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Deformation and mechanical characteristics of tunnel lining in tunnel intersection between subway station tunnel and construction tunnel

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ABSTRACT

Deformations and stress distributions in tunnel intersection areas are more complicated than those in common tunnels. The literature on deformations and stress distributions in tunnel intersections, in which the intersecting tunnel is in a different section, is limited. The Shangxinjie subway station in Chongqing, China, was selected to investigate the deformation, stress and plastic zone responses of a tunnel intersection using numerical simulations. Based on the numerical results, the scopes of influence with respect to the deformation, stresses and possible failure modes of the tunnel lining were further studied. The numerical results show that the deformation in a section close to the tunnel intersection was larger than the deformations in distant sections. Compared with the common section, the crown settlement reached the maximum value at the tunnel intersection, and the maximum rate of increase was approximately 28%. The range of the plastic zone at the tunnel intersection was much larger than that in the other areas, and it was mainly located in the side wall and tunnel crown. In the longitudinal direction, the lengths of the scopes of influence were 2.4 B and 1.6 B with respect to the deformation and stress, respectively. The magnitudes of the internal forces in the longitudinal and circumferential directions were almost equal. The bending moments of the tunnel lining within 135° and 225° significantly changed, but the axial force decreased dramatically. Tensile and compressive failures may occur at the tunnel intersection and in a section 5 m away. Locally thickening the supporting structures is suggested to improve the stability of the tunnel.

1. Introduction

Due to the urgent need to improve traffic and to develop environmental friendly infrastructures in congested urban areas, the number of subways worldwide has increased rapidly during the past decades. It is widely accepted that subway station tunnels have shallow depths, large spans and large sections. Generally, the cross-sectional area of a subway station tunnel is approximately 400 m^2. Such tunnels can be classified as extra-large cross-section tunnels according to the standard stipulated by the International Tunneling and Underground Space Association (ITA). To reduce the impact of subway station construction on ground transportation, especially in the busiest areas of urban cities, subway stations are often constructed using the mining method. In the mining method, a construction tunnel is essential for removing tunnel slag and to provide an open working face in the subway station tunnel. The stress states and displacements around the intersection areas are three-dimensional (3D) (Gercek, 1986). The surrounding rock masses in the intersection areas are more heavily disturbed than in common tunnels.

Considering the irregular and complex geometries in tunnel intersection areas, it is impossible to find an analytical solution for the 3D stress distributions (Chen and Tseng, 2010). In early research, photoelastic materials were adopted to investigate stress concentrations at tunnel intersections. For example, Riley (1964) used a photoelastic material to investigate the stresses at tunnel intersections subjected to uniaxial compression in which the orthogonal holes were of equal diameter. Afterward, Johnson and Leven (1977) studied stress-concentration factors for a number of cases of intersecting and nearly intersecting holes subjected to uniaxial tension. In recent years, numerical methods such as the finite difference method (FDM) and finite element method (FEM) have been employed to analyze the stress and perform deformation

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analyses of underground excavations (Liu et al., 2011; Shi et al., 2015). They have been widely employed by researchers to investigate deformations and stress distributions in tunnel intersections and in bifurcation tunnels (Guan et al., 1994; Gaspari et al., 2010; Elkadi and Huisman, 2002). Tsuchiyama et al. (1988) investigated the influence of a new obliquely crossing tunnel on an existing main tunnel using a 3D finite element analysis. Nonomura et al. (1985) analyzed the behavior of tunnel support members using a 3D FEM and evaluated the design properties by measuring the behaviors of support measures during construction. 3D excavation and support calculations under four conditions were simulated using the Ansys FEM software package for stress-deformation analyses of an intersecting tunnel in an underground engineering project (Liu and Wang, 2010). Bian et al. (2016) investigated the primary cause of lining cracking in an intersecting tunnel in an underground power station and verified their conclusions using an FEM. A breakout is often made for a perpendicular child tunnel, and the structural response on tunnel linings due to tunnel lining breakout have been discussed (Spyridis and Bergmeister, 2015). Lin et al. (2013) adopted the FLAC3D FDM software package to study the stability of tunnel intersections between the hydraulic turbines and tailrace tunnel, and the distributions of deformations, stresses, plastic zones and the reinforcement system were highlighted. For the purpose of studying the complicated stresses in the area of seven intersecting tunnels, Hsiao et al. (2004) adopted the FLAC3D 3D numerical analysis program for feedback analysis. Hsiao et al. (2009) examined 75 cases using 3D numerical analysis under various tunneling conditions to establish a criterion for assessing the effect of intersection angles on tunnel behavior.

