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Stochastic model generation for discontinuous rock mass media and numerical analysis using the NSCD method (case study: Saint-Béat gallery in the southwest of France)

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ABSTRACT: The processes of the stochastic generation of a discontinuous rock mass model are presented in this paper, using the orientation data measured directly in the abandoned underground gallery of Saint-Béat castle, in the southwest of France. This gallery is particularly interesting because, even without reinforcement, all the walls and the roof are perfectly stable. The fracture measurements are carried out in order to investigate the stability and design of a 1 km long tunnel, which will be part of the new ring road of the city of Saint-Béat. The statistical parameters extracted from the fracture measurements are then used in the code developed using the AutoCAD software in order to generate seven 3D stochastic models of jointed rock mass media. The stability analysis of the models is carried out using the LMGC90 code, based on the Non-Smooth Contact Dynamics (NSCD) method. In this paper, this method is used to simulate rock mass media, as large collections of rigid blocks under unilateral constraints and frictional Coulomb's law.

SUBJECT: Modeling and numerical methods

KEYWORDS: NUMERICAL MODELING, ROCK JOINTS, STABILITY ANALYSIS

1 INTRODUCTION

The appropriate modeling of the mechanical behavior of a jointed rock mass and the determination of its characteristics have an important role in the evaluation of the stability and deformation of structures in this type of medium (Jing & Hudson, 2002). After the pioneering work of Cundall (1971) and Cundall & Strack (1979), a number of calculation codes were developed to simulate the movement or the mechanical condition of a collection of bodies. At the moment, a majority of simulations in rock media, masonry or in granular media are carried out using these codes. The discretization algorithms of time (usually explicit) applied in the integration of the dynamic equations must use intervals of a very short time, and eventually the integration of an artificial damping to ensure the stability of numerical calculations.

In this paper we intend to introduce the application of an implicit approach for the mechanical modeling of jointed rock mass. The non-smooth contact dynamics method (NSCD) deals with frictional unilateral contact between rigid or deformable bodies. The basis of the contact dynamics method (CD) was developed in the 1980's by J.J. Moreau and later the NSCD method by M. Jean (1999) for use with more general applications. The NSCD method is summarized with the following characteristics: step by step temporal integration, implicit integration, explicit detection of contacts, irregular interaction laws. This method by its implicit numerical scheme makes it possible to calculate the dynamics of a large number of simultaneous contacts (for detailed explanations see (Moreau 1988, Moreau 1994, Moreau 2003 and Jean 1999))

2 GALLERY OF SAINT-BÉAT CASTLE

The processes of the stochastic generation of a discontinuous rock mass model are presented in this paper, using the orientation data measured directly in the abandoned underground gallery of Saint-Béat castle, in the southwest of France. This gallery is particularly interesting because, even without reinforcement, all the walls and the roof are perfectly stable, in a marble mass, next to a major regional fault (Fig.1). The fracture measurements are carried out in order to investigate the stability and design of a 1 km long tunnel, which will be part of the new ring road of the city of Saint-Béat. This ring road will be constructed for the national road 125 (RN 125) which is one of the few roads passing through the central Pyrenees mountains, at a medium altitude. The RN 125 crosses the town of Saint-Béat, built at the bottom of a steep slope on a narrow pass along the Garonne River valley (Gasc-Barbier et al. 2006, Guittard et al. 2005).

The measured fractures in the gallery are grouped in four main fracture families and then the parameters such as orientation and mean spacing distance are calculated for each fracture family (Table 1). These parameters are used in the code developed in the AutoCAD software in order to generate 3D stochastic models of jointed rock mass media (Rafiee & Vinches 2008(a), 2008(b)). The results obtained for seven 3D models which are generated by applying different methods of integrating the fracture families in the model (hierarchical or random methods), different values for fracture persistence and also different tolerances for fracture orientation are presented (Table 2). These

stochastically generated discrete models are used to study the mechanical behavior of the tunnel. Eventually, the obtained results from these seven investigated models concerning the stability state in the abandoned gallery can be used to choose more representative models for future complementary studies.

