Numerical Methods in Geotechnical Engineering – Benz & Nordal (eds)
 ISBN 978-0-415-59239-0

Analysis of a bolt-reinforced tunnel face using a homogenized model

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ABSTRACT: This communication deals with the effect of tunnel face reinforcement on the wall convergence and on the loads in the lining, studied by means of a homogenized anisotropic model for reinforced ground. While the tunneling process is generally handled in a plane strain framework (within the so-called convergence-confinement method), tunnel face reinforcement makes it necessary to take into account the three-dimensional nature of the problem. In the case of an isotropic and uniform initial stress state, and of a circular tunnel, analyses can be performed in axisymmetric mode. Within this framework, finite element simulations have been carried out, using the finite element software CESAR-LCPC, to simulate the process of tunnel excavation and lining construction. Results indicate that reinforcement of the tunnel face reduces tunnel convergence and decreases the compressive forces in the lining. In the last place, it is shown that results obtained with the anisotropic multiphase approach can be approximated with an isotropic model with adjusted parameters, which may be useful for preliminary design.

1 INTRODUCTION

Reinforcement of tunnel face by bolts is, in the first place, an efficient technique to improve the stability of the ground during construction. It is also seen as a way of decreasing deformations around the tunnel, in order to keep surface settlements within acceptable limits in the case of shallow urban tunnels. The technique is very often used in tunneling engineering. However, there is still no simple and well recognized design method to choose the number, length and diameters of bolts, or the type of bonding between the bolts and the ground, etc.

Numerous studies have been undertaken to get a better understanding of the influence of tunnel face reinforcement on the tunnel behavior: numerical analyses have proven that face reinforcement can reduce tunnel face displacements (Kavvadas & Prountzopoulos, 2009) as well as convergence and change the loads on the lining (Chungsik & Hyun-Kang, 2003). Such analyses remain difficult to perform, because of the number of bolts in the face (several tens) and their size. In this context, it can be efficient, to use homogenized approaches to take into account the role of the bolts (Bourgeois *et al*, 2002, Wong *et al*, 2004, Wong *et al*, 2006). In this paper, we use such a homogenization procedure to discuss the influence of bolt reinforcement on wall convergence and on compressive forces in the lining, on the basis of numerical simulations of the excavation process of a deep tunnel with circular section.

2 MULTIPHASE MODEL

2.1 *Principles*

The principle of the homogenization procedures is to replace the heterogeneous composite material made of the association of the ground with the bolts by a homogeneous material having "equivalent" mechanical properties. Recently, de Buhan and Sudret (1999) have introduced a model in which the reinforced ground is replaced by the superposition of two continua in mutual mechanical interaction. In such a framework, a displacement field and stress field is associated with each phase. Phases are connected to each other through an interaction law (Bennis & de Buhan, 2003). An example of application of this approach to tunnel reinforcement by bolts can be found in de Buhan *et al* (2008).

The multiphase approach has been introduced in the finite element code CESAR-LCPC (Humbert *et al*, 2005), and used for the analyses presented here, under the assumption that there is a perfect bonding between the ground and reinforcements: within this framework, one has to handle only one displacement field, common to both phases; however, the model still includes two distinct stress fields. The elastic properties of the reinforced ground as a whole are the sum of the elastic properties of the initial ground and of a uniaxial tensor increasing stiffness in the direction of the bolts. Thus, even if the ground is initially isotropic, the reinforced material has anisotropic elastic properties. Much in the same way, strength properties of the reinforced ground are improved in an anisotropic way.

2.2 *Overview of the general formulation*

The "multiphase model" is a generalized homogenization procedure in which the bolt-reinforced ground is represented, not by one single medium, but by the superposition of two continuous media: one, called the "matrix phase" represents the ground, whereas the "reinforcement phase" is the macroscopic counterpart of the bolts network. This leads to the introduction, at the macroscopic scale, of two displacement fields denoted by $\underline{\xi}_m$ for the matrix phase and $\underline{\xi}_r$ for the reinforcement phase. The matrix phase is associated with a Cauchy stress tensor $\underline{\underline{\sigma}}^m$, and the reinforcement phase with a (scalar) density of axial force in the bolts per unit area transverse to the direction of the bolts, denoted by σ^r.

