*Applied Numerical Modeling in Geomechanics – 2020 – Billaux, Hazzard, Nelson & Schöpfer (eds.)* *Paper: 03-09*
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# DEM modelling of grain crushing in element tests

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## 1 INTRODUCTION

For granular materials, crushing of gains can affect the mechanical behavior at both the micro and macro scale. However, due to the difficulties in observing the evolution of grain crushing in experiments, its effect on the mechanical behavior is still not well understood. Modeling the grain crushing effect with discrete element method is an alternative approach, which will lead to better understanding of the effects at the micro scale. By making use of the averaging methods, the macro scale effect can also be studied.

Modelling grain crushing with DEM still has many difficulties. For the crushing of grains are generally modeled by two kinds of methods, i.e. the replacement methods (Ciantia 2015, McDowell 2013) and agglomerate methods (Laufer 2015, De Bono 2014, McDowell 2002). The replacement methods use a pre-defined failure criterion to check whether particles of the grain ensemble break under the given arrangement of contact forces. Since a pre-defined failure criterion is used, the replacement methods cannot model the actual grain crushing processes, therefore the method is not accurate enough. On the other hand, the agglomerates methods employ crushable grains made of a large number of smaller grains, which are connected by breakable bonds (agglomerates). These methods require a large number of particles at the beginning of each simulation; therefore, it is very time costuming and can only be used to model limited number of particles.

In order to overcome these shortcomings, a combined method to model grain crushing with DEM is proposed. As the name implies, this method is developed by combining the strength of the replacement methods and the agglomerates methods. The combined method is implemented into a *FISH* subroutine in the particle flow code, *PFC*. Several element tests, such as biaxial tests, oedometer tests, and true triaxial tests are modeled with grain crushing effects.

## 2 DESIGN AND ANALYSIS

The combined method starts the simulation with individual particles and screen for highly stressed particles. These highly stressed particles are replaced by agglomerates, while the other particles remain as individual particles. In this way, the crushing of grains can be accurately modeled by crushing of agglomerates, which is dictated by the bond breakage. The combined method is proved to be more accurate than the replacement method and more efficient than the agglomerate method. A *FISH* subroutine is written to realize this method in both *PFC3D* (Itasca 2005a) and *PFC2D* (Itasca 2005b).

An agglomerate is a set of smaller particles bonded together with parallel bonds. The smaller particles have the same normal and shear stiffness as the original particle. The agglomerate should have the same size as the particle being replaced, as shown in Figure 1. The deformation of the parallel bonds depends on the bond stiffness, while the breakage of the bonds depends on the bond strength. The stiffness of the parallel bonds is set to be $10^6$ times of the contact stiffness of particles. In this way, the deformation of parallel bonds will be negligibly small, which means that the relative displacements of the small particles in an agglomerate is negligible. Hence, the high stiffness of the parallel bonds ensures that the agglomerate behaves like a single particle with very high stiffness. The breakage of agglomerate is defined by the bond strength. Therefore, bond strength controls the brittleness of the agglomerates.

Since the contact stiffnesses of big and small particles are the same, the time step only depends on the size of particles. The reduce of time step and increase of run time is similar as in the replacement methods or agglomerate methods.

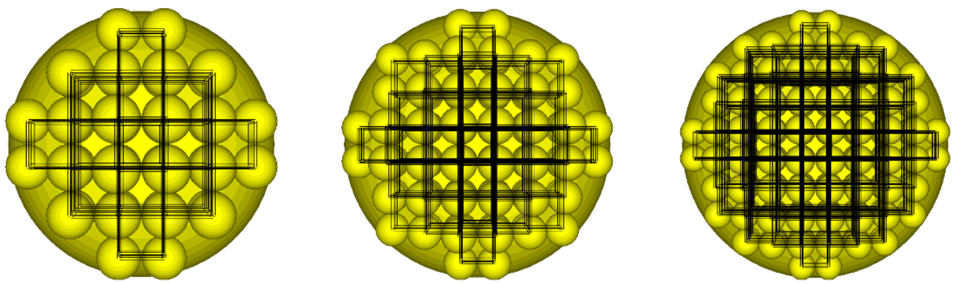

Figure 1. Agglomerate and the original particle in 3D.

Unlike the replacement method, there is no need to define the fragmentation a priori, since the breakage is dictated by the bond strength. An agglomerate can either break into particles or smaller agglomerate of different shapes. Smaller agglomerate can further break into even smaller agglomerates or particles depending on the external loading. However, if the stress on an agglomerate reduces, the agglomerate will not break and acts like the particle it replaced. Therefore, the combined method can model the crushing of each grain precisely. Although the contact force and particle shape will change by the replacements, our simulations have proved that the influence can be neglected if appropriate agglomerate size is chosen (Lin 2019).

The second stress invariant is used as the replacement criteria. By carefully chosen the threshold value, only a small percentage of particles will be replaced, which makes the combined method much faster than the agglomerate methods.

The smaller particles in an agglomerate can also be replaced by agglomerate with even smaller particles. Hence, further particle breakage can be modeled in this way. However, smaller particles mean more computational effort. In this abstract, only one level of replacement is considered.

