Discrete Modelling of Excavation in Fractured Rock by NSCD Method

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ABSTRACT: The presence of the network of discontinuities on intact rock is a special feature of nature rock masses. Non Smooth Contact Dynamics method (NSCD), a discrete numerical method with many strong advantages of the study on granular materials and has been recently used in rock engineering. LMGC90, the open-sourced numerical tool of NSCD, has demonstrated robust capacity in the modelling and mechanical analysis of diverse environments, masonry and rock included. In this study, a numerical modelling of a multi-phase-excavation in fractured rock was realized. The simulation of the tunnelling was conducted with the consideration of the state of the excavation and its neighbouring rock blocks. The obtained mechanical behaviours of the model were analysed, and three failure mechanisms of the excavation vicinity during the tunnelling were aimed. The observed phenomena showed typical effects of two components of the rock mass (rock structure and rock material) to the stability of the excavation and the host rock mass.

KEYWORDS: Fractured rock, NSCD, LMGC90, Multi-phase-excavation, Simulation.

1. INTRODUCTION

Any rock, either strongly or weakly fractured, can be defined as a continuous, discontinuous or hybrid medium when the scale of interest is macroscopic, microscopic or in between. The “continuous” or “discrete” nature of an object or a methodology is not absolute but relative, problem-specific, and dependent especially on the problem scale (Jing, 2003). In practice, to reach a quick or approximated engineering analysis, the presence of the discontinuities in the rock mass can be neglected and the characteristics of the intact rock mass can be used. This means that the rock media are considered as a CHILE material (Continuous, Homogenous, Isotropic and Linearly Elastic), (Jing & Hudson, 2002). The total rock mass can be thus assigned as the composition of several geological layers, the underground structures and some isolated geological objects. From that model, the behaviour of the underground structures and their surrounding environment is found by manual approaches or with the help of many efficient computer tools based generally on the continuous media mechanics. However, this approximation brings out an inaccurate image of the rock environment due to the lacking of its rock structure. Indeed, the presence of discontinuities strongly affects rock mass characteristic and behaviour. Any rock mass is always DIANE (Discontinuous, Anisotropic, Inhomogeneous and Not-Elastic) (Harrison & Hudson, 2000).

Different solutions to overcome this problem can be divided into two approaches: a) Maintaining the application of the continuous media; b) Finding another appropriate theoretical framework. The first thought is the search of an equivalent homogenous rock environment to replace the real one (intact rock mass and its discontinuities). However, the definition of a suitable model is the big challenge. The second option leads us to a discrete element environment where attention is paid to displacements and rotational degrees-of-freedom (DOF) of element and contact conditions between elements. Hence CHILE features are replaced by DIANE ones. The discrete methods (or discontinuous methods) analyse the research domain as the assemblage of the rigid or deformable blocks that have been created by the intersection of the rock structure. The correlation between displacement, force and equilibrium of the rock mass is analysed with the acceptation of the relative movement between two adjacent blocks. The basic difference between the discrete and continuous methods is the state of the contact patterns between particles of the medium with the deformation process: It changes continuously for the former, but fixes for the latter (Jing & Hudson, 2002).

For the application in rock and tunnel engineering, many methods have been proposed. Some representative continuous methods can be named as Finite Difference Method (FDM), Finite Volume Method (FVM), Finite Element Method (FEM), and Boundary Element Method (BEM). In our knowledge, FDM and FVM are found to be not suitable for the application in rock and tunnel engineering due to some reasons:

- The use of the regular grids of FDM or the cell-based grids of FVM blocks the modelling of the rock structure which distributes complicatedly with random configurations;
- Approximation of the fracture development are far to be obtained with reasonable accuracy.

C. Mattuissi (Mattuissi, 2002) commented that FDM and FVM can only use for the non-structure field, which can be translated as the denial of the application of two methods in rock and tunnel mechanics. FEM is the most widely applied numerical method in civil engineering. For the application in rock and tunnel engineering, this method has its own limits caused by its inherent disadvantages:

- The fracture development modelling is impossible ;
- The large strains or the detachment of rock blocks are unable to represented due to the assumption of the continuous condition of displacement at the nodes of grids (Hammah, Yacoub, & Corkum, 2008);
- The analysis of the complex objects (complex configuration, fractured condition, grand opening discontinuities, *etc.*) is not robust, especially when it is need to take into account their rotational motion.

