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Technical Note

Regression models for estimating ultimate and serviceability limit states of underground rock caverns

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ABSTRACT

Performances of underground rock caverns can be unsatisfactory as a result of either instability (collapse) or excessive movements. Collapse refers to ultimate limit state failure, in which the stresses exceed the strength of the rock masses. Failure of the serviceability limit state refers to excessive deformations resulting in difficulties during excavation such as lining placement and reinforcement installation. Both distinct limit states may need to be considered in design. This study used numerical modeling to assess both the ultimate and the serviceability limit states of underground single and twin rock caverns. The global factor of safety is used as the criterion for the ultimate limit state and the calculated percent strain around the cavern opening is adopted as the serviceability limit state criterion. Based on the numerical results, simple regression models were developed for estimating the global factor of safety and the induced percent strain of the single and twin caverns, respectively. Charts for assessing cavern stability for preliminary design use were developed. In addition, the use of the critical strain concept and the elastic and design line methodology to limit the induced strains was discussed.

1. Introduction

One of the major considerations in the design of an underground rock cavern is the evaluation of its stability since the excavation of the rock causes a redistribution of the stresses in the proximity of the underground opening, which can lead to failure. Empirical and numerical approaches are commonly adopted tools in the design of underground rock caverns. As empirical methods are simpler to use, they are generally applied at the early stages of a site investigation and the design phase. The tunneling quality index (*Q*) and the rock mass rating (*RMR*) are the two most widely used rock mass classification systems. A shortcoming of empirical methods is that they are mainly developed to assess structural resistance, which is only one of the design issues to be accounted for in the design. In addition, they are based on past case studies and assumed rock behaviors. Furthermore, these empirical methods fail to take into account design parameters (e.g., in situ stress fields and cavern shapes) as many as possible. Many researchers have used numerical methods to study the stability of rock caverns, and a number of approaches have been developed and applied (e.g., Chryssanthakis et al., 1995; Zhu and Li, 2000; Sitharam and Latha, 2002; Fan et al., 2004; Zhu and Zhao, 2004; Hao and Azzam, 2005; Cai et al., 2007; Jia and Tang, 2008; Hoek, 2011; Mohanty and Vandergrift, 2012; Tsesarsky et al., 2013; Zhang et al., 2014).

For multiple caverns, the construction of a new cavern close to an existing cavern modifies the state of stresses and movements around the existing cavern in an area called the "influence zone". Usually the size of this influence zone depends on the ground type, in situ stress, cavern span, width of the pillar separating the caverns, and excavation sequence. The subject of interaction between parallel caverns/tunnels has been studied by several authors who have reported the results of field measurements or analytical studies of the problem (e.g., Barla and Ottoviani, 1974; Ghaboussi and Ranken, 1977; Gercek, 2005; Zhao and Ma, 2009; Mortazavi et al., 2009; Karademir, 2010; Esterhuizen et al., 2011).

Conventional evaluation of stability of geotechnical structures and underground openings involves the use of a factor of safety (*FS*) which considers the relationship between the resistance and the load or the calculated displacements/strains. The former is usually used as the criterion for assessing the ultimate limit state while the latter is adopted as the serviceability limit state criterion. For underground caverns, however, neither the *FS* nor the induced strain value is known explicitly. Instead, it may be estimated only through repeated point-by-point numerical analyses with different input values. Generally, the performance function, expressing the dependent responses as a function of input design variables, is constructed artificially using polynomial or logarithmic regression methods (e.g., Basarir, 2008; Zhu et al., 2008; Goh and Zhang, 2012; Zhang and Goh, 2012; Siahmansouri et al., 2012). Alternatively, the multivariate adaptive regression splines (MARS) algorithm and the Artificial Neural Network approach (ANN) are also used to develop surrogate response surface models (Goh and Zhang, 2012; Lü

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Table 1
Rock mass properties with different *Q* values.

Q	*c* (MPa)	ϕ (°)	E_m (GPa)	μ	σ_t (MPa)
0.4	0.14	19.3	3.1	0.35	1.97
1	0.18	22.5	4.5	0.35	2.40
4	0.22	27.4	7.8	0.20	3.05
10	0.26	30.6	11.3	0.20	3.47
40	0.30	35.4	19.7	0.16	4.12
100	0.34	38.6	28.6	0.16	4.55

et al., 2012; Mahdevari and Torabi, 2012; Rafiai and Moosavi, 2012; Zhang and Goh, 2013; Adoko et al., 2013). Though slightly inferior to the MARS and ANN methods in terms of predictive capacity, the regression models remain popular due to their simplicity and model interpretability.

