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David Bertrand[1,2,3] — Philippe Gotteland[1]
Stéphane Lambert[1,2] — François Nicot[2] — Francis Derache[3]

[1]Lirigm – UJF Grenoble 1, BP 53, 1381 rue de la piscine
F-38031 Grenoble cedex 9
{firstname.name}@ujf-grenoble.fr
[2]Cemagref, 2, rue de la papeterie, BP 76, F-38402 St Martin d'Hères
{firstname.name}@grenoble.cemagref.fr
[3]France Maccaferri, 29, rue Rossini, BP 8, F-26901 Valence cedex 9

ABSTRACT. This paper focuses on the modelling of an innovative rockfall protection barrier built with cell assembly. The mechanical response of geo-composite structures subjected to an impact is analyzed. The modelling of the structure is based on a multi-scale approach. First the constitutive behaviour of a single cell is investigated. Different kinds of loading paths are considered (quasi-static and dynamical loading conditions). Then, the entire structure is considered. For this purpose each cell is described by a single node and the interaction between adjoining nodes is described by means of the constitutive model developed for each single cell. Preliminary structure impact simulations are finally commented.

KEYWORDS: impact, DEM Model, structure.

RÉSUMÉ. L'étude présentée porte sur l'analyse de la réponse mécanique d'une structure de protection contre les éboulements rocheux soumise à un impact. Un développement innovant consiste à concevoir ce type de structure sur la base d'un assemblage cellulaire. Les cellules sont des éléments géocomposites (géomatériau entouré de grillage). L'approche se fonde sur plusieurs échelles. A l'échelle locale, la cellule est modélisée en trois dimensions grâce à la méthode numérique aux éléments discrets. La réponse mécanique à différentes sollicitations quasi statiques et dynamiques permet de déterminer un modèle constitutif de la cellule. Ensuite, les résultats obtenus à l'échelle de la cellule sont utilisés pour la modélisation de l'ouvrage. La structure est discrétisée et l'interaction entre les éléments est décrite à l'aide du modèle constitutif déterminé à l'échelle locale. Il est alors possible de simuler la réponse de la structure à un impact.

MOTS-CLÉS : impact, modélisation MED, ouvrage.

1. Introduction

Protecting inhabitants of mountainous regions requires the construction of specific and adapted structures. In the case of rockfall mitigation, these structures can be rock sheds (Labiouse *et al.*, 1994), restraining nets (Nicot *et al.*, 2001) or dams (Yoshida *et al.*, 1999; Burroughs *et al.*, 1993; Hearn *et al.*, 1995).

The design of rockfall protection dams generally rests on an empirical approach. The examination of the previously published researches dealing with this topic underlines the lack of knowledge in the designing of these structures, in particular from a dynamic point of view (Schreler *et al.*, 2001; Burroughs *et al.*, 1993; Hearn *et al.*, 1995). Indeed, the behaviour of the constitutive materials of these rockfall barriers is still badly known under localised dynamic loading. Thus, there is a real need to advance in the prediction of the structure response during an impact. In particular, it seems necessary to bring elements in order to analyse the mechanical response of the structure according to the impact conditions or to assess the residual capacity of the structure after several impacts. The purpose of the study undertaken is to improve the design and the behavioural analysis of this kind of structures, with final goal to product a design-assistance tool for engineers.

The study specially concerns cellular rockfall barriers, namely rockfall protection structures made of an assembly of cellular elements. These elements, hereafter referred to as cells, are wire netting boxes that can be filled with different kinds of materials (e.g. assembly of limestone blocks, fine material, dissipative material, light materials, etc.) making it possible to adapt the mechanical characteristics of these basic elements to their place and function in the structure. For example, the face of the structure stroked by falling blocks is composed of cells filled with rocky elements whereas its core may be built with cells filled with lighter material (Figure 1).

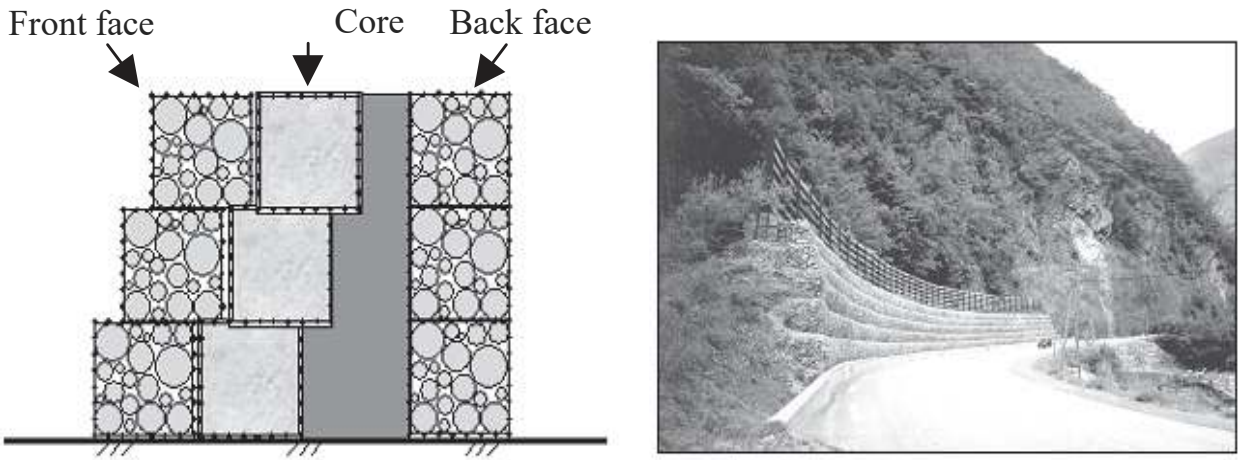

Figure 1. *Cellular structure against rockfall*

In order to model the structure a multi-scale approach is adopted. Thus the cell characteristics can be taken into account to model the structure. On the local scale, the purpose is to study the behaviour of a cell subjected to various loading paths such as confined and unconfined compression tests and dynamic impact. Then a constitutive relation for a cell under this type of particular loadings is identified and defined. On the global scale, each cell is replaced by an elementary part. In the end, such a modelling will lead to the development of computational software based on a discrete numerical approach. The interest of this approach is to have a simplified macroscopic description of the entire structure thanks to the constitutive models of the cells that accounts for the local behaviour of the structure.