Due to the usage of some limited types of standard elements, the generation of mesh becomes complicated, the stiffness mass tends to be ill-conditioned and the continuous mass is strictly kept from breaking into pieces (Jing & Hudson, 2002). As the result, the analysis is time consuming and less accurate. The biggest default of FEM is the impossibility of detachment modelling of rock blocks which is an inherent local and/or total failure phenomenon in tunnelling. Besides, when the rock mass is highly fractured, a FEM-based-analysis will lead to the complicated partial differential equations or low accuracy. Discretized only the boundaries but not the whole medium as three above methods, the BEM is limited for some cases of analysis:

- Objects of which the ratios between surface and volume are small (Bobet, 2010), (Katsikadelis, 2002);
- When stresses and displacements are only applied on the boundaries of the medium (Bobet, 2010);
- For static continuum and elastic behaviour analysis, that is not the case of rock masses.

This method has the difficulties in analyses of non-linear materials and inhomogeneous media due to the limitation of the sub-domains division (Jing & Hudson, 2002). Hence, BEM is not recommended for rock and tunnel modelling.

The group of Discrete Element Methods (DEMs) is considered to be the most widely applied for the granular material and for fractured domains. The rock mass is divided into small particles with random configuration and discrete features of mass, velocity, contact (Sykut, Molenda, & Horabik, 2007). Smooth Dynamics methods can be considered as the explicit solution of DEMs since the explicit discretization of time is used based on the theory of FDM (Acary, 2010), (Jing & Hudson, 2002), (Dubois & Renouf, 2011). Their most popular representative is the Distinct Element method of P.A. Cundall which has been applied as the fundamental for the some robust numerical tools in rock and tunnel engineering: UDEC, 3DEC and PFC. However, when there is a collision between two blocks, the interpenetration is accepted. This fact seems to be in appropriate for rock masses (Donzé, Richefeu, & Magnier, 2009). Non-Smooth Dynamics methods overcome this weak point of Smooth Dynamics methods by dealing with the unilateral contact. Two popular Non-Smooth Dynamics methods can be named as Event-Driven Method (EDM) and Non-Smooth Contact Dynamics (NSCD) method. The former uses the event-driven integrators, which was remarked to be not suitable for numerous contact systems (as soils, rocks, concrete) (Donzé, Richefeu, & Magnier, 2009). Using the time-driven integrators with the time integration implicit algorithm, the latter is at advantage. A popular FEM-DEM hybrid solution for rock and tunnel engineering is Discontinuous Deformation Analysis (DDA) method. DDA combines FEM's solution for stress-displacement problem with the DEM's detection of contact between discrete blocks along discontinuities. Also using the implicit time discretization like NSCD, DDA is able to use lager time step and to replace artificial damping by friction. However, the computation speed reduces significantly when large time step is used because of the open-close iterative procedure with highly nonlinear behaviour (Khan, 2010)

In this paper, NSCD and its numerical tool, LMGC90, is presented. Through a tunnelling simulation in a fractured rock mass, the application scope of NCSD in rock and tunnel engineering was proven. The combination of geometrical modelling by Discrete Fracture Network method (DFN) and the mechanical modelling by NSCD through a complicated simulation in LMGC90 is first presented. It aimed to understand the behaviour of the rock mass under the effect of the tunnelling procedure. The capacity of LMGC90 was widen in the simulation of rock mass with the real distribution of the rock structure.

