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ScienceDirect
Tunnelling and Underground Space Technology 23 (2008) 151–159
Tunnelling and Underground Space Technology incorporating Trenchless Technology Research
www.elsevier.com/locate/tust

A simple procedure for ground response curve of circular tunnel in elastic-strain softening rock masses

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Received 17 November 2006; received in revised form 3 February 2007; accepted 19 March 2007
Available online 1 May 2007

Abstract

This paper presents a simple procedure for the ground response curve of a circular tunnel excavated in elastic-strain softening rock mass compatible with a linear Mohr–Coulomb or a nonlinear Hoek–Brown yield criterion. The numerical stepwise procedure proposed by Brown et al. [Brown, E.T., Bray, J.W., Ladanyi, B., Hoek, E., (1983). Ground response curves for rock tunnels. J. Geotech. Eng. ASCE 109, 15–39] is modified by including the effects of elastic strain increments and variable dilatancy within the plastic region. The accuracy and practical application of the proposed procedure are shown through some examples. Four different combinations of dilatancy angle and softening parameter are considered to investigate the effects of elastic strain increments and variable dilatancy within the plastic region. The effects of variable dilatancy and peak dilatancy angle on the ground response curve are investigated for tunnels in poor-to-good-quality rock masses. The results show the importance of correctly estimating peak dilatancy angle in elastic-perfectly plastic and elastic-strain softening Hoek–Brown media.

Keywords: Tunnels; Ground response curves; Elastic-strain softening rock; Hoek–Brown yield criterion; Dilatancy

1. Introduction

Ground response curves, based on the convergence-confinement method, are widely used in tunnel design. In order to obtain ground response curves for circular tunnels, a number of analytical solutions have been presented by considering the elastic-perfectly plastic and elastic–brittle–plastic models of material behavior with the linear Mohr–Coulomb (M–C) and nonlinear Hoek–Brown (H–B) criteria (Brown et al., 1983; Detournay, 1986; Wang, 1996; Carranza-Torres and Fairhurst, 1999; Sharan, 2003, 2005; Carranza-Torres, 2004; Park and Kim, 2006).

For an elastic-strain softening model, Brown et al. (1983) presented a numerical stepwise procedure for the stresses and displacements in the H–B media by assuming the constant value of elastic strain in the plastic region such as that at the elastic–plastic interface and the constant dilatancy angle in the strain softening zone. Alonso et al. (2003) proposed the self-similarity solution by solving the system of ordinary differential equations of equilibrium, persistence, radial displacement velocity and flow rule.

In routine engineering application, the dilatancy of the rock is assumed to be constant. Ogawa and Lo (1987) investigated the effect of dilatancy on the elastoplastic stresses and displacements around a circular tunnel by using closed-form analytical solutions and a constant dilatancy angle. Hoek and Brown (1997) suggested the elastic–brittle–plastic, elastic-strain softening and elastic-perfectly plastic behaviors for very good, average and very poor quality rock masses, respectively, and recommended the use of constant dilatancy angle (ψ) values related to the friction angle (ϕ), such as $\psi = \phi/4$, $\phi/8$ and 0 for very good, average and very poor quality rock masses, respectively.

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doi:10.1016/j.tust.2007.03.002

However, Detournay (1986) pointed out the possible calculation errors with the use of constant dilatancy angle in elastic-perfectly plastic M–C media and suggested the use of variable dilatancy. Alejano and Alonso (2005) proposed the use of dilatancy factor with the peak dilatancy angle in elastic-perfectly plastic and elastic-strain softening M–C media.

The main objective of this paper is to develop a simple procedure for obtaining the ground response curve of a circular tunnel excavated in elastic-strain softening rock mass compatible with a linear M–C or a nonlinear H–B yield criterion. The paper consists of four parts. The first part deals with the definition of the problem by considering the effects of elastic strain increments and variable dilatancy within the plastic region in previous procedures by Brown et al. (1983) and Alonso et al. (2003). The second part describes the new procedure, which is modified from Brown et al. (1983) method by including those effects of elastic strain increments and variable dilatancy within the plastic region. In the third part, the accuracy and practical application of the proposed procedure are illustrated by solving some examples. Lastly the proposed procedure is used to investigate the effects of variable dilatancy and peak dilatancy angle on the ground response curve in elastic-perfectly plastic, elastic–brittle–plastic and elastic-strain softening H–B media.

