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Interaction between tunnel and unstable slope – Influence of time-dependent behavior of a tunnel excavation in a deep-seated gravitational slope deformation

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ABSTRACT

A back analysis of old tunnels in an unstable slope context leads to consider several situations of tunnel entering a slope: cross-cutting tunnel to the slope, oblique tunnel to the slope, or shallow tunnel parallel to the slope. Identified pathologies of structures vary depending on these situations. In the context of a shallow tunnel, the tunnel excavation leads to a slope destabilization due to a more or less important deconfinement of the surrounding massif. Construction techniques influence, on one hand, slope surface displacement acceleration, on the other hand, structural damages in the tunnel lining. Nevertheless, the interaction between tunnel and unstable slope depends on the distance between the slope surface and the tunnel lining plot according to the tunnel diameter (*D*) and on the geological, geomorphological, hydrological and seismic contexts of the slope. This research focuses on different mechanisms of slope instability in a glacial unloading context, especially in creeping contexts, and on damages affecting the structure of tunnels parallel to the slope. Through numerical simulations, the influence of the construction techniques was studied; so was the choice of the tunnel situation, more or less away from the slope surface. Mainly the delay time before tunnel structure implementation) on the damage lining processes, the interaction between tunnel and slope surface displacements and their time evolution have been taken into account for the most critical tunnel situation in the slope. The different situations of tunnel in the slope permit to set in evidence the safety distance from the slope in the context of a slow glacial unloading mechanism.

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1. Introduction

It has been reported that tunnel excavation may induce landslides (Koizumi et al., 2010). However, in the context of natural mountain slope affected by the glacial retreat, river erosion in slope toe, the slope surface displacement and slope destabilization may occur without any anthropogenic actions. In this previous context, the tunnel construction results in the increase of slope surface displacements or the slope destabilization with the development of shear zones. The monitoring of the slope allows to understand the mechanisms of movement activations as a result of natural or anthropogenic influence factors.

Furthermore, studies back analysis of unstable slope with a recurrent damage in the tunnel lining, it is necessary to distinguish on one hand factors associated to those geologic and geomorphologic conditions of the slope and their evolutions simultaneously, and on the other hand, factors corresponding to the method of excavation and construction of the tunnel.

The main point to distinguish the type of interaction between a tunnel lining and an unstable slope is the localization of tunnel in the slope (relative orientation/height/height of the cover). The relative orientation of tunnels is considered: cross-cutting tunnel to the slope, oblique tunnel to the slope or shallow tunnel parallel to the slope. According to this first classification, various pathologies on the tunnel structure characterizing these situations were identified (Wang, 2010).

In the context of a shallow tunnel parallel to the slope, the rate of tunnel lining damage strongly depends on the distance between tunnel lining and slope surface or slip surface (Koizumi et al., 2010; Ashtiani et al., 2010). Moreover, in their study "Numerical interaction of landslide behavior induced by tunnel excavation", Koizumi et al. (2010) set in evidence that at the base of the slope the tunnel contributes to accelerate the movements within the slope compared with the case without any tunnel. The slope displacements are more important, with a same distance between tunnels and

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slip surface, when the tunnel is located at the base of the slope compared with another higher position in the slope. Finally, in a weak rock, the shortest distance between the tunnel lining and the slope surface or slip surface shows that below a distance of 1.5 tunnel diameters (1.5D), the interaction between a slip surface and a tunnel structure increases significantly.

The tunnel construction was divided in two steps: first, excavation process, with or without pre-supporting and support, second the set-up of lining at a certain distance behind the tunnel front. This delay, even low, corresponding to this unsupported distance, is always considered, especially in the NATM (New Austrian Tunneling Method) construction (Yang et al., 2013). The choice of the maximal distance behind the tunnel front without support depends on the massif behavior. A relation (1) joins the distance without support (d) with the velocity of excavation (V_a) with the delay prior to the set-up of the lining (τ_a) (Panet, 1995):

$$\tau_a = d/V_a \tag{1}$$

In time-dependent numerical modeling context, this parametric study deals with the influence of delay prior to the lining set-up and the tunnel situation at the base of the slope. The interaction between tunnel lining and slope glacial retreat is put in evidence on the evolution of stress–strain and displacement of the tunnel lining and the influence of tunnel construction on the slope surface displacement near the tunnel.

2. Material and methods

In order to demonstrate the time-dependent modeling influence of a tunnel excavation in a slope context, the finite difference code FLAC has been used (Itasca Consulting Group, 2002). The aim of this theoretical study is to approach the influence of a tunnel excavation in the context of slope affected by a glacial retreat.

