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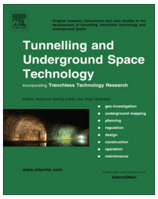

Technical note

Numerical parametric study on stability and deformation of tunnel face reinforced with face bolts

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ABSTRACT

Although face bolting has been used as a stabilisation technique in open-face tunnelling for decades, there is still a lack of systematic ways for determining the optimum parameters of face bolts. To optimise design for face bolting in soft ground, it is necessary to understand the influences of each parameter associated with face bolting on ground response. In this note, five series of numerical parametric studies are carried out, to investigate the effects of length, density, reinforcement area, axial rigidity of face bolts and strength of soil on tunnel face stability and deformation in soft rock. Based on the ground condition, geometries of tunnel and configurations of face bolts simulated, the optimum length, density and axial rigidity of face bolts are found to be 0.6H (H = height of tunnel), 1 bolt/m^2 and 195 MN, respectively. The optimum axial rigidity of face bolt appears to be independent of the bolt density. The computed results also reveal that it is more effective to reduce face deformation by installing face bolts around the tunnel periphery, than installing them near the central area of the tunnel face.

1. Introduction

The tunnel face instability is one of the major concerns related to open face excavation of tunnel in soft ground. To stabilise the tunnel face, various auxiliary methods have been proposed and applied in the industry, including prepoling, face bolting, vertical pre-reinforcement techniques, pre-grouting and ground freezing (Pietro, 2008). Among the existing face-stabilising techniques, prepoling (including umbrella arch method) and face bolting are of particular favour in the industry (Pietro, 2008).

The application of prepoling have been shown to substantially improve tunnel face stability by various researchers, through full-scaled field study (Ocak, 2008; Wang et al., 2014), centrifuge model testing (Hisatake and Ohno, 2008; Juneja et al., 2010; Wong et al., 2012) and numerical modelling (Aksoy and Onargan, 2010; Li et al., 2012; Zhang et al., 2014).

Compared to prepoling, face bolting is found to be even more effective for face stabilisation, as demonstrated by comparative studies through centrifuge testing (Kamata and Mashimo, 2003) and distinct element method (Funatsu et al., 2008). It is well recognised that the effectiveness of face bolting is related to many factors, including density, reinforcement area, axial rigidity, embedded length of bolts, as well as strength of soil. To determine the optimal parameters of the above-mentioned factors, some parametric studies have been carried out. Yoo and Shin (2003) carried out a series of reduced-scale model tests as well as 3D finite-element analyses (in sand) to study the effects of density, length and stiffness of bolts on the face deformation behaviour. Critical values of these parameters were reported. Calvello and Taylor (1999) performed a series of centrifuge tests to compare the effects of various reinforcement areas of face bolts on tunnelling-induced face deformation in clay. The test results showed that a more significant reduction in ground movements could be achieved by placing the nails around the tunnel periphery. Ng and Lee (2002) reported a numerical parametric study investigating the axial rigidity of a nail for improving the stability of tunnel face in stiff clay. An optimum axial rigidity of the nail were identified for a given nail density.

In spite of the afore-mentioned parametric studies on some selected parameters, the authors are not aware of any comprehensive study considering all the major factors governing the face stability, namely density, reinforcement area, axial rigidity, length of bolts and strength of soil. Therefore, there is still no systematic

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way for determining the parameters of face bolts (Kamata and Mashimo, 2003) and bolting design is still based on empirical or semi-empirical considerations (Maghous et al., 2012). For this reason, the major objective of this study is to carry out a comprehensive three-dimensional numerical parametric study, considering various densities, reinforcement areas, and axial rigidities, lengths of bolts as well as strength of the soil.

2. Finite difference analysis

2.1. Programme of numerical parametric study

As stated in the previous sections, this numerical parametric study investigates the effects of length, reinforcement area, density and axial rigidity of face bolts on deformation and stability of tunnel face. All numerical runs and variables considered in each run are summarised in Table 1. For simplicity, this study only focuses on face stability of a single tunnel. Piggyback and side-by-side twin tunnelling, which are frequently encountered in practice (Ng et al., 2014; Hong et al., 2015), are not considered.