The momentum balance is expressed for each phase separately as:

$$div\ \underline{\underline{\sigma}}^m + I\ \underline{e}_r = 0 \quad \text{(matrix phase)} \tag{1}$$

$$(\underline{grad}\ \sigma^r).\underline{e}_r - I = 0 \quad \text{(reinforcement phase)} \tag{2}$$

where $\underline{e}_r$ is the unit vector in the direction of the bolts, and $I\ \underline{e}_r$ denotes the volume density of interaction forces exerted by the reinforcement phase on the matrix phase (Volume forces have been omitted to keep equations simple).

Three constitutive laws describe the behavior of the reinforced ground mass: one for the ground, one for the reinforcement phase, and one for the interaction.

Since the volume of the bolts is small compared with that of the reinforced ground, it is assumed that the matrix phase has the same behavior as the initial ground. In what follows, we have adopted the usual Mohr-Coulomb constitutive model.

The behavior of the reinforcement phase is described by a linear elastic model:

$$\sigma_r = E^r\ \varepsilon_r \tag{3}$$

where ε_r denotes the vertical strain of the reinforcement; E^r is the product of the Young's modulus of fiberglass bolts E_b by the ratio η of the bolts volume over the overall volume of reinforced ground.

The density of interaction force between the matrix and the reinforcement phases is described by a one-dimensional constitutive law, that can be linear or not. In what follows, we use a simplifying assumption and it is not necessary to describe precisely the constitutive law associated with the interaction.

2.3 *The simplified case of perfect bonding*

We make the additional assumption that there is a perfect bonding between the bolts and the ground, in the sense that the displacement fields of the matrix and the reinforcement are equal: $\underline{\xi}_m = \underline{\xi}_r$. With this assumption, the numerical implementation of the multiphase model is much simpler, since we can use standard finite elements, without having to introduce extra nodal degrees of freedom. However, the stresses associated with the "matrix" and the "reinforcement" are computed separately, in order to compute the plastic strains in the ground.

3 NUMERICAL MODEL

In this study, we present simulations of the excavation of a tunnel with a sequential method. The tunnel section is assumed to be circular, with a radius R = 2.5 m, the depth of the tunnel axis is equal to 75 m and the initial stress state is isotropic, so that the coefficient of lateral pressure at rest K_0 is equal to 1. It is assumed that variations of the initial in-situ stress field can be neglected: the stress field is homogeneous, and the mean stress is equal to 1.5 MPa. Under these assumptions, the problem can be dealt with in axisymmetric conditions.

Simulations do not integrate the introduction of the bolts in the ground, but we assume that there is a pre-existing longitudinal reinforced zone along 35 m of the tunnel axis. This assumption simplifies greatly the preparation of data, but can be criticized because the typical length of actual bolts lies in the range between 10 to 25 m. However, it can be expected that the traction forces in the bolts are almost negligible beyond a given distance from the tunnel face, so that the length of bolts taken into account in the simulations makes little difference on the final results. This assumption is discussed later.

The density is equal to 1 bolt per square meter of tunnel face, which corresponds to a volume ratio of $\eta = 10^{-3}$ if the bolt diameter is equal to 35 mm.

Each step of excavation consists in excavating the stress over a length of 2.5 m. For practical reasons, the installation of the shotcrete lining is performed only after the excavation of the 2.5 m step is completed. There is therefore a given length of ground left unsupported behind the tunnel face. In the simulations, for each step of excavation, a 2.5 m-long concrete lining segment with a thickness e = 20 cm is installed to support the ground excavated during the previous step.

