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Redistribution and magnitude of stresses around horse shoe and circular excavations opened in anisotropic rock

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ABSTRACT

In this paper numerical analysis of underground structures, taking account the transverse isotropy system of rocks, was done using CAST 3M code by varying the shape of excavation and the coefficient of earth pressure k. Numerical results reveal that the anisotropy behavior, the shape of hole and the coefficient of earth pressure k have significant influence to the mining induced stress field and rock deformations which directly control the stability of underground excavation design. The magnitude of horizontal stress obtained for the horse shoe shape excavation (25.2 MPa for $k = 1$; 52.7 MPa for $k = 2$) is lower than the magnitude obtained for circular hole (26.4 MPa for $k = 1$; 59.5 MPa for $k = 2$). Therefore, we have concluded that the horse shoe shape offers the best stability and the best design for engineer. The anisotropy system presented by rock mass can also influence the redistribution of stresses around hole opened. Numerical results have revealed that the magnitude of redistribution of horizontal stresses obtained for transverse isotropic rock (12.1 MPa for $k = 0.5$; 25.2 MPa for $k = 1$ and 52.7 MPa for $k = 2$) is less than those obtained in the case of isotropic rock (27.6 MPa for $k = 1$; 48.6 MPa for $k = 2$ and 90.81 MPa for $k = 2$). The more the rock has the anisotropic behavior, the more the mass of rock around the tunnel is stable.

1. Introduction

Sustainable development of modern society requires the building of underground holes such as subways and railways, highways, material storage, sewage, water transport, hydropower structures [1–5]. All these underground excavations are very necessary, especially to ensure a greater transportation demand and preserve environmental quality [3–5]. Rock at depth is subjected to stresses resulting from the weight of the overlying strata and from horizontal stresses of tectonic origin.

When an opening is excavated in this rock, the stress field is locally disrupted and a new set of stresses are induced in the rock surrounding the opening.

Knowledge of the magnitudes and directions of these in situ and induced stresses is an essential component of underground excavation design since, in many cases, the strength of the rock is exceeded and the resulting instability can have serious consequences on the behavior of the excavations.

The redistribution of near-field stresses following tunnel excavation has been studied extensively using a number of analytical, physical and numerical modeling techniques [1–5]. An analytical solution for the stress distribution in a stressed elastic plate containing a circular hole was published and this formed the basis for many early studies of rock behavior around tunnels.

These studies concern in many cases, the circular shape of hole and the model most used are based on homogenous and isotropic rock with linear elastic behavior.

However to the best of our knowledge, the numerical analysis of redistribution of stresses around the circular and the horse shoe shapes of excavation, in the case of transverse isotropic system mass of rock, remains unaddressed.

The transverse isotropy system is a system typically found in the majority of rock and it has a great importance in rock mechanics [6].

In order to quantify state of stress and deformation for the designs of underground structures with different shapes, a two-dimensional boundary element numerical modeling will be performed by using CAST 3M code based on the finite element method. The aim of the study reported here is to examine the

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distribution of stresses around the opening after excavation and to decide how it varies with the shape and in situ stress state.

This paper is organized as follows. The system under study is presented and modeled in Section 2 using Raleigh Ritz's method and the constitutive law of rock mechanics. Section 3 is devoted to the numerical simulations of state of stress, deformation around the hole with different shapes (circular, horse shoe). Finally, the conclusion is given in section 4.

2. Theory

In this section, we consider an underground excavation opened at 500 m of depth in the granitic mass of rock, and a bloc of rock around the hole opened as shown in Fig. 1.

2.1. In situ stresses

Rock at depth is subjected to stresses resulting from the weight of the overlying strata and from horizontal stresses of tectonic origin. When an opening is excavated in this rock, the stress field is locally disrupted and a new set of stress is induced in the rock surrounding the opening. This is because rock, which previously contained stresses, has been removed and the load must be redistributed. The magnitudes of pre-existing in situ stresses have been found to vary widely, depending upon the geological history of the rock mass in which they are measured [7]. The weight of the overlying rock mass was recognized for more than a century as a primary source of stress around underground opening.

