DISCRETE NUMERICAL MODELLING OF THE MECHANICAL BEHAVIOUR OF ROCKFILL IN A OEDOMETER TEST WITH SUCTION CONTROL

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ABSTRACT

The effect of suction in the compressibility of rockfill along different stress paths is studied using the discrete element method. Rockfill particles are modeled as breakable clumped particles and reasonable consistency is found between the predicted and experimental results. The simulation highlights the influence of suction and the particle breakage on the mechanical behaviour of the assembly. The capabilities of the discrete element method are also explored to study the microscopic interactions that occur during the oedometer tests.

1. INTRODUCTION

After 1950, rockfill works have registered a relevant increase all over the world due to the technical improvements in excavation, compaction and transportation of these materials. Dams, port jetties, embankments for protection against floods, roads and airports have been some of the engineering structures where this material was (and still is) widely applied. Their major advantages, when compared to earthfill embankments, are, among others, the construction speed and lower material needs, mainly due to their high strength, allowing steeper slopes.

Since then, Portugal has became one of the pioneers in the construction of rockfill embankments. Paradela rockfill dam (built in 1958) became famous worldwide for being the tallest (110 m) of its kind (Veiga Pinto et al, 1988). This structure is a concrete face rockfill dam (*CFRD*) and it was built by dumping the rockfill from high lifts. This methodology had been successfully applied before in smaller structures (Pego do Altar dam, built in 1948 with 58 m height). However, in higher dams, highly deformable structures with poor compaction levels were obtained, which resulted in severe leakage problems due to the cracking of the concrete face. Consequently, a decrease had been registered in the construction of new rockfill dams in Portugal.

The change-over occurred with the evolution of equipment, in terms of dismantling, transportation and compaction processes, and when laboratories began to perform tests with rockfill materials, providing a better insight into this material behaviour. Also, the particle size distribution used in modern rockfills is less restrictive, allowing a wider range of particle sizes. These modifications have led to significant improvements in embankments structural behaviour. Nurek (1980) and Rogun (when completed) in Tajikistan are, probably, the greatest examples of this change, having both over 300 meters. They are the tallest dams in the world.

In order to allow the study of rockfill materials, laboratory test apparatus of considerable dimensions suitable to test rockfill materials had been designed and developed. Consequently, one-dimensional deformation and triaxial apparatus tests with diameters of 500 and 300 mm, respectively, have been routinely applied ever since. Moreover, *in situ* test procedures and construction specifications have been developed and are routinely performed as well.

In response to a given load, the constituent particles of a rockfill tend to break. Nakata et al. (1999) showed that the particle size influences the yield point of the material, when subjected to a one dimensional compression test, which is directly related to the strength to crushing of a particle. Typically, in a rockfill specimen smaller particles are more likely to break than larger ones, since the larger particles are surrounded by other smaller, inducing a stress distribution through the various contacts. In order to increase the number of contact points between particles and obtain a less compressible material (Sowers et al., 1965), granular materials must have a continuous particle size distribution (Marsal, 1973). Another aspect that influences the crushing strength is the applied load and load conditions. A stress increase in a sample of granular material leads to an increased probability of breakage of its components. The particle shape also plays an important role, with Lee and Farhoomand (1967) showing that angular particles are more likely to break, causing a higher compressibility, and rounded particles tend to be less influenced by the number of contacts.

The discrete element method (*DEM*) (Cundall and Strack, 1979) can be an effective tool for investigating size effects, provided it is capable of properly simulating grain failure mechanisms for several stress paths (Cheng et al, 2003; 2004; Lobo-Guerrero and Vallejo, 2006). It explicitly uses integration of differential of motion in time, in which time step is limited below a critical value due to stability and precision considerations. This value is conditioned by the body with the smallest mass and the contacts with highest stiffness.