It is very easy to implement the grain crushing subroutine in any other DEM simulations in *PFC3D*. In addition, a subroutine to study the change of grain size distribution has also be written, the details can be found in Lin 2019.

## 3 RESULTS AND DISCUSSION

Several element tests of granular material, such as biaxial tests, oedometer tests, and true triaxial tests are modeled in *PFC* with and without grain crushing effects. As an example, the stress-strain and volumetric-strain curves of biaxial tests in *PFC3D* are shown in Figure 2. Three different bond strength are modeled and compared to the results without grain crushing.

From experiments with real granular materials, it is well known that grain crushing leads to lower peak value in the stress strain curve. This effect is also visible in the DEM simulation "Low strength". It can also be observed that lower bond strength in agglomerates leads to less pronounced dilatancy. The influence of particle breakage on the critical state line is not very significant under small shear strain, which is consistent with the experimental observation by Bandini 2011.

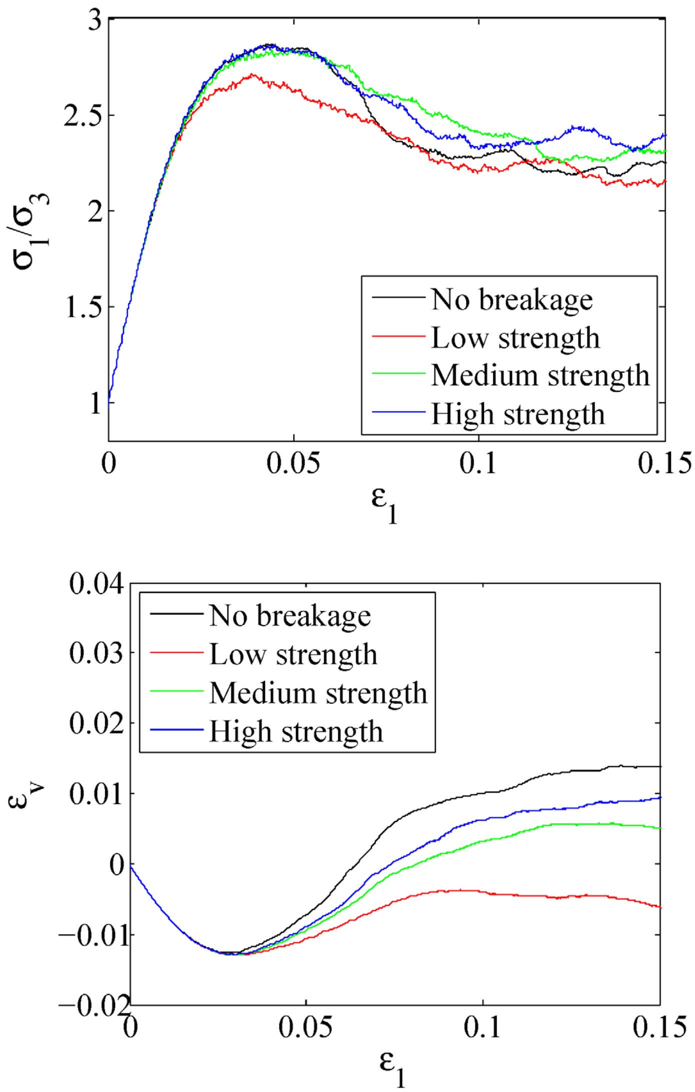


Figure 2. Stress-strain and volumetric-strain curves of the DEM simulations of biaxial test with and without grain crushing.

The simulations show that only 2%-3% of the particles are replaced. This means massive saving of computational effort compared with the replacement of all particles.

The significance of this method is not only that it can model the macroscale material behavior, but also the breakage process at the microscale. On the microscale, the replacement method just deletes the original particle and replaces it with broken pieces according to a predefined rule, regardless of the individual loading conditions of the particle. Therefore, the breakage mode of all particles is the same. While the combined method models the breakage of agglomerate due to its unique loading conditions.

Since the method is very efficient, implementing the method to DEM simulations of other element tests (oedometer tests and true triaxial tests) generates a lot of data in a short time. The micro and macro scale results are similar compared to the simulations of biaxial tests. Combing all these results, the grain crushing effects under different loading conditions will be better understood. The change of yield surfaces due to grain crushing effects can be quantified by the DEM simulations. Based on the data, a constitutive model with grain crushing effects will be developed for granular materials.

## 4 CONCLUSIONS

We present a numerical approach based on DEM for the simulation of grain crushing. This approach is developed by combining the strength of the widely used numerical methods, i.e. the replacement method and the agglomerate method. The method is realized by a *FISH* subroutine and can be easily implemented into any DEM code. The method is proved to be both accurate and efficient. Several element tests including biaxial tests, oedometer test and true triaxial tests are modeled with the combined method in DEM, the micro and macro scale results are discussed. The results of these simulations will be used to develop a new constitutive model considering the grain crushing effects.


## ACKNOWLEDGEMENTS

The authors would like to express thanks to Prof. Erich Bauer from TU Graz for his help in developing the combined grain crushing methods. We would also like to express our gratitude to our project partner Itasca Consultants GmbH, which have given us a lot of help for using the software.


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