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Analytical solution for a circular roadway considering the transient effect of excavation unloading

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ABSTRACT

The rocks surrounding a roadway exhibit some special and complex phenomena with increasing depth of excavation in underground engineering. Quasi-static analysis cannot adequately explain these engineering problems. The computational model of a circular roadway considering the transient effect of excavation unloading is established for these problems. The time factor makes the solution of the problem difficult. Thus, the computational model is divided into a dynamic model and a static model. The Laplace integral transform and inverse transform are performed to solve the dynamic model and elasticity theory is used to analyze the static model. The results from an example show that circumferential stress increases and radial stress decreases with time. The stress difference becomes large gradually in this progress. The displacement increases with unloading time and decreases with the radial depth of surrounding rocks. It can be seen that the development trend of unloading and displacement is similar by comparing their rates. Finally, the results of ANSYS are used to verify the analytical solution. The contrast indicates that the laws of the two methods are basically in agreement. Thus, the analysis can provide a reference for further study.

1. Introduction

With the continuous development of the economy and the further expansion of energy needs, underground engineering will move to deeper surrounding rocks. In the early 1990s, it was found that the deformation produced by excavation unloading of high rock slopes was difficult to control in the permanent ship lock of the three gorges project. The phenomenon made the excavation unloading problem of rock mechanics to be studied by other researchers [1]. When the in-situ stress in a rock mass is small, it is feasible to deal with excavation unloading and its mechanical effect using quasi-static conditions [2,3]. But, in the case of medium and high geostress, this analysis method produces large errors. Thus, the transient effect of excavation unloading must be considered.

The excavation of a roadway or chamber is an unloading or progressive disturbance condition in a high stress environment. The in-situ geostress is considered as a static load while blasting vibrations and excavation unloading are regarded as dynamic loads. Numerous scholars have conducted research on the failure mode of rock, strength criteria and constitutive relations under dynamic load [4,5]. In addition, dynamic analysis has been conducted during the study of zonal disintegration. Zhou and Qian [6] selected a parabolic function as the unloading form to explain the mechanism of zonal disintegration. But the Bessel functions are replaced by approximate expressions in the solution process. Zhou et al. [7] used the Laplace integral transform and residue theorem to analyze the unloading process of an isotropic rock surrounding chamber buried deeply under dynamic excavation. Li et al. [8] employed PFC to analyze excavation unloading and obtain the effect of unloading rate and unloading path on the total stress field. Chen et al. [9] performed a model test to study Dingji coal mine in the Huainan mining area and obtained the main characteristic and law of the zonal disintegration phenomenon. Li et al. [10] used the time domain variational principle of Hamitom to derive perturbed stress, perturbed strain and perturbed displacement of rock surrounding tunnels under dynamic excavation and revealed the zonal characteristics of alternate appearance of tension and compression. For the zonal disintegration problem, most scholars thought that the reason is a circumferential crack produced on the interface between the elastic zone and the plastic zone, whereas Qian et al. [11,12] proposed a non-Euclidean geometry

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model to explain this phenomenon. All researches were conducted to analyze incompatible deformation of rocks produced during excavation unloading, but the analysis method did not create united knowledge. Thus, it is necessary to perform a transient study of unloading in order to analyze these special phenomena.

Previous results, such as those given in Ref. [6], explain some approximate aspects of the process.

The modified Bessel functions $I_0(k_d r)$ and $K_0(k_d r)$ are approximately equal to $e^{k_d r}/\sqrt{2\pi k_d r}$ and $e^{-k_d r}\sqrt{\pi/2k_d r}$. In this paper strict mechanical principles are followed to study transient effects and the dynamic process of excavation unloading and the unloading model is established. Laplace integral transform method is employed to solve this problem and obtain the stress change law of surrounding rocks. The research can provide a reference for understanding the unloading process.

2. Computational model and basic equations

2.1. Computational model

A roadway is subjected to uniform stress whose magnitude is equal to p_0. The radius of the roadway is assumed to be r_0. According to the dynamic process of excavation, the following conditions are obtained:

$$\begin{cases} p(t) = p_0, & t = 0 \\ p(t) = 0, & t = t_0 \end{cases} \tag{1}$$

The mechanical model of dynamic excavation of a circular roadway is illustrated in Fig. 1.

The calculation model shown in Fig. 1 is broken down into two sub-models as shown in Fig. 2. The final stress field can be obtained by the superposition of stress fields of two sub-models.