In this study, both the ultimate and the serviceability limit states of underground single and twin rock caverns are numerically investigated. The global factor of safety obtained using the shear strength reduction technique is used as the criterion for the ultimate limit state and the calculated percent strain around the opening is adopted as the serviceability limit state criterion. Based on the numerical results, regression models were developed for estimating the global factor of safety and the induced percent strain of the single and twin caverns, respectively. Charts were developed for preliminary design use and for checking the cavern stability. In addition, the use of the critical strain concept and the elastic and design line methodology to limit the induced strains was discussed.

2. Methodologies

2.1. Rock mass classifications and correlations

When performing numerical analysis, particular attention must be given to the selection of appropriate input parameters, especially in the preliminary stage of an engineering design. Various indirect empirical relations have been proposed to calculate the rock mass properties such as the deformation modulus E_m, the shear strength parameters cohesion c and friction angle ϕ, the rock mass uniaxial compressive strength σ_{cm} and the tensile strength σ_t. For the numerical analyses that were carried out, the following equations (Eqs. (1)–(7)) were adopted for determining the rock mass properties. The empirical equation from Tugrul (1998) was used to estimate *RMR* from *Q* instead of Barton (1995) and Bieniawski (1984) as it gives more conservative estimations of *RMR*.

$$RMR = 7\ln Q + 36 \quad (1)$$

(Tugrul, 1998)

$$E_m(GPa) = 10^{(RMR-10)/40} \quad (RMR \le 50) \quad (2)$$

(Serafim and Pereira, 1983)

$$E_m(GPa) = 2RMR - 100 \quad (3)$$

(Bieniawski, 1978)

$$c(MPa) = 0.005(RMR - 1.0) \quad (4)$$

(Bieniawski, 1989)

$$\phi(^\circ) = 0.5RMR + 4.5 \quad (5)$$

(Bieniawski, 1989)

$$\sigma_{cm}(MPa) = RMR \quad (6)$$

(Palmstrom, 2000)

$$\sigma_t(MPa) = \sigma_{cm}/15. \quad (7)$$

Adopting the above empirical equations, the *Q* value of each category and its corresponding rock properties are shown in Table 1. In Table 1, the Poisson's ratio ν values are assumed based on commonly used values. For simplicity, density of 2670 kg/m^3 is assumed for rock mass for all the ranges of *Q*. It should be noted that these relationships are intended to provide the initial estimates of the rock mass properties for preliminary design and should be used with great caution in engineering design.

It should be noted that herein the use of *Q* and the empirical relationships may introduce errors. These errors include measuring errors in determining *Q* values and uncertainties in transforming *Q* to engineering properties through empirical equations.

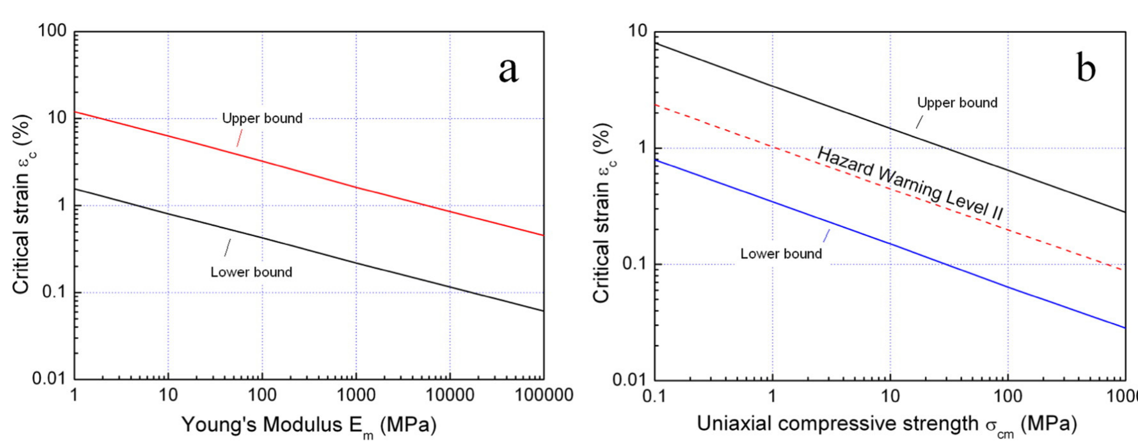

Fig. 1. Sakurai's relationship between: (a) ε_c and E_m and (b) ε_c and σ_{cm} and Hazard warning level II.
Adapted from Sakurai (1986, 1997).