2. NON SMOOTH CONTACT DYNAMIC METHOD (NSCD) AND ITS NUMERICAL TOOL

2.1 NSCD – a prominent discrete method for rock and granular media

The discontinuous mechanics and its numerical methods are widely applied in the rock engineering because of its robust capacity in modelling the rock structure. They are relatively young in comparison with the continuous mechanics but they have been developing impressively rapidly in computational mechanics (Jing & Hudson, 2002). With the acceptation of the relative movement between two adjacent blocks, discrete methods are capable to model the large displacement, the block rotation and the detachment of rock blocks. This group of methods is robust for analysing the large amount of particles, for various kinds of contact following various contact laws with the auto-recognition of new-born contacts during the calculation (Jing, 2003), (Bobet, 2010), (Beyabanaki, Mikola, & Hatami, 2008). Moreover, discrete methods are capable to model the propagation and the development of the fractures, which are weak points of the continuous methods. Discrete Element Methods (DEMs) form a branch in the discrete mechanics family. When iteration is realised in time steps by the implicit integration method and the non-smooth solution is used for the contact discretization, the group of Non-Smooth Dynamics methods (or non-regular approaches) is classified. Non-Smooth Dynamics methods are DEM solutions that solve the correlation between the contact force, the displacement and the configuration of rock blocks in the model. The forces are bilateral and determined from the solution of local nonlinear equations by taking consideration of the restitution of: a) Newton type related to velocity; b) Poisson type related to impulsion; c) Stronge type related to energy (Dubois & Renouf, 2011). Avoiding the interpenetration of the contacts, a damping which is proportional to the stiffness and the size of the particles is added. The Coulomb friction law is used to express the constitution law for the tangential forces between contacting blocks. The non-smooth viewpoint is built from three nonlinear aspects: a) Spatial non-linearity with non-interpenetration contact; b) Time nonlinearity with shocks between particles; c) Nonlinear contact law. The collision and other non-smooth phenomena are handled with the addition of the right continuous and the left continuous functions of the vector of generalized DOF in the equation of motion. The implicit discretization of time is used for the integration in each large time step: It calculates the state of the domain at the next time step by involving the states in the current and the next time step (Jing & Hudson, 2002), (Dubois & Renouf, 2011), (Acary, 2006), (Acary, 2010). It gives closed form integrations to the stiffness matrices (Jing, 2003).

The representative of Non-Smooth Dynamics methods is said to be the Non-Smooth Contact Dynamics (NSCD) method (or the former name Contact Dynamics (CD) method) developed by J.J. Moreau, M. Jean *et al*. (Moreau, 1994), (Jean, 1996), (Jean, 1999), (Dubois & Jean, 2006). This is suitable solution for the analysis of rigid and deformable objects in rock and granular media. It is based on the use of the "coefficient of restitution" in order to represent changes in the relative velocity of a rigid particle before and after the collision (Pecol, Pont, Erlicher, & Argou, 2011). Two principal characteristics of a contact between two objects are given in NSCD: a) The contact is unilateral and punctual; b) Two objects do not attract each other. At the same time, two discretization operations are realised (Jean, 1996), (Jean, 1999):

- Time discretization: The discrete variables are not defined at the milestone time steps but over the time intervals. Hence, the discrete contact relations are described by the time intervals.
- Configuration discretization: The discretized configuration space $D_k(X)$ is the combinatorial model of the classical configuration space of k individual blocks in the X-dimensional-space. The evolution of the mass is then expressed by a continuous time function, and the left and right limits of a point of time are used for other expression of the mass.

The implicit algorithm of time integration, which is more efficient for the analysis of the strong changeable variables of the large particle body, is also applied for this method (Jean, 1996), (Jean, 1999), (Dubois & Renouf, 2011). The Non Liner Gauss-Seidel (NLGS) algorithm and its implementations are applied for solving the dynamic equation (Dubois & Renouf, 2011):

- Store Delassus Loop strategy (SDL);
- Exchange Local Global Strategy (ELG);
- Store Delassus Loop strategy (SDL): parallel treatment;
- Quasi NLGS.

