8th International Congress on Civil Engineering,
May 11-13, 2009, Shiraz University, Shiraz, Iran

The elasto-plastic analysis of a circular opening excavated in a generalized Hoek-Brown rock material

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Abstract
A new rigorous approach for calculating the distribution of stresses and displacements around a circular opening excavated in a strain-softening generalized Hoek-Brown rock mass is presented. After the yield criterion, the plastic potential function, and the evolution of Hoek-Brown strength parameters are defined, the differential equilibrium equation and equation of compatibility of deformations are solved simultaneously by means of Runge-Kutta forth-order method. In addition, the applicability and accuracy of the proposed method is shown through an example. Finally, the influence of the softening parameter, appearing in the evolution of Hoek-Brown parameters, is examined through the establishment of the ground response curves.
Keywords: Circular opening, elasto-plastic analysis, strain-softening, Hoek-Brown criterion.

1. INTRODUCTION

Prediction of stresses and displacements around a circular opening has been one of the most fundamental problems in geotechnical, petroleum, and mining engineering. Estimation of the support required to stabilize a tunnel, stability assessment of circular openings such as boreholes, design of mineshafts, and confirmation of numerical methods and computer software are among the most important applications of displacement analysis around circular openings; thus, elasto-plastic analysis of a circular opening subjected to hydrostatic far-field stress has been extensively performed by a large number of authors in the past. A literature review shows that there are a large number of techniques whose objective is to determine the stresses and displacements around a circular opening excavated in different rock masses with elastic-perfectly plastic, elastic-brittle plastic, and elastic-strain softening behaviors. Although many authors have contributed to obtain the closed-form solution for this problem, the solution was elusive unless they made numerous simplifying assumptions. In most of the performed analyses, the rock mass was assumed to obey the linear Mohr-Coulomb failure criterion, while further studies and experimental observations reveal that this failure criterion is not justifiable for various rock messes such as a jointed rock mass and the strength envelope for rock-like materials is not linear. Among the non-linear yield criteria, the one which was proposed by Hoek and Brown in 1980 has been widely used and applied in a great number of projects around the world.

The Hoek-Brown (H-B) failure criterion was originally proposed for hard rock masses and was later generalized to include poor and very poor quality rock masses [1]. In fact, the strength parameter ‘ a ’, that is constant in the original form of this criterion, has been updated so that it varies from o.5 for very good quality rock masses to 0.6 for very poor rock masses. As using the generalized form of the H-B failure criterion, in which the strength parameter a is no longer constant, complicates the derivation of a neat closed-form expression for the tunnel problem, most of the existing elasto-plastic solutions consider an intact rock (i.e., $a = 0.5$).

Hoek and Brown suggest that the elastic-strain softening behavior is particularly pertinent to average quality rock masses, while soft rock masses behave in a perfectly plastic or ductile way and hard rock masses behave in an elastic-brittle plastic way. Besides, it is widely observed that beyond the peak strength, rock materials experience damage due to micro-cracking and faulting, which leads to a strain-softening response [2]. Since most of the existing elasto-plastic analyses are relevant to elastic-perfectly plastic and elastic-brittle plastic materials, addressing the need for elasto-plastic analysis of a circular tunnel excavated in an elastic-strain softening rock mass is worthwhile. Brown et al. [3] proposed a step-wise sequence of calculations for an elastic-strain softening material in H-B media. Later, further researches reveal some errors in predicting the plastic radius in Brown et al’s solution, which underestimate the convergence of the tunnel wall. Moreover, Alonso et al., [2] proposed a sound solution, yet it was too complicated for practical uses. Guan et