The existing literature has mainly studied the stresses and deformation responses in orthogonal intersecting tunnels that have the same section. For tunnel intersections in a subway station, the dimensions of the subway station are much larger than the dimensions of the construction tunnel, which has resulted in large differences in the calculated stress-deformation responses in tunnel intersections in the existing literature. Fewer studies have been reported that have examined the stresses and deformation responses in the intersection areas between the subway station and the construction tunnel. Given the rapid development of subways in recent years, the stresses and deformation responses in tunnel intersection areas should be given more attention to improve stability during tunnel construction.

In this study, numerical simulations using the Midas-GTS 3D FEM software package were used to investigate the deformations and stress responses of the surrounding rock mass and tunnel lining at a tunnel intersection. The deformations, stresses, plastic zone distributions, traces of the principle stress and the internal forces in the tunnel lining were specifically examined. The deformations and stresses at the tunnel intersection and in sections far from the intersection were compared to identify the influence scope and the stress concentration factor. The internal forces along the entire section were extracted to compare with the ultimate bearing capacity of concrete to further identify possible failures and their corresponding locations. To improve the stability of the intersection during tunneling, it is suggested that the thicknesses of the supporting structures at the intersection are increased.

2. Materials and methods

2.1. Project description

The Shangxinjie subway station in Chongqing, China, was designed to be a transfer station for Metro Line 6 and the Circle Line. The total length of the station is 210 m. Referencing the design document, the tunnel section is an arched straight wall that has a height of 17.45 m and a width of 22.10 m. It was designed to be constructed using the double side drift method. The section of the construction tunnel is similar to that of a subway station tunnel, but the dimensions are much smaller than those of a subway station tunnel. The width and height are 8.0 m and 6.6 m, respectively. The engineering site is in a macroscopic tectonic denudation shallow hill landform. The eastern part is higher than the western part, and the slope angle varies between 3° and 20°. The relative positions of the subway station and construction tunnel are shown in Fig. 1.

2.2. Numerical modeling

The intersection of the subway station tunnel and the construction channel was selected to build a 3D numerical model to analyze the influence of the intersection on the deformations and internal forces of the tunnel lining. A perspective view of the numerical model is shown in Fig. 2. To reduce the influence of boundary effects on the accuracy of the numerical results, the distance between the side of the station tunnel and the boundary of the numerical model was set equal to three times the width of the station tunnel, and the total length of the numerical model was 151 m. The distance between the bottom of the station tunnel and the numerical model was set equal to three times the height of the station tunnel. The top of the numerical model was established in accordance with the site conditions, and the total height was 60 m. To reflect the effects of the tunneling process on the deformations and internal forces, the width of the numerical model was set to 60 m. The rock mass was simulated using tetrahedron elements. The thickness of the preliminary tunnel lining was set to 250 mm and was simulated as a plate element. In total, there were 130,235 elements and 22,625 grid-points. To simulate the boundary conditions, the nodes on all sides of the model were fixed in the horizontal directions on the x–z and y–z planes (i.e., $x = -75.5$, $x = 75.5$, $y = -30$ and $y = 30$), whereas the nodes at the base of the model ($z = 0$) were fixed in the vertical (z) direction.

2.3. Physical and mechanical parameters of the rock mass

Based on the geological survey report, the rock masses that surround the tunnel are mainly composed of mudstone and sandstone. To obtain the physical and mechanical parameters of the sandstone and sandy mudstone, laboratory tri-axial compression tests were carried out using an MTS-815, which is an electro-hydraulic servo-controlled rock mechanics testing system. Fig. 3 shows the stress–strain curves of a sandstone sample and a mudstone sample under confining pressures of 2 MPa and 1.5 MPa. From Fig. 3, it can be seen that the sandstone and mudstone exhibited linear elasticity before reaching their peak strengths. The peak axial stresses were approximately 55.0 MPa and 20.0 MPa, respectively. Significant drops in the brittle stresses occurred when the axial stresses reached their peak values. This indicates that the sandstone and mudstone experienced brittle failure. For the mudstone sample, the residual stress was approximate 4.8 MPa. In total, 10 sandstone samples and 8 mudstone sample were tested. The test results for the sandstone and mudstone samples are listed in Tables 1 and 2, respectively. The peak strengths of the sandstone and mudstone samples increased as the confining pressure increased (Figs. 3 and 4).

In general, the rock mass was assumed to obey the Mohr–Coulomb failure criterion. To determine the shear strengths of the mudstone and sandstone, experimental data, including the axial stresses and the corresponding confining pressures, are depicted in Fig. 4, and fit lines were obtained to describe the relationship between the axial stresses and confining pressures. The slopes and intercepts of the fit lines were calculated from the fit formulas.