2.2 LMGC90 code

Developed at the LMGC laboratory of the University of Montpellier 2 (France) by F. Dubois et al, LMGC90 is the open sourced numerical tool of NSCD (Dubois & Jean, 2006). Written in Fortran, C/C++ and Python languages, LMGC90 is dedicated to the modelling of various kinds of interacting objects (in 2D or 3D) with complex mechanical behaviours. The principal of the discrete analysis of LMGC90 was interpreted by F. Dubois *et al.* (Dubois & Renouf, 2008), (Dubois, 2010), (Dubois, 2011) as the combination of:

- Non-Smooth Dynamics framework;
- Implicit time integration;
- Implicit contact solver.

The code is also able to implement other complicated tasks such as the molecular dynamics, the explicit time integration and the quasi-static evolution, *etc*.

A basic model on LMGC90 is characterised by (Dubois & Renouf, 2008), (Dubois, 2010), (Dubois, 2011):

- Shape: The objects of the model are 2D or 3D in the convex forms of various types that can be selected from the dictionary of the code. Each prototype is defined by its specific contact detection.
- Bulk behaviour: The objects are rigid or deformable. If they are deformable, they can be elastically linear or non-linear: hyper-elastic, viscous, plastic, *etc*. There are some other options: meshless, lattice, *etc*.
- Interaction law: The basic frictional contact laws used in LMGC90 are: a) Signorini unilateral conditions involving the gap and the normal relative velocity; b) Coulomb law. Besides, there are many available laws in the dictionary of the code. The choice of a law is depended on the bulk behaviour of the contact couple (rigid-rigid, rigid-deformable, or deformable-deformable). These laws are expressed by the application of the Convex Analysis theory proposed by J.J. Moreau (Moreau, 1994).
- Multi-coupling and multi-physics nature: The complex behaviour of an object can be described by the combination of the thermic, fluid dynamic, hydraulic effects for normal or mixed objects.

Each object is hence defined by five necessary features: 1) the material parameters; 2) the physical model and the behaviour law; 3) the interaction law; 4) the visibility table of the contact; 5) the avatar (physical object) (Martin, Bagneris, Dubois, & Mozul, 2011). The characterization of a 3D object is given by the setting of its DOFs: 1 DOF for a thermal object, 3 DOFs for a deformable object, 4 DOFs for a porous object, and 6 DOFs for a rigid object.

The bulk behaviour of the object is assigned either by its inertia centre and its volume mass, or by the mesh attached to the object. The surface or volume mesh, which helps to compute the inertial mass of the objects, is required for the deformable objects and optional for the rigid ones. LMGC90 proposes several solutions for meshing an object:

- Directly in LMGC90;
- Via the integration of the GMSH code.

The configuration diversity of the contactors is one strong point of LMGC90 over other discrete codes. This option helps the user to describe the object as its real appearance. For rock masses, we proposed the polyhedron to be the representation of the constitutive rock blocks of the medium in LMGC90. This choice helps to well generate the vertices and the non-regular configuration of the rock blocks. Another strong point of the code is its capacity to deal with the objects in dynamical detections. The contact detection between two neighbouring objects is described by: contact locus, local frame, gap between two objects, contact force, and other options, if any. It is a process consisting in three operations (Dubois & Renouf, 2011):

- Neighbourhood construction: The determination of a space for the contact detection is based on the sort of closed bodies using the surrounding box or the tessellation method;
- Rough detection: The research of the neighbouring objects in the space is determined from the neighbourhood construction;
- Accurate detection: The research of the contact points is realised on the objects in the list of the neighbouring objects from the rough detection.

Different iterative solvers of contact are available in LMGC90 (Dubois, 2010):

- Non-linear Gauss-Seidel (NLGS): It can be used for all shapes of objects (2D or 3D) and supports all types of interaction law;
- Conjugate Projected Gradient Algorithm(GPCP): It can be used for all shapes of objects (2D or 3D) but only supports some types of interaction law;
- Bi-potential: It is very close to the NLGS solve;
- Interface with the external solvers from other analysis codes.