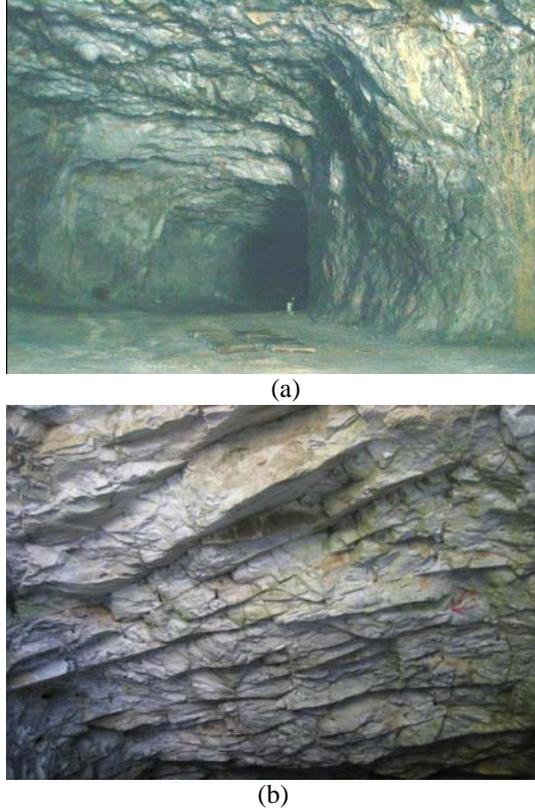


Figure 1. Abandoned underground gallery of Saint-Béat, (a) stable vertical walls, about 10 m high, (b) stable roof without reinforcement (Gasc-Barbier et al. 2006oi).

Table 1. Direction of average unit normal vectors for each discontinuity set and real spacing distance for each set in m

Set	Dip (°)	Dip direction (°)	Spacing (m)
F1	74	147	0.5
F2	85	204	1
F3	84	319	1
F4	7	279	1.2

3 STABILITY ANALYSIS BY THE NSCD METHOD

The stability analysis of the models is carried out using the LMGC90 code (Dubois & Jean 2003) which is based on the NSCD method and was developed in the mechanical and civil engineering laboratory, of Montpellier University (France). In this paper, the NSCD method is used to simulate rock mass media, as large collections of rigid blocks under unilateral constraints and frictional Coulomb's law.

The results presented in this study concern the 3D models created for the abandoned gallery of Saint-Béat. The

stability state of the seven stochastic models having characteristics shown in Table 1 and 2 are investigated using the LMGC90 code. The direction of the gallery is considered North-South and the gallery has a span of 11 m and a height of 9 m. The stability analyses were performed over a 3D volume: with a 30m×30m cross-section and a thickness of 10 m (Rafiee 2008).

Table 2. Parameters taken into account in generating the tunnel models

Model	Method	Average persistence (%)	Orientation tolerance (°)	Numbers of blocks
I	Hierarchical (4, 3, 2, 1)	35	0	843
II	Random	50	15	1694
III	Hierarchical (4, 3, 2, 1)	50	15	1382
IV	Random	40	15	1311
V	Hierarchical (4, 3, 2, 1)	60	15	1766
VI	Hierarchical (4, 3, 2, 1)	50	15	1288
VII	Hierarchical (4, 3, 2, 1)	75	15	2791

The stability state of the models is studied by considering that the rock mass is surrounded by six fixed sides. The density for the limestone mass is assumed to be 2000 kg/m³, and the results obtained only for a dry friction coefficient of 0.7 are presented in the current study. It should be mentioned that in the LMGC90 code, we have possibilities of using diverse constitutive models such as a cohesive condition for the different sets of joints. The stability states observed for the seven models are illustrated in Figure 2, in which the distribution of vertical displacement is presented respectively for all of the models. As can be observed almost of the models show removable blocks except the model III, of course the results presented here, represent a conservative condition, only considering dry friction with a friction coefficient of 0.7. In deteriorated conditions, with a friction coefficient of 0.6, even the model III exhibits an instability condition with few removable blocks from the gallery roof. The other considerable finding is that the models present stable walls, nearly without any removable blocks, and even in this pessimist condition, there is no sign of the gallery collapse.