2. Numerical modelling

A Discrete Elements Method (DEM) is used for the numerical modelling of the cell and the structure. This method is particularly adapted for static and dynamic simulation of granular matters (solid granular material with and without cohesion, grains flows, etc.). The DEM is based on a molecular dynamics approach (Cundall, 1979) and simulates dynamic evolution of discrete elements.

In this study, the discrete elements used (referred to as particles) are spherical. Mutual interaction forces exist between particles whether they are in contact or not (Figure 2). The model used to describe the magnitude of the force between two contacting particles is a linear elastic contact model in the direction normal to the contact and a linear elastic perfectly plastic model in the tangential direction. The interactions are governed by three parameters: the contact stiffness, k_n and k_s, and the inter-particles friction coefficient f. The remote interactions between particles are used to simulate the wire netting surrounding the fill material of the cell. The dynamic evolution of the entire mechanical system is calculated at each time step.

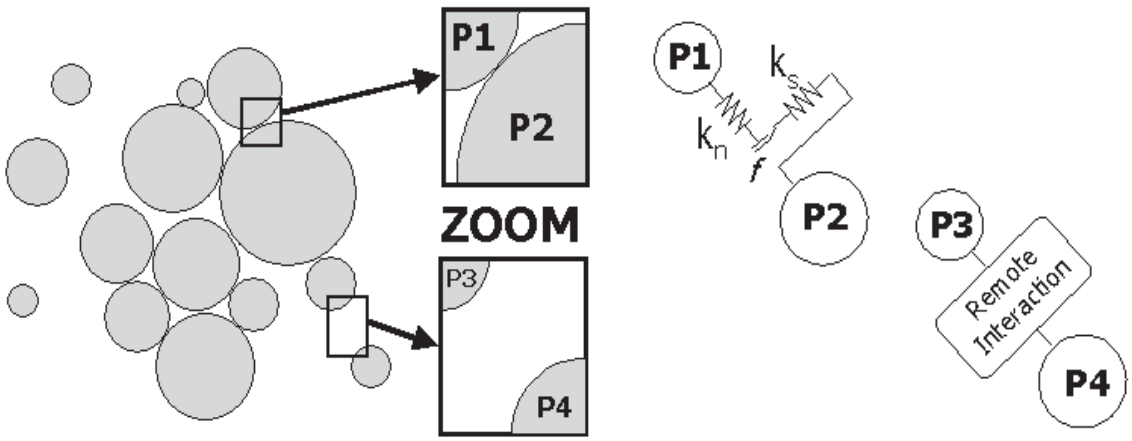

Figure 2. *Interaction model between particles: contact (k_n, normal stiffness, k_s shear stiffness, f friction coefficient) and remote model*

During a time step, two calculation stages are required. First, Newton's second law is applied to get the current positions of the particles. Then, the forces applied to each particle are computed.

3. Cell modelling

3.1. *The wire netting*

The wire netting box is described by a set of spherical particles. The particles are located at the physical nodes of the mesh, *i.e.* at the wire intersection (Figure 3). Forces accounting for the mechanical behaviour of the wires are applied to the wire netting particles. The mechanical behaviour of the wires is modelled by an elasto-plastic relation with failure. Experimental tensile tests on single wires were carried out to calibrate the parameters of the elasto-plastic relation (Figure 3). The force between two adjoining particles $\underline{i}$ and j depends on the distance between the corresponding nodes, so that the following general expression can be inferred:

$$\left\| F_{ij} \right\| = \tilde{f}\left(\left\| \vec{x}_i - \vec{x}_j \right\| \right) \qquad [1]$$

where $\left\| F_{ij} \right\|$ is the force applied by the particle j on particle i and $\left\| \vec{x}_i - \vec{x}_j \right\|$ is the distance separating the two particles ($\vec{x}_i$ and $\vec{x}_j$ are the respective position vectors of particles i and j). $\tilde{f}$ is the rheological functional governing the mechanical behaviour of wires. The direction of the forces is expressed as follows:

$$\vec{F}_{ij} = \left\| \vec{F}_{ij} \right\| \vec{n}_{ij} \qquad \text{where } \vec{n}_{ij} = \frac{\vec{x}_i - \vec{x}_j}{\left\| \vec{x}_i - \vec{x}_j \right\|} \qquad [2]$$

$\vec{n}_{ij}$ is the unit vector giving the direction of the force $\vec{F}_{ij}$. Afterwards, mechanical equilibrium is made on the considered particle and the out-of-balance force is applied to the particle.

Figure 4a shows the boundary conditions during the uni-axial tensile test and displays the geometrical shape of the mesh during the simulation. The numerical results show a good agreement with the experimental data (Figure 4b). A detailed presentation of the wire netting modelling and of its validation is given in Bertrand *et al.*, 2004a and 2004b.