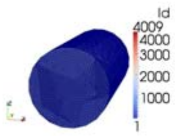
3. SIMULATION OF A MULTI-PHASE-EXCAVATION PROCEDURE IN FRACTURED ROCK MASS

In our study, we applied NSCD through LMGC90 on the mechanical behaviour analysis of a fractured rock mass which was undergone a multi-phase excavation. The geometrical modelling was created by RESOBLOK code (Merrien-Soukatchoff, Thoraval, & Korini, 2011), then imported into the Pre-Processor of LMGC90 after the meshing by GMSH script (Geuzaine & Remacle, 2009) which was coupled to LMGC90. All constituted blocks of the model were rigid and free in all DOFs. The rock mass was fractured in 3D space without the presence of hydraulic, thermic or multi-physics coupling conditions. Geological conditions of the rock mass were defined by the mass density (ρ = 2600 kg/m^3) and the contact condition between blocks (Coulomb dry friction contact with the friction coefficient $\mu = \tan(\varphi) = 0.4$ and no cohesion). The tunnel excavation was simulated by phasing out all rock blocks in the target zone of the excavation followed a given chronological order. The variation of the mechanical behaviour of the rock medium and of the excavated faces of the tunnel during the simulation was analysed. Based on the obtained data, the stability assessment of the tunnel and its surrounding rock medium was realised. A brief introduce of the simulation is presented in the following parts.

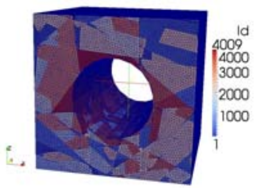
3.1 Generation of the numerical rock mass

Discrete Fracture Network method (DFN) was applied for the generation of the numerical geometrical models of a cubic rock mass (a = 10m) by the using the theory of D. Heliot (Heliot, 1988) and the Block Generation Language (BGL) on RESOBLOK code (Merrien-Soukatchoff, Thoraval, & Korini, 2011). For the geometrical model creation of a fractured rock mass, the rock structure was replaced by the main discontinuity families and isolated fracture (if any) in the space. A discontinuity family was declared by: a) Family centre; b) Distribution law of the family; c) Extension state at the intersection with other families. An isolated fracture was defined as a polygonal line which was declared by their configuration or by its distribution law. Two models were created in RESOBLOK: a cylindrical rock core (H = 5D = 10m) (called Model 1), and a voided cubic rock mass (a = 10m) (called Model 2). After redirecting the assemblage of rock blocks of the models, their surface meshing using the triangle element grids was realised by GMSH before immersing respectively in LMGC90. Model 1, which represented the excavation zone, was placed in the voided zone of Model 2, which represented the rock mass in the vicinity of the excavation. At the initial simulation time t = 0(s), they formed the total numerical rock mass (called Model 3) as illustrated in the Figure 1.

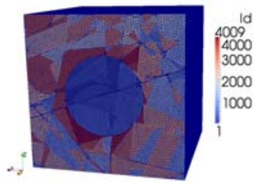
With the application of DFN through RESOBLOK, the geometrical model was generated with the consideration of the rock structure as its real distribution. Since “kinematics” is the study of movement without considering the cause of the motion, the stability analysis on RESOBLOK is limited to the application of the gravity. The consideration of the rock natural stresses in the vicinity of the tunnel in the analysis is possible. However, after the first iteration, their influence is nearly ignorable due to the redistribution of stress in the model (Merrien-Soukatchoff, Thoraval, & Korini, 2011). It was the reason why we had ignored the stability analysis option in RESOBLOK and had exported the obtained geometrical model into LMGC90 for a comprehensive DEM-based analysis of the mechanical behaviour of the models.



a) Cylindrical rock core model which represented the excavated rock area after the tunnelling



b) Voided cubic rock mass model which represented the rock mass after the tunnelling



c) Total rock mass model which represented the whole rock mass before the tunnelling

Legend: "Id" was the identified number of the rock blocks. The colour scale indicated the identified number magnitude of the rock blocks.