The mesh used is presented in Figure 1. All elements are of quadratic type. Elements far from the tunnel are triangular; elements close to the tunnel are quadrangular. The mesh includes 3100 nodes and 1300 elements. The simulation of the excavation process (deactivation of excavated zones, activation of the lining in sequence) leads to defining 34 different zones. The interest of the multiphase model lies in the fact there is no need to describe each bolt separately.

The behaviour of the unreinforced ground is described by the Mohr-Coulomb model with a linear isotropic elasticity. We adopted the following values of the parameters

E = 150 MPa ; $\nu = 0.4$;

c = 100 kPa ; $\phi = 32$ degrees, $\psi = 2$ degrees.

The behavior of bolts is linear elastic with $E_b = 20$ GPa (Young's modulus for fiber-glass bolts). Bolts are parallel to the tunnel axis.

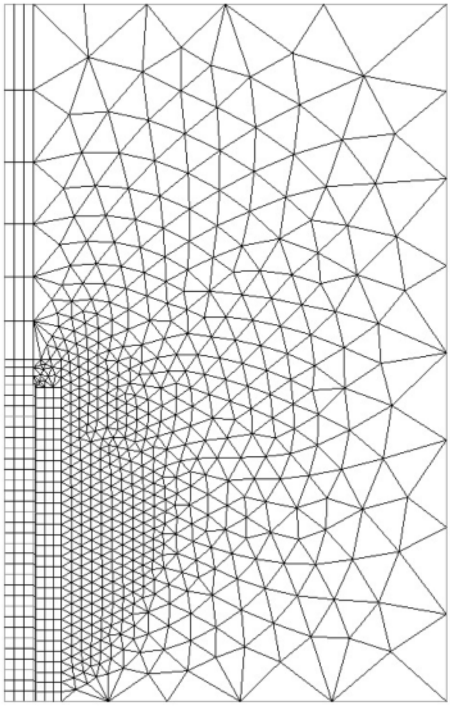

Figure 1. Mesh used in CESAR-LCPC.

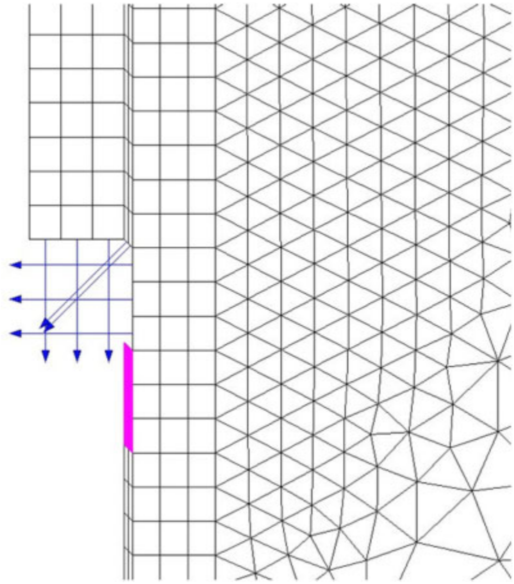

Figure 2. Generic step of the modeling sequence of tunnel drilling: forces are applied on the boundary of the excavated zone (arrows); a lining segment is activated behind the tunnel face.

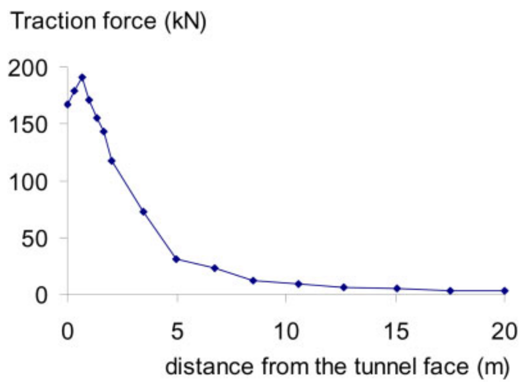

Figure 3. Traction force in a bolt placed in the center of the tunnel face.

The lining segments are assumed to behave as a linear elastic material with $E_C = 5000\,\text{MPa}$ and $\nu = 0.25$.