The 7th and most fractured model, containing 2791 blocks, is not anticipated to collapse. Figure 3a illustrates the evolution of the dissipated energy in Joules for the first second of the computation for the model VII. As can be seen, the model remains stable after the detachment of a few blocks at beginning. This can be noted from the change of the number of sliding contacts during computation (Fig. 3b). After 0.3 second, the number of sliding contacts is negligible; as a result the model remains in a stable condition after the fall of a few blocks.

The stability state of the model III, which illustrates no block detachment for a friction coefficient equal to 0.7 (Fig.2c), is particularly investigated for a deteriorated friction coefficient of 0.6. By decreasing the coefficient of friction to 0.6, we find that the block detachments have occurred from the gallery roof. Figure 4a shows the calculated results for this model by considering a

deteriorated friction. In this model we have over 35,000 points of contact. The evolution of these points of contact between sliding contact and “stuck contact”, during the calculation time, is presented in the graph in Figure 4b. As observed for other models, in this model only a few detached blocks can be observed and the model becomes stable after a primary instability. This is demonstrated by the graph of the contact evolution (Fig.4b), the number of sliding contacts becomes again negligible at the end of the calculation time.

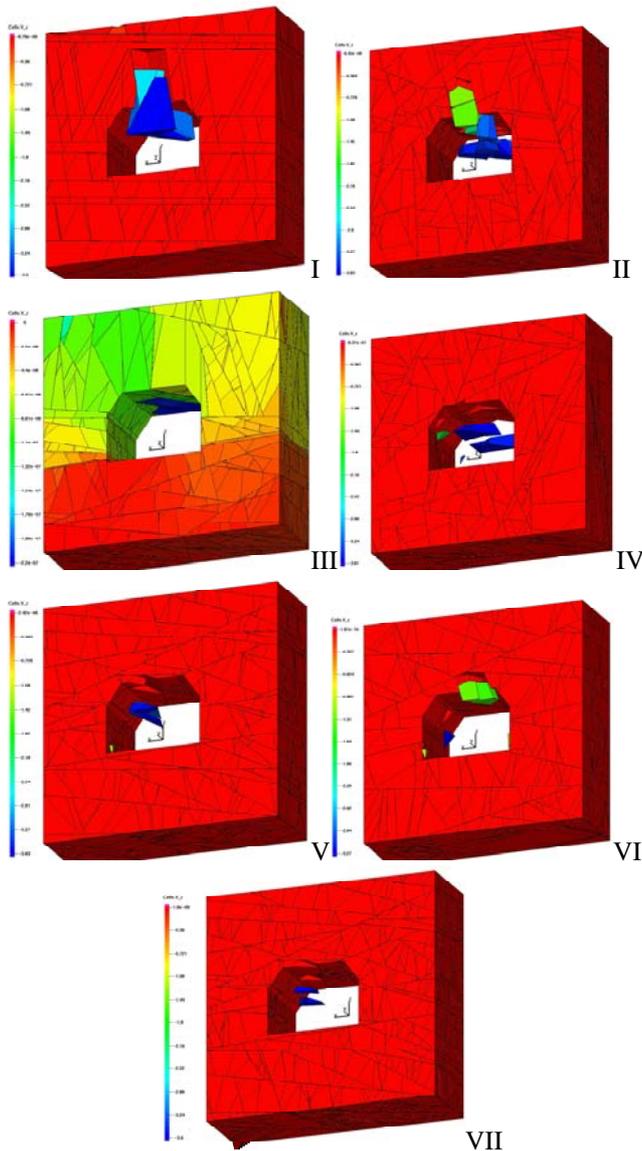
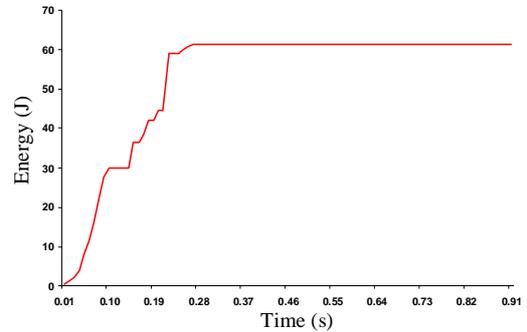


Figure 2. Stability state of seven models generated for the abandoned underground gallery of Saint-Béat castle (see Table 2), vertical displacement distribution is shown in meter.