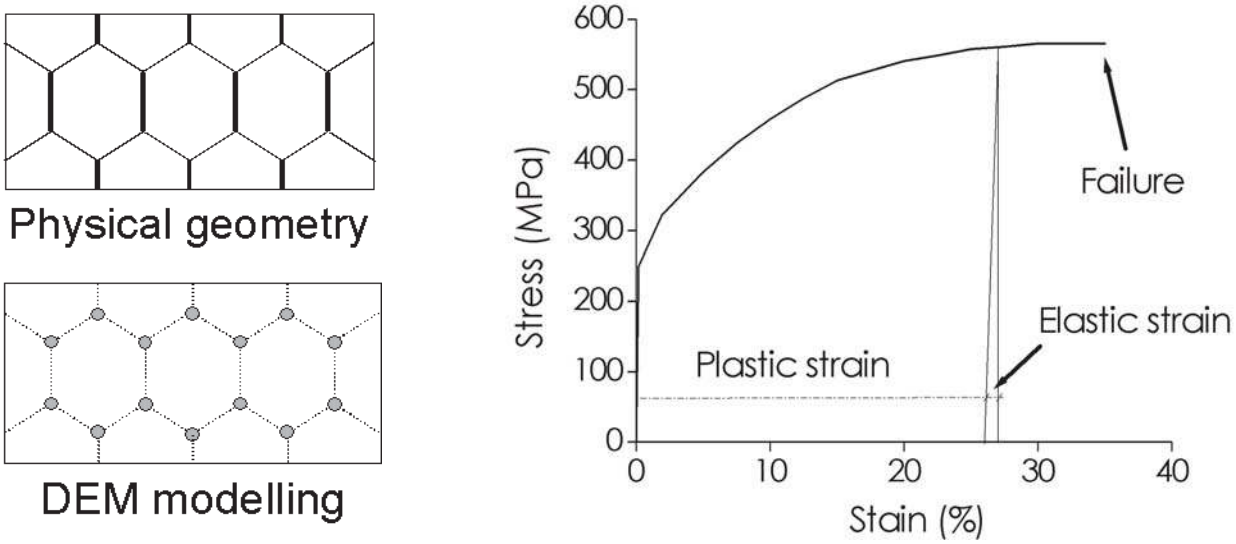

Figure 3. *DEM modelling of the wire netting and elasto-plastic model with failure implemented into the computational code*

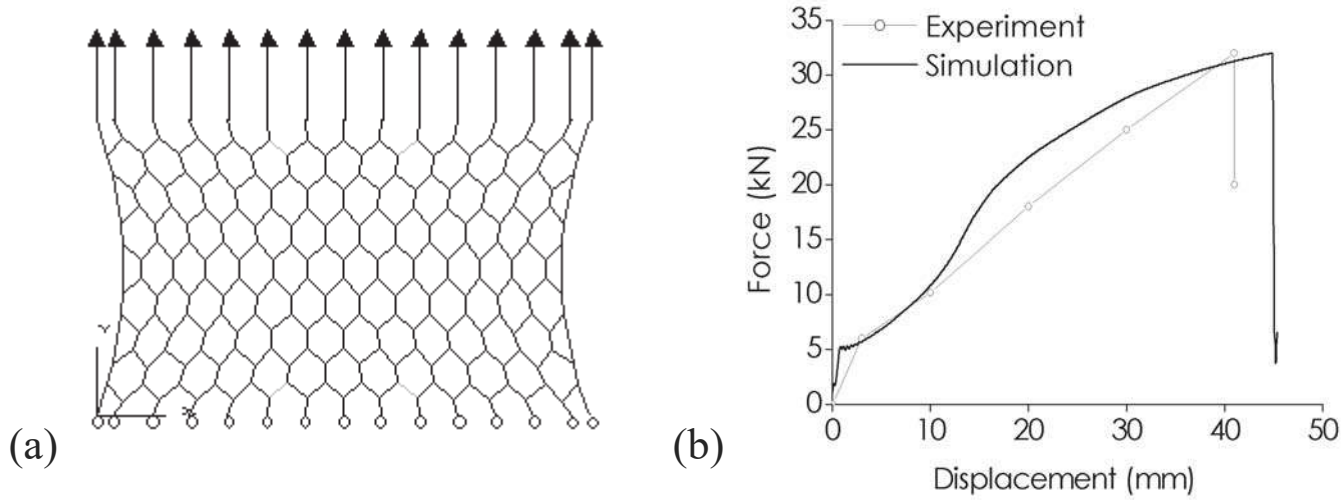

Figure 4. *Tensile strength test on wire netted sheet (a), Wire netted sheet features: 500 mm x 1 000 mm – stitch 80 mm x 100 mm, (b) comparison between numerical and experimental results*

3.2. *Fill material*

The cell is filled with crushed blocks of irregular, angular shape. Different types of shape can be generated in order to obtain a realistic block modelling (Bertrand *et al.*, 2005). For this purpose aggregates of bonded spherical particles are created. Their initial shape is parallelepipedic. The edges of this aggregate of particles are then cut out to modify their angularity. The aggregates are calibrated numerically to fulfil with the grain size requirements of the Standard for this specific technique (NFP 94-325-1). The size of the aggregates placed in the cell follows a statistic Gaussian distribution fitting with experimental grain size distributions (Figure 5).

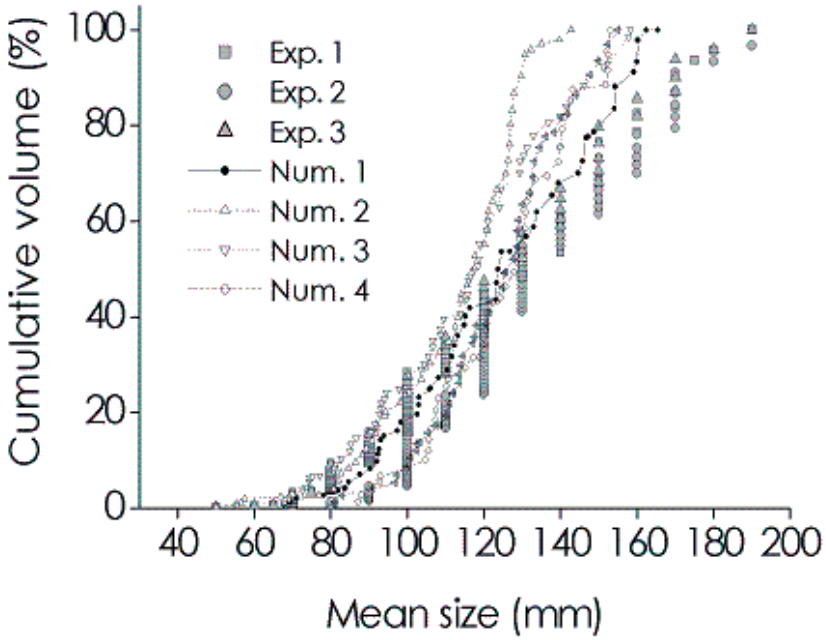

Figure 5. *Numerical (Num. i) and experimental (Exp. i) grain size distributions of several cells*

Finally, the aggregates are positioned above the cell and gravity makes them falling into the cell.