The initial (in situ) stresses in the model are introduced and then, excavation steps are carried out. Each simulation step of the construction process includes several elements (Figure 2):

- the stiffness of the elements of the zone to be excavated is set to zero;
- the excavated ground exerted on the ground that remains a system of forces that must be « removed ». The finite element procedure consists in computing the appropriate nodal forces to take into account this « unloading ». On the whole, the remaining ground was subjected to compression forces from the excavated ground ; in the final state, it is subjected to zero surface forces : the excavation process is therefore equivalent to applying tensional forces, shown in figure 2;
- activating the lining segment corresponding to the previous excavation step.

The excavation process starts from the bottom of the mesh and the tunnel face moves upwards.

4 RESULTS

4.1 *Traction forces in the bolts*

Figure 3 shows the values of the traction forces computed in the bolts placed in the tunnel face (after 10 excavation steps). The results show clearly that the traction force decreases rapidly ahead of the tunnel face, in such a way that the traction in the bolt is negligible at a distance of 10 m from the tunnel face. In other words, assuming that the ground is reinforced over a distance larger than that of the actual bolts has no significant influence on the results of the simulations.

4.2 Wall convergence

Figure 4 shows the convergence (i.e. the radial displacement) of the tunnel wall along the axis of the tunnel. The abscissa x = 25 m corresponds to the position of the tunnel face after the completion of the tenth

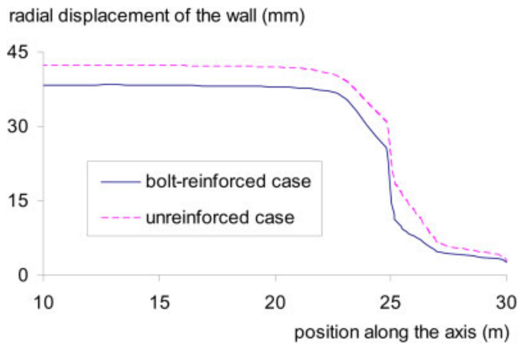

Figure 4. Comparison of the radial displacement of the wall along the tunnel axis, in the reinforced and unreinforced cases, after completion of 10 excavation steps (tunnel face is located at x = 25 m, the excavated zone being on the left).

excavation step (the section of the tunnel already excavated is on the left, for x < 25 m, and the ground not yet excavated corresponds to x > 25 m).

In the first place, it is worth noting that displacements are almost uniform at a distance larger than 5 m behind the tunnel face, showing that the lining is stiff enough to prevent further convergence of the ground.

Besides, with the parameters taken for simulations presented here, the radial displacement in the case where the tunnel face is reinforced is about 10% smaller than in the case without bolting (38 mm vs. 42 mm).

4.3 *Compressive force in the lining*

For a circular section, it is possible to find the compressive force in the lining. Since the lining is a thin ring (R/e > 10), the compressive force N can be calculated by (Panet, 1995):

$$N = \left(K_{sn} + K_{sf}\right) u_{r_{mean}} \tag{4}$$

where:
u_{rmean} is the mean radial displacement of the lining,
K_{sn} is the normal stiffness of the lining:

$$K_{sn} = \frac{E}{1-\nu^2}\frac{e}{R} \tag{5}$$

K_{sf} is the flexural stiffness of the ring, given by:

$$K_{sf} = \frac{E}{1-\nu^2}\frac{I}{R^3} \ , \ I = \frac{e^3}{12} \tag{6}$$

The simulations presented above give a compressive force in the lining of 9 MN/m without bolts and 8.1 MN/m in the reinforced case. This shows that tunnel face reinforcement can not only improve tunnel face stability, but also decrease tunnel wall convergence and the compressive force in the lining.