Several approaches were adopted to study particle breakage using *DEM*. Some considered subparticles joined by bonding or cohesive forces (Cheng et al, 2003; Wang et al., 2013). Another approach replaced a particle which verified a predefined failure criterion with an equivalent group of smaller particles (Tsoungui et al., 1999, Bruchmuller et al., 2011). These techniques were employed with either disks in 2D or spheres in 3D. When considering particles with general shapes, the technique consisted in bonding unbreakable and rigid subparticles creating a breakable particle. If the bond between these subparticles broke, breakage occurred (Hosseininia and Mirghasemi, 2006). Other researchers proposed a method that combined the finite element method (*FEM*) with discrete element implementations (Ma and Zhou, 2015). In this method, particle movements and interactions were determined using *DEM* (Munjiza, 2004) and the deformation of the rockfill material was computationally solved according to the rheological behaviour of the material, adopting a finite element mesh for each particle.

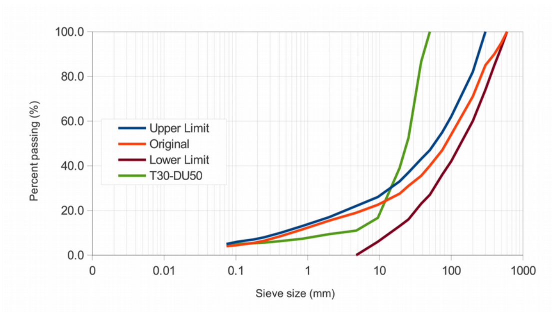
The main purpose of this paper is to develop a discrete model capable of simulating the effect of suction in rockfill compressibility. A series of oedometer tests, performed on rockfill materials collected from Montesinho dam site, located in the north of Portugal, will be described and analysed. Then, a numerical methodology will be adopted to simulate the experimental tests, using clumps of elementary disks. The model parameters will be calibrated, using the experimental tests, for different relative humidity conditions, and the methodology assessed. The numerical results will allow to analyse the influence that relative humidity conditions have in the behaviour of this material.

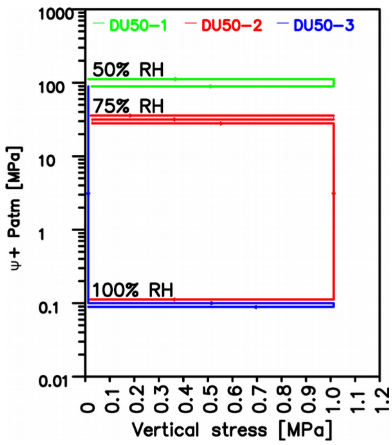
2. EXPERIMENTAL STUDY

The material tested was a granite used in the construction of Veiguinhas dam, a rockfill dam located in the Montesinho Natural Park, with a bulk density of 2400 – 2540 kg/m^3 . Taking into consideration the American Standard Test Sieve Series (*ASTM*), the sizes of rockfill particles used for testing ranged from 9.5 to 50.4 mm, were divided into four intervals: 9.5–19.1, 19.1--25.4, 25.4--38.1, and 38.1–50.4 mm. This procedure considerably simplified the handling of the material in the preparation of each experimental test. Oedometer tests were performed at various relative humidities (50, 75 and 100 %) to study the effect of suction in the compressibility of rockfill.

The material particle size distribution plays an important role in the behaviour of geotechnical structures, since their construction period (Ortega, 2008), and one important aspect to considerer is their gradation. A well graded rockfill (non uniform) contains particles of a wide range of sizes. The compaction of this material returns a compact structure, with a low void ratio and many points of contact between their particles. On the other hand, poorly graded rockfill comprises particles of nearly the same size range, characterised by an excess or deficiency of a particular particle size range. When compacted, the obtained material presents high void ratio and less contact points between particles. This results in a high concentration of stresses at contact points, leading to a large amount of particle breakage and, inevitably, highly deformable structures.