Figure 1 Geometrical model of the rock mass at the start of simulation

3.2 Loading conditions

There are two options for the load assignment in LMGC90: a) Fixed: the value and direction does not change during the simulation time; b) Variable: the value and direction follows a given function during the simulation time. One load is applied on the outer boundaries of the model at the precise 3D coordination (x, y, z) of the loading position. In our simulation, the loading condition was the combination of the gravity and the normal component of 3D in situ stresses measured at site by the overcoring techniques (INERIS, 2011). All loads had been assigned as dead ones and their values were as followed: σ_x = 2.7MPa; σ_y = 0.7MPa; σ_z = 1.2MPa of which the positive values represent the compression action.

3.3 Excavation algorithm

On the meshed Model 3, the simulation of the multi-phase-excavation was created by the disappearance of the constituted blocks of Model 1 according to a given excavation schedule so that the disappearing length of Model 1 was developed along the simulation time. By designing a numerical multi-step schedule in the simulation, a real tunnelling rhythm as the composition of many different working phases (preparation, excavation, finishing, completion, *etc*.) can be approached. Finally, the tunnelling simulation during 100 time steps that contained of a 20-time-step-preparation-period, four 10-time-step-excavation-phases, and a 40-time-step-finishing-period were chosen to be executed. The visualization displays of the model alteration under the excavation algorithm was shown in the Figure 2.

a) Before all excavation phases

b) During the excavation phase

c) After all excavation phases

Figure 2 Geometrical model changes during the tunnelling simulation (half-of-model-vision)

The aim for such a long finishing period was to monitor the stability alteration of the rock mass in the vicinity of the excavation after the completion of the excavation.

3.4 Selection of the simulation parameters

The NLGS solver was used for solving the contact detection in the model. The relevant numerical parameters were assigned:

- Parameter θ of the Crank-Nicholson method: θ = 0.5;
- Time step: dt = 0.1s;
- Convergence norm: tol = 10^{-6};
- Maximal number of calculations in an iterative loop: gs_it_1 = 5000;
- Numbers of loops in the iteration for each convergence check: gs_it_2 = 20.

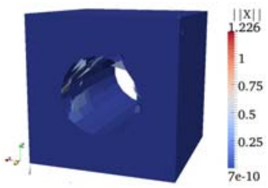
Once the simulation and analysis was stared, the mechanical responses of the model were recorded each 10 time steps in algebra data and in graphical visualization displays by using PARAVIEW code (Ayachit, 2015).

3.5 Failure mechanisms of rock mass

Once the simulation began, the following mechanical responses of all constituted blocks of Model 3 were obtained:

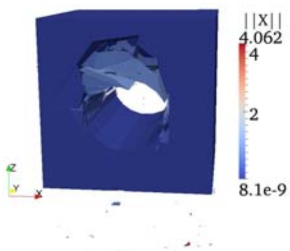
- Displacement, velocity and their evolution;
- Forces (external force, contact force, inertia force) and their evolution;
- Redistribution of the block contact force and the block contact stress;
- Variation of contact conditions during the simulation.

Analysing the recorded data, three failure mechanisms that thread the stability and the wholeness of the model were observed. Firstly, the gravity fall of rock blocks on the crown of the excavation was detected by studying the displacement variation of the relevant blocks during the simulation. This phenomenon (which was demonstrated in the Figure 3 and the Figure 4) had developed together with the excavation lengthening, and reached the failure when the crown was collapsed. It is shown that tunnel supports were required, especially after the excavation completion, to ensure the stable condition for the whole rock mass.



Legend: ||X||(m) was the absolute displacement of the rock blocks in the simulation. The colour scale indicated the recorded displacement magnitude of the rock blocks.

Figure 3 Failure of model due to the gravity fall of rock blocks at the 49th time step (end of four excavation phases)



Legend: ||X||(m) was the absolute displacement of the rock blocks in the simulation. The colour scale indicated the recorded displacement magnitude of the rock blocks.

Figure 4 Failure of model due to the gravity fall of rock blocks at the 99th time step (end of the tunnelling simulation)

Secondly, the stress concentration on the contact faces between rock blocks was found to be another dangerous phenomenon of the model. In order to investigate the redistribution of contact force in the rock mass under the effect of the tunnelling, a thin slice of Model 3, which was located perpendicularly to the mid-length cross-section of the excavation, was monitored during the simulation. The changing of the stress concentration location was indicated visually on the display output as showing in the two following figures (Figure 5 and Figure 6), for instance.