However, the initial porosity of numerical cells filled only applying gravity is higher than the experimental ones. The experimental average initial porosity is about 42% whereas numerical values are close to 50%. A vibration process of the aggregates reduces the cell porosity by about 5%. In the following, all the mechanical tests are performed considering the same initial aggregate assembly with an initial porosity of 43.6%.

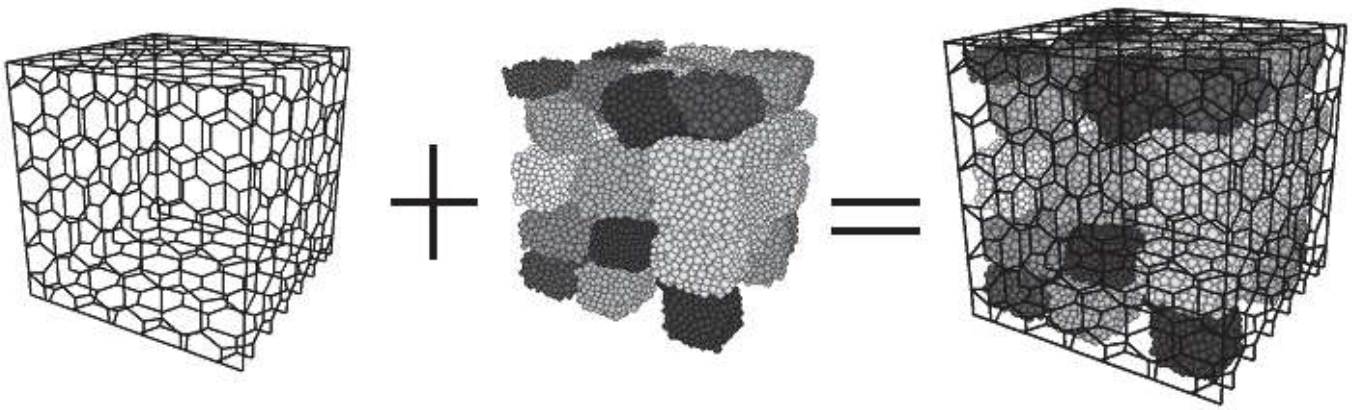

Figure 6. *Cell modelling. Wire netting and fill material coupling*

3.3. *Mechanical tests*

After their generation the fill material and the wire netting are added together (Figure 6). At this stage, the cell is ready to undergo loading. The numerical results are compared with the experimental values obtained in similar conditions (Lambert *et al.*, 2004). First, the mechanical calibration of the cell is undertaken in quasi-static conditions (Figure 7). Confined compression tests (CC tests) are carried out in order to calibrate the numerical model parameters of the fill material, and specially the normal and tangential stiffness of the contact model. Then, unconfined compression tests (UC tests) are performed. Finally, the mechanical response of the cell under a dynamic impact loading is explored for confined compression impact tests (CCI tests) and for unconfined compression impact tests (UCI tests) as well.

Normal and tangential stiffness are estimated thanks to confined compression tests (CC tests). The boundary conditions of the compression test are defined with six rigid walls acting on each face of the cube (Figure 7a). From a qualitative point of view, numerical and experimental results are not similar if the contact stiffness is maintained constant over the mechanical test (Figure 8).

Axial force vs. axial displacement simulated curves exhibit a power law like relationship whereas experimental curves shows that the mechanical response of the cell develops a quasi-linear evolution.

