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Research Paper

Moving least squares method for reliability assessment of rock tunnel excavation considering ground-support interaction

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ABSTRACT

A practical approach is proposed in this paper for the reliability assessment of rock tunnel excavations using the moving least squares method (MLSM) and the uniform design. The failure probability is computed by the first-order and the second-order reliability method (FORM/SORM), which is based on the generated MLSM response surface (MLSM-RS) via an iterative algorithm. The proposed approach is first implemented in the analysis of a circular tunnel that consists of three limit state functions to illustrate the efficiency and accuracy of the approach. Then, the method is applied to a non-circular tunnel to demonstrate the feasibility and validity of the method for practical problems, in which numerical procedures are commonly employed to solve the implicit limit state functions.

1. Introduction

Rock tunnel excavation is usually subjected to considerable uncertainties due to the inherent high variation in the rock mass properties and/or the inaccuracy of measurement and modeling [1]. In conventional tunnel design, these uncertainties are usually addressed in a deterministic manner by assigning a prescribed value to a safety factor, which utilizes the average values of rock mass strength and deformation characteristics. A deterministic safety factor analysis can only partially reflect the margin of safety because the uncertainties in the underlying parameters and their impact on the design are not properly considered. A probabilistic approach provides a more rational perspective that explicitly considers the inherent uncertainties and correlations of the design parameters and distinguishes between major uncertainties and minor uncertainties; therefore, it has attracted significant research interest in recent years [2–14].

For example, Hoek [3] presented a reliability analysis of a circular tunnel using Monte Carlo simulation (MCS). Mollon et al. [4] performed a probabilistic analysis of circular tunnels in homogeneous soil using the polynomial response surface method (RSM) and first-order reliability method (FORM) to evaluate the reliability index and the corresponding failure probabilities concerning the tunnel face stability and the ground settlement, respectively. Li and Low [5] employed the FORM algorithm of Low and Tang [15] to compute the reliability index of a circular tunnel that is subjected to a hydrostatic stress field. Oreste [16] proposed a probabilistic numerical approach for the design of primary tunnel supports based on the hyperstatic reaction method. MCS was adopted to model the uncertainties of the geomechanical index of the rock mass and the mechanical parameters of the support material. Goh and Zhang [17] evaluated the probability of instability for deep underground rock caverns. Low and Einstein [18] studied the stability of a roof wedge for a circular tunnel by FORM. Zeng et al. [19] implemented the probabilistic analysis of circular tunnel face stability with RSM and importance sampling. Zhang and Goh [20] investigated both the ultimate limit state and serviceability limit state of underground rock caverns using a polynomial regression model and FORM. In most cases, the performance function of a tunnel, which is often implicitly evaluated via numerical procedures, cannot be explicitly expressed. This will result in difficulties with the direct use of a reliability method (e.g., FORM and SORM) to analyze or design underground excavations. To overcome this limitation, response surface methodology is commonly employed to approximate the implicit performance function with simple closed-form solutions [4,6,7].

In the traditional RSM technique, polynomial functions were adopted to fit the unknown limit state surface (LSS) in the vicinity of the most probable failure regions. However, polynomial-based RSM may require expensive computational costs in specific cases in which the number of required samples exponentially increases

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with the order of the employed polynomial, e.g., the polynomial with the cross terms when a large number of random variables are involved [6]. The quadratic polynomial approximation may experience non-convergence issues [4] and produce a pseudo-limit state surface [8] when an iterative algorithm is employed. These problems worsen when the LSS is highly nonlinear. In this regard, advanced approaches such as artificial neural network (ANN), support vector machine (SVM) and Kriging can be alternatively employed; they can attain more accurate response surfaces that are very close to or exactly the same as the real LSS. These models have been applied for reliability analysis in geotechnical engineering and are referred to as surrogate models. Deng et al. [21] presented an ANN-based FORM, an ANN-based SORM and an ANN-based MCS. Panda and Manohar [22] performed a reliability analysis by constructing a Kriging-based response surface. Zhao [23] employed an SVM to approximate the implicit performance functions and applied the SVM to a slope reliability analysis by FORM. Many other applications of these models in geotechnical engineering have been extensively reported in the literature [8,24–26]. Some drawbacks, such as low convergence, local minimums, over-fitting problems for ANN models and the vast space and time requirements of large samples for SVM models, are distinct [27,28]. The moving least squares method (MLSM), which is an alternative to these surrogate models, has been proposed and applied to structural reliability analysis [29–31].

