DISCRETE ELEMENT METHOD SOFTWARE APPLICATION FOR COHESIONLESS SOIL MODELS

APPLICATION DES PROGRAMMES D'ELEMENTS DISCRETS POUR LES MODELES DE SOLS NON COHERENTS

Adrian Priceputu[1]
[1] *Technical University of Civil Engineering, Bucharest, Romania*

ABSTRACT - The paper shows a numerical application developed for the PC that uses the high computing capabilities of the modern graphical processors to employ the discrete element method (DEM) in the modeling of the granular media behavior subjected to external and internal actions. The discrete element method is usually a suitable way to simulate the behavior of media and dynamic phenomena that have a discrete nature, such as soils liquefaction, erosion, or the propagation of instability through soil or snow masses. DEM is more precise for these types of phenomena due to the fact that a pseudo-continuous approach doesn't succeed to properly model them after the state of equilibrium has been lost. The paper shows the basic principles of DEM, an iterative computation example using computational software, as well as the developed software application that uses an existing solver to handle up to about 5000 particles in real time computation.

1. Introduction

The discrete element method (DEM) is a numerical model (Cundall and Strack, 1979) able to describe the mechanical behavior of granular environments. These may be particle assemblies such as spheres, cubes, or any other geometrical shape which interact with each other only in the contact points. The method is based on using an explicit numerical approach in which the particles interaction is modeled contact by contact and the particles movement is modeled particle by particle. Due to the discrete character of the environment, its mechanical behavior when subjected to loading and unloading conditions is rather governed by the contact phenomena than by constitutive laws that describe the material.

The computations involved in a DEM approach are quite trivial, alternating two numerical steps (Malone and Xu, 2008) - the second law of Newton and a force-displacement law in the contacts. The second law of Newton handles the particles movement under applied forces, while the force-displacement law is used to compute the contact forces out of virtual displacements.

The normal and tangential contact forces are obtained using a constitutive model for the contact between two rigid particles (Figure 1 shows a contact modal for two-dimensional discs). This paper considers the contact to be characterized by a normal and a tangential stiffness (K_n and K_d), a friction coefficient μ and a normal damping coefficient c_n (Onate and Rojek, 2004).

One of the assumptions of the discrete element method is that the deformations of individual particles are negligible compared to the deformations of the entire assembly, which is mainly due to the rearranging of the particles as rigid bodies. This enables us to focus on the movement and interactions of the particles and treat them as rigid bodies while neglecting their respective deformations.

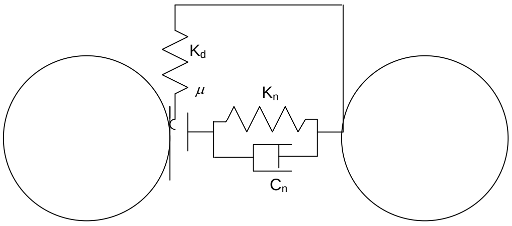

Figure 1. General contact interface model (Onate and Rojek, 2004)

The DEM models may employ two distinct approaches: "soft-sphere" and "hard-sphere" (Duran, 2000). The soft-sphere method, introduced by (Cundall and Strack, 1979), was the first method for simulating the dynamic behavior of granular materials published in literature. This technique allows the particles to virtually overlap, enabling the computation of the contact forces resulted from collisions. A main feature of this approach is the possibility of running multiple simultaneous collisions between particles. On the other hand, in a hard-sphere model (Hoomans et al. 1996) a succession of collisions is processed, without allowing any overlaps, each being unique and instantaneous, often the forces between particles not being explicit. This method is advantageous when modeling rapid granular flow (with applications to rapid landslides phenomena and avalanches). This paper employs the soft-sphere approach, often being considered the most suitable for general simulations of granular media.

This paper employs the "soft-sphere" approach (Cundall and Strack, 1979) for contact handling, which enables virtual superposition of particles, often being considered the most suitable for general simulations of granular media, as opposed to the "hard-sphere" approach (Hoomans et al. 1996), which doesn't allow particles to overlap thus the forces between particles not being explicit.

