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Numerical analysis of surface subsidence in asymmetric parallel highway tunnels

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ABSTRACT

Tunnelling related hazards are very common in the Himalayan terrain and a number of such instances have been reported. Several twin tunnels are being planned for transportation purposes which will require good understanding for prediction of tunnel deformation and surface settlement during the engineering life of the structure. The deformational behaviour, design of sequential excavation and support of any jointed rock mass are challenging during underground construction. We have raised several commonly assumed issues while performing stability analysis of underground opening at shallow depth. For this purpose, Kainchi-mod Nerchowck twin tunnels (Himachal Pradesh, India) are taken for in-depth analysis of the stability of two asymmetric tunnels to address the influence of topography, twin tunnel dimension and geometry. The host rock encountered during excavation is composed mainly of moderately to highly jointed grey sandstone, maroon sandstone and siltstones. In contrast to equidimensional tunnels where the maximum subsidence is observed vertically above the centreline of the tunnel, the result from the present study shows shifting of the maximum subsidence away from the tunnel centreline. The maximum subsidence of 0.99 mm is observed at 4.54 m left to the escape tunnel centreline whereas the maximum subsidence of 3.14 mm is observed at 8.89 m right to the main tunnel centreline. This shifting clearly indicates the influence of undulating topography and in-equidimensional noncircular tunnel.

1. Introduction

Opening created in rocks tends to release pre-existing stresses and modify the stress field around it which may result in elastic deformation; however, the rock deforms inelastically if the stresses are sufficiently high. The later mechanism results in fracturing of the rocks, which reduces the load bearing capacity of the rock mass (Ewy and Cook, 1990). Excavation associated with shallow tunnel is likely to induce both lateral and vertical surface movements. To ensure safety of both underground and surface facilities, ground settlement (vertical surface movement) must be predicted before excavation (Dindarloo and Siami-Irdemoosa, 2015; Zhang et al., 2016a). Many researchers have reported that shallow depth of tunnelling and soft ground inevitably lead to ground settlement (Ma et al., 2014; Dindarloo and Siami-Irdemoosa, 2015). Tunnelling through medium-strength jointed rock mass has challenged geotechnical engineers. Any kind of misjudgement regarding strength of jointed rock mass may lead to over- or under-estimate of support system which ultimately affects the overall health and cost of the tunnel design.

A number of investigations regarding stability analysis of single tunnels are reported (Hoek, 2001; Panji et al., 2011; Sharifzadeh et al., 2013; Goel, 2014; Lisjak et al., 2015). Construction of double or multiple tunnels and double-deck tunnel practice has started since few decades back. Therefore, very limited literature is available in stability of double tube tunnels (Soliman et al., 1993; Osman, 2010; Sahoo and Kumar, 2013; Fang et al., 2015; Zhang et al., 2016b).

Researchers have employed physical, analytical, empirical methods and artificial neural network to study tunnel deformation; however, due to the interaction between several parameters and various complexities, numerical methods have become favourite

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among rock engineers. In this regard, Zhang et al. (2016b) performed three-dimensional (3D) finite element analysis for URUP (ultra rapid under pass, developed in Japan) to observe the ground settlement and lateral displacement due to twin-tunnel excavation in silty clay. Sahoo and Kumar (2013) carried out upper bound finite limit analysis to study the stability of twin unsupported circular tunnels aligned horizontally in two soil types: (a) cohesive-frictional soil, and (b) purely cohesive soil. Soliman et al. (1993) adopted finite element approach for stress and deformation analyses in two tube underground railways for both shield-driven tunnels as well as tunnels driven by simple excavation and shotcreting, and their results showed relative changes in stress and deformation of twin tunnels due to mutual influence of consecutive tunnels. Fang et al. (2015) presented a case study of closely spaced twin tunnels constructed beneath two other closely spaced tunnels and proposed a superposition method to describe the settlement profile. Their result satisfactorily matches with measured settlement reading. Addenbrooke and Potts (2001) investigated nonlinear finite element analysis for twin tunnels construction using two models. In the first model, two parallel tunnels run side by side, whereas in the second one, piggyback (one above the other) model is simulated.

