Tunnelling and Underground Space Technology 82 (2018) 66–81

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Difference solution for a circular tunnel excavated in strain-softening rock mass considering decayed confinement

Fengyun Wang, Deling Qian*

Department of Civil Engineering, Hefei University of Technology, Anhui 230009, China

ARTICLE INFO

Keywords:
Strain-softening behavior
Variable dilatancy angle
Variable critical plastic parameter
Hoek-Brown failure criterion

ABSTRACT

Recent research regarding the strain-softening behavior of rock masses has demonstrated that the dilatancy angle ψ and the critical softening parameter η^* are both strongly related to the confining stress. However, in many studies, ψ is assumed to be a constant or to vary linearly, and η^* is also assumed to be a constant. The assumption of a constant ψ or η^* is an approximation that does not correctly reflect the variable process in the plastic zone. In this paper, to describe the confinement-dependent characteristics of ψ and η^* and their effects on the stress and displacement of tunnels in strain-softening rock masses, four dilatancy cases are defined as different combinations of ψ and η^*. First, two dilatancy models, the **v**ariable **d**ilatancy **m**odel (VDM) and **c**onstant **d**ilatancy **m**odel (CDM) are introduced. Then, a finite difference method for the strain-softening model is proposed to consider the variation of ψ and η^* in analyzing the strain-softening behavior of rock masses. The accuracy of this method is verified by comparing the results with those calculated using the methods of Lee and Pietruszczak and Wang et al. Finally, using this proposed method, relevant comparisons are made among the four dilatancy cases for good-quality to poor-quality rock masses to reveal the confinement-dependent effects of ψ and η^* on the evolution of several parameters, including the softening parameter, the critical softening parameter, the dilatancy coefficient, strength parameters, stress components, ground response curves, and plastic radii. It is concluded that in the plastic zone, ψ and η^* varies nonlinearly with decreasing confining stress for underground tunnels excavated in different qualities of strain-softening Hoek-Brown rock masses. ψ and η^* affect each other, and their relationship further influences the transition location from the plastic softening zone to the plastic residual zone. The effects of the confining dependency in ψ and η^* for good-quality rock masses are less than those for poor quality rock masses. To guarantee simplicity and security in analyzing the stress and displacement of tunnel excavation problems, a constant ψ with a constant η^* and a variable ψ with a variable η^* are recommended as analysis models for good-quality and poor-quality rock masses, respectively.

1. Introduction

During tunnel excavation the mechanics of the rock mass surrounding the underground opening produces a significant stress distribution and plastic deformation. Correctly estimating stress and displacement during tunnel excavation is essential for assessing the stability and optimizing the design of support structures. Therefore, the rock mass mechanics are of great importance for analyzing the stress distribution and displacement of underground tunnels.

In the past several years, many elasto-plastic approaches (Brown et al., 1983; Carranza-Torres, 1998; Hoek and Brown, 1997) have been proposed for tunnel problems using elasto-plastic, elasto-brittle-plastic and strain-softening models (Alonso et al., 2003; Alejano et al., 2010; Carranza-Torres and Fairhurst, 1999, 2000; Park and Kim, 2006; Sharan, 2003, 2008; Wang et al., 2010; Zhang et al., 2012, 2016). Using the first two models, closed-form solutions for the elasto-plastic analysis of rock masses can be obtained for the sake of simplicity. However, experimental and field observations (Alejano and Alonso, 2005; Cai et al., 2004, 2007; Hoek and Brown, 1997; Hoek et al., 2002; Hoek and Diederichs, 2006) have shown that the strain-softening model appropriately reflects the mechanisms of average-quality rock masses during the post-failure stage. A number of studies have attempted to better understand strain-softening characteristics. Existing studies mainly use numerical solutions to address strain-softening issues (Lee and Pietruszczak, 2008; Park et al., 2008; Wang et al., 2010; Zhang et al., 2012; Cui et al., 2015a). Based on the concept of dividing the potential plastic zone into a finite number of concentric rings, two dividing methods exist in the numerical solutions for strain-softening behavior of a rock mass: the method of Lee and Pietruszczak (2008) and the method of Park et al. (2008). The former divides the potential plastic zone with

* Corresponding author.
E-mail addresses: fengyunwang_sc@sina.com (F. Wang), dlqian@sina.com (D. Qian).

https://doi.org/10.1016/j.tust.2018.08.001
Received 16 January 2018; Received in revised form 2 July 2018; Accepted 3 August 2018

an equal radial stress increment for each ring, whereas the latter divides the potential plastic zone with an equal tangential strain increment for each ring. Subsequently, Cui et al. (2015a) improved on Lee and Pietruszczak's method (Lee and Pietruszczak, 2008) by considering the confinement-dependent response of the tunnel excavation problem in the plastic zone according to Alejano et al.'s method (Alejano et al., 2010).

The limitation of previous studies on strain-softening behavior is the lack of attention paid to the evolution of the dilatancy angle as confining stress decreases in post-failure mechanics. Most existing studies on the dilatancy model mainly focus on a rock mass, and simply regard the dilatancy angle as a constant or a linear variable for analyzing circular underground problems (Alonso et al., 2003; Alejano et al., 2010; Cui et al., 2015a,b; Lee and Pietruszczak, 2008). However, based on published references (Alejano and Alonso, 2005; Detournay, 1986; Yuan and Harrison, 2007), the assumption of a constant dilatancy angle incorrectly describes the dilatancy mechanism during the development of plastic deformation; this assumption is only an approximation for calculating the tunnel displacement. For example, the decay dilatancy model proposed by Alejano and Alonso (2005) was inspired by the dilatancy formula of jointed rock and considered the effect of confining stress and plastic shear strain on the dilatancy angle. Furthermore, to account for the effects of both confining stress and plastic shear strain, a mobilized dilatancy angle model was proposed by analyzing the compressive data from rock samples (Zhao and Cai, 2010). Unfortunately, the above dilatancy models cannot be used to analyze the stress and displacement for circular openings, where the confining stress gradually decreases from the deeper ground to the opening surface.