The vertical stress can be estimated by the weight of the overburden.

$$\sigma_v = \gamma g H \tag{1}$$

where $\gamma = 2600\ \text{kg/m}^3$ is a density of granitic rock specimen, $H = 500$ m is the depth of the overlying rock mass, and g the constant of gravity.

However it is very difficult to estimate the horizontal stresses. In general the horizontal stresses are estimated by assuming a suitable lateral earth pressure ratio [8].

$$\sigma_h = k\sigma_v = \frac{v}{1-v}\sigma_v \tag{2}$$

where v is the Poisson's modulus and k is the stress ratio.

High horizontal stresses are caused by factor relating to erosion, tectonics, rock anisotropy, local effects near discontinuities and scale effect.

2.2. Finite element method

Many underground excavations are irregular in shape and are frequently grouped close to other excavation.

In addition, because of the presence of geological features such as faults and intrusions, the rock properties are seldom uniform within the rock volume of interest. Consequently, the closed form solutions described earlier are of limited value in calculating the stresses, displacements and failure of the rock mass surrounding underground excavations. These problems require using numerical techniques. In this work, CAST 3M code, based on finite element method, is applied to simulate the stress and strain distribution around different holes. The finite element method uses Raleigh–Ritz's method based on principle of potential energy minimum to establish the equation of displacement as function of external forces.

Recent field and laboratory studies have shown that, even at very small strains, many soils exhibit non-linear stress–strain behavior. Nevertheless, because of its convenience, linear elasticity will continue to play an important role in the analysis of such problems as settlement, deformation and soil-structure interaction.

Let consider an elastic and isothermal bloc of rock around excavation, and submit to external force as shown in Fig. 1, the potential energy is given by:

$$\Pi = \frac{1}{2}\int_v \sigma^t \varepsilon dv - \int_v u^t f dv - \sum_i u_i^t p_i - \int_s u^t T ds \tag{3}$$

where σ is the internal stress of the rock, ε the strain of the rock, u the displacement of the rock, p the punctual external force, T the external stress applied, s the surface of the bloc of rock and V the volume of the bloc of rock.

By applying the Raleigh Ritz's method, the potential energy becomes:

$$\Pi = \frac{1}{2}q^t K q - q^t F \tag{4}$$

where K is the matrix of rock rigidity which contains the elastic constancies of the rock (elastic modulus, Poisson's modulus), q the global displacement vector of the knot, F the global charges vector.

By minimizing the potential energy of the rock, we obtain the general equation of global displacement of the knot as a function of applied forces, given by:

$$[K]q = F \tag{5}$$

The algorithm of the resolution of this equation in the case of linear elastic and anisotropic medium is given by Fig. 2.

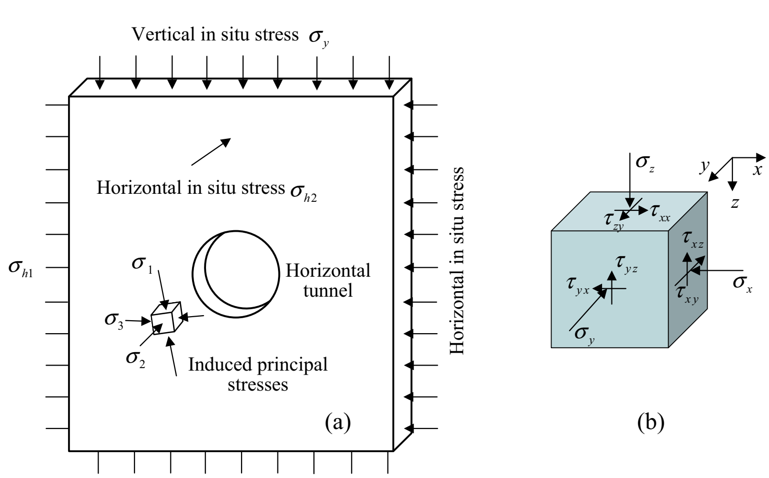

Fig. 1. Geometry of tunnel opened (a) and the enlargement of the bloc of rock around excavation submitted to stresses (b).