2. Numerical example using seven particles subjected to normal elastic contacts

A numerical example of the discrete element method was constructed employing a simple 2D model using seven circular planar particles (discs) that undergo normal elastic collisions. The calculations were made using computational software that allowed us to plot functions describing the particles' positions at certain steps of time (Figure. 2 ÷ Figure. 4). It was noticed that even in this simple case, four iterations were needed to pass from one state of equilibrium to another.

For simplicity, a linear-spring-dashpot (LSD) contact model was employed in this example (Cundall and Strack, 1979), (Malone and Xu, 2008), which is basically a reduction of the one depicted in Figure 1, neglecting the tangential contact parameters.

Initially, the particles were given certain positions in space and such initial velocities that collisions were expected. The figures below show both the initial (Figure 2) and final (Figure 4 right), state of equilibrium as well as the intermediate steps (Figure 3 ÷ Figure 4 left), that were needed to achieve equilibrium.

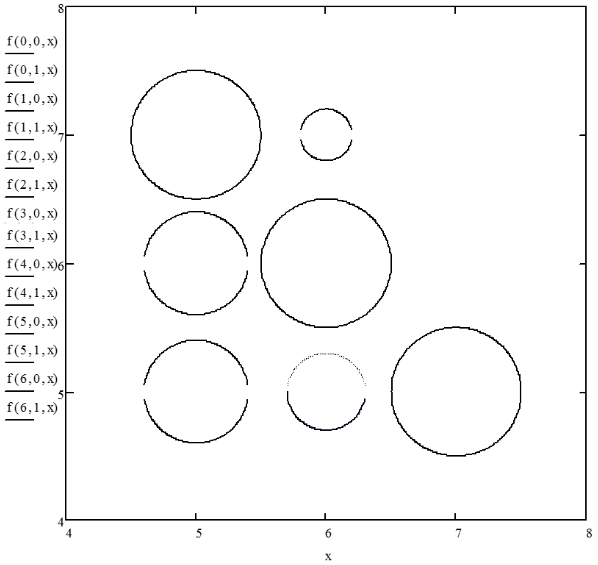

Figure 2. Initial state of equilibrium

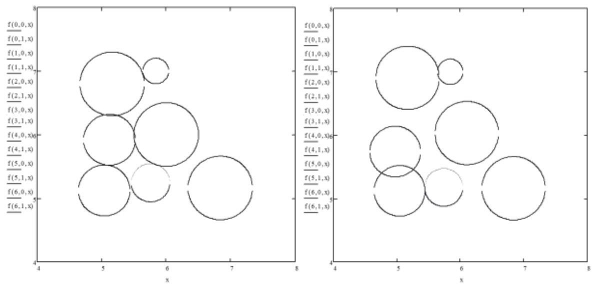

Figure 3. Particles positions after itteration 1 (left) and 2 (right)

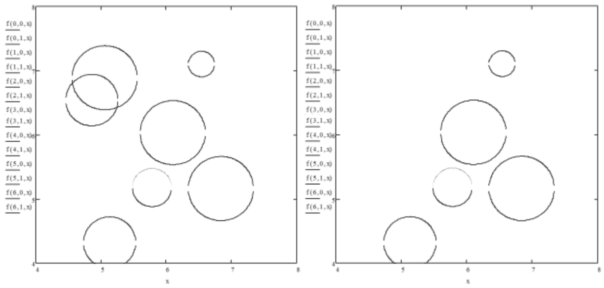

Figure 4. Particles positions after itteration 3 (left) and final state of equilibrium (right)

The intermediate positions define the supposed positions of the particles after a time increment of Δt, which are required to determine the collision forces. The operation is repeated only after no particle superposition is detected, thus obtaining the final state of equilibrium after a time increment of Δt.