The experimental program included three oedometer tests performed on specimens with the continuous particle size distribution presented in Figure 1a. The cell had a height of 0.474 m and a diameter of 0.5 m. The main objective of these tests was to analyse the effect of suction (indirectly by controlling the relative humidity) in the rockfill compressibility and the collapse phenomenon.





a) b)

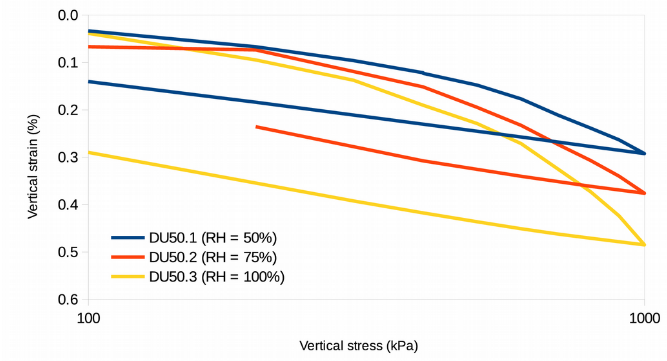
Figure 1 - Oedometer tests. a) Particle-size distribution before testing. b) Vertical stress-total suction paths adopted in tests DU50.1, DU50.2 and DU50.3.

Figure 1b shows the stress-suction path adopted for the test DU50.1. It consisted in an initial phase of allowing the material to establish an equilibrium condition with a relative humidity of 50 % (by means of air-flow circulation through the specimen). Then, keeping this condition constant, the specimen was loaded up to 1.0 MPa, with 100 kPa increments (in steps of 24 hours). After this, the specimen was unloaded, using steps of 200 kPa.

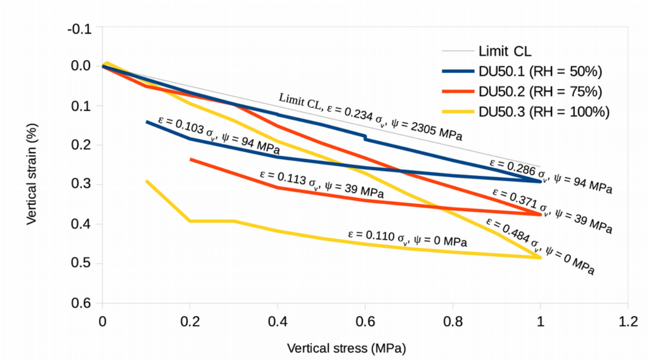
Figure 1b presents the suction-stress path of the test DU50.2, which consisted in an initial phase of allowing the material to reach equilibrium with a relative humidity of 75 %. Then, keeping this condition constant, the specimen was loaded up to 1.0 MPa with increments of 100 kPa, and then unloaded, with decrements of 200 kPa. The reloading phase was divided in steps of 200 kPa and, at the maximum stress of 1.0 MPa, the sample was flooded. These conditions were maintained constant during five consecutive days, until it was considered that the collapse strains stopped. This change in the relative humidity (by flooding the specimen) resulted in a

vertical displacement of 0.257 mm. After this, the specimen was unloaded. In this test, each step had a duration of 24 hours.
The suction-stress path of test DU50.3 is also presented in Figure 1b. In this test, the specimen was initially flooded, with the application of a residual stress, due to the configuration of the oedometer cell. The objective of applying a small vertical stress was to increase the contact between the rubber and aluminium rings of the cell, in order to prevent any leakage. No swelling was registered in the material during flooding. After flooding, the specimen was loaded with 100 kPa increments (steps of 8 hours) up to 1.0 MPa. The unloading phase was divided in steps of 200 kPa in periods of 2 hours.

Figure 2 presents the rockfill compressibility in the tests DU50.1, DU50.2 and DU50.3. The vertical stress is plotted in logarithmic scale (Figure 2a) and natural scale (Figure 2b). It can be observed that as suction decreases, compressibility increases. Naturally, the specimen that was initially flooded (DU50.3) presented a greater compressibility, when comparing to the other tests. Linear relations were fitted to the obtained results, which are presented in Figure 2b.



a) Vertical stress in logarithmic scale.



b) Vertical stress in natural scale.

