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Technical Note

Elasto-plastic analysis of a circular borehole in elastic-strain softening coal seams

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1. Introduction

The stress and deformation of surrounding rock in underground engineering are of significant importance for excavation optimization design and stability evaluation in civil, mining and petroleum engineering and energy development, as well as in geology and geophysics science. In the past decade, many researchers[1,2] have studied the ground reaction curve (GRC), the support characteristic curve (SCC) and the longitudinal deformation profile (LDP) of circular tunnel in the elasto-plastic, elasto-brittle–plastic and strain-softening rock masses, and employed the Mohr–Coulomb (M–C), Hoek–Brown (H–B) and generalized Hoek–Brown (GHB) criteria. Laboratory tests and field measurements have revealed that the behavior of the rocks, including shale and coal, is nonlinear, especially in the states of deep underground and high confining pressure and thus could not be explained solely by elastic analysis. Furthermore, Hoek and Brown[3] suggested that the average quality rock masses behave in a strain-softening model in the field of underground rock engineering, and the elastic–brittle–plastic, elastic-strain softening and elastic–perfectly plastic behavior for very good, average and very poor rock masses, respectively. Gonzalez-Cao et al.[4] indicated that rock masses behavior models can be classified according to the post-failure behavior in elastic–perfectly plastic, elastic–brittle, and elastic-strain softening materials, as shown in Fig. 1, and elastic-strain softening model could be considered as the most general case, since the elastic–perfectly plastic and elastic–brittle models are simply particular types of elastic-strain softening: elastic–perfectly plastic is a type of elastic-strain softening material in which the peak and residual failure criteria coincide, and elastic–brittle is a particular case of elastic-strain softening in which stress jumps from the peak strength to the residual strength without strain relaxation during failure. Therefore, it is of practical importance to study the mechanical behavior of normal rock masses with strain-softening behavior.

Since the early 1970s, strain-softening behavior has been investigated numerically, analytically and in the laboratory.[5,6] The stress–strain curve of softening rock mass could be simplified as a broken line chart as Fig. 1(b).[4] For instance, the experimental result depicted in Fig. 1(d) that,[7] with further increase of the axial strain, the strength of the material decreases, after peak strength of the rock mass.

Wang et al.[8] developed a procedure for modeling the elasto-plastic behavior of a circular opening in strain-softening rock masses based on the methodology for analyzing brittle–plastic rock mass which was simplified as a series of stress drops and plastic flow. Zhang et al.[9] proposed a multi-step brittle–plastic

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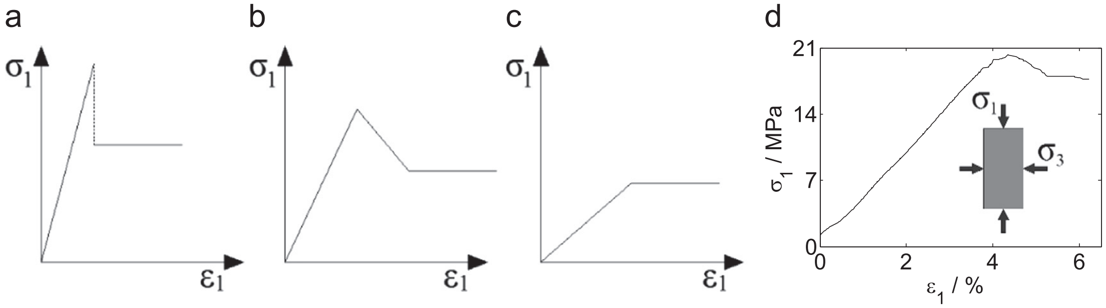

Fig. 1. Rock mass behavior models.

