horizontal displacement.

(a) Normal stress = 50kPa (b) Normal stress = 100kPa

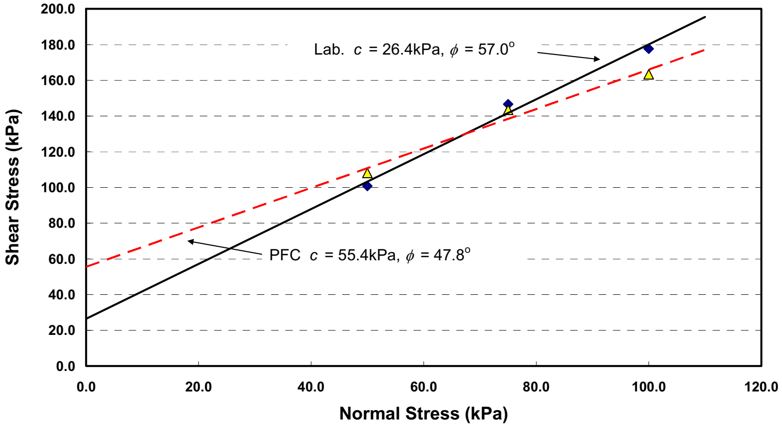


Figure 6 : Failure envelope of PFC and Lab material

4 CONCLUSIONS

In this study, modelling of the behaviour of crushed stone with a maximum size of 10mm was conducted. In order to consider the irregular shape of crushed stones, clump logic was introduced into the algorithm, allowing the particle size distribution and void ratio to be considered. It was found hat a direct shear test on an actual sample could be modelled with some successful.

Comparing the modeled and actual direct shear test results, the shear stress versus horizontal displacement relationships were well matched at the lower normal stress (50kPa), but not so well at high normal stress (100kPa). The internal friction angle calculated from the model was less than the laboratory result by approximately 10 degrees, although the intercepts on the vertical axis are different. The cause is though to be the adoption of a larger minimum particle size to reduce the computation time, which would have reduced the interlocking between the particles, in turn reducing the internal friction angle of the material.

In addition, the thickness of the shear box is a problem that has to be solved in future studies. For the wall element provided by PFC2D, the thickness of the element itself cannot be considered. However, it is believed that preventing upper particle leakage by extending the wing wall on the side of the vertical wall element will be a better method than simply modelling with a vertical wall element.

Based on the results of this study, material behaviours will be able to be described in more detail using this approach, including the incorporation of construction materials such as geosynthetics and other tests conventionally carried out on granular soils.

5 ACKNOWLEDGEMENT

This research was supported by Korean Ministry of Construction and Transportation under Grant No. C105A1000017-05A0300-0170. The financial support is gratefully acknowledged.

REFERENCES

Itasca.(1995). PFC2D(Particle Flow Code in 2 Dimensions) Version 1.1, Itasca Cons. Group.

Potyondy, D.O. and Cundall, P.A. (2004). A bonded-particle model for rock. Int. J. Rock Mech Min. Sci. 41, 1329-1364.

Jensen, R.P., Bosscher, P.J., Plesha, M.E. and Edil, T.B.(1999). DEM simulation of granular media - structure interface : Effects of surface roughness and particle shape. Int. J. Num. and Anal. Meth. in Geomech. 23, 531-547.

Thomas, P.A. and Bray, J.D.(1999). Capturing nonspherical shape of granular media with disk clusters. J. of Geot. and Geoenv. Eng. 125, 169-178.

Guo, Y. and Morgen, J.K.(2004). Influence of normal stress and grain shape on granular friction: Results of discrete element simulations. J. Geophys Res-SOLID EARTH. B12, Art. No. B12305.

Gupta, S.C. and Larson, W.E.(1979). A model for predicting packing density of soils using particle-size distribution. Soil Science Society of America Journal. 43, 758-764.

Hansen, D.(2002). An equation to represent grain-size distribution: Discussion. Can. Geotech. J. 39, 1433-1436.

Hwang, S. and Powers, S.E.(2003). Using particle-size distribution models to estimate soil hydraulic properties. Soil Sci. Soc. Am. J. 67, 1103-1112.

Fredlund, M.D., Fredlund, D.G. and Wilson, G.W.(2002). An equation to represent grain-size distribution: Reply. Can. Geotech. J. 39, 1437-1438.