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Probabilistic analysis of tunnels considering uncertainty in peak and post-peak strength parameters

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ABSTRACT

Stability analysis of rock tunnels is a complex problem because of various types of uncertainties present in the rock mass properties and hence probabilistic approaches are used to systematically consider these uncertainties in the analysis. While the uncertainty in deformation modulus and peak strength parameters has been considered previously it has been observed that the uncertainty in post-peak strength parameters is generally neglected in earlier studies. Post-peak strength parameters are among the most important factors which significantly influence the plastic zone development and displacements around the tunnel and hence neglecting uncertainty in post-peak strength parameters is not appropriate. In the current study, a quantitative approach based on the Geological Strength Index (GSI) has been used to estimate the uncertainty in peak strength, residual strength and deformation parameters. Then the uncertainty in yield zone and displacement around the tunnel is estimated using Hong's point estimate method coupled with finite element method. The approach was used to estimate the displacements around tunnels of different shapes in three case studies in average quality rock mass and the predicted displacements were compared with the in-situ measurements. A comparison is provided with the generally adopted conventional probabilistic approach in which uncertainty in peak strength parameters and deformation modulus is considered and rock mass is assumed as elastic-perfectly plastic. It was observed that predicted displacements were matching well with the measured displacements for all the tunnels by considering uncertainty in residual strength parameters while displacements were underestimated when the conventional approach was used. A parametric study was conducted to estimate the influence of Coefficient of Variation (COV) of different parameters on the plastic zone development and displacements of rock tunnel by selecting one of the case studies. It was observed that COV of yield zone depth and displacement was varying with the COV of the intact rock properties and thus influencing the probability of failure.

1. Introduction

Precise determination of rock mass properties is very difficult because of the presence of different sources of uncertainties. Some common types of uncertainties include spatial, statistical and systematic uncertainties emerging from in-situ testing, laboratory testing, joint mapping, joint condition, etc. (Duzgun et al., 2002; Cai, 2011). Though it is well established that probabilistic methods provide a rational and efficient means of considering these uncertainties in the analysis systematically still the application of probabilistic methods in the field of rock mechanics is not very common (El-Ramly et al., 2002; Abdellah et al., 2014). One of the most important fields in rock mechanics for which probabilistic analysis has become an important tool is rock tunnels stability analysis. It has been observed from earlier studies that while uncertainty in deformation properties and peak strength properties are considered in the analysis (Cai, 2011; Idris et al., 2015), uncertainty in post-peak strength parameters are not properly considered in the analysis which can be an important factor.

Studies on post-peak strength behavior of intact rocks were started in late 60s and early 70s after the development of stiff servo-controlled testing machines (Rummel and Fairhurst, 1970; Wawersik and Fairhurst, 1970; Hudson et al., 1971; Wawersik and Brace, 1971). After these earlier studies, many studies have been conducted on intact rock samples to investigate the effect of confining stress and rock mineralogy on failure patterns, strength and deformational behavior of rock (Santarelli and Brown, 1989; Yang et al., 2012; Arzua and Alejano, 2013; Walton et al., 2015). However, results of the intact rock behavior could not be applicable in the in-situ conditions because the intact rock samples tested in the laboratory are free from large scale defects which might govern the behavior of the rock mass (Wawersik and Brace,