2.1. The Burger-creep viscoplastic model

The CVISC model in FLAC is characterized by an elasto-plastic volumetric behavior and a visco-elasto-plastic deviatoric behavior (Fig. 1). The visco-elastic behavior law corresponds to a Burger model constituted by Kelvin cell in series with a Maxwell component. The plastic behavior law corresponds to a Mohr–Coulomb model (Sharrifzadeh et al., 2013).

In Fig. 1b, the superscripts K and M correspond to Kelvin, Maxwell plastic bodies. The variables K, G and η correspond to the bulk, shear modulus and the dynamic viscosity parameters.

2.2. The critical time-stepping

In FLAC, for a time-dependent constitutive model like a creep run, the time-step in computation code represents a real time. A special analysis of the time step is necessary in order to ensure the stability of the time-dependent numerical solution (Sharrifzadeh et al., 2013). In other terms, the time-dependent stress increment must not be large compared to the strain-dependent stress increment; otherwise, inertial effects may affect the solution.

For time-dependent computations such as creep phenomena, the user may choose a time-step. The results may be affected by the time-step, with one step in the equations of constitutive law for creep.

For a CVISC model, the maximum creep time-step depends on the visco-elastic parameters as follows (2):

$$\Delta t^{cr}_{max} = \min\left(\frac{\eta^K}{G^K};\frac{\eta^M}{G^M}\right) \tag{2}$$

For more accuracy, it is advisable to adapt the creep time-step to the period phenomena (glacier melting or tunnel excavation).

2.3. Model description

Fig. 2a shows the slope model used for this parametric study. This model arises from a bibliographic study of stress–strain–time numerical modeling of a deep-seated gravitational slope deformation (DSGSD) resulting from the melting of a glacier (Apuani et al., 2007). The aim of this bibliographic article is to approach the instability process caused by the action of unloading due to the glacier melting and the creeping in a gneissic rock mass with several constitutive models (Mohr–Coulomb, Maxwell visco-elastic, Burger visco-elasto-plastic model).

The rock mass defined by the Burger model exhibits limitless deformation under limited stress. However, it is advisable to set viscoelastic parameters representing a real viscoelastic time of the rock mass behavior.

We use the mechanical parameters (Table 1) of Apuani article (Apuani et al., 2007) with the CVISC constitutive model to represent the influence of a tunnel excavation in case of this natural slope. Depending on stress level and deformation, each type of formation has its own creep parameters. Regarding to the literature review, the range of creep parameters for several formations corresponds to: $G^K = 450$ MPa, $\eta^K = 4 \times 10^{14}$ Pa s and $\eta^M = 4 \times 10^{13}$ Pa s (Athanasopoulos et al., 2012). Comparing these creep parameters values with those chosen in the article (Table 1), we notice that, for our study, creeping is slower for gneissic masses than in various types of formations.

The boundary limits of our model (Fig. 2a) were reduced from the bibliographic slope model to permit to refine the mesh around the tunnel structure (Fig. 2b1). However, the influence of boundaries on the results was similar to the case of slope model with the same mesh as in the bibliographic study. The results of ground displacements with our slope model are smaller than those in the slope model with same the mesh as in the bibliographic model only due to the refine mesh.

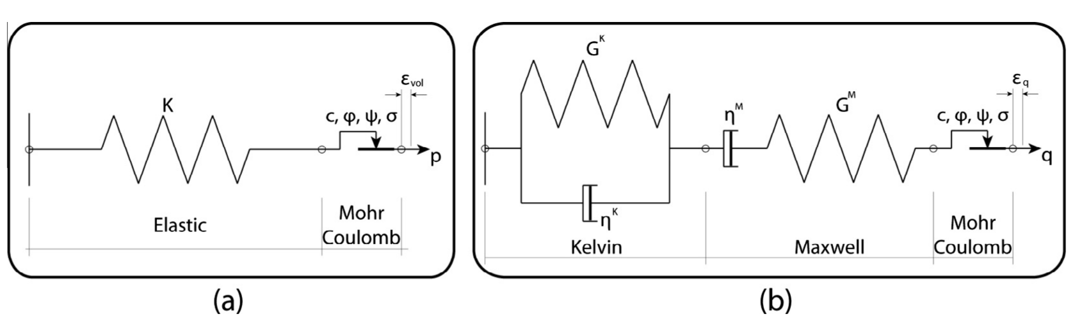

Fig. 1. Schematic representation of CVISC model: (a) volumetric behavior and (b) deviatoric behavior (Sharrifzadeh et al., 2013).

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