Legend: R(N) was the magnitude of normal contact force of the rock blocks in the simulation. The colour scale indicated the recorded force magnitude of the rock blocks. The circle showed the critical rock face of which the normal contact force was maximal.

Figure 5 Stress concentration on contact faces between rock blocks at the 29th time step (after the first excavation phase)

Legend: R(N) was the magnitude of normal contact force of the rock blocks in the simulation. The colour scale indicated the recorded force magnitude of the rock blocks. The circle showed the critical rock face of which the normal contact force was maximal.

Figure 6 Stress concentration on contact faces between rock blocks at the 59th time step (after the last excavation phase)

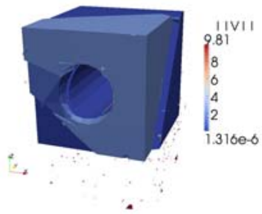
Thirdly, the correlation between the two components of the contact force which influenced the stability state of the rock block was also analysed. Once the contact condition of the model was governed by the dry friction law of Coulomb, the mobility of a rock block was expressed by the stability parameter K that is given by the following equation:

$$0 \leq K = \frac{R_T}{\mu . R_N} \leq 1 \quad (1)$$

With:
K: Stability parameter of the blocks
R_T: Tangential component of the contact force of rock blocs (N)
R_N: Normal component of the contact force of rock blocks (N)
μ: Friction coefficient, $\mu = \tan(\varphi) = 0.4$
φ: Internal angle of friction (radian or degree)

One knows that:
- When K = 0, the blocks are completely fixed.
- When 0 < K < 1, the blocks are stable. The tangential components of contact forces are smaller than the sliding threshold, or the normal components of the contact forces are strong enough to prevent the blocks from moving.
- When K = 1, the rock blocks move by sliding on the contact faces between them. The tangential component of contact force surpasses the sliding threshold of rock.

The variation of K and of the contact face quantity in the model was analysed. On the other hand, by observing the deformation procedure of the whole model, the occurrence probability of a sliding plane (as captured in the Figure 7) that destructed the model was found. The phenomenon of the failure along the plane of weakness was assigned to this case.



Legend: ||V||(m/s) was the absolute displacement velocity of the rock blocks in the simulation. The colour scale indicated the recorded velocity magnitude of the rock blocks.

Figure7 Destruction of the rock mass model due to the occurrence of a sliding plane

Three above observed failure mechanisms are typical for tunnels in hard rock and showed clearly effects of two components of the rock mass (rock structure and rock material) to the stability of the excavation and the host rock mass.

3.6 Commentary

With the idea of the DFN-NSCD combination through the RESOBLOK-LMGC90 connection, we hoped to propose a comprehensive solution to the analysis of natural rock mass with:
- Geometrical modelling by DFN on RESOBLOK;
- Mechanical modelling and simulation by NSCD on LMGC90.

In this study, the combination was published for the first time. Many challenges had been overcome thanks to great efforts of F. Dubois and CALAMI team at LMGC laboratory (University of Montpellier 2, France). The initial results showed the auspicious ability of the work as the backbone of the proposed comprehensive methodology in rock engineering. However, some limitations of the couple were also listed as follows:
- Difficulties in the generation order and directional convention;
- Vertex matching on the common edges of blocks;
- Meshing problem of the model and the load distribution on the rock mass.

We aimed at further studies on those issues and heading for the amelioration of the connection between the two codes.