3. The developed software for DEM modeling

The software was developed using C++ and DirectX technology for three-dimensional rendering. The environment is 3D and the computations are performed in real time. The software development was focused on the pre- and post-processors. The solver used was developed by AGEIA, based on NovodeX, a physics engine developed NovodeX AG, spinoff of ETH Zurich. The solver uses the graphics processing unit (GPU) to accelerate the computations required in DEM contacts.

3.1. Software key features

The program enables the definition of spherical particles following a certain particle size distribution. The interface allows the user to define an inferior and superior limit for the PSD curve, which is then generated within the desired limits with a given number of distinct diameters (Figure 5). If the two limits coincide, then the result will be a PSD curve similar to the two input curves.

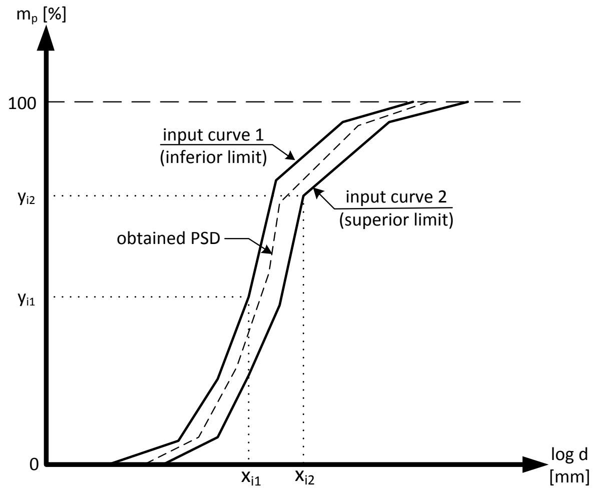

Figure 5. Imposed grading strip for PSD generation

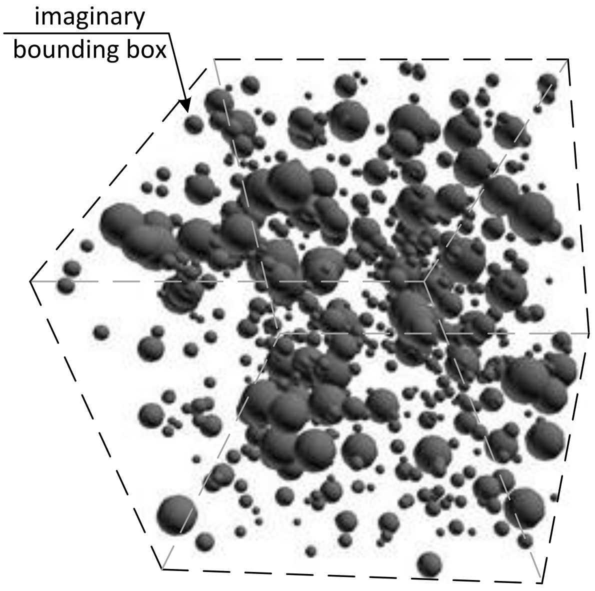

Figure 6. Snapshot of the initial positions of 2000 generated particles

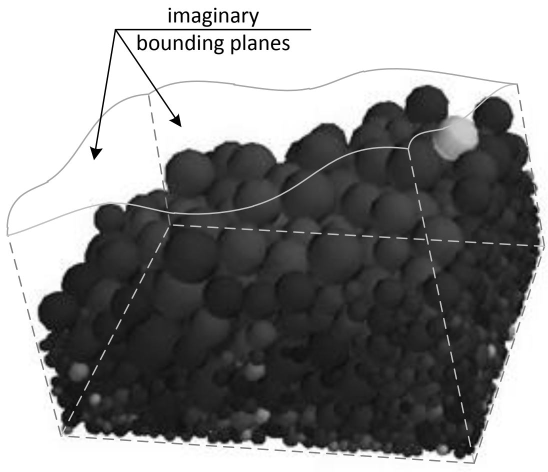

Figure 7. Snapshot of the settled positions of 2000 generated particles

The generated particles are created at random positions within a user-defined imaginary box in the three-dimensional space (Figure 6). When the simulation is ran, the particles settle naturally until they reach a stable state (Figure 7).