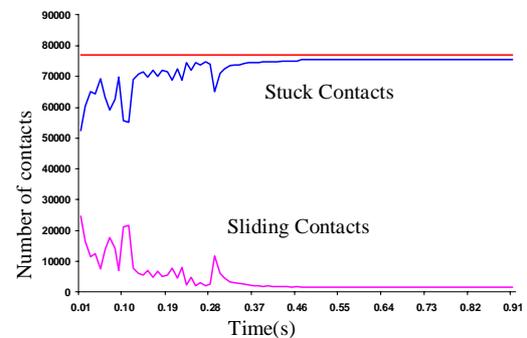
4 CONCLUSION

In this study a series of analysis was performed in order to investigate the stability condition of an underground abandoned gallery, in a fractured rock mass, using a distinct

element code (LMGC90) in which the non-smooth contact dynamic method is used. Firstly, the representative models of the jointed rock mass are stochastically generated by the code developed using the AutoCAD software in which the statistical parameters extracted from the field fracture measurements are taken into account.



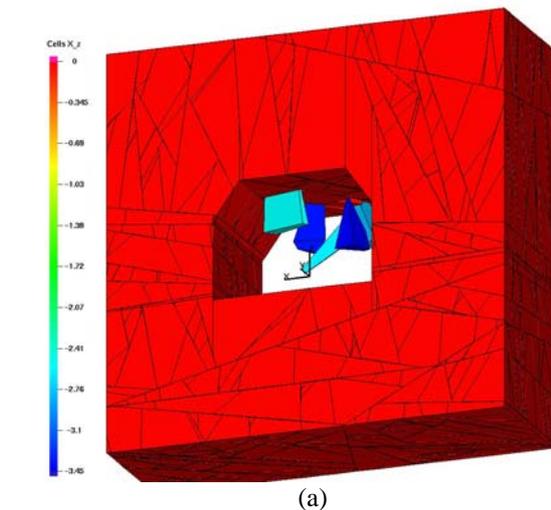
(a)



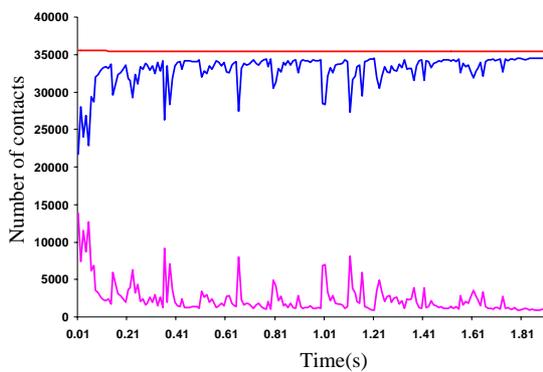
(b)

Figure 3. (a) Evolution of the dissipated energy for the first second of computation (Model VII), (b) changes in the number of sliding and stuck contacts during the calculation (Model VII).

Afterwards, the stability analyses are carried out over these models considering a dry contact condition. The obtained results for seven 3D models are presented in the current study, showing that only one of them is completely stable, even for the pessimistic friction parameters: six others illustrate instable states at the beginning of the computation but gradually, after the fall of the removable blocks, they became stable too. This is demonstrated by diverse post-processing data generated by the LMG90 code. The obtained results for this abandoned gallery, in a fractured rock mass, are particularly interesting because, even without reinforcement, this gallery is perfectly stable in place: a behavior very similar to the stability state presented in the studied models. Finally the results obtained for the gallery, and the methodology presented for the design of the fractured mass numerical model, will provide the control parameters of the study and design of the tunnel which will be part of the new ring road of the city of Saint-Béat.



(a)



(b)

Figure 4. (a) Stability state for the deteriorated contact conditions (model III), (b) changes in the number of sliding and stuck contacts during the calculation (model III).

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