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Numerical modeling of a bolt-reinforced tunnel in a fractured ground

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ABSTRACT: During the drilling of galleries in the deep underground laboratory of ANDRA in Meuse Haute Marne, it has been observed that the excavation process created in the surrounding ground fractures with very specific shapes. A research programme was undertaken to model the mechanical behaviour of the fractured zone and the influence of radial bolts on the ground deformation around the galleries. For simplicity, the tunnel section is assumed to be circular and the problem is analyzed in axisymmetric mode. An original approach was used, that combines two homogenization procedures, to account for the role of the fractures and of the bolts. This approach was implemented in the finite element code CESAR-LCPC. Computations give larger wall displacements if fractures are taken into account, and show that the most efficient way to reduce wall convergence is to place bolts perpendicular to the axis of tunnel, regardless of the inclination of fractures.

1 INTRODUCTION

In finite element simulations of tunnelling in rock masses, it is often assumed that the ground behaviour is homogeneous and isotropic. However, discontinuities of the rock mass can induce anisotropic deformability properties. Since it remains difficult to deal with a large number of fractures in a numerical model, it is worth using an "equivalent" anisotropic model for the fractured ground.

In practice, the stability of deep underground excavation is improved by means of bolts placed in the tunnel walls. Since bolts are placed in an ordered manner, the reinforced zone can be modelled using a homogenisation approach too.

In the present paper, the process of drilling a tunnel through a fractured ground, whose walls are reinforced by bolts, is modelled by a general finite element code. Two homogenization procedures are used to account for the role of the fractures and of the bolts. The paper presents a preliminary parametric study of the influence on wall convergence of the orientation of the fractures and of the direction in which bolts are placed. Analyses are carried out in axisymetric condition.

2 MODELLING OF FRACTURED GROUND

During the drilling of galleries in the deep underground laboratory of ANDRA in Meuse Haute Marne (France), it was observed that the excavation process resulted in the creation of fractures in the vicinity of the galleries. Fractures show a complex three-dimensional shape, and form a network of discontinuities more or less uniformly distributed along the axis of the tunnel, illustrated on Figure 1 by three plane sections. It is not our purpose to explain the fracture pattern here, but it reflects :

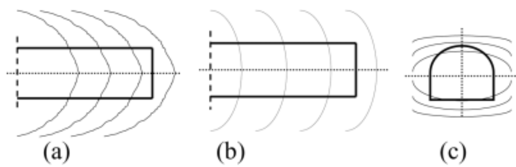

Figure 1. Geometry of fractures with chevron shape ; (a) vertical plane parallel to the tunnel axis, (b) horizontal plane, (c) vertical plane orthogonal to the axis.

- a complex initial behaviour of the ground (including material anisotropy),
- the anisotropy of the initial stress field (observations show that the geometry of the fractures depends on the direction of the gallery axis),
- and of the excavation technique itself.

Unfortunately, it is very difficult to get undisturbed samples to improve the understanding of the rock behaviour.

In what follows, an equivalent anisotropic model is used for the fractured zone. It is assumed that the shape of fractures can be simplified as conical, as shown in Figure 2.

For the initial intact ground, the elastic–perfectly plastic Drucker – Prager model is applied with a linear and isotropic elasticity. As a preliminary step, it

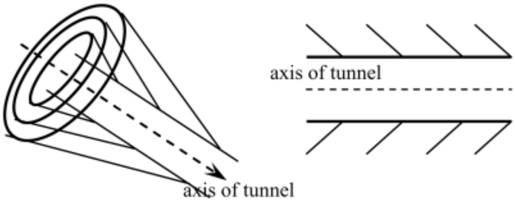

Figure 2. Simplified geometry: fractures are replaced by cones (having the same axis as the tunnel).

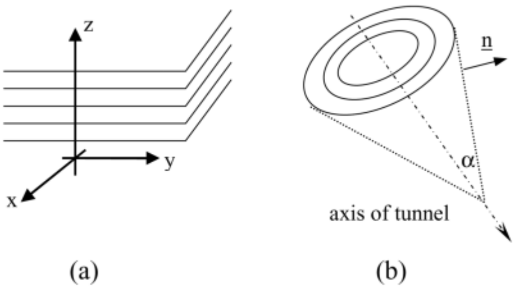

Figure 3. (a) Multi-layered system; (b) unit vector n.

is assumed that the fractures change the elastic characteristics of the ground, but the strength remains the same as that of the intact ground. An homogenization procedure makes it possible to replace the fractured discontinuous ground by a continuum with equivalent anisotropic elastic properties.