2. Definition of the problem

Fig. 1 shows a circular tunnel being excavated in a continuous, homogeneous, isotropic, initially elastic rock mass subjected to a hydrostatic stress p_o. The tunnel surface is subjected to an internal pressure p_i. As p_i is gradually reduced, the radial displacement occurs and a plastic region develops around the tunnel when p_i is less than the initial yield stress. The material behavior of elastic-strain softening model used in this study is shown in Fig. 2. There are three different zones around the tunnel: the elastic zone, the softening zone, and the residual zone. After initial yielding, the strength of rock drops gradually with increasing strain and follows the post-yield softening behavior. It is required to solve for the stresses and displacements in the plastic region to obtain the ground response curve.

2.1. Elastic strain increment and variable dilatancy

Because of the axial symmetry of the problem, the nonlinear H–B yield criterion can be expressed with the radial and circumferential stresses, σ_r and σ_θ, such as

$$\sigma_\theta = \sigma_r + \sqrt{m_p\sigma_c\sigma_r + s_p\sigma_c^2} \text{ for peak strength} \tag{1}$$

$$\sigma_\theta = \sigma_r + \sqrt{\bar{m}\sigma_c\sigma_r + \bar{s}\sigma_c^2} \text{ for strain softening strength} \tag{2}$$

$$\sigma_\theta = \sigma_r + \sqrt{m_r\sigma_c\sigma_r + s_r\sigma_c^2} \text{ for residual strength} \tag{3}$$

in which σ_c = the uniaxial compressive strength of the intact rock material, m and s = material constants which depend on the properties of the rock and on the extent to which it has been broken before being subject to the stresses ($s = 1$ for intact rock and $s < 1$ for previously broken

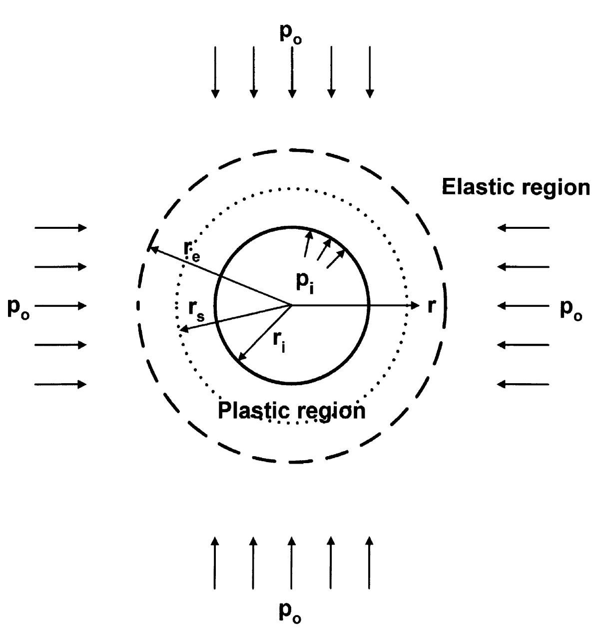

Fig. 1. A circular tunnel in an infinite medium.

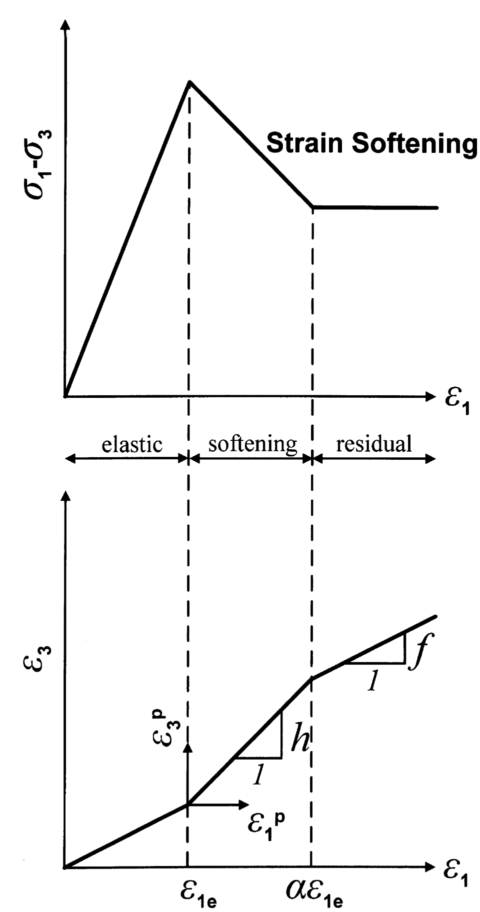

Fig. 2. Elastic-strain softening model (Brown et al., 1983).