Figure 2 - Rockfill compressibility for different stress and suction paths.

3. NUMERICAL MODELLING

Nakata et al. (2001) compared the results of single-particle crushing tests with the one-dimensional compression of specimens of the same uniformly graded sand. The results showed that the macroscopic stress level required to cause crushing and irrecoverable compression in a sand specimen, was much smaller than that required to break individual grains. They attributed this to the unequal distribution of internal contact forces within an aggregate of grains. Cundall and Strack (1979) found that only a number of heavily loaded chains of particles respond to externally applied stress, which had been observed experimentally by Oda and Konishi (1974), while the remaining particles within the mass are only slightly loaded. Their main contribution to the system is the stabilisation of the main loading chains. As a result of this particle breakage, several authors (Cheng et al., 2003; Tran et al., 2009) have studied diametrically loaded single particles. Cheng et al. (2003) described two breakage phases: an initial one, governing the beginning of individual grain breakage, and a second one in which further breakage continued as the compression proceeded. In a rockfill specimen, agglomerates are supported by nearby agglomerates, increasing the coordination number (average number of contacts per particle). This aspect should distribute stresses along its contacts, leading to a reduction in tensile stress, when compared to single particle crushing tests (McDowell and Bolton, 1998). Therefore, a particle in a rockfill specimen might break at an applied stress even higher than the crushing strength, registered between two platens. A possible explanation for this difference may be due to the concentrated force chains (Oda and Konishi, 1974; Cundall and Strack, 1979), which lead to stress concentrations acting on individual particles.

3.1. Specimen generation

Rockfill particles were created and loaded in order to verify the applicability of the presented simulation approach. The objective of the present model was to simulate the material response during an oedometric test and to reproduce its grain size evolution. The agglomerates could break if their strength was exceeded and their shape would change due to the broken fragments, which remained in the simulation. The nomenclature of Nakata et al. (2001) was adopted in this paper.

The numerical test started by creating an initial set of *exo-disks* placed randomly with a size slightly smaller than required, without overlaps between themselves. After that, they were expanded to the final size and cycled until equilibrium was reached, reducing unwanted gaps. Table 1 presents the characteristics of the model. Following Cheng et al. (2003) and Robertson (2000), the shear stiffness and the friction coefficient were reduced to zero, while the lateral wall stiffness was reduced ten times the initial normal stiffness, which was increased 100-fold during the process of preparing the specimen (Table 2).

Table 1 - Characteristics adopted to model the oedometer test.

Input parameter	Numerical value
Specimen height [m]	0.474
Specimen width [m]	0.500
R min [mm]	9.5
R max [mm]	19.1
Clump size [mm]	10.0 +/- 0.2
Density [kg/m 3]	2052
Friction coefficient	0
Shear stiffness [N/m]	0
Normal stiffness [N/m]	$5 \cdot 10^8$
Wall stiffness [N/m]	$5 \cdot 10^8$

A linked list containing the coordinates of exo-disks centres was created, allowing to insert the particles with the centre located at the listed coordinates. Each disk was replaced by a regular assembly of disks in hexagonal close packing, without initial overlap. The radius of the disks within this assembly were 20 % of the original disk. Then, the clump logic was continuously activated until all particles were clumped. The new assembly was cycled again until equilibrium was reached. In order to reduce the possibility of breaking the bonds during the preparation of the specimen, their strengths were initially set very high ($1 \cdot 10^9$ Pa). This objective was achieved and no bonds broke during the specimen preparation process, after introducing the clumps, for an equilibrium stress of 5 kPa.

Table 2 - Adopted properties for specimen preparation. DU50 tests.