In order to derive the elastic tensor behaviour, the fractured medium is considered in a first step as the superposition of homogeneous layers separated by plane of finite but small thickness joints. For layers perpendicular to the z-axis (Figure 3a), the equivalent compliance matrix of the system is calculated. In a second step, one takes into account the local orientation of the fracture by replacing the z-axis by the direction og the unit vector n perpendicular to the plane tangent to the cones in a global coordinate system as shown in Figure 3b. Four parameters mentioned below are added to the existing Drucker – Prager model in order to consider the fractures:

- normal stiffness of fractures, k_n
- tangential stiffness of fractures, k_t
- distance between two successive fractures, D
- angle of orientation of fractures, which is equal to the angle between the axis of symmetry and the plane tangent to the conical fracture, α.

As a consequence, the stress-strain relationship for the fractured material is given by:

$$\sigma_{ij} = C_{ijkl}\, \varepsilon_{kl} \tag{1}$$

where:

$$C_{ijkl} = b_1\delta_{ij}\delta_{kl} + b_2(\delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk}) + b_3(\delta_{ij}n_k n_l + \delta_{kl}n_i n_j) + b_4(\delta_{ik}n_j n_l + \delta_{il}n_j n_k + \delta_{jk}n_i n_l + \delta_{jl}n_i n_k) + b_5 n_i n_j\, n_k\, n_l \tag{2}$$

Denoting by E and ν the Young modulus and Poisson's ratio of intact material, respectively, parameters in equation (2) are given by:

$$\begin{aligned} b_1 &= \nu\,(1 + M_n + \nu)E/M \\ b_2 &= [0.5(1 + M_n)(1 - \nu) - \nu^2]E/M \\ b_3 &= -\nu M_n E/M \\ b_4 &= E/[2(1 + \nu) + M_t] - b_2 \\ b_5 &= [2(1 - \nu) + M_n]E/M - 4E/[2(1+\nu)+M_t] \end{aligned} \tag{3}$$

with

$$\begin{aligned} M &= (1+\nu)[(1 + M_n)(1-2\nu) - 2\nu^2] \\ M_n &= E/k_n D \\ M_t &= E/k_t D \end{aligned} \tag{4}$$

3 MODELLING OF REINFORCED GROUND

The role of the bolts is taken into account by means of the so-called multiphase model introduced for reinforced materials by de Buhan and Sudret (2000). The framework is an extension of classical homogenization methods. In this model, the whole medium constituted by a ground mass and the bolts it contains is represented by two continuous superposed media (or "phases"), one representing the ground and the other standing for inclusions. In other words, there are, in every geometrical point, two material particles in mutual mechanical interaction. Different kinematic fields are associated with each phase, and the model includes a description of the mechanical interaction between them (Bennis and de Buhan, 2003). The overall properties of the equivalent material are elastically and plastically anisotropic. In the present study, the interaction between phases is described as a perfect bonding.

4 CASE STUDY AND NUMERICAL MODEL

The present case study includes the process of drilling a 5-meter diameter gallery with a length of 25 m. The tunnel is drilled in ten successive steps. The ground is isotropic prior to drilling. However, the drilling process generates fractures in the ground around the gallery. The extent of the fractured zone is assumed to be 2 m beyond the wall and 2.5 m ahead of the tunnel face. The tunnel is supposed to be excavated at a depth of 75 m with an isotropic ($K_0 = 1$) initial stress state ($\sigma^\circ = 1.5$ MPa).

The problem is dealt with in axisymmetric condition The problem is simulated by a "research version" of the finite element code CESAR-LCPC, in which both homogenization techniques are implemented. The dimension of the mesh used for the problem is 35 m by 55 m. All elements are quadratic. Far from the tunnel, triangular elements are used; however, quadrangular elements are used around the excavated zone.

