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Reliability based design optimization for a rock tunnel support system with multiple failure modes using response surface method

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ABSTRACT

Reliability-based design optimization (RBDO) is applied to a rock tunnel support system, considering the ground-support interaction and the parametric uncertainties. Both reliability index approach (RIA) and performance measure approach (PMA) are employed as the RBDO algorithms. The first-order reliability method (FORM) and the response surface method (RSM) are used to perform the reliability analysis. The shotcrete thickness and its installation position are considered as two design variables to be optimized in an illustrative example of a circular rock tunnel. The influence of the two design variables on the reliability results is first investigated with respect to three failure modes, namely, the support capacity criterion, the tunnel convergence criterion and the rockbolt length criterion. Then, the proposed RBDO procedure is used to seek for the design variables of minimum shotcrete thickness and the optimal installation position for the rock tunnel example. The computational efficiency and stability between RIA and PMA are compared. The influences of the rock mass quality, the variation of the shotcrete thickness and the target reliability requirement on the optimized results are also investigated and discussed.

1. Introduction

The determination of support dimensions and installation positions that are required to stabilize the highly stressed rock mass and to control the final tunnel convergence is always the focus of concern in tunnel design. The conventional deterministic methods are commonly used to assess the performance of tunnels, in which the mean values of the physical parameters and a factor of safety (FoS) are usually involved. However, it has been well recognized that considerable uncertainties exist in rock mass, support and in-situ stresses due to the inherent variability of physical parameters or the lack of knowledge (Hoek, 2007; Hadjigeorgiou and Harrison, 2012). Thus, such a deterministic method does not reflect the uncertainties of the physical parameters, and may even be likely to yield misleading results (Li et al., 2016). Instead, the reliability-based analysis and design approach is more rational to explicitly deal with the parametric uncertainties and their statistical correlations, and therefore, has attracted extensive research interests in recent years (Hoek, 1998; Oreste, 2005; Mollon et al., 2009; Lü et al., 2011, 2012, 2013; Lü and Low, 2011; Low and Einstein, 2013; Gong et al., 2014, 2015; Wang et al., 2016; Li et al., 2016; Zeng et al., 2016).

The reliability-based analysis and design of tunnels mainly focuses on the excavation-induced instability of the advancing face and the stressed rock mass, the deformation and capacity of the support, and so on. Past researches mostly considered individual component failure and rarely involved the system reliability with multiple failure modes. Furthermore, reliability-based design to account for the high uncertainties in tunnel support system and to mitigate the related risk is still limited so far. When tunneling in rock with drilling and blasting, the NATM (new Austrian tunneling method) which aims to stabilize the ground around the excavation by making extensive use of the bearing capacity of the ground may be the most frequently used method (Stipek, 2012). Currently, NATM has been developed as a highly efficient and economical tunnel construction method. But how to ensure the tunnel design to be both economical and safe is still a big challenge in practice.

More recently, some design optimization methods have been applied to tunnels as reported in the literature. For example, Perez-Romero et al. (2007) presented the optimization of the cross-section of the tunneled area, support and lining by making joint use of geotechnical investigation campaigns, convergence measurements and numerical simulations. Yin and Yang (2000) proposed a topology optimization method for the design of tunnel support. Ozturk et al. (2016)

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performed the optimum cost design of cut and cover reinforced concrete shallow tunnels using artificial bee colony and genetic algorithms. However, most of these applications are based on the deterministic models, which are referred to as deterministic design optimization. At present, the design optimization combined with probabilistic analysis, referred to as reliability-based design optimization (RBDO), is less commonly reported for tunneling in rocks.

This study presents a RBDO procedure for both economical and safe design of a circular rock tunnel. The uncertainties in rock, support and in-situ stress are considered in the design. The convergence-confinement method (CCM) is employed to perform the ground-support interaction analysis. The proposed procedure uses both reliability index approach (RIA) and performance measure approach (PMA) as RBDO algorithms, and adopts the first-order reliability method (FORM) and the polynomial response surface method (RSM) to compute the reliability index with respect to three failure modes. Two design optimization variables (DOVs), namely, the minimum shotcrete thickness and its optimal installation position, are determined via the proposed RBDO procedure. The influences of the rock mass quality, the variation of the shotcrete thickness and the target reliability requirement on the yielded optimized results are investigated.

The purpose of this paper is to provide some new insights for designing the tunnel in a more rational manner.

2. Ground-support interaction analysis using CCM

For a circular tunnel, the convergence-confinement method (CCM) is regarded as one of the most realistic and appropriate way to consider the actual mechanical interaction of tunnel support system (Carranza-Torres and Diederichs, 2009). The principle of CCM has been well-documented in the literature, e.g., Carranza-Torres and Fairhurst (2000), Oreste (2003), Alejano et al. (2010) and Cui et al. (2015), among others. In general, this method requires to construct three basic curves: (1) the Longitudinal Deformation Profile (LDP) which describes the relationship between tunnel deformation and the position related with the distance to tunnel face, (2) the Ground Reaction Curve (GRC) that represents the relationship between fictitious inner pressure and radial displacement in tunnel wall, and (3) the Support Characteristic Curve (SCC) that characterizes the stress-strain behavior of the support system, as illustrated in Fig. 1.