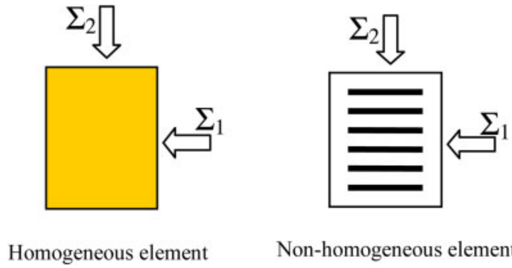

Figure 5. Homogeneous (two-phase) and non-homogeneous elements.

5 SIMPLIFIED ANISOTROPIC MODEL FOR THE REINFORCED ZONE

The ground is modeled as an isotropic elastic- perfectly plastic material; however, the reinforced zone overall behavior is anisotropic. In this section, we discuss the possibility to use an isotropic model for the reinforced ground as a whole, with "improved" values of the parameters.

The role of reinforcement element in the reinforced ground is to increase the rigidity as well as the strength of the ground in the direction of bolts. In what follows, we propose to account for the increase in strength provided by the bolts by replacing the cohesion of the initial unreinforced ground by an "equivalent" increased cohesion, all other parameters remaining unchanged. The improved cohesion is denoted by c^H and its value is estimated as follows.

Consider a reinforced soil element as shown in Figure 5 in which the reinforcements are placed horizontally.

The element is subjected to a mechanical loading defined by major (Σ_2) and constant minor (Σ_1) principal stresses. Now, it is possible to simply replace it by a homogeneous two-phase element. Since there is a perfect bonding between phases, the equilibrium condition results in:

$$\Sigma_1 = \sigma_1^m + \sigma^r \ , \ \Sigma_2 = \sigma_2^m \qquad \varepsilon_1^m = \varepsilon^r \tag{7}$$

where σ_i^m (i = 1,2) and σ^r correspond to local stress components in matrix and reinforcement phases, respectively. ε_i^m and ε^r are the local strain components in the same order.

Consider the failure criterion of the soil as follows:

$$\sigma_2^m - \sigma_1^m = 2c\cos\phi + \left(\sigma_2^m + \sigma_1^m\right)\sin\phi \tag{8}$$

Substituting (7) in (8), one gets:

$$\Sigma_2 = \left(\frac{1+\sin\phi}{1-\sin\phi}\right)\Sigma_1 + \left(\frac{2c\cos\phi}{1-\sin\phi}\right) - \left(\frac{1+\sin\phi}{1-\sin\phi}\right)E^r\varepsilon^r \tag{9}$$

where E^r is the stiffness of the reinforcement phase (equal to the product of the modulus of the bolts E_b by

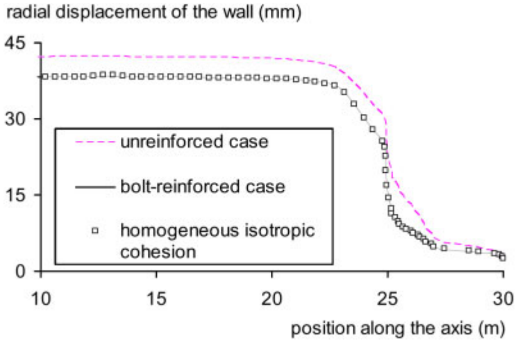

Figure 6. Comparison of convergences obtained between with an isotropic and an anisotropic model (reinforced tunnel face).

their volume fraction η). On the other hand, if the new soil element with c^H is subjected to the same stress conditions defined by Σ_1 and Σ_2, failure is associated with the following condition:

$$\Sigma_2 = \left(\frac{1+\sin\phi}{1-\sin\phi}\right)\Sigma_1 + \left(\frac{2\cos\phi}{1-\sin\phi}\right)c^H \qquad (10)$$

By comparing equations (8) and (10), the value of the cohesion c^H can be assessed as:

$$c^H = c - \left(\frac{1+\sin\phi}{2\cos\phi}\right)E^r\varepsilon^r = c - \left(\frac{1+\sin\phi}{2\cos\phi}\right)E^r\varepsilon_1^m \qquad (11)$$

The cohesion found depends on the deformability of the reinforcement phase. It can be noted that Equation (11) is similar to the expression stated by Charmetton (2001) if the term $E^r\varepsilon^r$ is replaced by ultimate tensile strength of the reinforcement phase.

