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Simultaneous effects of joint spacing and joint orientation on the penetration rate of a single disc cutter

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ABSTRACT

This paper describes the influence of joint spacing and joint orientation on the penetration rate of a Tunnel Boring Machine (TBM) disc cutter as modeled by the Discrete Element Method (DEM). The input data for the simulations were obtained from the sandstone along the Alborz tunnel that is currently being excavated in Iran using a 5.2 m diameter open TBM. Three joint spacings, 150, 200, and 300 mm, were modeled together with seven values of joint orientation; 0°, 15°, 30°, 45°, 60°, 75°, and 90°. The results show that the penetration increases when joint orientation increases from 0° to 75°, but it decreases as the joint orientation increases further from 75° to 90°. This is true for each joint spacing. In addition, for a given joint orientation increasing the joint spacing causes the TBM penetration to decrease. The optimum joint orientation, from the viewpoint of TBM penetration, is about 60–75°.

1. Introduction

Rock mass parameters, including the presence of weak surfaces, are the most important parameters that should be taken into account when analyzing rock penetration by disc cutters. By now many experimental, theoretical, and numerical simulation based studies have been performed to examine the interaction between TBM disc cutter performance and joint spacing and orientation. A brief review of some of this work is given in Table 1 [1–20]. However, the influence of joint spacing and orientation on the penetration rate of the disc cutter and on chip formation has been typically studied independently. In this paper the simultaneous effects of joint spacing and joint orientation on the rock indentation and fragmentation process are described. The Discrete Element Method (DEM) is used to model the actions of a single TBM disc cutter on the rock. Three joint spacing intervals and seven different orientations of the joints (i.e., 21 conditions in total) were considered in this study.

The Alborz tunnel, which is part of the Tehran-Shomal freeway, was chosen as a case study for numerical modeling of the simultaneous effects of joint spacing and joint orientation on single disc cutter indentation in rock. This approximately 120 km long freeway connects the capital Tehran to Chalus city in the northern part of Iran. At this time traffic runs on small roads bypassing the Alborz Mountains and the journey takes from 5 to 6 h. Upon completion of the tunnel traveling time will be reduced to less than 2 h and the road will have an overall higher capacity. The freeway route has more than 30 twin tunnels for double lanes. The Alborz tunnel will be the longest of these, with a length of 6400 m at an altitude of 2400 m (Fig. 1). The Alborz service tunnel is now being excavated with a 5.2 m diameter open TBM (a Wirth 520E Gripper). The results of geological site investigations show that the main lithological units through which the tunnel will be driven consist of sandstone, tuff, gypsum, shale, and limestone layers (Fig. 2). The required input data for numerical simulations were obtained from the sandstone existing along the Alborz tunnel [21].

2. Configuration of the numerical model

The simulations used Universal Distinct Element Code (UDEC) to model rock fragmentation by a single TBM disc cutter. The key concepts of the DEM are the domain of interest, which is treated as an assemblage of rigid or deformable blocks and/or particles, and the identification and updating of the contacts between distinct particles during the deformation/motion process. The contacts are represented by appropriate constitutive models [22].

Three joint spacings, 150, 200, and 300 mm, and seven joint orientations were considered during modeling. The dip direction of the joints is assumed to be in the same direction as the cutting load, and the joint dip angle (α in Fig. 3) was set at 0°, 15°, 30°, 45°, 60°, 75°, or 90°. The model configuration is shown schematically in Fig. 3. The dimensions of the model are 1×1, 1.5×1.5, and 2.5×2.5 m for joint spacings of 150, 200, and 300 mm, respectively. The cutter is modeled as a normal force applied at mid

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Table 1
Some studies of joint spacing and orientation effects on TBM disc cutter performance.

Author	Comment
Howarth (1981)	Impact of joint spacing on TBM performance; experimental studies [1]
Lindqvist et al. (1983)	Behavior of the crushed zone in rock indentation [2]
Sanio (1985)	Effect of rock mass anisotropy, including bedding and shistosity, on cutter load [3]
Nelson et al. (1985)	TBM performance prediction using rock fracture parameters [4]
Zhao et al. (1994)	Indentation fracture mechanics and rock disc-cutting [5]
Tang (1997)	Numerical simulation of progressive rock failure and the associated seismicity [6]
Bruland (1998)	Introducing a fracture factor into the NTNU TBM performance prediction model [7]
Kou et al. (1999)	Numerical simulation of the cutting of inhomogeneous rocks [8]
Innaurato et al. (2001)	Performance and modeling of indenters and cutting tools used for the assessment of bore-ability in rock tunneling [9]
Liu et al. (2002)	Numerical simulation of the rock fragmentation process induced by indenters [10]
Sapigni et al. (2002)	TBM performance estimation using rock mass classifications [11]
Gong et al. (2005)	Investigating the effects of joint orientation on rock fragmentation by TBM cutters with numerical modeling [12]
Gong et al. (2006)	Investigating the effects of joint spacing on rock fragmentation by TBM cutters with numerical modeling [13]
Gong et al. (2007)	In situ TBM penetration tests and rock mass bore-ability analysis, in hard rock tunnels [14]
Innaurato et al. (2007)	Experimental and numerical studies on rock breaking with TBM tools under high stress confinement [15]
Yagiz (2008)	Utilizing rock mass properties for predicting TBM performance in hard rock conditions [16]
Gong et al. (2009)	Development of a rock-mass-characteristic model for TBM penetration rate prediction [17]
Farrokh et al. (2009)	Effect of adverse geological conditions on TBM operation during the Ghomroud tunnel conveyance project [18]
Khademi et al. (2010)	Performance prediction of hard rock TBM using a Rock Mass Rating (RMR) system [19]
Gholamnejad et al. (2010)	Application of artificial neural networks to the prediction of tunnel boring machine penetration rate [20]

