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# Discrete element models for grain breakage

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## Abstract:

The study of rockfill behaviour shows important experimental difficulties, due to the big grain size and the need of big-dimension apparatus to test and characterize these materials. The empirical methods used in building rockfill structures, the complexity of compaction procedures, and the effects of water and temperature, can result in particle breakage, which may lead to considerable, and sometimes dangerous, long term settlements.

Numerical approaches are often adopted to describe and predict the behaviour of this material, offering the possibility to test various parameters and evaluate the effect of each parameter on the general behaviour of the material. The discrete element method is often used to represent the behaviour of such discontinuous materials, distinguished by grain breakage, taking in input physical parameters.

In the work presented here, we adopted this type of simulation to model grain breakage in oedometric tests.

Many models are used in literature to describe grain breakage in numerical discrete simulations. These models can be divided into two groups.

In the first group, a breakage criterion is set consisting of a threshold value of a stress or a force, that may vary in accordance to the size of the grain following Weibull's distribution [1]. When a grain—considered as one object—breaks, it is replaced by a certain number of smaller grains (*Figure 1*), either conserving the total mass, or losing part of it in the breakage. Most models are in 2D, with a few 3D models. Using a smooth contact method, in which overlapping generates a repulsion force, Åström and Herrmann [2] and Tsoungui [3] tested two breakage criteria: the threshold value for the pressure on a grain, and the threshold value for the largest compressive contact force on a grain, replacing a broken disc with a number of smaller discs, conserving the total mass. Ben-Nun and Einav [4] suggested a different technique, consisting of computing the mean force of the normal contact forces on a disc, and when the threshold is exceeded, the broken disc is replaced by discs small enough to avoid overlapping, then expanding their radius to conserve the mass. McDowell and De Bono [5], dealt with 3D simulations, with a sphere model following the same breakage configuration as Åström and Herrmann [2], setting a threshold value for the induced tensile stress inside a sphere, and when broken, replacing it with two spheres overlapping, along the direction of the minor principal stress. Cantor et al. [6] simulated polygonal rigid grains that can split in the direction of the principal stress when the induced tensile stress inside the polygon  $\sigma_{t_{net}}$  exceeds a threshold value  $\sigma_{crit}$  determined experimentally. Using Abaqus simulations, they established a formula that allows estimating the induced tensile stress inside a polygon, taking its geometry into account. Lobo-Guerrero and Vallejo [7] simulated discs that break when both the induced tensile strength  $\sigma_t$  exceeds a threshold value  $\sigma_{max}$ , and the coordination number of the disc is less or equal to 3. The replacing discs do not overlap, however, mass is lost in the procedure.

In the second group of models, a grain is considered as an assembly of smaller particles, joined together by a cohesive bond (*Figure 2*). Breakage of these contact bonds leads to the breakage of the grain; no other breakage criterion is needed. Cheng et al. [8] joined spherical particles to create a spherical grain, and removed 20% of the particles to add defects to the grain. Silvani et al. [9]

simulated two-dimensional oedometric tests using rigid discs bonded together by a time-dependent Mohr Coulomb interaction law, to reproduce long-term behaviour. Nguyen et al. [10] split a circular grain into smaller particles using Voronoï tessellation, and also applied a Mohr Coulomb type cohesive bond between particles.

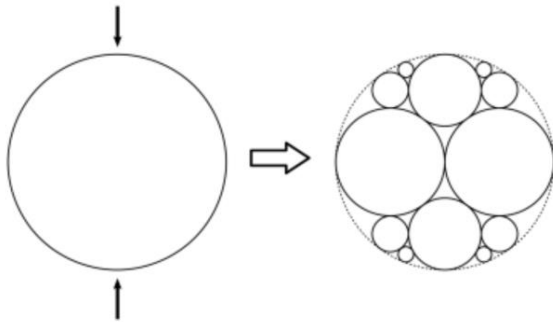


Figure 1 – Grain breakage using the replacement method [6]

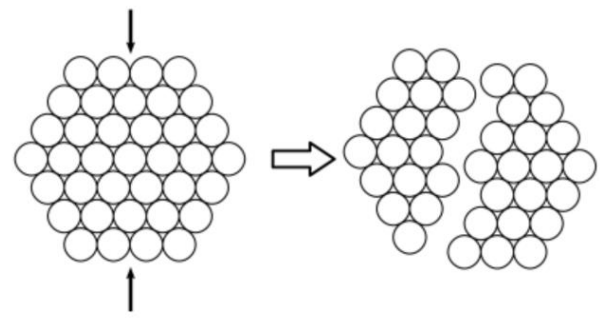


Figure 2 - Grain breakage using the agglomerate method [6]

To simulate grain breakage, we have also adopted the discrete element method (DEM), and more specifically the Non-Smooth Contact Dynamics (NSCD) method [11, 12, 13] implemented in the software LMGC<sup>90</sup>. The goal of the NSCD method is to obtain the overall behaviour of a collection of objects by considering the dynamics of each element, taking into account the interactions between bodies. The problem is studied at two levels: movement equations of the particles expressed using global variables (kinematic variables) and the interactions described using local variables (contact variables).