Analyzing the results of the simulation for the non-reinforced tunnel problem, one observes that the axial strain in the vicinity of the tunnel face is about 2.5%. Assuming that the strain would be about 1% in the case of a bolt reinforced face, the value of the improved "equivalent" cohesion c^H is approximately equal to 280 kPa.

A simulation with this value of the cohesion gives for the axial strain a value of 0.8% which is close to the value of 1% taken into account to estimate the equivalent cohesion. In Figure 6, the result of the new isotropic analysis is compared with the simulation carried out with the (anisotropic) multiphase model. As can be seen, the agreement between the results of both models is very satisfactory: the radial displacements obtained with the homogeneous isotropic cohesion are almost equal to those obtained with the multiphase model. In other words, the homogeneous equivalent model, with a modified value of the cohesion and all other parameters (especially stiffness parameters) unchanged, makes it possible to reproduce the increase of stiffness of the ground mass as a whole.

It can be expected that a simulation in which the elastic moduli of the reinforced ground were increased to account for the bolts would lead to smaller radial displacements, and would not provide a better agreement.

Sensitivity analyses (not detailed here) also show that results are entirely different if the increased homogeneous cohesion is associated with the whole ground mass and not only with the ground ahead of the tunnel face. They also show that the radial displacement depends strongly on the value of the increased cohesion.

6 CONCLUSION

Reinforcement of tunnel faces by bolts is a common practice, but a difficult problem for designers. The difference between the dimensions of the bolts and the area in which the stress state is modified by the excavation, the mechanical interaction between the bolts and the ground, and the three-dimensional nature of the problem make it difficult to build models to analyze the performance of the technique.

It is worth mentioning that the role of radial bolts placed in the tunnel wall, in planes perpendicular to the tunnel axis, can be taken into account in classic plane strain analyses (using the convergence confinement method), the bolts being seen as an increase in stiffness of the ground surrounding the excavation. In the case of bolts placed in the tunnel face, things are more complex, because the area reinforced by the bolts is eventually excavated and the bolts are destroyed as the tunneling process goes on.

The finite element simulations presented here are based on a homogenized approach that makes it possible to overcome the main difficulties of the problem. They are based on several assumptions that can be discussed, but provide a way of overcoming the complexity of the problem. It can be pointed out that the simulations presented here are carried out in axisymmetric conditions, but the model is available to perform fully three-dimensional simulations if necessary (in the case of a non-circular section, or if the initial stress state is not isotropic and homogeneous).

Results tend to show that tunnel face reinforcement reduce both the convergence of tunnel wall and the compressive forces in the lining. The decrease is of the order of 10%, which remains moderate, but it must be recalled that many parameters are involved in the analysis (one could account for elastic non linearities, or discuss the influence of the length of unsupported ground behind the tunnel face).

From a qualitative point of view, it is interesting to note that a longitudinal increase in stiffness due to bolts results in a decrease of the wall convergence. This is clearly the result of the modification of the three-dimensional stress distribution due to bolts: it seems therefore difficult to take them into account in a plane strain analysis (as is usually done using the usual convergence-confinement method). Unlike the reinforcement of the surrounding ground by radial bolts, the use of longitudinal bolts in the tunnel face cannot be analyzed without taking into account the three dimensional nature of the problem.

It is also recalled that the model provides an estimated of the traction forces in the bolts, which may be useful to choose the number and diameter of bolts.

In the last place, a simple analysis makes it possible to model the reinforced zone with a classical homogeneous isotropic model, provided that a suitable increased value of cohesion is taken into account. The increased cohesion depends on the deformability of the bolts, and requires making an assumption regarding the axial strain in the bolts close to the tunnel face. This assumption has to be based on engineering judgment, empirical knowledge, or numerical analysis.

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