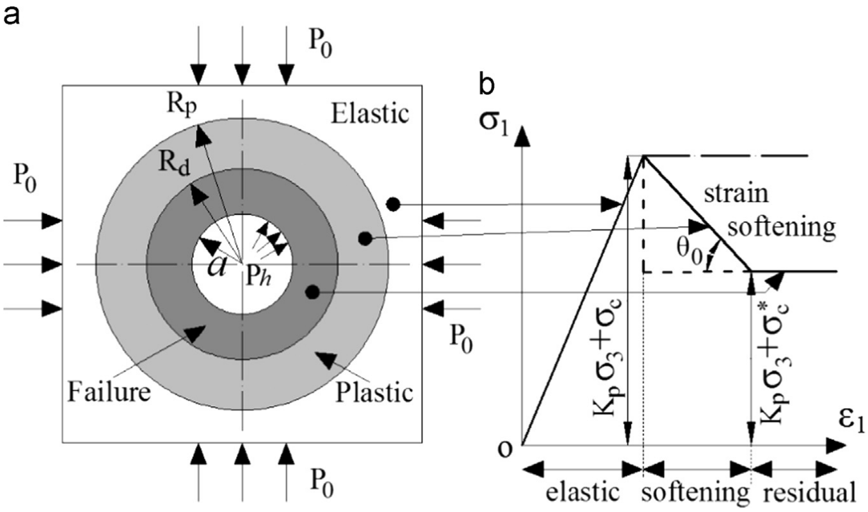

Fig. 2. Elastic-strain softening model.

model (MBPM) on the assumption that rock mass properties were uniform in a very small region. Then the post-peak rock mass can be divided into a number of annular regions and the rock mass in each region can be considered to conform to classical plasticity theory. Pourhosseini and Shabanimashcool[10] developed a constitutive model to describe the nonlinear behavior of intact rocks under static loading. The model includes the pre-peak elastic and the post-peak strain-softening behavior, as well as dilation, and employs the shrinking of the failure criteria by progress of plastic deformation to consider the strain-softening behavior of rocks. The crack propagation in rock during post-peak deformation was a cohesion-losing process, and during this process the frictional angle was constant.

Most of the investigations were done on ground reaction curve (GRC) of circular tunnel. The surrounding rock compression and contraction were generally analyzed by various elastic, elasto-plastic models in the past. In addition, the problems of cavity expansion and contraction have attracted much attention in geotechnical problems with application to the bearing capacity of deep foundations, interpretation of pressure meter tests, and breakout resistance of anchors, pile driving, wellbore instability, underground excavation and blasting fracturing by explosives. Specially, the stress transformation and deformation distribution of the surrounding rock in the process of hydraulic fracturing are quite different from that in the tunnel cavitation. The borehole of the hydraulic fracturing will not only experience the contraction after the borehole is drilled and before the injected fluid reaches the in situ stress, but also the expansion after the hydraulics pressure exceeds the in situ stress. Actually, the borehole expansion that has been rarely investigated in the past, is the function of the hydraulic fracturing, which has been widely used for the stimulation of petroleum, shale gas and coal bed methane. The prevailing analytical solutions for hydraulic fracture mainly depended on linear elastic fracture mechanics.[11,12] These methods could give reasonable prediction for hard rock, but were ineffective in predicting hydraulic fractures in strain-softening materials, such as ductile shale and sandstone.[13]

Cavity expansion theory was first studied by Bishop et al.[14] for the metal indentation problems and was later applied to geotechnical problems by Gibson and Anderson[15] for in-situ measurement of soil properties with pressuremeter. Different constitutive models have been used to obtain cavity expansion solutions that could consider the frictional, cohesive and dilatant behavior of sand.[16,17] Cheng[18] discussed the errors arising from the assumption that small displacement around the cavity with no volume change in the plastic zone and modified Kastner's formula for cylindrical cavity contraction and expansion in Mohr–Coulomb medium for circular tunnel in isotropic medium. Chen et al.[19] proposed an analytical approach predicting the development and progress of the plastic zone around a wellbore drilled in linear hardening or softening Drucker–Prager rocks in a theoretically consistent way. In a word, it is important to investigate the borehole contraction and expansion together with the elastic-strain softening model for wellbore/tunnel opening, as well as the stability and the elasto-plastic problem of borehole surrounding rock masses which are controlled by the stresses and the strength of the surrounding rock.

In the present study, a simple elastic-strain softening model with brittleness coefficient was used for analyzing the plastic behavior of the surrounding rock, including the elastic zone, plastic zone and failure zone. The analytical stress distributions in the three different zones were calculated for the borehole compaction