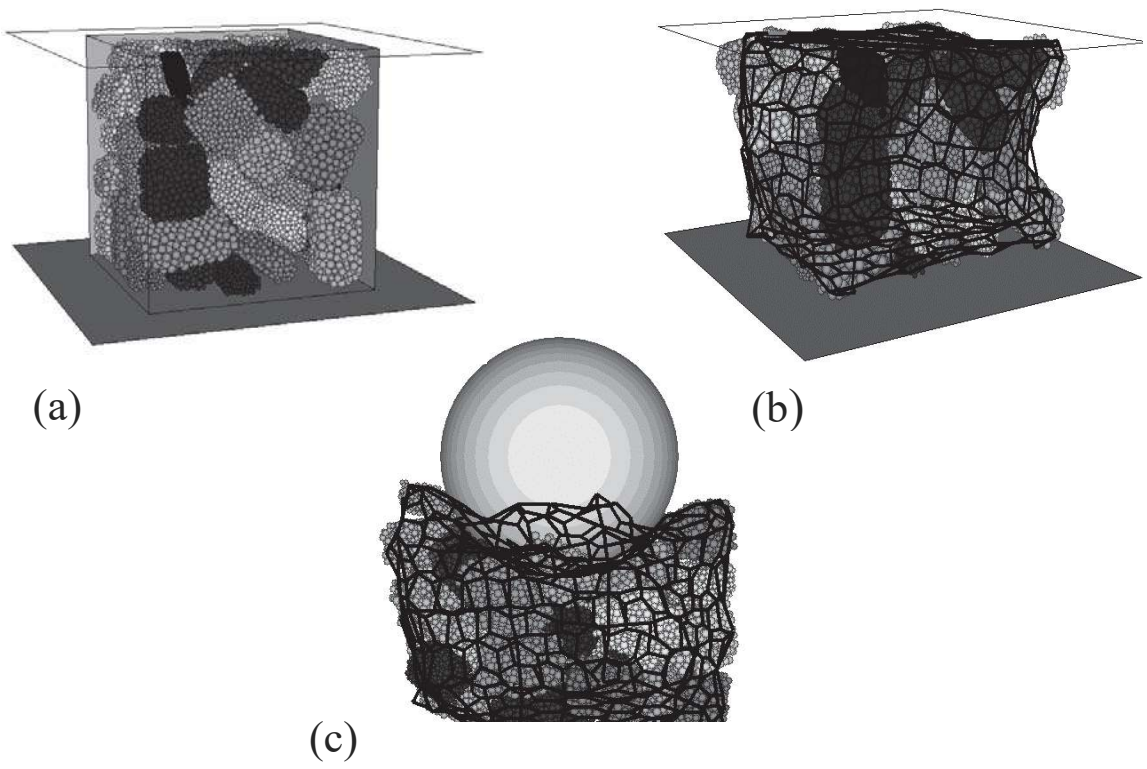

Figure 7. *Cell compressions: a) confined condition (CC tests), b) unconfined condition (UC tests), c) unconfined condition under impact (UCI tests)*

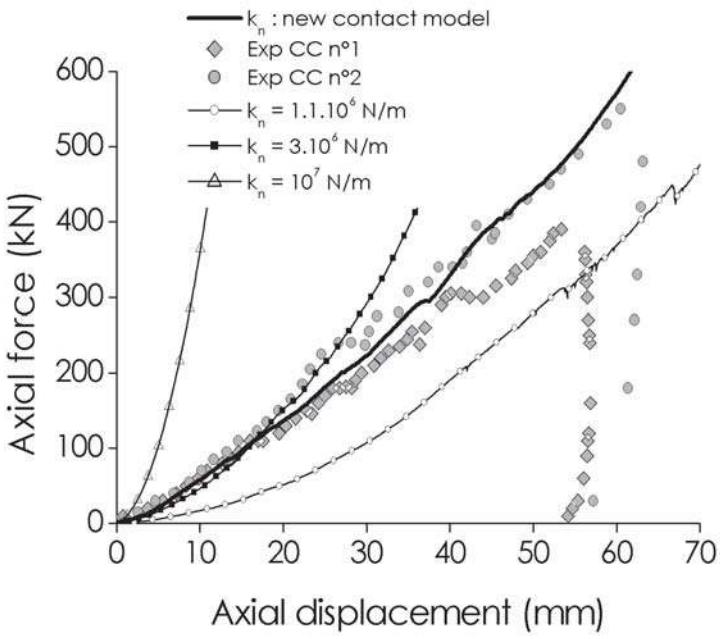

Figure 8. *Numerical response of a cell in confined condition (CC tests)*

This difference between numerical and experimental results is, in large part, due to the degradation process of the material in the vicinity of the contact areas. This phenomenon is observed experimentally and occurs from a 1% axial displacement in confined compression tests. In order to take into account the degradation of the particles in the vicinity of the contacts during the test, a more refined contact model was considered. Considering that the local degradation process is similar to a local reduction of the stiffness at the contact points, the contact stiffness is reduced according to the contact force $F_c^n(t)$ at time t by introducing an elasto-plastic relation in the normal direction of contact. The contact model becomes:

– if $F_c^n(t) = F_{\lim}$ and $\Delta U_c^n > 0$ then

$$F_c^n(t+\Delta t) = F_{\lim}$$

$$\Delta U_c^{n,elast} = 0 \text{ and } \Delta U_c^{n,plast} = \Delta U_c^n$$

– if $F_c^n(t) < F_{\lim}$ or $\{ F_c^n(t) = F_{\lim}$ and $\Delta U_c^n < 0 \}$ then

$$\Delta F_c^n = k_n \, \Delta U_c^n$$

$$\Delta U_c^{n,elast} = \Delta U_c^n \text{ and } \Delta U_c^{n,plast} = 0$$

Where $F_{\lim}$ is the maximum contact force, ΔU_c^n is the overlap between two contacting elements and $\Delta U_c^{n,elast}$ the elastic part and $\Delta U_c^{n,plast}$ the plastic part and k_n the stiffness of the contact.

Once the contact stiffness magnitude is assessed, unconfined compression tests (UC tests) were performed (Figure 7b). The numerical results are compared with experimental data in Figure 9a. For similar cells filled with the same particles, the initial packing of the grain assembly was shown to have a very high influence on the cell response (Bertrand *et al.*, 2006). This feature is all the more pronounced since the number of particles (in both experimental and numerical tests) is small. Thus, a significant variability is observed between the different tests. The numerical simulations are in agreement with the experimental results for a friction angle ϕ of 27° (Figure 9b), corresponding to a friction coefficient *f* of 0.5. The friction angle reduces the possible displacement of the elements, contributing to the resistance of the cell: the higher the friction angle, the higher the cell resistance. As a matter of fact, it contributes to the stability of the so-called force chains existing in granular assemblies. In the granular assembly some columns made up of contacting particles exist in which the major part of the force applied on the assembly transits.