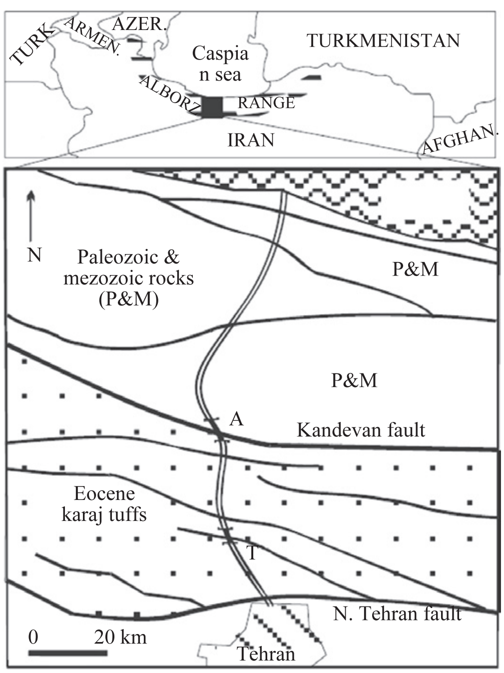

Fig. 1. A sketch showing the location of the Tehran-Shomal freeway: location of the Alborz tunnel along the freeway indicated as the letter "A".

height to the left boundary through contact thickness of 15 mm. The rolling force acting on the cutter is ignored in the two dimensional model. The upper, lower, and right side boundaries are fixed displacement boundaries. In all the models the contact point between the cutter and the rock is at the center of two joint outcrops. The physical and mechanical properties of the sandstone along the tunnel are listed in Table 2 [21].

3. Rock fragmentation by a single disc cutter

A single disc cutter modeled with different joint spacings and orientations shows two influences of joint orientation on initiation and propagation of cracks in the jointed rocks. Values of 0°, 15°, 30°, 45°, and 90° give cracks that are immediately initiated beneath the disc cutter and then propagate towards the joint plane; subsequently a chip is formed. But a joint orientation of 60° or 75° gave crack initiation in the joint plane that reached the free surface while increasing the penetration. Figs. 4 and 5 illustrate this point. There the crack initiation zone and its rapid propagation beneath the cutter, for different steps of the UDEC simulation, are illustrated with a joint spacing of 300 mm and for joint orientations of 15° or 60°. In these figures a circle denotes tensile failure and a cross denotes compressive failure.

When the joint orientation is 15°, the cutter first acts on the rock by forming a fan-shaped rock failure (crushed) zone as shown in Fig. 4. As the penetration increases the crushed zone includes a compression failure zone and a tensile failure zone. Note that in

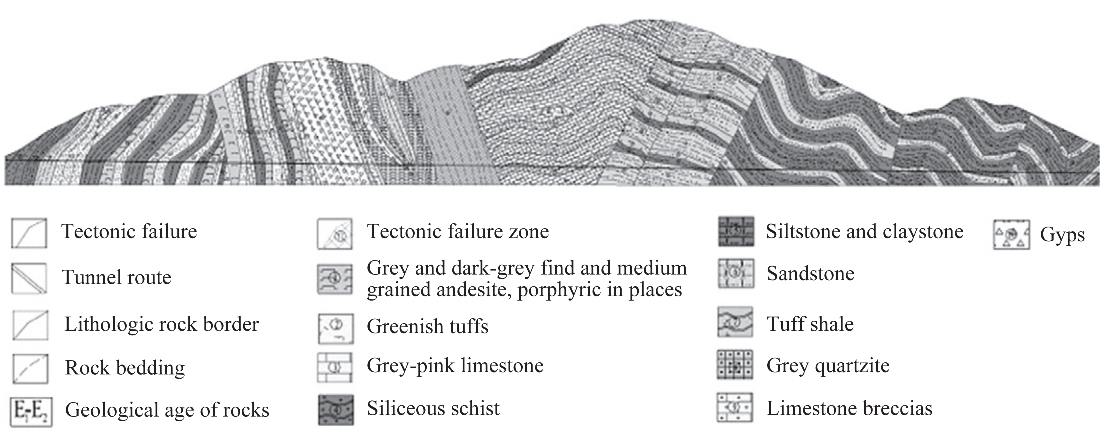

Fig. 2. Longitudinal geological profile of the Alborz tunnel.