The friction and damping coefficients used to describe particle contacts can be altered by the user, as well as the direction and magnitude of "gravity". Also, virtual bounding planes can be defined in order to establish the boundaries of the environment (Figure 7).

3.2. Software capabilities

The capabilities of the software are described employing two landslide scenarios: a progressive (Figure 8) and a regressive (Figure 9) landslide.

Then most difficult part when modeling landslides is establishing the instability propagation. Stability analysis employing both finite element method (FEM) and limit equilibrium method (LEM) study the landslide triggering without being able to accurately anticipate the sliding mass displacement, due to the restrictive formulations of the aforementioned methods (LEM assumes non-deformable soil slices while FEM loses stability in Lagrange formulations at large deformations, and Euler formulations have not yet been successfully employed in landslide modeling). When using DEM, the sliding mass propagation can be studied by modeling the interaction between the particles. Furthermore, the slide triggering mechanism can also be studied using DEM.

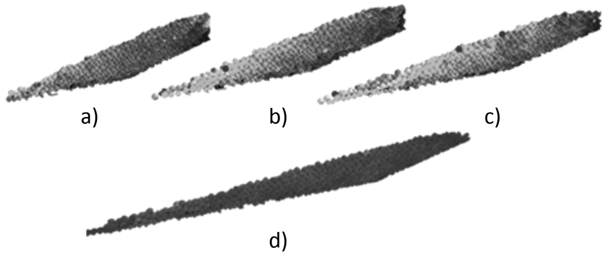

Figure 8. Progressive landslide simulation

Figure 9. Regressive landslide simulation

When simulating the progressive landslide, a stable slope was constructed (Figure 8 a) and the contact parameters between particles were changed, simulating a change in the soils mechanical properties, which may be caused by water infiltration. It was easily noticed how a progressive landslide developed (Figure 8 b and c) until a new stable slope was obtained (Figure 8 d).

For the second simulation, the toe of a stable slope (Figure 9 a) was removed, allowing us to visualize the development of a regressive landslide (Figure 9 b and c), until a new state of equilibrium is achieved (Figure 9 d). This phenomenon may occur in cases of natural toe erosion, or even in cases of bad management of stabilized landslides.

3.3. Future development goals

Further development of the software will focus on making the application more user-friendly and more suitable for running parametric calibration models.

To achieve this, the future development will focus on the following features:

- the ability to save the state of the model at key points in order to facilitate parametric studies ran on similar configurations;
- the ability to record and visualize the contact forces;
- the possibility of enforcing boundary planes movement, with given velocities and directions, to simulate different laboratory tests for the purpose of model calibration;
- the ability to employ user defined objects in order to create realistic environment for the simulations;
- the possibility of defining different particle shapes, since the influence of the particle shape on material behavior was already highlighted by Lu and McDowell (2007);
- the ability of running Monte-Carlo simulations to obtain statistical data on pre-defined scenario models.

4. Conclusions

The use of limit state equilibrium or finite element methods in geotechnical modeling often has its limitations in studying a model's behavior with large deformations. It has been shown in the past few years that DEM can be a suitable tool for simulating granular material behavior, such as soil.

Developing a software application that implements DEM shows great advantages, some of the most important being the flexibility of load configurations, particle sizes (through granulometric distributions) and shapes, as well as material properties through particle density and contact characterization. So far, the available discrete element method software are either too difficult to use in practice due to the complexity of the pre- and post-processors, or have limited computing capabilities, since they perform CPU-based (Central Processing Unit) computations.

The presented program employs the advantages of the modern graphics processing units (GPUs), which are much faster than the CPUs. The software employs a user-friendly windows-based interface and allows the user to work in a three-dimensional environment and watch the simulations run in real-time.

Some of the DEM-related features of the software are presented together with some of its capabilities, employing two landslide scenarios, which show good qualitative results.

However, no real quantitative results have been obtained, since the work on the program is still in the first stages. Some useful features are planned for future development, which will allow more flexibility in creating and calibrating models and more ways to interpret the obtained results.

5. References

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