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Transient characters of energy changes induced by blasting excavation of deep-buried tunnels

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ABSTRACT

As energy release plays an important role in engineering disasters such as rockburst, seismicity induced by deep rock mass excavation via drill and blast, energy changes caused by excavation have been studied for a long time. However, previous studies ignored the time factor and took the unloading of in-situ stress on the excavation boundary as a quasi-static process. In this paper, energy changes induced by quasi-static unloading of in-situ stress (QSUIS) and transient release of in-situ stress (TRIS) were analyzed for the case of circular excavation under the condition of in-situ hydrostatic stress. Results show that, different from energy changes caused by QSUIS, the dynamic adjustment of strain energy induced by TRIS which first decreases and then increases, is a transient process. With the propagation of the unloading stress wave from the excavation boundary to the far surrounding rock masses, energy is transmitted by the way of radial stress doing work from the far surrounding rock masses to the near ones which causes the transient aggregation of strain energy. Comparison based on the effects of energy changes on the damage range indicates that higher aggregation degree of strain energy causes larger damage range induced by TRIS than that induced by QSUIS. In addition, a practical application in Jinping II hydropower project was presented as a verification.

1. Introduction

With the increase of energy demands and decrease of shallow resources, more and more deep mineral resources are being mined worldwide. Deep mining may bring geological disasters such as rockburst and seismicity (Cook, 1963, 1966, 1976; Kisslinger, 1976). These human-activity induced hazards not only have negative effects on the safety of mining, but also cause serious economy and life losses. Therefore, deep rock mechanics problems associated with excavation have become one of the research foci for a long time. Achievements through theoretical studies, numerical simulations, and laboratorial tests indicated that the rockbursts, seismic events and other disasters induced by deep mining are the results of energy release (Hodgson and Joughin, 1966; Toksöz and Kehrer, 1972; Singh, 1988; Mikhalyuk and Zakharov, 1997; Wang and Park, 2001; He et al., 2010). As strain energy plays an important role in engineering disasters, it is necessary to study energy changes caused by excavation.

As early as 1977, a reasonably comprehensive study on energy changes caused by mining was made by Walsh, in which new light was thrown on expression of energy changes (Walsh, 1977). Then, by studying the energy changes and stability in underground mining, Brady and Brown introduced a design application of boundary element methods (Brady and Brown, 1981). Afterwards, Salamon proposed that high in-situ stress endows the rock mass with large strain energy and energy changes occur during the process of mining (Salamon, 1983). A further research by Salamon who emphasized the significance of energy considerations in the study of problems induced by tabular excavations, indicated that if mining from the initial state to excavation geometry takes place, energy transformations would occur (Salamon, 1984). Based on the fundamental results derived by Salamon, Napier developed a unified method for calculating energy changes that take place when multiple discontinuities are extended incrementally (Napier, 1991). A simple finite element model was proposed by Mitri to calculate the seismic energy release rate and strain energy storage rate (Mitri et al., 1999). It should be mentioned that most of these studies ignore the time factor and take the unloading of in-situ stress as a quasi-static process. This kind of approximate treatment may match the fact if the level of in-situ stress is low. However, if the in-situ stress reaches a level of 20–50 MPa or higher, the

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release of in-situ stress is a transient process (Zhao et al., 1999; Lu et al., 2012; Yang et al., 2013; Li et al., 2014; Zhu et al., 2014) and its effect on energy changes should be taken into account.

The purpose of this paper is to find out the difference between the energy change caused by the quasi-static unloading of in-situ stress (QSUIS) and that induced by transient release of in-situ stress (TRIS), and on this basis, to study the effects of energy changes on the damage range. To achieve this goal, energy changes caused by QSUIS were first analyzed through the theoretical analyses for a case of circular excavation under hydrostatic stress field. And then, dynamic changes of energy induced by TRIS were studied based on the solution of dynamic equations. Afterwards, the influences of dynamic energy changes on damage range were discussed. Finally, for a case of practical application in Jinping II hydropower project, the calculated and measured damage ranges were compared as a verification.

2. Energy changes induced by QSUIS

In order to simplify the analysis, an assumption was made that a circular and infinitely long tunnel with radius a is excavated under the condition of in-situ hydrostatic stress P_0. According to common sense, this is a plane-strain problem. For the case of quasi-static unloading of in-situ stress (QSUIS) on the excavation boundary, the redistributed stress and displacement of surrounding rock masses can be directly quoted from plane-strain axisymmetric results as shown in Eqs. (1) and (2) (Shen and Chen, 2006):

$$\left.\begin{aligned} \sigma_1 &= \sigma_\theta = P_0(1 + a^2/r^2) \\ \sigma_2 &= P_0 \\ \sigma_3 &= \sigma_r = P_0(1 - a^2/r^2) \end{aligned}\right\} \tag{1}$$

$$u_r = \frac{(1+\mu)P_0}{E_0} \cdot \frac{a^2}{r} \quad (r \geqslant a) \tag{2}$$

Here, σ_1, σ_2, σ_3 are the principal stresses, σ_r, σ_θ, u_r are the radial stress, tangential stress, and radial displacement, respectively, E_0 is the elastic modulus, μ is the Poisson's ratio, and r is the distance from the circle center.