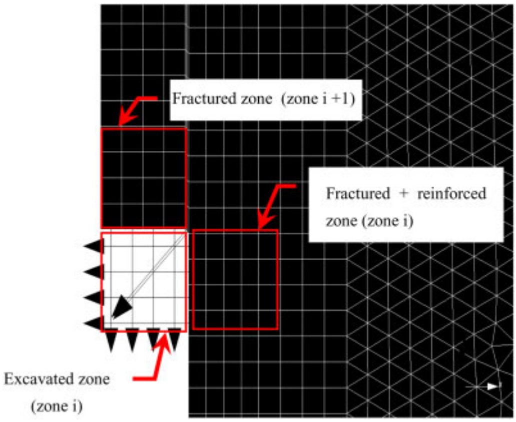

Figure 4. Modelling sequence of tunnel drilling.

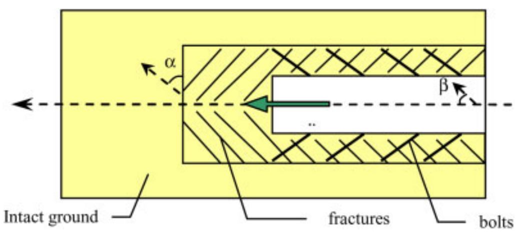

Figure 5. Definition of angles α and β.

For each step of drilling, the simulation of construction process consists of (Figure 4):

- deactivating the zone to be excavated,
- introducing boundary forces representing the forces applied by the excavated zone,
- associating the fractured model with the ground in front of the tunnel face,
- associating the combination of the fractured model and the multiphase model to the ground next to the wall in the excavated zone.

The constitutive law for the ground is described by the Drucker-Prager model with $E = 50$ MPa, $\nu = 0.35$, $\phi = 30$ degrees, $\psi = 20$ degrees.

For the fractured ground, additional parameters are: $k_n = 50$ MPa/m, $k_t = 5$ MPa/m, $D = 0.2$ m.

For the opening of the cones that represent the fractures, computations were made for six values of the angle α between the vertical plane containing the tunnel axis and the plane tangent to the cones: $\alpha = -60, -45, -30, +30, +45$ and $+55$ degrees.

Bolts are assumed to be elastic, made of steel (Young's modulus $E^b = 210$ GPa), with a diameter of 25 mm. The density of bolts is taken equal to 1 bolt per square meter of tunnel wall. Three values were studied for the angle β between the tunnel axis and bolt direction $\beta = 30$, 60, and 90 degrees. The schematic definition of α and β angles is presented in Figure 5.

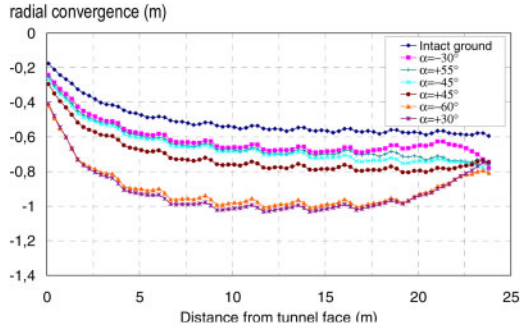

Figure 6. Variation of convergence of wall tunnel along the tunnel axis (non-reinforced ground).

5 RESULTS

The results of analyses are presented in terms of tunnel convergence (i.e. of radial displacements of the tunnel wall) along the axis.

5.1 *Effect of fracturing*

Figure 6 compares the convergences obtained for a non-reinforced tunnel with different directions of fractures. It is found that displacements are larger in a fractured rock mass than in an intact ground, but it is not possible to establish a simple relationship between the convergence and the fractures inclination.

On the other hand, convergences obtained with $\alpha = +30°$ and $\alpha = -30°$ are obtained very close to those obtained with $\alpha = -60°$ and α $+55°$, respectively. It is more obvious especially for distances far from the tunnel face.

5.2 *Effect of bolting*

The calculated tunnel convergence is presented for different bolting directions ($\beta = 30$, 60, and 90 degrees) for all cases of fractured ground in Figure 7. It is very interesting to observe that the inclination of fracturing has no effect on the optimized direction of bolting. The more inclined the bolts, the smaller the convergence. In other words, the best way of stabilizing the radial wall displacement is to place the bolts perpendicular to the tunnel axis, regardless the inclination of fractured ground around the tunnel.