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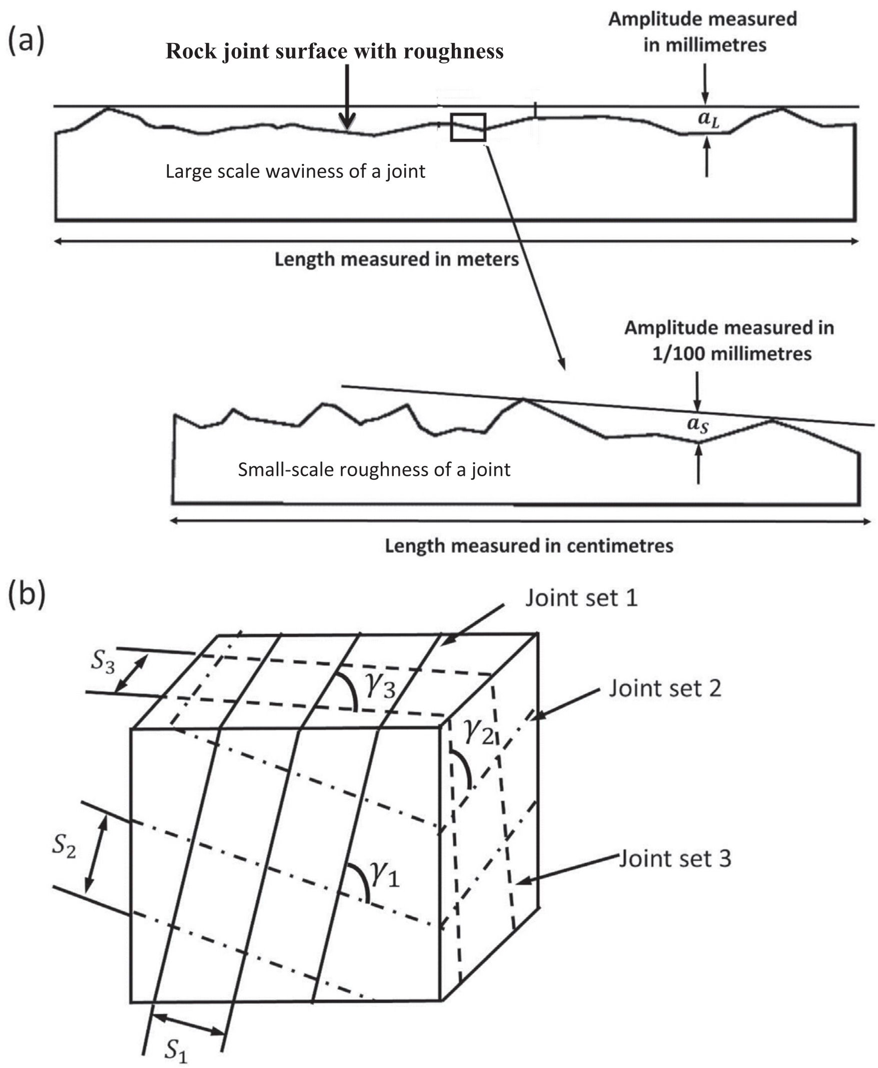

Fig. 1. Description of different parameters required for estimation of peak GSI (a) Rock joint roughness parameters (b) Rock block volume demarcated by three joints.

1971). As compared to the intact rocks, studies on post-peak behavior of jointed rocks are limited (Ribacchi, 2000; Crowder and Bawden, 2004; Tiwari and Rao, 2006a, 2006b). Because of the scarcity of the studies and methods to quantify post-peak strength parameters of rock mass, uncertainties in post-peak strength parameters were not properly considered in the earlier studies (Hoek, 1998; Cai, 2011; Langford and Diederichs, 2013). However, the literature suggests that the deformation and plastic radius around tunnels for average quality rock mass i.e. rock mass with GSI ranging between 35 and 65 is highly dependent on post-peak strength parameters (Cai et al., 2007; Alejano et al., 2009, 2012). Hence, ignoring uncertainty in post-peak strength parameters may underestimate the coefficient of variations of displacements and yield depth around the tunnel which may lead to underestimation of probability of failure. Song et al. (2016) used analytical method with First Order Reliability Method (FORM) to estimate the probability of failure for a circular tunnel. However it is not easy to develop analytical methods for all tunnel shapes, complicated stress and ground conditions. Hence, there is a need for an approach based on numerical method for the probabilistic analysis of tunnels which can consider uncertainty in peak and post-peak strength parameters in average quality rock mass.

In the current article, a Geological Strength Index (GSI) based quantitative approach was used to carry out probabilistic analysis by considering uncertainty in deformation modulus, peak and residual strength parameters. Sensitivity analysis was carried out in-order to show the importance of residual strength parameters along with peak strength parameters and deformation modulus on the response parameters (Yield zone depth and Displacements). The method suggested by Cai et al. (2007) was included in the probabilistic framework to estimate the uncertainty in the residual strength parameters, which were later used to estimate the uncertainty in yield zone depth and displacements around the tunnel. The approach was demonstrated using three case studies of tunnels with different shapes and stress conditions situated in average quality rock mass to verify the applicability of this approach. A comparison is provided between estimated results using current approach and conventional approach. In the conventional approach, uncertainty in peak strength parameters and deformation modulus was considered and post-peak behavior of rock mass was assumed as deterministic i.e. elastic-perfectly plastic. It was observed that for the practical applications, the method can be used for determination of distributions of yield zone depth and displacements for tunnels of complex shapes and stress conditions with the determination of appropriate range for GSI.

2. Calculation of variability in strength properties and deformation modulus

Estimation of statistical parameters and Probability Density Functions (PDFs) of peak and residual strength parameters and deformation modulus is discussed in this section. In the first step, statistical parameters of peak and residual GSI were estimated which were later used along with statistical parameters of intact rock properties to