The elastic strain energy density of rock masses can be calculated by the following formula (Solecki and Conant, 2003):

$$U = \left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3)\right]/2E_0 \tag{3}$$

where U is the elastic strain energy density. Before excavation, the strain energy density of the original rock masses U_B is (Hua, 2003):

$$U_B = P_0^2[3(1-2\mu)]/2E_0 \tag{4}$$

After excavation, the strain energy density of surrounding rock masses U_A can be obtained by substituting Eq. (1) into Eq. (3) (Hua, 2003):

$$U_A = P_0^2[3(1-2\mu) + 2(1+\mu)a^4/r^4]/2E_0 \tag{5}$$

Therefore, after excavation, the strain energy density of rock masses increases and its increase value ΔU is:

$$\Delta U = U_B - U_A = P_0^2[(1+\mu)a^4/r^4]/E_0 \tag{6}$$

To the whole surrounding rock masses, the total increment of strain energy J_Q can be obtained by the following formula:

$$J_Q = \int_a^{r_{+\infty}} \Delta U \cdot 2\pi r \cdot dr = \frac{\pi(1+\mu)}{E_0} \cdot a^2 P_0^2 \tag{7}$$

For the case of quasi-static unloading of in-situ stress (QSUIS) on the excavation boundary, the stress of excavated rock masses to remaining rock masses P_0 is unloaded in a very slow speed. During this process, the work done by unloading stress W_{1Q} is:

$$W_{1Q} = -\frac{1}{2}P_0 \cdot 2\pi a u_a = -\frac{\pi(1+\mu)}{E_0} a^2 P_0^2 \tag{8}$$

An assumption was made that there is a cylinder interface with infinite radius $r_{+\infty}$ in the surrounding rock masses. According to Eq. (2), the displacement of rock mass on this cylinder interface $u_{+\infty}$ is little, but the influenced area is huge. Hence, the work done by radical stress on this cylinder interface should be considered. The value of this work W_{2Q} is:

$$W_{2Q} = 2\pi r_{+\infty} \cdot 1 \cdot P_0 \cdot u_{+\infty} = \frac{2\pi(1+\mu)}{E_0} \cdot a^2 P_0^2 \tag{9}$$

Combining Eqs. (7)–(9), an equilibrium equation is not difficult to find:

$$W_{1Q} + W_{2Q} = J_Q \tag{10}$$

This energy balance equation implies that the far rock masses ($r > r_{+\infty}$) releases strain energy by doing work to the near surrounding rock masses ($a < r < r_{+\infty}$). Part of this released strain energy enlarges the strain energy of surrounding rock masses ($a < r < r_{+\infty}$), and the other part of this released strain energy is translated into the work done against the unloading stress acting on the excavation boundary.

3. Dynamic adjustment of strain energy caused by TRIS

3.1. Calculation model

As described by Hino (1956) that during the deep-buried tunnel excavation by drill and blast, when an explosive detonates in a blasthole, an enormous amount of energy is released in the form of huge pressure (50 GPa) and high temperature (5000 K). Under the effect of high pressure of shock load and detonation gases, a crushed zone is first formed around the blasthole. Then, the stress wave and great pressure of detonation gases stimulate the generation and propagation of cracks, and as a result, a fractured zone forms around the crushed zone. Accompanying the connection of cracks between the blasthole and its adjacent blastholes, fragments are thrown away, and a new boundary is formed, as shown in Fig. 1(a). Consequentially, the initial stress of the excavated rock masses to the remaining rock masses is transiently unloaded on the newly formed excavation boundary. This transient release of in-situ stress (TRIS) only sustains for 2–5 ms (Lu et al., 2012) and its effect on energy changes should not be ignored.

When the pressure induced by explosion on the excavation boundary decays to a level which is equal to the in-situ stress, the TRIS starts. For the case of circular excavation with radius a under the condition of in-situ hydrostatic stress P_0, only the radical stress $p(t)$ on the excavation boundary is linearly unloaded from P_0 to 0 in a short time. This TRIS process as shown in Fig. 1(a) can be divided into two parts: the in-situ stress field (Fig. 1(b)) and the TRIS on the excavation boundary (Fig. 1(c)) (Li et al., 2014; Zhu et al., 2014). To obtain the strain energy changes caused by TRIS, the dynamic stress motivated by TRIS needs to be calculated.

3.2. Solution method

By a cylindrical coordinate description, the governing equations for the TRIS on the excavation boundary (Fig. 1(c)) can be written as (Miklowitz, 1960; Yang and Zhang, 1988; Carter and Booker, 1990):

$$\begin{cases} \dfrac{\partial^2 u(r,t)}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial u(r,t)}{\partial r} - \dfrac{u(r,t)}{r^2} = \dfrac{1}{C_p^2}\dfrac{\partial^2 u(r,t)}{\partial t^2} \\ \sigma_r'(r,t) = (\lambda + 2G)\frac{\partial u(r,t)}{\partial r} + \lambda\frac{u(r,t)}{r} \\ \sigma_\theta'(r,t) = \lambda\frac{\partial u(r,t)}{\partial r} + (\lambda + 2G)\frac{u(r,t)}{r} \end{cases} \tag{11}$$