2.2. Mesh, constitutive model and model parameters

Fig. 1 shows an isometric view of the mesh of a typical numerical case. It is 100 m long, 150 m high and 50 m wide. All four lateral boundaries of the mesh were fixed by roller supports while the bottom of the model was fixed using pinned supports. Cross section of the tunnel was in horseshoe shape, which had a height (*H*) and a width (*B*) of 13.5 and 15 m, respectively. Cover depth (*C*) of the tunnel was 97.5 m. The tunnel was simulated to be excavated in soft rock. These dimensions are identical to a real tunnelling project in soft rock in Xi'an China, as reported by Li (2007). To minimise the required computational time for the parametric study, only half of the problem was analysed, because of symmetry. The tunnel was excavated using the open face excavation method, with a lining installed during the advancement of the tunnel. Although it would be more realistic to model lining segments and bolts between each segment (Wang et al., 2011a,b), they are not simulated in this study for simplicity. A commercial finite difference software FLAC^{3D} was used for analysis.

The mesh consists of 31,680 elements. The soil, face bolts and concrete lining were modelled using eight-noded brick elements, two-noded beam elements and four-noded shell elements, respectively.

The soil and the face bolts were modelled using an elasto-plastic model with Mohr–Coulomb failure criterion. The related parameters were obtained from the laboratory testing results of Xi'an soft rock, as reported by Li (2007). The tunnel lining were modelled by an elastic model. Material parameters of the soil and the lining are summarised in Table 2. In this numerical investigation, uncertainty, spatial variability of strength parameters and non-uniformity of soil, which could significantly affact the computed results of geotechnical instability problems (Li, et al., 2011; Wang et al., 2011a,b; Cao and Wang, 2014; Jiang et al., 2014; Li et al., 2014), are not taken into account.

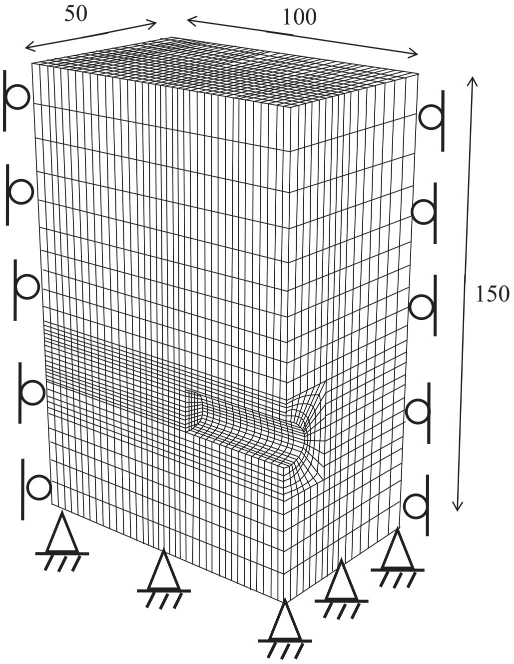

Fig. 1. Finite difference mesh and boundary conditions.

Table 2
Parameters of soil or rock and lining.

	E (GPa)	*c* (kPa)	φ (°)	v	γ (KN/m^3)
Ground	0.8	60	27	0.35	1850
Lining	21	–	–	0.2	2500

Note: *E*, *c*, φ, v and γ denote elastic modulus, cohesion, friction angle, Poisson's ratio and bulk density of soil/lining.

Table 1
A summary of the numerical parametric analyses.

Series	Objective	Number of numerical runs	Variable				
			L (m)	Reinforcing area	ρ (bolt(s)/m^2)	*EA* (MN)	*C* (kPa)
1	Effects of bolt Length (*L*)	6	5 6 7 8 9 10	Full scope	1.25	216	60
2	Effects of reinforcing area	3	8	Summarised in Fig. 8			
3	Effect of density (ρ)	4		Full scope	0.5 0.75 1.0 1.25		
4	Effect of axial rigidity (*EA*)	7			0.75 and 1.25	Summarised in Table 4	
5	Effect of strength (*c*)	10	N/A	N/A	N/A	N/A	Summarised in Table 6