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3D numerical parametric study of the influence of open-pit mining sequence on existing tunnels

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ABSTRACT

The development of open-pit mines can adversely affect and even damage existing access tunnels. To ensure the safety and serviceability of them, it is essential to know potential adverse effects of the mining sequence on existing tunnels such as displacements of the lining and additional loads on the lining. In this paper, three-dimensional numerical parametric study is performed to explore this complex interaction. This study investigates the effects of different parameters that may affect the tunnel response. These parameters are: excavation sequence method, horizontal/vertical stress ratio, slope angle, and tunnel diameter. This study shows that the mining sequence affects the stability of the tunnels. The open-pit mining activities lead to both higher axial forces in rock bolts and normal forces and bending moments in the lining. The results of the analysis also demonstrate that the mining sequence causes tunnel heave and significant tensile forces in the lining. Based on the study in this paper a better understanding of the interaction between open-pit mining sequence and tunnels will be obtained.

1. Introduction

Access tunnels are considered to be one of the main underground structures in mines and widely used for transportation, drainage, exploration, etc. The development of mines and mining operations affect the stability of the existing access tunnels. They cause stress changes in the ground leading to rock movements which may cause potential damages to the tunnels. Due to the critical role access tunnels play, instability of them jeopardies the economy and safety of mines. Thus, it is essential for designers and engineers to assess excavation induced movement and tensile forces in existing tunnels so that the tunnels can continue to operate safely during the mining activities.

There are several studies on the effects of tunneling on existing tunnels.

Cooper et al. developed a new empirical method for estimating the settlement trough caused by the second of twin tunnels and proposed it for use as a preliminary predictive tool [1]. For this purpose, they used the data from three 9 m-diameter parallel tunnels constructed crossing below twin existing tunnels at London Heathrow Central Terminal Area station for the Heathrow Express project at Heathrow Airport in the United Kingdom as well as a database of case histories of twin tunnels prepared from reported information worldwide. Liu et al. investigated effects of tunneling on existing support systems in the Sydney region [2,3]. Geotechnical influence on existing subway tunnels induced by multiline tunneling in Shanghai soft soil in China was investigated by Zhang and Huang [4]. Li et al. studied the effect of new shield tunneling on an existing underlying large-diameter tunnel [5]. A realistic field monitoring application to evaluate close proximity tunneling effects of a new tunnel on an existing railroad tunnel in Korea was presented by Yun et al. [6]. Standing focused on how existing tunnels lined with cast iron segments responded to new tunnels construction beneath them [7]. For this purpose, they studied the Crossrail project, currently underway in London, involving tunneling beneath numerous existing tunnels and examined how the stresses develop within a cast iron segmental lining as it deforms. Do, Dias, Oreste investigated the influence of a new tunnel construction on an already existing one [8]. Recently, effect of twin tunnels construction beneath existing shield-driven twin tunnels in Beijing, China was studied by Fang et al. [9].

Moreover, the effects of open excavation on existing tunnels have been investigated by several researchers. The effect of a deep open excavation for an office block on the underlying tunnel complex in the center of Prague in Czech Republic was investigated by Dolezalova [10]. Zheng and Wei studied the response of existing tunnel due to overlying excavation using 2D FEM [11]. Liu et al.

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conducted a case study of protecting existing tunnels during the construction of a new cut and cover tunnel above in Nanjing, China [12]. Three-dimensional numerical parametric analyses were carried out to investigate the effects of a basement excavation on an existing tunnel by Ng et al. [13]. Huang et al. performed a finite element parametric study of existing tunnel behavior caused by nearby deep excavation in Shanghai, China [14]. The soil unloading effects in foundation pit excavation on existing tunnels were investigated by Zhang et al. [15]. Recently, Shi et al. conducted a three-dimensional numerical parametric study of the influence of basement excavation on existing tunnel and Tan investigated the effects of an oversized pit excavation on an existing metro line in stiff clay in Suzhou in China [16,17].