6 CONCLUSION

The generation of fractures during tunnelling and the reinforcement of the wall can be modelled using a combination of homogenization procedures. Numerical simulations show that the wall convergence is larger in a fractured ground than in an intact ground and that the best way of reinforcing the tunnel wall is to place the bolts perpendicular to the tunnel axis, regardless the inclination of fractures. In other words,

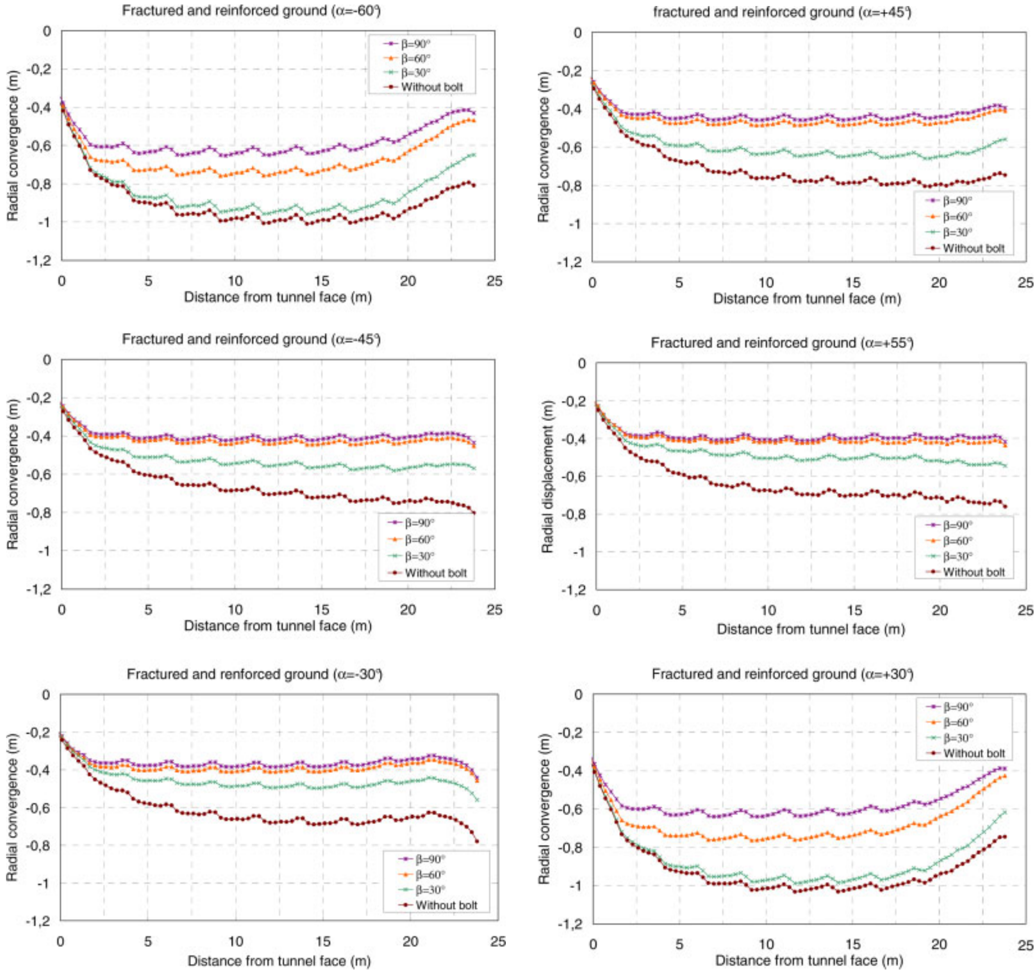

Figure 7. Variation of convergence of wall tunnel along the tunnel axis (fractured and reinforced ground).

anisotropy in the ground around the excavated zone has no effect on the pattern of bolting. It is important to recall that in the models used here, anisotropy is only taken into account for the elastic part of the behavior of the fractured ground: the influence of fractures on plastic properties will be considered in future studies.

Besides, results presented here only reflect numerical analyses and should be confirmed by comparisons with in situ observations.

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