Input parameter	Numerical value		
	DU50.1	DU50.2	DU50.3
Friction coefficient		0	
Shear stiffness [N/m]		0	
Normal stiffness [N/m]		$5 \cdot 10^{10}$	
Wall stiffness [N/m]		$5 \cdot 10^{7}$	
Normal and shear stiffness (parallel bonds) [N/m]	$0.95 \cdot 10^{8}$	$1.0 \cdot 10^{8}$	$1.1 \cdot 10^{8}$
Normal and shear strength (parallel bonds) [MPa]		$1.0 \cdot 10^{9}$	
Radius multiplier (parallel bonds)		0.5	

3.2. Calibration methodology

Shear and normal stiffness played a very important role in the specimen behaviour, specially in its preparation process. These parameters influenced the particle rearrangement and, indirectly, the plastic behaviour of the material. During the specimen preparation process, when an equilibrium stress of 5 kPa was being imposed, larger shear and normal stiffness originated a specimen with larger void ratio resulting in higher levels of rockfill deformability during the test, for the same loading and unloading paths, whereas lower values of shear and normal stiffness returned specimens less deformable. This was taken into account when modelling the different experimental tests, in equilibrium with different relative humidity conditions. Table 2 presents the adopted parameters for each specimen preparation.

Before starting the test, bond strengths, contact shear and normal stiffness and the friction coefficient were set to their final values, which are presented in Table 3.

Table 3 - Adopted properties for modelling rockfill compressibility. DU50 tests.

Input parameter	Numerical value		
	DU50.1	DU50.2	DU50.3
Friction coefficient		0.5	
Normal and shear stiffness (parallel bonds) [N/m]		$2.0 \cdot 10^{10}$	
Normal and shear stiffness (parallel bonds) [N/m]	$0.95 \cdot 10^{8}$	$1.0 \cdot 10^{8}$	$1.1 \cdot 10^{8}$
Normal and shear strength (parallel bonds) [MPa]		$1.0 \cdot 10^{3}$	
Radius multiplier (parallel bonds)		0.5	

In order to model the effect of suction on rockfill compressibility, it was decided to change the values of shear and normal stiffness, keeping the remaining properties constant (Tables 2 and 3).

This methodology seemed capable of mimicking the effect and had the advantage of simplifying the process of calibrating the models.

3.3. Oedometer compression analysis

Several displacement rate-limited loading tests were performed in order to check for possible inertia effects on the location of the normal compression line. Then, it was decided to adopt a displacement rate of 0.01 m/s, since it was considered slow enough to eliminate rate effects, due to any bouncing that could occur initially for unloaded agglomerates.

Figure 3 shows the layout of particles used in the simulation of test DU50.3, where the suction was null since the specimen was flooded. The oedometer test consists in vertically loading the sample while restraining lateral deformation by using rigid walls. This specimen comprised 317 numerical rockfill grains, 1520 clumps and a total of 6023 elementary disks. These numbers were chosen to originate a model that achieved reasonable computation times and was capable of properly simulating the material behaviour. The oedometer test consisted in ten loading stages of 100 kPa until reaching 1 MPa. During each loading stage the top and bottom walls moved progressively together, fixing the position of the other pair of walls to achieve the desired boundary conditions. The speed of the walls was limited to a maximum value in order to reach the desired stress. The \textit{stress} was determined by summing and averaging all contact forces on the top wall. The void ratio was calculated considering the solids volume as the total area of the circles, resulting in an initial value of 0.26, which is nearly the value of the real rockfill (0.29).

