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Numerical analysis of the effects of rock bolts on stress redistribution around a roadway

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ABSTRACT

Besides opening geometry, in situ stress and material properties, opening support also has significant effects on stress redistribution around a roadway. To investigate these effects of rock bolts on the stress redistribution around a roadway, a series of numerical studies were carried out using the finite difference method. Since the stress changes around a roadway caused by rock bolting is small relative to the in situ stress, they cannot obviously be observed in stress contour plots. To overcome this difficulty, a new result processing methodology was developed using the contouring program Surfer. With this methodology, the effects of rock bolts on stress redistribution can obviously be analyzed. Numerical results show that in the three patterns of rock bolts installed in the roof, in the roof and the two lateral sides, and in all the four sides of the rectangular roadway, the maximum stress magnitude of the increase is 0.931 MPa, 2.46 MPa, and 6.5 MPa, respectively; the bolt number of 5 can form an integrated ground arch; the appropriate length and pre-tensioned force of the rock bolt is 2.0 m and 60 kN, respectively. What is more, the ground arch action under the function of rock bolting is able to be effectively examined. The rock bolts dramatically increase the minor principal stress around a roadway which results in significant increase in material strength. Consequently, the major principal stress that the material can carry will greatly increase. With adequate supports, an integrated ground arch which is critical for the stability of roadway will be formed around the roadway.

1. Introduction

Underground excavation in a stressed rock mass induces stress redistribution around the opening, depending on the geometry of the opening, the in situ state of stress existing before the excavation is excavated and on the material properties as well as the pattern and capacity of the opening support [1–10]. Investigating these stress redistribution characteristics is very essential for the opening stability [11–16]. Numerical simulation seems to be the most suitable approach to study these issues and a number of studies have been done using this approach [17–23]. Eberhardt [1] has carried out a series of three-dimensional finite-element studies to examine the changes in magnitude and orientation of the principal stress with the development of a tunnel. Various in situ states of stress and two different models, namely elasto-plastic and elastic, have been considered in his studies. Goel et al. [2] have conducted a parametric study using the numerical analysis code FLAC3D to obtain the influence of various shapes of underground openings on the maximum induced boundary stress. Different in situ states of stress and different opening shapes have been considered in their study. Ren et al. [3] have presented a new approach using the finite element method to optimize the shape of underground excavation under different virgin stress states. Karakus et al. [4] have conducted 2D finite difference method to assess tunneling-induced settlement, stress redistribution phenomena along with movements around shallow soft ground tunnels. The studies mentioned above have made a number of significant conclusions with considerations on in situ state of stress, opening geometry and material properties. However, little attention has been focused on the effects of opening supports on stress redistribution. Funatsu et al. [5] have conducted a number of numerical simulations using the distinct element method to study the effects of dowels, lining, forepoling and face bolts on the stress redistribution around roadways. Their studies have demonstrated that supports restrain the reduction in minor principal stress around a tunnel and enhance the circumferential stress. Muya et al. [6] have examined the effects of rock bolting on the stress redistribution by using the

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ANSYS software with elastic and elasto-plastic models. They have stated that rock bolting can significantly reduce both the intensity and the size of the region of stress concentration.

In a previous study, we have made a numerical study on the effects of pre-tensioned rock bolts on stress distribution [7]. In that study, however, only the pre-tensioned force of rock bolts has been introduced in numerical models. Both the in situ stress and the excavation of roadway have not been considered. The reason is that, under the condition of the in situ stress, stress changes caused by rock bolting are so small compared with stress changes caused by the excavation of the roadway. Unfortunately, the effects of in situ stress and the excavation of the roadway are very essential for the characteristics of stress redistribution. In the present study, we carry out a series of numerical studies to investigate the effects of rock bolts on stress redistribution around a roadway. A new result processing methodology is developed so that the effects of rock bolts can be obviously and efficiently analyzed. What is more, the ground arch action of rock bolting can effectively be evaluated with this methodology. Using this methodology, the effects of rock bolts on stress redistribution are closely analyzed. Then, the influence of rock bolting parameters, including bolt spacing, length and pre-tensioned force is discussed.