In strain-softening behavior, the critical softening parameter η^*, which controls the location of the transition from the softening stage to the residual stage, and the dilatancy angle ψ, which is related to the failure process, are two important parameters for investigating the characteristics of tunnel excavation. Based on the existing findings (Alonso et al., 2003; Alejano and Alonso, 2005; Alejano et al., 2009, 2010; Cui et al., 2015a), η^* is strongly affected by the confining stress and dilatancy angle ψ. Furthermore, ψ is also associated with the confining stress and value of η^* (Alejano and Alonso, 2005; Detournay, 1986). In other words, η^* and ψ mutually affect each other, and both are affected by the confining stress. The schematic diagram of the stress-strain relationship shown in Fig. 1 indicates that η^* increases as the confining stress σ_r increases. Although the effect of confining stress on η^* is considered by Cui et al. (2015a), it is unreasonable to neglect the effects of confining stress and η^* on ψ for a tunnel. Therefore, it is essential to consider the effect of confining stress on the variation of η^* and ψ, to study the distribution of stress and displacement for circular excavations during plastic deformation. However, few studies have focused on the variation of ψ with confining stress and its mutual influence on η^*.

In this study, we compare results considering the effect of a variable η^* and ψ on the strain-softening behavior of rock masses in circular excavations to select the correct combinative models. The paper is organized as follows: First, the variable path of confining stress, the variable η^* and the variable ψ are examined. Second, a numerical procedure using the finite difference method is described to consider the variable η^* and ψ. Third, a verified example is used to confirm the accuracy of the proposed method. Finally, the results for four cases of different rock mass qualities, which are defined by different combinations of η^* and ψ, are compared to recommend the correct dilatancy model for underground excavations in strain-softening Hoek-Brown (H-B) rock masses.

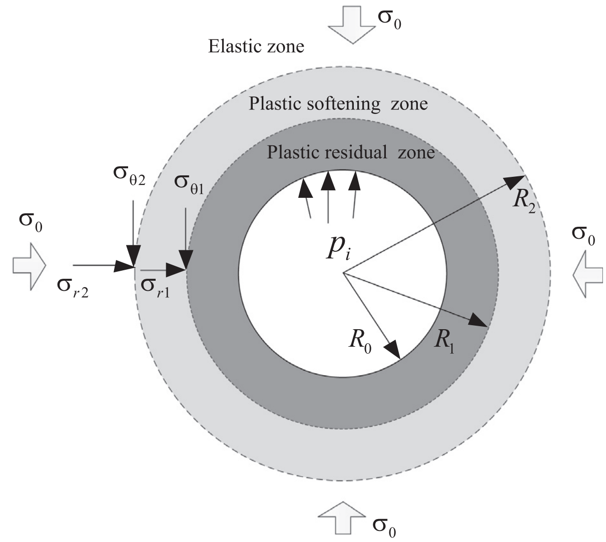

Fig. 2. Schematic diagram of a circular opening after excavation.

2. Description of the problem

The schematic diagram of a circular opening with radius R_0 is depicted in Fig. 2. An initial hydrostatic stress field σ_0 exists before excavation. Along the excavation surface, the support pressure p_i is uniformly distributed, and $\sigma_{\theta 2}$ and σ_{r2} are the tangential stress and the radial stress at the elasto-plastic boundary, respectively. Additionally, $\sigma_{\theta 1}$ and σ_{r1} are the tangential stress and the radial stress at the softening-residual boundary, respectively. If $p_i < p_i^{**}$, then the plastic softening zone occurs. If $p_i < p_i^{*}$, then the plastic residual zone occurs. p_i^{**} and p_i^{*} are assumed to be the critical support pressures when the plastic zone and the plastic softening zone occur, respectively. Based on the equilibrium of forces at the elasto-plastic boundary and the softening-residual boundary, p_i^{**} and p_i^{*} are equal to σ_{r2} and σ_{r1}, respectively. R_2 and R_1 are the radii of the plastic zone and the plastic residual zone,

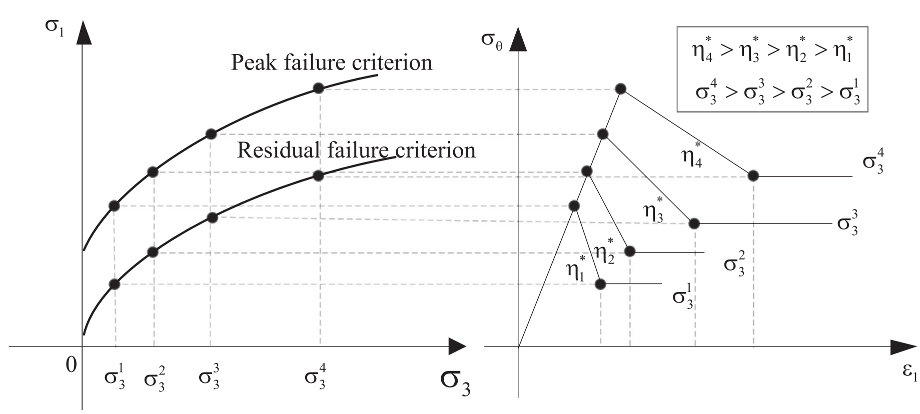

Fig. 1. Diagrams for stress-strain relationship under different confinements.