Through this study, we did not attempt to develop NCSD but to prove the application scope of this method in rock and tunnel engineering. It was not until this time that natural rock masses were modelled and analysed by LMGC90 with respect of the real rock structure arrangement. With the multi-phase tunnelling simulation, we would like to underline the importance of the rock stability analysis during the whole construction procedure rather than at some dead points of time. By adjusting the number of time step for each data record (in either algebra or graphical form), the monitoring of the evolution of motion, contact forces and contact stresses of the constitutive rock blocks in the rock mass were straightforward. It helped to predict the failure phenomena in the medium, the creation of the sliding planes, and the determination of the plane of weakness of the model. The 2D and 3D graphical presentation in PARAVIEW showed obviously the redistribution of the contact and internal stresses during the simulation schedule, the stress concentration zones, and the over-loaded blocks and/or contacts. The list of the critical blocks and/or contacts in the medium due to some pre-defined criteria (critical values of velocity, displacement, energy, force or stress) could be exported for further analysis, allowing a more efficient design of appropriate reinforcements for those critical zones if necessary. The stability of the excavation and of the neighbouring rock mass was thus controlled.

However, some limitations were found:

- The rock blocks were rigid and the contacts between them were governed by the dry fiction Coulomb law. The choice of rigid bulk behaviour led to the non-deformable state of rock block during the simulation. This option was suitable for hard rock while the deformable bulk behaviour option was likely to be more appropriate to weathered rocks, soft rocks, rock under water condition, *etc.;*
- The morphology of the discontinuity walls was considered to be smooth and the eventual presence of fillings was neglected. Nevertheless, the effect of the wall roughness, aperture and infilling to the shear strength of rock discontinuities are evident (Barton & Choubey, 1977);
- Only the simplest structure of a tunnel (without its provisional or definitive support structure) was modelled. As the matter of fact, the simulation shown the need of support structure for the excavation in low cohesion fractured rock (Wojno & Toper, 1999);
- Due to the limitation of our computer, the size of the rock mass was small (the rock mass was 10x10x10(m) and the excavation diameter was 5 m). Normally, the thickness of the surrounding medium in the vicinity of the tunnel should be about five times of the future tunnel radius. However, when the model size augments, the time consumption and the required computer robustness become a challenge;
- Due to the lack of real data on the rock mass responses during a real multi-phase excavation tunnelling, the comparison between the in situ measurements and the numerical obtainments was missed.

We are trying to overcome them in our late studies.

4. CONCLUSION

The presence of the discontinuity network in the rock masses is evident and its influence on the hosting rock mass mechanical behaviour is strong and complex. The consideration of the discontinuities in rock is thus necessary, although it remains a challenge. Converting a fractured rock into an equivalent ideal homogenous medium or finding an equivalent model using some standard regular-shaped elements leads to an easier analysis but the relevance of the results can always be questioned. Discrete element methods, considering collections of many solids, can be considered as an alternative to tackle the problem of the discontinuous nature of the rock mass. The group of methods is considered to be the most appropriate tools for the research of the rock fractures and for granular materials. For the concretization of the discrete solutions in engineering analysis, supplement theories have been proposed. Non Smooth Contact Dynamics (NSCD) method is an alternative choice that deals with frictional unilateral contact between rigid or deformable bodies. It can be used for the numerical simulation of dynamic fracture of many materials and structures. It concerns the entire fracture process from crack initiation, growth, propagation, rupture to post fracture behaviour when solid fragments interact (Dubois, 2005).

In the scope of our research, the implicit DEM that is concretized through NSCD in LMGC90 was used for the simulation and analysis of an excavation in fractured rock. The numerical model of the rock mass, which had been geometrically modelled by the theory of D. Heliot, and had been mechanically modelled by NSCD with the Coulomb dry friction contact condition, was simulated a continuous construction procedure with the multi-phase-excavation period. Analysing the obtained responses and the deformation of the model through algebra and visual data, the behaviours of the modelling under the simulation were studied and three failure mechanisms that affected the stability of the rock mass and the excavation were found. In general, the mechanical responses of the numerical model were quite close to the normal states of a real tunnel construction in hard rock that had been found in related technical documents (Hoek, 2007), (Edelbro, 2010), (Nyung &Stacey, 2014). This study has proved the competence of NSCD in rock and tunnel engineering, and demonstrated the capability of its numerical tool in the modelling of a complex tunnelling procedure. Further benchmark studies on LMGC90 are in progress to promote it as an independent or crosschecking solution for controlling and predicting the behaviour of the tunnel and its vicinity during the construction.

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