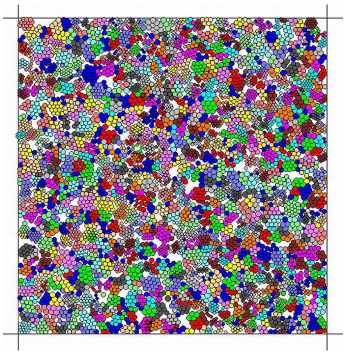
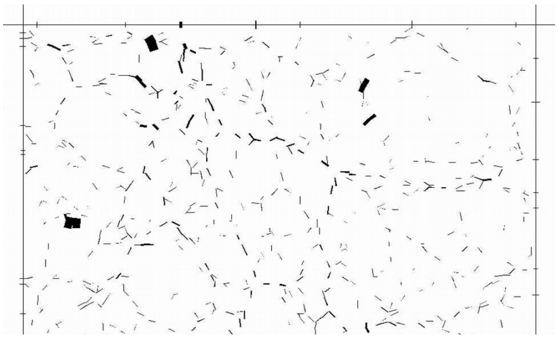


Figure 3 - Rockfill specimen of 1520 clumps.

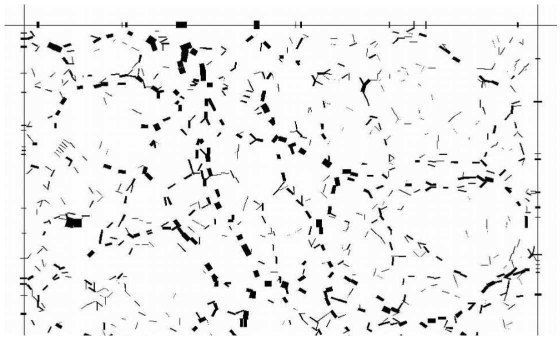
Figure 4 presents a schematic representation of the contact force distribution, inside the numerical oedometer. Three steps of the loading phase and one of the unloading phase are represented. In order to better visualise the force distribution only a detail of the top of the specimen is shown. Force chains are clearly visible and are enhanced with the increase of the external load. It can also be seen that some chains disappear during the oedometer test and, through force redistribution, are replaced by new ones.

The specimen was loaded by continuously increasing vertical stress up to 1 MPa, using the referred stepping scheme (ten steps of 100 kPa). During loading it was observed that irrecoverable compression was registered beyond 100 kPa, and that, for the range of stresses simulated, the behaviour could be mainly attributed to particles rearrangement, since a small amount of bonds broke (less than 10 %). During unloading (swelling curve) of the simulated rockfill specimen, the behaviour was inelastic and bond breakage practically stopped.

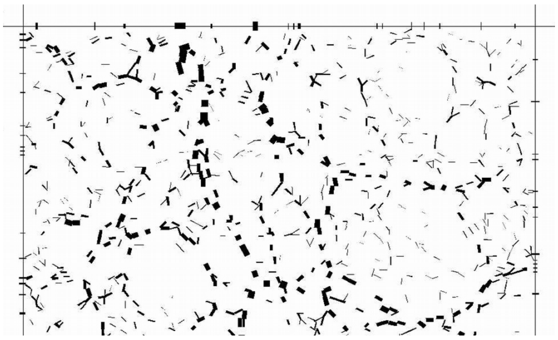
Figure 5a compares oedometer compression curves between the DU50.1 test and the *DEM* simulation with a platen displacement rate of 0.01 m/s. During loading, both shapes are very similar (although the numerical curve presents larger compressibility) and the *DEM* simulation captures the transition from particle rearrangement, due to elastic compression, into what may be described as clastic compression. Clastic yielding happens when the applied stress causes the onset of particle crushing, assuming that the onset of particle breakage leads to the bend of the normal compression line, causing the rapid increase of the material compressibility index (Oldecop and Alonso, 2003). During unloading, the simulated rockfill also showed good similarities with the laboratory test.



