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Elastic modulus deterioration index to identify the loosened zone around underground openings

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ABSTRACT

In order to effectively identify the loosened zone around underground openings by using continuum modeling, this paper proposes an index called elastic modulus deterioration index based on the following two steps. First, the response of surrounding rock mass in underground openings as obtained from ultrasonic tests before and after excavation is investigated. Based on the attenuation of the P-wave velocities of the rock mass after excavation compared to the P-wave velocities before excavation obtained from ultrasonic tests, an index (χ) is defined to assess the excavation-induced rock mass damage. Second, by introducing an empirical relationship between the static and dynamic elastic moduli, the index χ is modified to represent the static elastic modulus evolution, volume change, and stress redistribution of the rock mass based on an elasto-plastic numerical model. Furthermore, this study verifies the performance of the elastic modulus deterioration index to identify the loosened zone around underground openings by comparing its predictions with the results from ultrasonic testing of the loosened zones around two tunnels in the Jinping II hydropower station. The comparisons show that the loosened zones as identified by the elastic modulus deterioration index agree well to those from ultrasonic testing. Analysis of the effects of key input parameters and initial shear strength parameters on the elastic modulus deterioration index in identifying the loosened zone demonstrate that: (1) the sensitivity of the index to the key input parameters except the residual static elastic modulus is not significant; and (2) the index has better fault tolerance performance compared to the indices based on plastic zone in terms of the selection of initial shear strength parameters.

1. Introduction

Loosened zone around an underground opening is the zone where measurable and permanent changes in rock mass properties have taken place after excavation. The loosened zone is the core area for the stability control measures of the rock mass around underground openings. The lengths of pre-tensioned rock bolts and grouted rock bolts for supporting the surrounding rock mass both depend on the extent of distribution of the loosened zone. Thus, it is important to identify the loosened zone of underground openings before designing a reinforcement system against surrounding rock mass instability. In engineering practice, ultrasonic testing along the probe holes in the surrounding rock mass is one of the most common methods to identify the loosened zone (see Fig. 1), in which: (1) depth of the loosened zone at a location in an ultrasonic test is equal to the distance between the entrance of a probe hole and the change of the P-wave velocity along the probe hole depth; and (2) boundary of loosened zone is determined by connecting the coordinates that correspond to the mutated locations of the P-wave velocity. Nevertheless, the ultrasonic testing method cannot completely identify the overall spatial distribution of the loosened zone around large complex underground openings owing to the limited number of test points and the cost and time involved in field ultrasonic testing. Therefore, some other methods are employed to refine the identification of the loosened zone as preliminarily identified by field ultrasonic test results.

Currently, continuum modeling is one of the most common tools to predict the response of rock mass (e.g., Eberhardt, 2001; Hajiabdolmajid et al., 2002; Jing, 2003; Cai et al., 2007; Eberhardt, 2008), and even to analyze the discontinuous problems such as the damaged zone of the surrounding rock mass (e.g., Li et al., 2013; Jia

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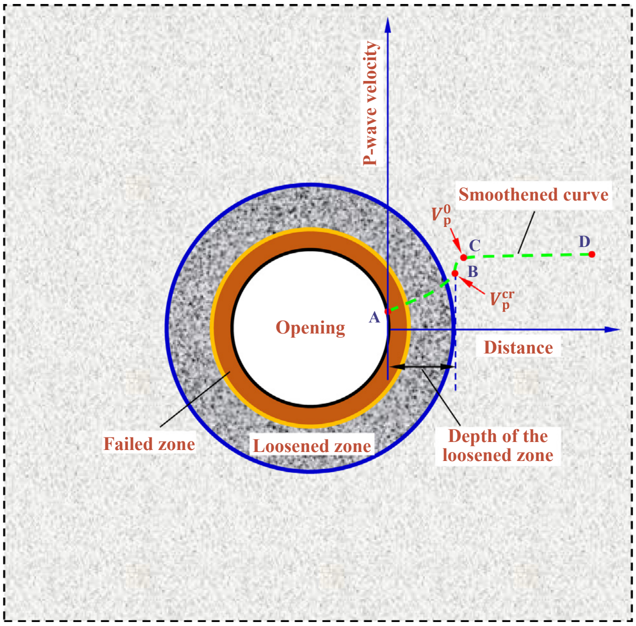

Fig. 1. Illustration of a loosened zone as identified by ultrasonic testing. (V_p^0 is the P-wave velocity of the rock mass before excavation or outside the loosened zone; V_p^{cr} is the P-wave velocity of the rock mass at the boundary of loosened zone).

and Zhu, 2015). The method is popular because it identifies the loosened zone through some indices. These indices can be classified into the following three classes: (1) the plastic zone, adopted by numerical analysis tools, such as FLAC (Itasca Consulting Group Inc., 2005), FLAC3D (Itasca Consulting Group Inc., 2005), Phase2 (Rocscience Inc., 2007) and ANSYS (ANSYS Inc., 2004); (2) the failure approach index (*FAI*) (Zhang et al., 2011); and (3) the plastic-strain gradient or the plastic strain (e.g., Hajiabdolmajid et al., 2002).