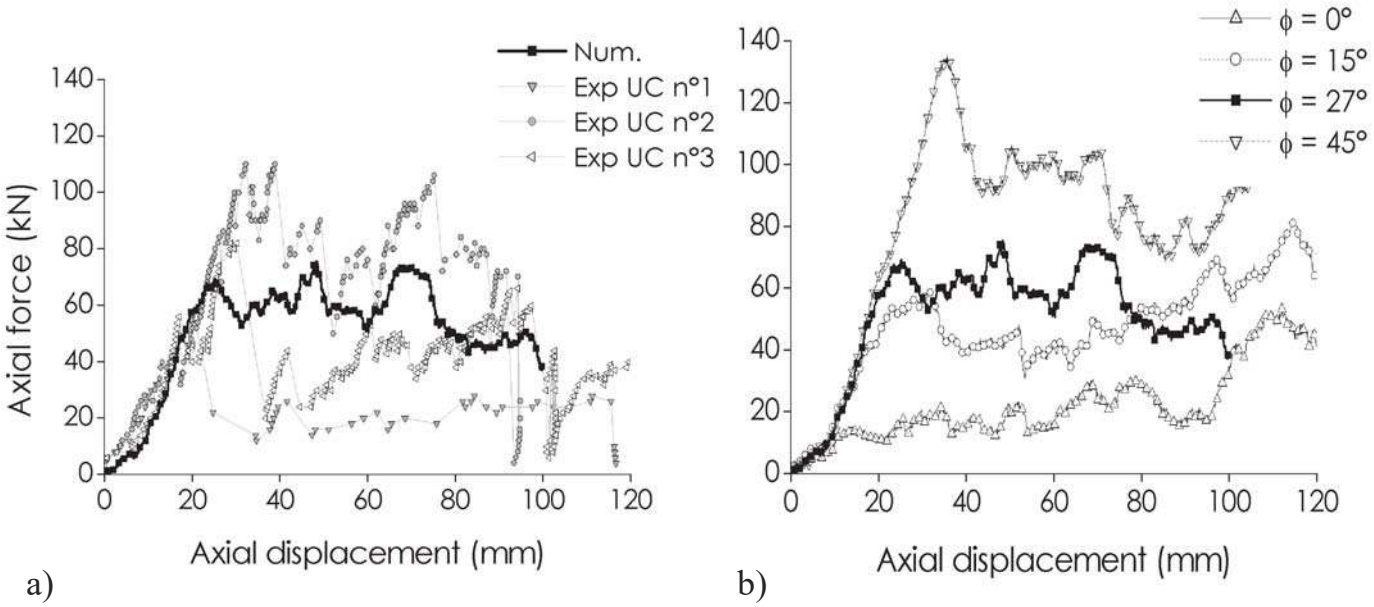

Figure 9. *Numerical response of a cell in UC tests: a) comparison between both numerical and experimental results; b) friction influence on numerical results*

Brutal force drops are caused by the collapse of some of the principal force chains. The origin of the collapse is either geometrical (displacement of elements), or mechanical (failure of one or several elements). However, the numerical model does not make allowance for the possible element failure, inducing an overestimation of the force leading to the first occurrence of force drop.

The next step consists in studying the mechanical behaviour of a cell under impact dynamic loading. A cell is impacted with a spherical boulder of 500 mm in diameter. The impact is carried out in unconfined condition (UCI tests, Figure 7c). The initial spherical boulder velocity before impact ranges between 8 m/s to 30 m/s. The friction angle of the elements appears not to have a significant influence on the mechanical response (Figure 10a). As impact simulations are carried out in unconfined conditions (lateral sides of the cell are free), they can be compared to results shown in Figure 9 (unconfined compression test). For the range of velocities experienced, the penetration depth of the impacting boulder has an order of magnitude of 20 mm. In Figure 9b, it can be shown that the influence of the friction angle is negligible while the axial displacement does not exceed 20 mm. The effect of the initial velocity on the force over the impact is given on Figure 10b. Further experiments required to make comparison with these numerical results are now in progress.

The ultimate step will consist in integrating these local results (cell scale) into the global model dedicated to the structure.

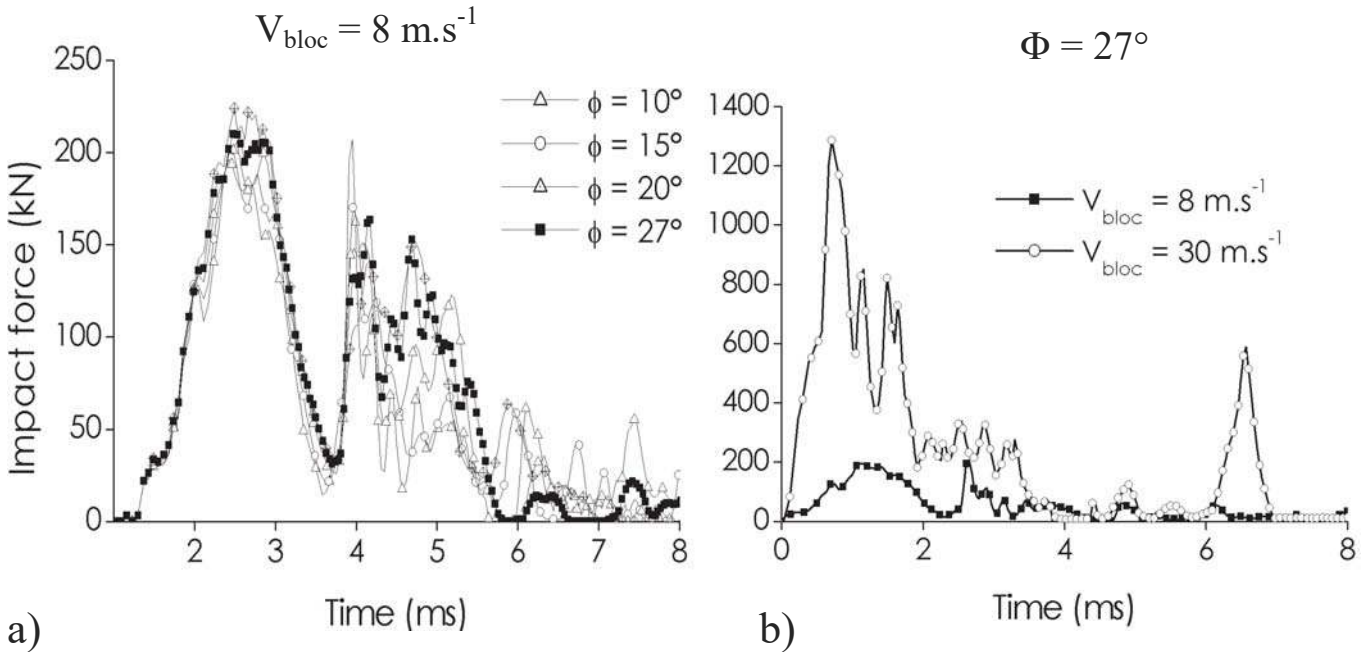

Figure 10. *Numerical response of a cell for UCI tests, a) influence of the friction angle; b) influence of impact velocity*