2.2. Basic equations

The surrounding rocks are assumed to be a homogeneous and isotropic medium. Polar coordinates are employed. The radial stress and circumferential stress are denoted by σ_r and σ_θ, respectively. The radial strain and circumferential strain are expressed as ε_r and ε_θ, respectively. The problem is analyzed according to plane strain theory.

(1) Differential equation of motion (ignoring the body force).

$$\frac{\partial \sigma_{1r}}{\partial r} + \frac{\sigma_{1r} - \sigma_{1\theta}}{r} = \rho \frac{\partial^2 u_1}{\partial t^2} \tag{2}$$

where ρ is the volume density of surrounding rocks; the subscript “1” denotes sub-model (a).

(2) Geometric equations:

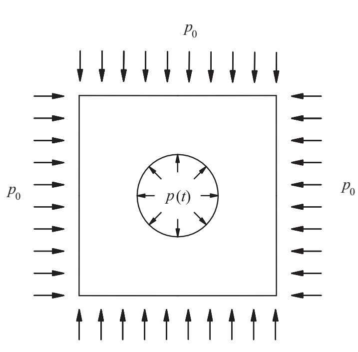

Fig. 1. Transient analysis model of excavation unloading in circle roadway.

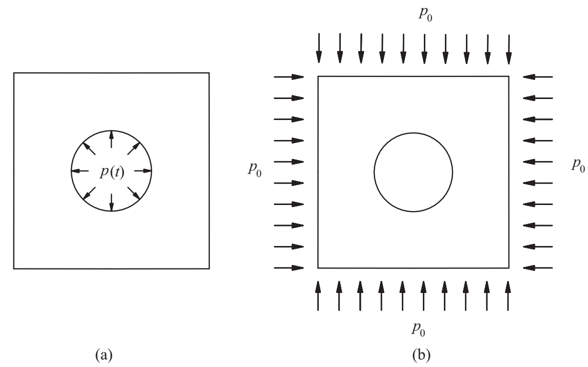

Fig. 2. Sub-model.

$$\begin{cases} \varepsilon_r = \frac{\partial u_1}{\partial r} \\ \varepsilon_\theta = \frac{u_1}{r} \end{cases} \tag{3}$$

(3) Physical equations:

$$\begin{cases} \sigma_{1r} = (\lambda + 2\mu)\varepsilon_{1r} + \lambda \varepsilon_{1\theta} \\ \sigma_{1\theta} = (\lambda + 2\mu)\varepsilon_{1\theta} + \lambda \varepsilon_{1r} \end{cases} \tag{4}$$

where λ and μ are Lame parameters of the surrounding rocks.

Based on Ref. [6], the function relationship between excavation load and time is shown in Fig. 3.

The unloading function is expressed as:

$$p(t) = \begin{cases} p_0\left(1 - \frac{t^2}{t_0^2}\right) & 0 \leqslant t \leqslant t_0 \\ 0 & t \geqslant t_0 \end{cases} \tag{5}$$

where t_0 is the completed time of excavation.

Eq. (5) indicates that the excavation load is the parabola form. In fact the simplest unloading form is a linear type [8]. According to the principle that impulse is equal, the linear form of unloading function can be expressed as

$$p(t) = \begin{cases} \frac{4p_0}{3}\left(1 - \frac{t}{t_0}\right) & 0 \leqslant t \leqslant t_0 \\ 0 & t \geqslant t_0 \end{cases} \tag{6}$$

The unloading function of triangular form is also simple. Based on the equal impulse principle, $p(t)$ can be derived as:

$$p(t) = \begin{cases} \frac{\pi p_0}{3} \cos \frac{\pi t}{2t_0} & 0 \leqslant t \leqslant t_0 \\ 0 & t > t_0 \end{cases} \tag{7}$$

The boundary conditions of the problem can be obtained as follows:

$$\begin{cases} r = r_0, & \sigma_{1r} = p(t) \\ r \to \infty, & u_1 = 0 \end{cases} \tag{8}$$

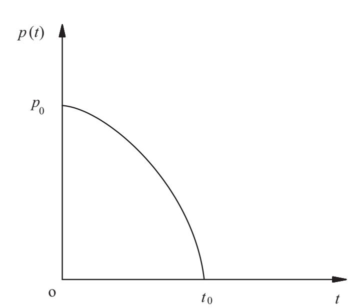

Fig. 3. Relationship between excavation load and time.