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Analytical solutions for the stresses and deformations of deep tunnels in an elastic-brittle-plastic rock mass considering the damaged zone

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ABSTRACT

The excavation impact (e.g. due to blasting, TBM drilling, etc.) induces an excavation damaged or disturbed zone around a tunnel. In this regard, in drill and blast method, the damage to the rock mass is more significant. In this zone, the stiffness and strength parameters of the surrounding rock mass are different. The real effect of a damage zone developed by an excavation impact around a tunnel, and its influence on the overall response of the tunnel is of interest to be quantified. In this paper, a fully analytical solution is proposed, for stresses and displacements around a tunnel, excavated in an elastic–brittle–plastic rock material compatible with linear Mohr–Coulomb criterion or a nonlinear Hoek–Brown failure criterion considering the effect of the damaged zone induced by the excavation impact. The initial stress state is assumed to be hydrostatic, and the damaged zone is assumed to have a cylindrical shape with varied parameters; thus, the problem is considered axial-symmetric. The proposed solution is used to explain the behavior of tunnels under different damage conditions. Illustrative examples are given to demonstrate the performance of the proposed method, and also to examine the effect of the damaged zone induced by the excavation impact. The results obtained by the proposed solution indicate that, the effects of the alteration of rock mass properties in the damaged zone may be considerable.

1. Introduction

In order to analyze a tunnel, it is essential to understand the various rock mass behaviors after an excavation. The original properties of a rock or rock mass near a tunnel are changed after the excavation. The characteristics of an excavation damaged or disturbed zone (EDZ) vary with the rock mass properties, excavation method, and opening geometry. Such a disturbance can significantly influence the response of the rock mass and the overall performance of the tunnel. Therefore, investigating the influence of the EDZ around an underground excavation is of paramount importance. From this point of view, the characteristics of an EDZ have been extensively investigated for various rock engineering projects, including dam construction, tunnel construction, and waste repository projects.

An EDZ can be defined as a rock zone where the rock failure and stiffness parameters have been changed due to the processes related to an excavation. Different mechanisms are related to the development of an EDZ. Major factors related to the development of an EDZ are (a) the excavation impact; and (b) the stress redistribution after the excavation.

Based on the factor (a), both TBM and drill and blast excavation disturb the surrounding rock mass. However, in contrast to blasted tunnels, in TBM tunnels, the annular thickness of the EDZ and the rock mass alteration in the EDZ are expected to be insignificant. The extent of the damaged zone induced by excavation impact depends on the rock properties, shape of the tunnel, excavation method and its quality, etc., but it can range from few centimeters in tunnels with TBM to several decimeters and up to several meters with drill and blast (Beackblom and Martin, 1999; Martino and Chandler, 2004). For this reason, the blast-induced damaged zone (BIDZ) has to be considered in the analysis and design of tunnels; while, the TBM drilling-induced damaged rock can be ignored. However, for very high quality controlled blasting, the damage to the rock mass is negligible due to a well-designed blasting pattern and detonation sequence and accurate drilling control. In contrast, the lack of a good blast design and absence of any control on the drilling can result in the significant damage.

On the other hand, based on factor (b), due to the stresses induced by the tunnel excavation, a disturbed plastic or fractured zone will develop around the tunnel. However, the elastoplastic

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Nomenclature

D	disturbance factor
GSI	Geological Strength Index
p_0	hydrostatic in situ stress
r	radial distance from the center of the tunnel
R_p	radius of the plastic zone
r_i	radius of tunnel
u_r	radial displacement
ε_1	major principal strain in rock mass
ε_3	minor principal strain in rock mass
ε_θ	circumferential strain
ε_r	radial strain
v	Poisson's ratio of rock mass
σ_c	uniaxial compressive strength of intact rock

σ_1	major principal stress
σ_3	minor principal stress
σ_r	radial stress
σ_θ	circumferential stress
φ, C	material constants for Mohr–Coulomb rock mass
m, s	material constants for Hoek-Brown rock mass
Ψ	dilation angle
Subscript 'D'	refers to quantities corresponding to damaged rock
Superscript 'e'	refers to elastic part of strain
Subscript 'r'	denotes the values of rock mass parameters for plastic zone
Subscript 'i'	denotes the initial values of rock mass parameters
Superscript 'p'	refers to plastic part of strain

response of the tunnel is affected by the damaged zone developed by the excavation impact. It can be concluded that, the factor (b) is influenced by the factor (a). Thus, for an elastoplatic analysis of a tunnel, the effects of the BIDZ developed by the excavation impact must be taken into account.