4. Modelling of the cellular structure

The structure is modelled by replacing each cell of the structure by a single spherical particle located at the cell centre (Figure 11). Each pair of particles describing two adjoining cells interacts, as indicated in Figure 2. It is convenient to adopt a discrete modelling of the structure since this method is particularly well adapted to describe phenomena where large strains occur. Furthermore, the same

computational environment as that used to model the single cell (PFC-3D) can be used again.

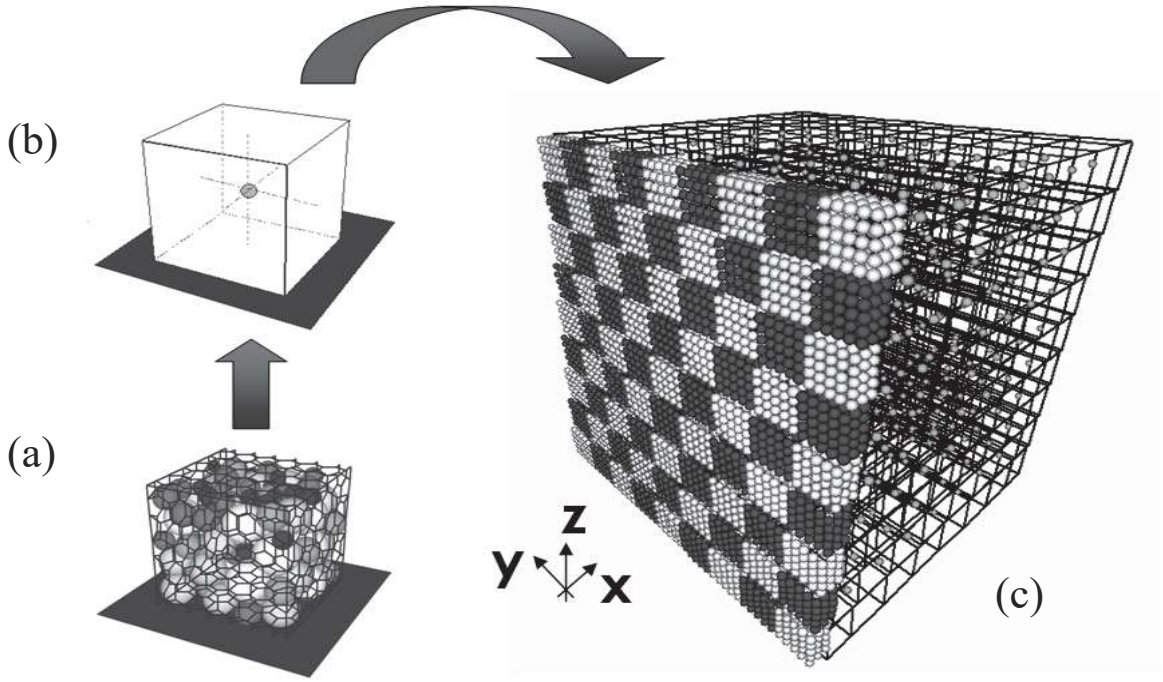

Figure 11. *Structure modelling: multi-scale approach*

Let us denote x the direction normal to the front face of the structure. The case of impacts oriented along x-direction will only be considered hereafter. As a first approximation, it can therefore be assumed that each cell moves along x-direction. Due to the confinement of cells within the structure, it seems reasonable to consider that the displacements along both y- and z-directions are negligible with respect to the displacements along x-direction. Thus, once a boulder impacts the structure, each cell behaves so that the four lateral sides do not displace along both directions y and z. As a consequence, it can be assumed that the interaction between two adjoining nodes along x-direction (cell *i* and cells 3 or 5 in Figure 12) can be modelled by the mechanical response of a unique cell along a confined loading path. Investigations carried out on single cells (previous sections) have shown that a standard elastic-perfectly plastic model could be advantageously used. This simplified model makes it possible to compute both forces $F^n_{i,3}$ and $F^n_{i,5}$. During confined compression tests, the lateral sides of the cell are subjected to a reaction force that is nearly proportional to the axial force (Bertrand *et al.*, 2006). A reaction force is therefore applied to the four lateral sides perpendicular to the directions y and z (both forces $F^n_{i,2}$ and $F^n_{i,6}$ in Figure 12). Assuming that a Coulomb friction takes place between adjoining cells (namely, between cell *i* and cells 1, 2, 4 and 6 in Figure 12), tangential forces ($F^t_{i,2}$ and $F^t_{i,6}$) are thus generated. These tangential

forces play a fundamental role since they induce a so-called lateral diffusion of the impact effect towards the neighbouring cells.

The front face of the structure (impacted face) is described by using cubic elements in order to model the interaction between the impacting boulder and the core of the structure. The front face slope can be modified by changing the positions of the frontal cells.