2. Approach and input parameters

FLAC3D numerical analysis code developed by ITASCT has been used for the study. This code is based on the finite difference numerical method with the Langragian calculation method. The Finite Difference Method (FDM) can be better applied to modeling of stress distribution around an underground roadway in comparison to other numerical techniques [8].

2.1. Model generation

A numerical model has been generated for present studies, as shown in Fig. 1. The length and width and height of the model are 72, 1 and 72 m respectively. A rectangular roadway (4 m × 4 m) is placed in the center of the model. The typical element size in the region of interest is approximately 0.4 m × 0.4 m × 0.5 m.

The model is a plane strain model, and is constructed as plates of unit thickness, with a boundary condition of zero-displacement applied on both faces. The vertical displacements at the bottom and at the top of the model are both fixed. The horizontal stresses in both directions and the vertical stress have been assumed to have the same magnitude, 15 MPa. The boundary and initial conditions mentioned above eliminate the influence of boundary conditions and in situ stresses on the study results. The model is single-material. The strain-softening constitutive model has been employed to present stress-strain behavior of the rock material. The material properties are listed in Table 1.

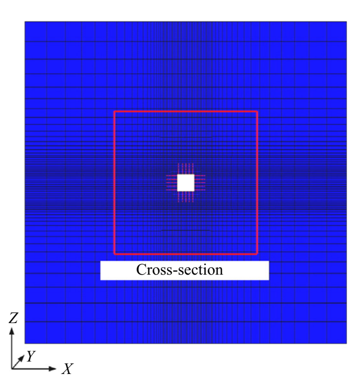

Fig. 1. Model geometry used in present study.

2.2. Methodology of rock bolting simulation

The structure element called "Cable" has been used to model rock bolts. The free length of a rock bolt is modeled by setting two parameters of the cable element, the grout stiffness per unit length and the grout shear strength per unit length to zero. The bearing plate, which is a component of the rock bolting system, is modeled by creating a rigid node-to-zone connection between the head node of the cable element and the zone element closest to the node. The pre-tensioned force is applied on the free length of the rock bolt with the 'set cable pretension' command. Furthermore, in order to simulate the actual effect of pre-tensioned stress on a roadway surface, which is provided by straps and screens in field applications, an additional stress S_P is applied on the surface where rock bolts have been installed. The additional stress S_P is calculated by the follow equation:

$$S_P = \frac{n \times P}{S} \tag{1}$$

where n is the number of the rock bolts installed on the surface; P is the pre-tensioned force of a rock bolt and S is the surface area.

The input parameters of rock bolts used for the model are given in Table 1.

3. Numerical results and discussion

The effects of rock bolts on stress distribution around a roadway can be accessed by comparing stress contour plots obtained from the models among which only rock bolting patterns are different. Fig. 2 shows the major principal stress distribution around a roadway obtained from the unsupported model and the rock bolt supported model respectively. When the roadway is excavated, no matter whether this roadway is supported or not, stress relaxation will be observed around the roadway. It has been proved that supports like rock bolts could reduce this relaxation [5]. However, comparison of the two plots fails to show an obvious difference. The reason is that stress changes between the two models are so small, compared with in situ stresses which have initially been applied on the models, that they could not be noticeably observed in these stress contour plots. Therefore, to obviously access the effects of rock bolts on stress distribution characteristics, the contouring and 3D surface mapping program. Surfer, which has been

Table 1
Input parameters for ground and rock bolt.

Input parameters	Parameters	Value
For ground	Density (kg/m^3)	1400
	Bulk modulus (GPa)	2.67
	Shear modulus (GPa)	1.60
	Cohesion (ε_p, MPa)	0.0, 2.0 0.0005, 2.0 0.03842, 0.1050 0.1, 0.1050
	Friction angle (ε_p,°)	0.0, 23 0.0005, 30 0.0370, 30
	Tensile strength (MPa)	10
For rock bolt	Length (m)	2.4
	Tensile yield strength (kN)	304.1
	Grout cohesive strength pre unit length (N/m)	4.25×10^5
	Grout stiffness per unit length (N/m)	2×10^9
	Number of rock bolts for each side	5
	Anchored length (m)	1.0
	Pre-tensioned force (kN)	60

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