In this regard, one of the significant reasons for assessing the BIDZ around tunnels is its effect on the tunnel stability. This, therefore, implies the need for considering this zone during the tunnel design. Full consideration of the interplay that exists among construction activities, the EDZ, support characteristics, and time requires the use of numerical methods in which all factors can be considered (see, for example Cho et al., 2006; Saiang and Nordlund, 2009a, 2009b; Saiang, 2010).

No closed-form solutions exist that include the full complexity of such a problem. Analytical solutions, however, if found, have the potential of providing an insight into the problem, and are very useful to identify the most important variables for a given subject, and contribute to the understanding of the excavation–rock–liner interaction problem. Analytical solutions, however, suffer from distinct limitations, because they usually require a number of assumptions and simplifications that often apply to the problems with limited practical interest. Nevertheless, the advantages of having a closed-form solution often outweigh the limitations. In this regard, no notable analytical solutions that consider the effect of the BIDZ are currently available for analyzing the elastoplastic response of tunnels. In elasto-plastic solutions, proposed by Brown and Bray (1982), Carranza-Torres and Fairhurst (1999), Sharan (2003,2005), Alonso et al. (2003), Park and Kim (2006), Park et al. (2008), Lee and Pietruszczak (2008), Fahimifar and Zareifard (2009, 2012, 2014), Zareifard and Fahimifar (2012, 2014, 2015), Alejano et al. (2010), Cheng (2012), effects of the BIDZ have not been considered, and they are presented for tunnels excavated in initially homogenous conditions. In practice, the global damage induced by blasting is taken into account by using the damage factor D introduced by Hoek et al. (2002). In this method, the blast damage factor D is applied to the entire rock mass surrounding the tunnel. This is a common modeling method which can greatly underestimate the strength and stability of the overall rock mass. In this regard, the blast damage factor D is more appropriate to be applied to the actual zone of damaged rock.

In this paper, a fully analytical elastic–brittle–plastic solution for a deep circular tunnel in a Mohr–Coulomb or Hoek–Brown rock mass, considering a cylindrical and homogenous BIDZ is presented. For the models in this paper, it is assumed that the damage induced by blasting is finite in extent and is in the form of a cylindrical zone. Beyond the BIDZ, it is assumed that the rock is not damaged and; therefore, the undamaged rock property values are used.

The discussion of this paper is restricted to the stable solution, so the topics concerning the instability such as bifurcation and strain localization in the plastic regime (Varas et al., 2005; Alonso et al., 2003) are not considered.

In the present exact analytical solution, simple formulas are derived without having to solve complex differential equations. This is useful for acquiring an additional insight into the problem on an opening within a damaged zone; because only a minimal computational effort is needed and considerable economic benefits can be gained by using it in the preliminary stage of a tunnel design. In addition, the exact solution is useful for the verification of the numerical codes and semi-analytical solutions. Furthermore, the proposed solution can also be applied for a tunnel reinforced by means of a grouting zone with increased strength parameters.

2. Definition of the problem

The problem considered is shown in Fig. 1. A circular deep tunnel of radius r_i is excavated in an initially elastic rock mass characterized by Young's modulus E, and Poisson's ratio v. Due to a blasting impact a cylindrical blast-induced damaged zone (BIDZ) will develop around the tunnel with different behavior parameters. In this regard the Young's modulus and the Poisson's ratio of BIDZ are E_D and v_D, respectively.

Axial symmetry conditions for geometry and loading can be assumed for the problem of the tunnel under a uniform initial stress p_0. A uniform internal pressure $\sigma_i = \sigma_{r(r_i)}$ is considered to act on the periphery of the tunnel as a result of a lining installation.

The stress redistribution and displacements will take place, due to excavation of the tunnel, installing the lining and the alteration of the rock mass in the BIDZ.

As σ_i is gradually reduced, a radial displacement occurs and a plastic zone develops around the tunnel as σ_i becomes less than the initial yield stress. After failure, the strength of the rock suddenly drops and follows the post-failure softening behavior. In this study, both the damaged and undamaged rock masses are considered to be elastic–brittle-plastic (in special case: perfectly plastic) as shown in Fig. 2.

Two different zones may forms around the tunnel: an external elastic zone and an internal plastic zone of radius R_p. In this respect, three different cases can be considered, depending on the extent of the BIDZ and the plastic zone (Fig. 1):

Case (a): the radius of the plastic zone is larger than the BIDZ.
Case (b): the radius of the BIDZ is greater than the plastic zone.
Case (c): the radius of the BIDZ is equal to the radius of the plastic zone.