Finally, several authors have studied the effects of other construction activities on existing tunnels. Schroeder et al. assessed the influence of pile group loading on existing tunnels using the Finite Element Method (FEM) with the aim of improving the current restrictive guidelines [18]. For this purpose, the response of the existing Victoria line tunnel in London to loading of piles located on both sides of the tunnel was studied. The results of these analyses were used to formulate design guidelines relating the clear distance between the pile rows and the tunnel to maximum allowable tunnel deformations both in terms of tunnel distortions and global movements. Yoo conducted a 3D numerical investigation on the effect of bridge construction on existing tunnel [19]. The results of this study showed that the effect of pile-supported bridge construction on a tunnel may be ignored when the clearance between the pile tip and the tunnel lining exceeds 1.0D and 0.5D for centrally and eccentrically loaded tunnels, respectively. Shin et al. investigated the effect of blast-induced vibration on existing tunnels [20]. They adopted a numerical method for the dynamic modeling of a tunnel in soft rock and evaluated a two-dimensional blast load by modifying the detonation pressure formula based on the results of field tests. Tunnel behavior due to the blast-induced vibration was investigated in terms of particle velocity, displacement and stress of the linings, and a guideline for the blast protection zone was proposed based on a parametric study on blast location, tunnel depth, and the amount of explosives. Liang et al. studied the effect of blast-induced vibration from a new railway tunnel on existing adjacent railway tunnel in Xinjiang, China by using laboratory tests, in situ monitoring and numerical simulations [21]. Based on the results from in situ monitoring and numerical simulations, the original blasting design and corresponding parameters were adjusted to reduce the maximum blasting vibration velocity. The authors also studied the effect of both the static stress before blasting vibrations and the dynamic stress induced by blasting on the total stresses in the existing tunnel lining. Yu evaluated the influence of the vibrations generated by blasting construction on existing tunnels in soft soils [22]. For this purpose, a 3D numerical model of an existing road tunnel in the city of Shanghai was established by a finite element software. The sequential characteristics of vibration velocities and accelerations of the tunnel structure were obtained from the field blasting tests and the numerical simulation results were confirmed by field monitoring data. This study presented a thorough understanding of the safety criterion of the blasting vibrations for an existing tunnel in soft soils. Recently, Zhao conducted an experimental and numerical investigation on the effect of blast-induced vibration from adjacent tunnel on existing tunnel in China [23]. They studied axial and radial blasting vibration velocity distributions of the existing tunnel under the effect of blast-induced vibration from adjacent tunnel. This study showed that numerical simulation and field monitoring experiment can optimize blasting excavation program and provide a reference for other similar projects.

In summary, the literature reviewed above indicates that an extensive amount of research has been carried out on the effects of excavation and construction activities on existing adjacent tunnels. Moreover, a lot of studies have been conducted on the open-pit slope stability [24–26]. However, until now, no research has been reported for investigating the effects of open-pit mining sequence on existing tunnels. In this paper, three-dimensional numerical parametric analyses are conducted to investigate the interaction between open-pit mining sequence and existing tunnels. Effects of excavation sequence method, horizontal/vertical stress ratio, slope angle, and tunnel diameter are explored and their influence is quantified.

2. Three-dimensional numerical analysis

Three-dimensional numerical analyses were conducted to investigate the mining sequence-tunnel interaction. For this purpose, the effects of excavation sequence method, horizontal/vertical stress ratio, slope angle, and tunnel diameter were examined.

2.1. Numerical analysis program

All the numerical analyses have been performed using the commercial software MIDAS GTS (Geotechnical and Tunnel Analysis System) NX 2015 which is a simulation program developed for the evaluation of ground-structure interaction based on the finite element method.

2.2. Finite element mesh and model parameters

Fig. 1 shows the three-dimensional finite element mesh used to model the open-pit mine. The domain analyzed is 200 m × 158 m × 440 m. The height and width of the benches are assumed to be 15 and 10 m, respectively. In this study, different bench angels (70°, 60°, and 50°) and tunnel heights (7.5, 6, and 5 m) are considered. The rock mass is modelled by solid elements while existing tunnel lining is simulated by shell elements. The truss elements are embedded into the solid elements to model the interaction between the rock bolts and the surrounding rock mass. During modelling, several locations are monitored to quantify the effects of mining sequence on the existing support system as shown in Fig. 1b and c.

In this study, the behavior of the rock mass is modelled by an elasto-plastic constitutive relationship based on the Mohr-Coulomb criterion, with a non-associated flow rule. The main physical–mechanical parameters of the rock mass are a Young's modulus $E = 3$ GPa, a Poisson's ratio $\upsilon = 0.25$, a cohesion $C = 800$ kPa, a friction angle $\varphi = 30°$, and a mass density of 2500 kg/m^3, which are common in mining applications. Moreover, it is assumed that the rock mass is homogenous and considered as a continuum medium. Different horizontal/vertical stress ratios ($K_0 = 0.5$, 1, and 2) are considered in this study. The tunnel lining is assumed to be a composite liner consisting of shotcrete with the thickness of 20 cm and W6 × 25 steel sets with 0.5 m spacing. Also, 2 m long rock bolts on 1.5 m × 1.5 m grid spacing are considered at the crown of the tunnel as shown in Fig. 1c.

The behavior of the lining is assumed to be governed by a linear-elastic relationship using shell elements. Young's modulus and Poisson's ratios of the shotcrete and steel ribs are assumed to be $E_c = 30$ GPa, $\upsilon_c = 0.25$, $E_s = 200$ GPa, and $\upsilon_s = 0.3$, respectively. The behavior of the rock bolts is also assumed to be linear elastic with a Young's modulus $E = 200$ GPa and a Poisson ratio $\upsilon = 0.3$.

The external vertical boundaries of the finite element model permit only vertical displacements. The bottom boundary is fixed in both vertical and horizontal directions. All of the degrees of freedom at the top surface are free, i.e. the top surface is unrestrained.