A preliminary investigation of the previous work on stability analysis of twin tunnels demonstrated that most researchers simplify their numerical models by considering at least three basic yet critical assumptions. The first assumption is modelling perfectly horizontal ground surface above the tunnels (Sahoo and Kumar, 2013; Addenbrooke and Potts, 2001). Secondly, the shape of the tunnel is assumed perfectly circular for most of the cases (Chu and Lin, 2007; Chehade and Shahrour, 2008; Panji et al., 2016). Finally, the tunnel dimension is kept constant (Soliman et al., 1993; Zhang et al., 2016b). However, in general, the actual ground surface above the tunnel may have undulated topography, depending on the geomorphology of the area and often the tunnels are noncircular and asymmetric. Therefore, we suggested that these fundamental aspects should not be neglected in numerical simulations for any underground excavation. However, the first assumption (i.e. horizontal ground surface) may be neglected for very deep excavations, but for shallow tunnels, topographic undulations may influence tunnel stability and should be considered to obtain more accurate results.

Tunnel construction through low-strength anisotropic Himalayan rocks like shale, phyllites and schist has generated new thoughts in accessing and anticipating problems posed by such rocks (Bhasin et al., 1995). According to Panthi and Nilsen (2007), Himalayan region is tectonically active and squeezing of underground excavations has been a significant problem. In addition to squeezing, problems like overbreak, chimney formation at roof, heavy water ingress and high horizontal stresses have attracted many researchers around the world to investigate the stability of underground openings. These reasons have compelled the researchers to select a similar situation in the Himalayan region. The purpose of this study is to determine the stability of asymmetric parallel tunnels in moderately jointed rock mass using numerical simulation and highlight the influences of surface topography, tunnel geometry and dimension on surface settlement. For validating the views presented in this study, a project site has been selected in Himachal Himalayas, India.

2. Study area

2.1. Geology

The Kainchi-mod Nerchowck tunnel is located from 31°13′58.35″–31°13′45.50″N latitude to 76°39′51.70″–76°39′29.30″E longitude, south of the Sutlej River, Bilaspur district of Himachal Pradesh, India. The Paleogene rocks of Lesser Himalaya of Himachal Pradesh are exposed in a NW–SE trending belt bounded in the north by the Krol thrust and in the south by the main boundary fault. The succession comprising Subathu, Dagshai and Kasauli formations rests unconformably over the Shimla group of late Precambrian age (Kumar, 2010). The rock formations of the northwestern Himalaya have been correlated with the Dagshai and Kasauli formations, and are grouped into the Dharamshala and Muree groups (Table 1).

The Dharamshala group consists of alternate fine to medium grained grey to maroon sandstones and clays. The succession is often divided into lower and upper formations (Kumar, 2010). The most dominant rocks present in the study area are maroon and grey sandstones. The rocks contain three dominant joint sets. The attitudes of the joints J1, J2 and J3 are S42°E/62°, N40°W/20° and S83°E/78°, respectively.

2.2. Project overview

Two asymmertric parallel tunnels of 1800 m in length (refered to as main tunnel and escape tunnel) are under construction with diameters of 12 m and 8.5 m, respectively. The tunnel is located in Kiratpur-Neirchowck national highway in Himachal Pradesh, India (Fig. 1), trending N40°E. There is a clearance of 13 m between the tunnels. The overbuden depths above the main and escape tunnels are 26 m and 36 m, respectively. The southwestern portal of both the tunnels is kept at an elevation of 719.84 m while the northeastern portal is at 680.42 m. The grey and maroon sandstones encountered during excavation are of upper Dharamshala formation and are moderately jointed. The grain size of these sandstones varies from fine to very fine. The attitude of the beds in the main tunnel at chainage 12 + 803 m is N35°W/10°–15°. Full-face excavation method is adopted due to relatively smaller size of escape tunnel; however, heading and benching excavation technique is being used in the main tunnel. Nevertheless, size is not the only criterion to choose an excavation methodology. The factors like

Table 1
Geological succession of the type locality (Jamwal and Wangu, 2012).

Age	Group		Formation	Rock type
Plio-Pleistocene	Siwalik super group	Upper	Boulder conglomerate Pinjor Tatrot	Coarse sandstone, grit and conglomerate with local clay bed
Mio-Pliocene		Middle	Dhokpathan Nagri	Coarse micaceous sandstone with interbeds of earthy clay
Miocene		Lower	Chinji Kamlial	Sandstone–clay alternation
Eocene-Miocene	Sirmur		Kasauli/upper Dharamshala Dagshai/lower Dharamshala	Grey sandstone, siltstone, shale Maroon sandstone, siltstone