In the first class, the loosened zone is viewed as the plastic zone, i.e., the zone in which the stresses satisfy the yield criterion. However, the rock mass in a loosened zone is in equilibrium not at the point of peak strength but at a point of post-peak strength. Therefore, the extent of a loosened zone is much less than that of the plastic zone. Accordingly, the length and density of rock bolts are often overestimated by the extent of plastic zone as obtained from numerical modeling. In the second class, the plastic zone is subdivided into the loosened and failed zones in accordance with the damage degree assessed by *FAI*. It means that the determination of the thresholds of *FAI* to the initial looseness depends upon both the field information and the engineering experience. In the third class, a plastic zone is subdivided into loosened and failed zones on the basis of the damage degree given by the plastic strain gradient or the plastic strain. It indicates that the thresholds of plastic strain to the initial looseness and of the ultimate plastic strains to the failure are determined on the basis of both the field information and the engineering experience. Generally, the three indices referred above are established from the perspective of rock mass strength degradation. However, the ultrasonic testing results of surrounding rock mass provide only the acoustic wave velocities after excavation, and cannot provide information of rock mass strength degradation due to excavation. Thus, a problem remains in which the loosened zone as identified from ultrasonic testing cannot directly correspond to that predicted by the three indices. Since acoustic wave velocities have strict theoretical relationships with dynamic elastic properties, it may be a valuable alternative to establish indices from the perspective of the elastic modulus deterioration of rock mass for solving this problem.

This paper proposes a numerical approach to resolve the issues related to the comparison between the numerical predictions and the P-wave velocity testing results of the loosened zone around underground openings. The approach relies on the rock mass elastic modulus deterioration induced by excavation. Suitability of the approach is verified by comparing the numerical predictions with ultrasonic testing results for typical engineering examples.

2. Proposed elastic modulus deterioration index

2.1. Damage assessed by P-wave velocity attenuation

In engineering practice, P-wave velocity is regarded as one of the fundamental indices for rock mass classification, because it can indirectly reflect the changes in rock mass structure induced by the internal macro-fracture propagation and coalescence. In order to assess the rock mass damage during excavation by using results of P-wave velocity, the attenuation index χ is proposed as:

$$\chi = (V_p^0 - V_p)/V_p^0 = 1 - V_p/V_p^0 \tag{1}$$

where V_p is the P-wave velocity of the rock mass after excavation or inside the loosened zone.

2.2. Damage assessed by the deterioration of elastic modulus

For a given rock mass, V_p^0 and V_p can be expressed as follows:

$$V_p^0 = \sqrt{E_d^0(1-\nu_d^0)/\rho_0(1+\nu_d^0)(1-2\nu_d^0)} \tag{2a}$$

$$V_p = \sqrt{E_d(1-\nu_d)/\rho(1+\nu_d)(1-2\nu_d)} \tag{2b}$$

where E_d^0 and E_d, ρ_0 and ρ, and ν_d^0 and ν_d are the dynamic elastic moduli, densities, and dynamic Poisson's ratios of a rock mass before and after excavation, respectively. Then, the ratio V_p/V_p^0 can be obtained from Eq. (2) as:

$$V_p/V_p^0 = k\bullet\sqrt{E_d\bullet\rho_0/E_d^0\bullet\rho} \tag{3}$$

where $k = \sqrt{(1-\nu_d)/(1+\nu_d)(1-2\nu_d)}/\sqrt{(1-\nu_d^0)/(1+\nu_d^0)(1-2\nu_d^0)}$.

For a given rock mass, mass m remains same before and after excavation. Accordingly, ρ_0 and ρ can be calculated by the following equations:

$$\rho_0 = m/Vol_0 \tag{4a}$$

$$\rho = m/Vol \tag{4b}$$

where Vol_0 and Vol are the volumes of the rock mass before and after excavation, respectively.

Close correlations between the static elastic modulus E and the dynamic elastic modulus E_d have been observed from numerous testing results of rock specimens and rock masses (e.g., Ukhov and Panenkov, 1968; King, 1983; Van Heerden, 1987; Eissa and Kazi, 1988; Lacy, 1997; Ohen, 2003; Ameen et al., 2009; Brotons et al., 2014; Najibi et al., 2015). Empirical relationships between E and E_d are listed in Table 1, and can be classified into the following three equations:

$$E = aE_d + b \tag{5a}$$

$$E = a(E_d)^b \tag{5b}$$

$$E = a(E_d)^2 + bE_d \tag{5c}$$

where a and b are constant parameters.

Van Heerden (1987) proposed that a and b in Eq. (5b) are stress-dependent. In the present study, the influence of confinement stress on the elastic constants is considered, so Eq. (5b) is adopted to describe the relationships between E and E_d. However, the data of the two parameters provided by Van Heerden (1987) showed that the value of b fluctuates little with different confinement stresses. Then, for simplification, parameter b is treated as a constant for a given rock mass under any confinement stresses. A relationship between the parameter a and confinement stress σ_m (i.e., the mean stress of the three principal