Today, there are many 2D models. In the work presented here, we enriched the modelling creating 3D grain models using the concept of particles assembly, and cohesive bonds. The first model consists of applying a cohesive bond between spherical particles, in order to create a spherical grain (Figure 3).

In order to find a model closer to reality, a second grain model was generated, with tetrahedral particles (Figure 4). Three input parameters are therefore set: the number of vertices and the minimal and maximal dimensions of the grain  $R_{\min}$  and  $R_{\max}$ . Using spherical coordinates, we place the vertices on semi-circles in space, at a distance between  $R_{\min}$  and  $R_{\max}$  from the centre (Figure 5). The grains are then divided into tetrahedral particles using an automatic mesh generator, and imported into LMGC<sup>90</sup> with a cohesive bond applied between the particles.

A third model, inspired by the works of Mollon et al. [14], is also used: polyhedrons are generated and divided into Voronoï cells (Figure 6).

To validate the numerical simulations, oedometric tests were carried out in collaboration with IRSTEA of Aix-En-Provence, on limestone ballast of dimensions between 20 and 40mm (Figure 7).

Correlation and stereo correlation techniques were used, to study displacement and breakage fields.

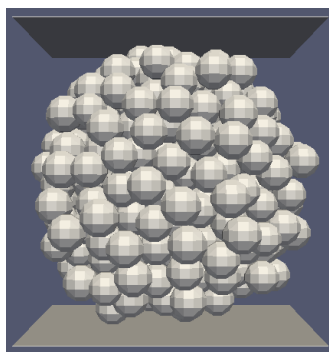


Figure 3 - Grain composed of spherical particles

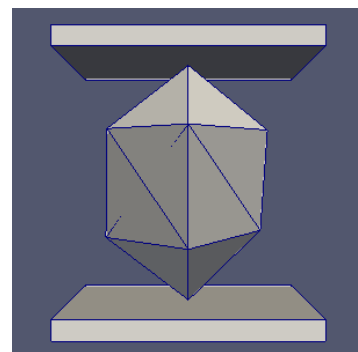


Figure 4 - Grain composed of tetrahedral particles

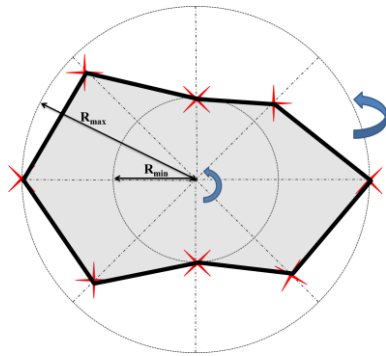


Figure 5 - Generation of a polyhedral grain

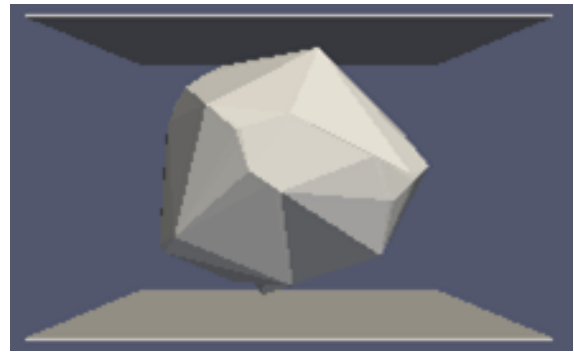


Figure 6 - Grain composed of polyhedral particles

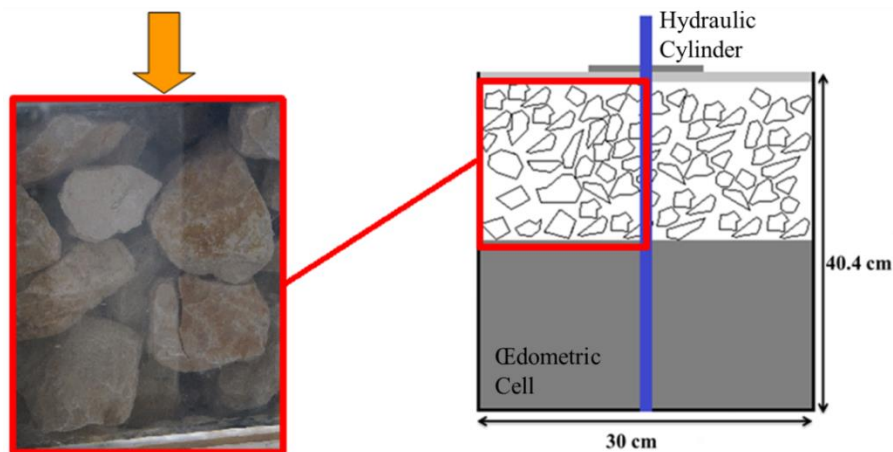


Figure 7 - Oedometer tests on limestone ballast

Simulations of a single grain crushing test were performed with the different models. The tests showed that the grain strength depends on its dimensions, particles dimensions and cohesive strength of the bond joining the particles, as expected.

Then, many samples were created, of various dimensions and shapes, in order to simulate the experimental oedometer tests. A parametric study is carried out to quantify the effect of factors influencing the grain breakage, under imposed displacement and imposed loading. The number of cohesive bonds is monitored throughout the simulations, in order to establish the grain breakage ratio and granular size distributions.

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