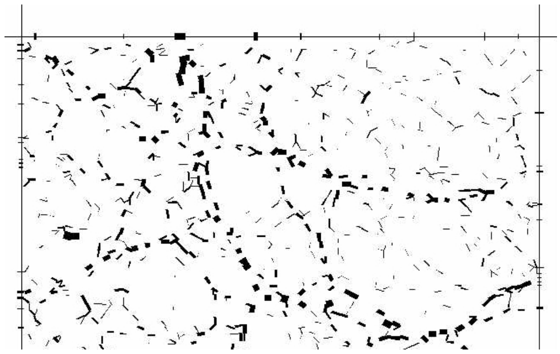
a) Axial stress of 0.1 MPa.



b) Axial stress of 0.5 MPa.

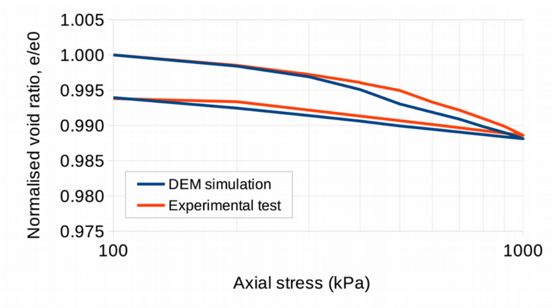


c) Axial stress of 1.0 MPa.

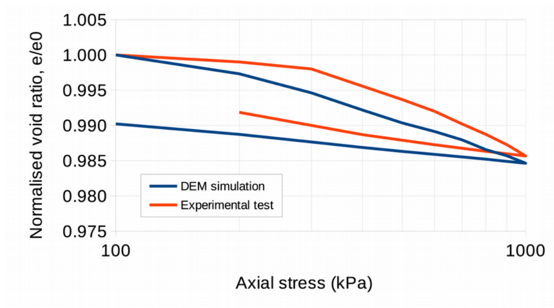


d) Axial stress of 0.5 MPa (unload).

Figure 4 - Schematic representation of the contact forces during oedometer tests (detail).



a)



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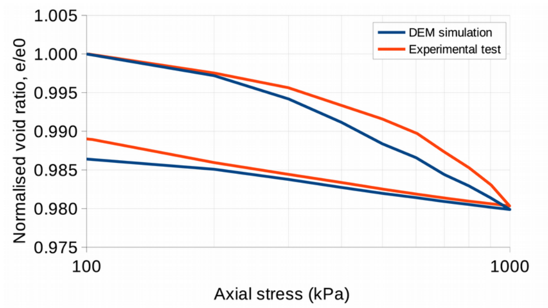

c)

Figure 5 - Normalised oedometer compression curves obtained by numerical modelling of test: a) DU50.1, b) DU50.2 and c) DU50.3.

Figure 5b compares oedometer compression curves between the DU50.2 test and the *DEM* simulation. It seems that the *DEM* simulation is not capable of capturing the transition from particle rearrangement, due to elastic compression, into what may be described as clastic compression (characterised by the onset of particle breakage). In the real rockfill, the bend of the normal compression line, causing the rapid increase of the material compressibility index occurred at 0.3 MPa, but the numerical model produced a smoother normal compression line. During unloading, both the real material and the simulated rockfill presented similar slopes.

Figure 5c compares the experimental with the numerical oedometer compression curves for test DU50.3. During loading, both shapes are similar, but the numerical specimen presented a smoother compressibility rate, obtaining a similar normalised void ratio compared to the experimental, at the maximum stress. During unloading, the elastic modulus were similar in both results, and at the end of the test the numerical result slightly separated from the experimental.

4. CONCLUSIONS

Oedometer compressibility on rockfill was generally approached through *DEM* modelling by providing a careful specimen preparation in the model and defining the parameters based on laboratory test results.

The developed model adopted the clump logic to simulate rockfill particles allowing them to randomly subdivide into smaller shapes. This has been achieved by introducing the idea that a rockfill grain can be considered to be an agglomerate of bonded micro-elements, here represented as clumps. Breakage occurred in the specimen when a bond between sub-particles broke. This approach seemed to be capable of creating a lifelike distribution of grain crushing strengths and rockfill compressibility behaviour.

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