Due to the tunnel face supporting effect, the radial displacement at tunnel circumference starts from a certain distance ahead of the tunnel face, and increases gradually away from the face, and finally reaches its maximum at the position far enough away from the face. Therefore, when support is installed at a certain distance to the face, only partial deformation of the surrounding rock occurs. With the advancement of the face, the rock and the support interact together to bear the load induced by the subsequent deformation of the rock. Thus, the problem is that if the support is installed too close to the face, the load applied to the support is large. While, if the support is installed too far away from the face, the uncontrolled tunnel convergence may be too large to induce rock stability issues. Such complicated ground-support interaction mechanism can be analyzed by using CCM. As shown in Fig. 1, assume that the support is installed at a distance L_s from the tunnel face, at this time partial radial convergence has already developed at the position where the support is installed by a magnitude given by u_r^{in} (point B of LDP). As the tunnel face advances, the ground and the support deform together at the section under investigation. The pressure of the support increases (from point D of SCC) while the fictitious support pressure provided by the tunnel face decreases (from point F of GRC). Once the tunnel face has advanced sufficiently far ahead, its supporting effect on the section of concern becomes negligible, and the tunnel support system reaches its equilibrium at point K (i.e., the intersection of GRC and SCC). At this point, the pressure p_s^D defined by point K then represents the final design pressure that the ground transmits to the support and u_r^D represents the final deformation of the support system. Thus, two key problems need to be addressed for the tunnel support design in CCM: (1) determining the radial displacement of tunnel wall at the time of support installation, and (2) seeking the intersection point of GRC and SCC which is related to the support installation position and support system parameters.

Accordingly, the major procedure of the CCM could be summarized into three steps:

(1) Estimating the initial tunnel convergence u_r^{in} (i.e., the displacement just before support installed) at a certain distance L_s from the tunnel face using the LDP in Fig. 1. The empirical formulas developed by Vlachopoulos and Diederichs (2009) is used herein to establish the LDP curve and compute the initial tunnel convergence u_r^{in}.
(2) Determining the required internal support pressure p_i^r corresponding to u_r^{in} using the GRC in Fig. 1 which is plotted from elasto-plastic stress-strain analysis of tunnels in rocks. Analytical solutions, e.g., Carranza-Torres (2004) and Duncan Fama (1993), are available for circular tunnels under hydrostatic in-situ stress. The Carranza-Torres (2004) solution, which is based on the generalized Hoek-Brown yield criterion (Hoek et al., 2002), is employed herein to construct the GRC.
(3) Finding the final displacement u_r^D of the ground-support system and the final design pressure p_s^D transmitted from ground to support using the SCC in Fig. 1. They correspond to the final equilibrium state of the tunnel support system. For a circular tunnel, equations of SCC based on the assumption that the support conforms to an ideally elastic-perfectly plastic behavior have been established for some commonly used support systems, such as rockbolts, shotcrete linings and steel sets (Carranza-Torres and Fairhurst, 2000; Oreste, 2003). The equations for shotcrete lining and radial rockbolts proposed by Oreste (2003) are adopted herein to calculate the SCC parameters.

In this study, the above-mentioned method and procedure are coded in MATLAB (www.mathworks.com) for the analysis of a circular tunnel. If desired, the MATLAB code can be converted readily for the use in other platforms.

3. Parameters and limit state functions of a circular tunnel

3.1. Problem description and its parameters

In the section to follow, a circular rock tunnel previously investigated by Lü et al. (2013) is revisited as an illustrative example. As shown in Fig. 2, the tunnel has a radius of 3 m and will be excavated in a jointed sandstone at a depth of 500 m, subjected to a hydrostatic in-situ stress of 13.5 MPa (equal to the overburden). Steel fiber-reinforced shotcrete lining combined with radial rockbolts are installed as the support to stabilize the stressed rock mass.

The rock mass is regarded as an equivalent homogeneous and isotropic material with dense joints; thus, only the stress-controlled instability mechanisms are investigated. The structurally-controlled mechanisms which are formed by intersecting discontinuities are not considered in this study. The equivalent rock mass properties are described by an elastic-perfectly plastic model obeying the generalized Hoek-Brown failure criterion (Hoek et al., 2002). The rock mass herein is regarded as weak rock mass that the GSI is equal to 30. Thus, the elastic-perfectly plastic model could be used to represent the behavior of the poor quality rock masses according to Hoek and Brown (1997). However, the elastic-perfectly plastic assumption may be inappropriate for rock masses of average or high quality (that is, with a GSI > 30) (Alejano et al., 2009). For rock masses with a GSI > 30, the strain-softening behavior models are more suitable; and for very high quality rock masses (GSI > 75), a type of elastic brittle behavior can be anticipated. More details can refer to Alonso et al. (2003) and Alejano et al. (2009, 2010, 2012) for different quality rock masses.