In this paper, the MLSM is employed to construct the response surface (referred to as MLSM-RS) to approximate the true LSS for a probabilistic analysis of underground rock excavation. The uniform design (UD) is employed to prepare the sampling points for determining the unknown parameters of the MLSM-RS. The sampling points are selected in the standard normal space (U-space) and transformed to the original space of the random variables (X-space) for the convenience of reliability computations. An iterative algorithm is proposed to obtain the final reliability index and the corresponding design point that satisfies the required accuracy. Three failure modes that concern the support capacity, permissible tunnel convergence and plastic zone extent are investigated for the two illustrative examples.

2. Deterministic ground-support interaction analysis model

The ground-support interaction analysis of rock tunnel excavations is a typical 3D problem. As shown in Fig. 1, a circular tunnel of radius R_t is excavated in rocks. The support is installed at the distance L_s behind the face. Due to the support effect provided by the tunnel face, the radial displacement at the tunnel boundary starts from a certain distance in advance of the face and reaches only parts of its final value at the position where the support is installed (refer to Fig. 1). As the face advances, the ground and the support simultaneously deform. The loading on the support and the deformation of the ground-support system continue to increase until the section of interest is sufficiently far from the face.

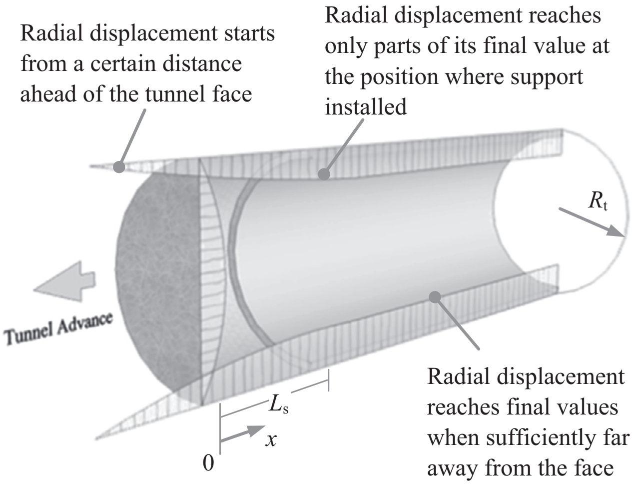

Fig. 1. Patten of deformation in the rock mass surrounding an advancing tunnel (after [1]).

For a circular tunnel that is subjected to hydrostatic in situ stress, the actual mechanical interaction of the ground and the support is often analyzed using the convergence-confinement method (CCM). The CCM has been extensively employed as a basic tool to estimate the support that is required to stabilize a tunnel excavation and predict the final convergence of the wall in tunnel design. The principle of CCM is well documented in the literature [32–34]. The major procedure of the CCM is summarized as follows:

(1) The initial ground displacement u_r^{in} (i.e., displacement prior to support installation) at the distance L_s from the tunnel face is estimated using a longitudinal deformation profile (LDP) computed by empirical formulas (e.g., Vlachopoulos and Diederichs [35]).
(2) The required internal support pressure p_i^r that corresponds to u_r^{in} is determined using the ground reaction curve (GRC) that is plotted from elasto-plastic stress-strain analysis of the rock mass. Analytical solutions (e.g., Carranza-Torres [36]) are available for circular tunnels that are subjected to hydrostatic in situ stress.
(3) The final displacement u_r^D of the ground-support system and the final design pressure p_s^D that is transmitted from ground to support are determined using the support characteristic curve (SCC). They correspond to the final equilibrium state of the tunnel support system. For a circular tunnel, the SCC for commonly employed support systems, such as rock bolts, shotcrete linings and steel sets, may be evaluated from established equations based on the assumption that the support conforms to an ideal elastic-perfectly-plastic behavior (e.g., Carranza-Torres and Fairhurst [33] and Oreste [34]).

The two main problems of this procedure are determining the initial ground displacement u_r^{in} and seeking the equilibrium point of GRC and SCC, which is controlled by the support installation position and the system parameters. In this study, the approach proposed by Vlachopoulos and Diederichs [35] is adopted to evaluate u_r^{in}. The Carranza-Torres solution [36], which is based on the generalized Hoek-Brown yield criterion, is used to construct the GRC. Equations for the concrete lining proposed by Oreste [34] are employed to calculate the SCC parameters. The numerical procedures are coded and automatically executed in MATLAB.

3. Performance function of tunnel support system

According to the principle of the CCM, the performance functions (limit state functions) of the circular tunnel support system are given by

$$g_1(\mathbf{x}) = p_s^{max} - p_s^D \tag{1}$$

$$g_2(\mathbf{x}) = \varepsilon_u^{max} - u_r^D/R_t \tag{2}$$

$$g_3(\mathbf{x}) = \xi_{pl}^{max} - R_{pl}/R_t \tag{3}$$

where $\mathbf{x}$ is the vector of random variables, p_s^{max} is the support capacity, p_s^D is the equilibrium pressure that acts on the support, R_t is the