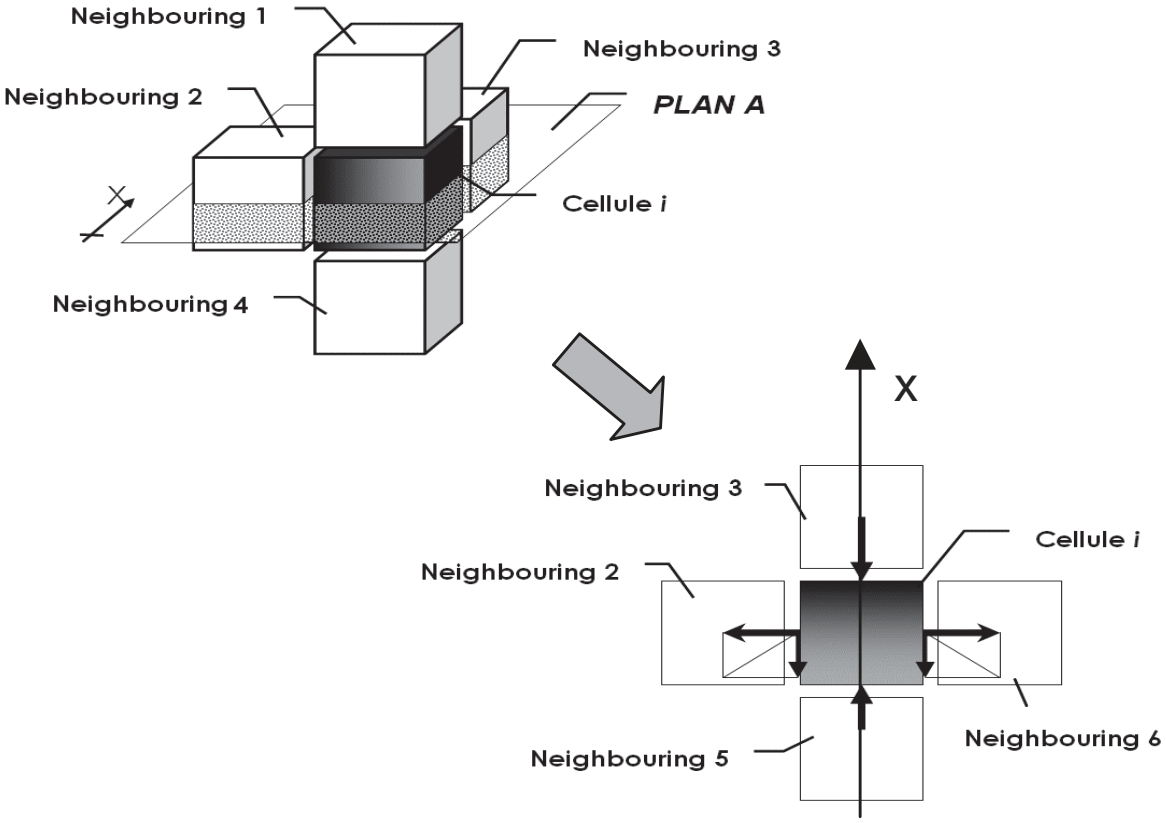

Figure 12. *Cell interactions into the structure*

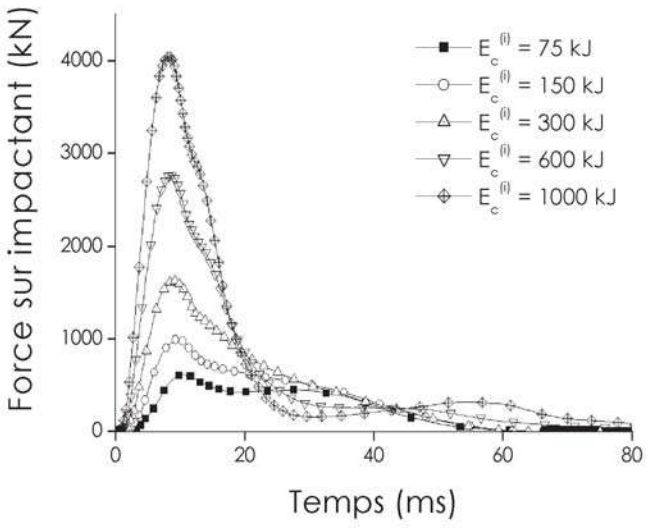

Figure 13. *Impact force reaction for several initial impact energies (Ec(i))*

As a first result, Figure 13 shows the influence of the kinetic energy of the impacting boulder onto the response of the structure. Several simulations were run with the same boulder, with different initial velocities. For these simulations, the size of the boulder corresponds to the size of the cells. The change in the reaction force applied to the boulder is analyzed over impact duration. It clearly appears that the initial velocity of the boulder strongly influences the peak reached by the reaction force, even though the duration of the impact seems to be unchanged.

5. Conclusion

The multi-scale modelling of a cellular rockfall barrier has been undertaken. On the local scale the mechanical behaviour of a single cell is investigated. A cell is composed of two mechanical systems: the wire netting and the fill material. The wire netting was modelled by taking into account the elasto-plastic behaviour with failure of wires. The comparison between simulations and experiments has provided encouraging results. The fill material was modelled by generating angular aggregates. Calibration of the parameters was performed from confined compression tests. Afterwards, numerical unconfined compressions were carried out. From both qualitative and quantitative points of view, the results are in agreement with the experimental observations. Finally, first results obtained from impact simulations are presented.

The structure is described by an assembly of particles: each cell is replaced by a spherical particle, and a specific interaction law was introduced to model the contact interaction between neighbouring cells. This interaction law was inferred from constitutive modelling of a single cell along confined compression tests. This kind of approach makes it possible to take into account the influence of various parameters such as both the shape and the size of the structure, as well as the mass and the velocity of the impacting boulder. Parametric analyzes are now in progress in order to get valuable data to improving the design of such protective structures.

Acknowledgments

This research was completed within the framework of the research network VOR: Risk Vulnerability of Structures. This network is funded by the French Ministry of Research and combines different laboratories in Rhône-Alpes region. This project was financed by France Maccaferri SA, part of the Maccaferri group. The support of both the research consortium VOR and the PGRN (Natural Hazard Pole of Grenoble) from the General Council of Isère Department, as well as the technical assistance supplied by the Technological University Institute of Grenoble are gratefully acknowledged. We extend special thanks to all the members of the research group for the interest they have shown in this work.

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