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The effect of weak interlayer on the failure pattern of rock mass around tunnel – Scaled model tests and numerical analysis

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ABSTRACT

Weak interlayer is one of unfavorable geological discontinuities often encountered in underground engineering. Many failures of underground openings were reported to be closely related to the existence of weak interlayer nearby. For the purpose of exploring the effect of weak interlayer on failure pattern of rock mass around tunnel, both physical model tests and numerical analysis were carried out to simulate tunnel excavation near an interlayer. In the model tests, by comparison of the failure patterns between homogenous ground and ground with a weak interlayer, it was found that the weak interlayer affected the stability of tunnel by increasing the failure zones and causing asymmetrical stress distribution. The results of model tests were then verified by numerical analysis. Furthermore, based on the numerical analysis results, the location, dip and thickness of the interlayer as well as the distance from the interlayer to the tunnel were proved to be important factors influencing tunnel stability, and the relationships of the induced damage zones with these parameters of the weak interlayer were established. These results can provide a useful guidance for support design and safe excavation of tunnel near or crossing through a weak interlayer.

1. Introduction

A weak interlayer is formed by geological deposition or ground movement, commonly existing in all types of rock masses. Due to its low strength and stiffness, it has a great influence on the tunnel stability. Many failures of underground openings were reported to be closely related to the occurrence of a weak interlayer nearby (Suorineni et al., 1999; Bruneau et al., 2003). Although a tunnel should be designed away from a weak interlayer, sometimes it is inevitable to encounter a weak interlayer because of complex ground geology and special requirements of highway construction. Therefore, it is very important to understand the failure pattern of surrounding rock mass of a tunnel near or crossing through a weak interlayer, for the purpose of desirable support design and safe excavation.

In order to accurately simulate the construction process, physical model test has been one of the most effective means to investigate the rock response to the underground excavations, e.g., the failure mechanism and stability of the tunnel face and the unsupported span (Li et al., 2005). In these model tests, isotropic ground material was commonly used. Zhu et al. (2011) investigated the spalling and failure mechanism of the caverns in a hydropower station under high in situ stresses. Lee and Schubert (2008) studied the relationship between the stability of face and the round length for tunneling in weak rock. Seki et al. (2008) discussed the heaving phenomenon in tunnels under different in situ stress conditions and section. Sterpi and Cividini (2004) discussed the failure behavior of a shallow tunnel. Furthermore, some model testes were carried out for studying the stability of jointed rock mass around a tunnel. He et al. (2010) conducted physical modeling of deep ground excavation in geologically horizontal strata based on infrared thermograph. Chu et al. (2007) studied the mechanical behavior of a twin circular tunnel in multi-layered formations under different initial stress and modulus ratio. Jeon et al. (2004) investigated the effect of interlayer, weak plane, and grouting on the stability of a tunnel. In these model tests on the self-stability of surrounding rock mass, the effects of a weak interlayer were hardly considered, because of the difficulty to find an appropriate substitute of the weak interlayer. For instance, Fei et al. (2010) employed a temperature-analogue material to simulate the decreasing strength of the weak interlayer, but no favorable results were achieved.

On the other hand, the numerical analyses for the effects of a weak interlayer on underground structures have already been carried out. In the existing numerical analysis, continuum-based and

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discontinuum-based methods are two major approaches. The continuum-based methods include finite element method (FEM), finite difference method (FDM), boundary element method (BEM) and meshless method (MM), etc. For example, Huang and Xiao (2010) simulated the construction of a double arch tunnel through a weak interlayer based on Mohr–Coulomb yield criterion by FLAC3D. Dhawan et al. (2002) analyzed the effects of weak zones in the rock mass and creation of multiple cavities in the inhomogeneous rock mass using FEM. Lee and Kim (2003) assessed the influence of fault zones under different in situ initial stresses using hybrid method of FEM and BEM. As for the discontinuum-based methods, the discrete element method (DEM) and the discontinuous deformation analysis (DDA) became popular recently. Hao and Azzam (2005) studied the effects of interlayer dips, interlayer shear strength and interlayer locations relative to the underground structure by UDEC. Yeung and Leong (1997) investigated the effects of joint attributes on tunnel stability by DDA. The boundary element method (Shou, 2000), lattice solid model (Place and Mora, 2000) and key block theory (Zhang, 2009) were also applied to analyze this problem. However, many numerical analysis attempts are proved to be inherently limited by computational constraints and inadequate understanding of correct physical response of complex media under complex loading conditions (Day and Potts, 1994; Jing, 1998).

In this paper, model tests and numerical simulation are combined to investigate the effect of the weak interlayer on the failure patterns of the rock mass around a tunnel, which makes up the respective disadvantages of two methodologies.

2. Physical model tests

2.1. The law of similarity and material of ground

Physical models must satisfy a series of similarity requirements in terms of geometry, physical–mechanical properties, boundary conditions, and initial stress conditions. In the present tests, the prototype referred is Grade IV surrounding rock mass according to the design codes of a road tunnel in China. The reduced scale of dimension C_l in the model tests was selected as 50. According to the similarity theory, the general law of similarity between the prototype parameters and the model parameters can be deduced, as shown in Table 1. Herein, the subscript "p" represents the prototype and "*m*" represents the test model.

Since a mixture of artificial materials has been proved to be appropriate for a scaled model test (Meguid et al., 2008), a model material is developed in this study for satisfying the requirements of the scaled test, that is, a mixture of barite powder, sand, plaster powder, water, and liquid laundry detergent. The mixing ratio is adopted as:

$$\text{Barite} : \text{sand} : \text{plaster} : \text{water} : \text{detergent} = 12 : 4 : 2 : 0.92 : 0.35 \quad (1)$$

Table 1
The general law of similarity of the model experiment.

Parameters	Definition	Relations	Reduced scale
Length	$C_l = L_p/L_m$	$C_l = C_l$	50
Displacement	$C_\delta = \delta_p/\delta_m$	$C_\delta = C_l$	50
Stress	$C_\sigma = \sigma_p/\sigma_m$	$C_\sigma = C_l C_\gamma$	50
Strain	$C_\varepsilon = \varepsilon_p/\varepsilon_m$	$C_\varepsilon = C_\delta/C_l$	1
Density	$C_\gamma = \gamma_p/\gamma_m$	$C_\gamma = C_\sigma/C_l$	1
Elastic modulus	$C_E = E_p/E_m$	$C_E = C_\sigma/C_\varepsilon$	50
Poisson's ratio	$C_\mu = \mu_p/\mu_m$	$C_\mu = C_\varepsilon$	1
Overload	$C_{\bar{\sigma}} = \bar{\sigma}_p/\bar{\sigma}_m$	$C_{\bar{\sigma}} = C_\sigma$	50
Friction coefficient	$C_f = \varphi_p/\varphi_m$	$C_f = C_\mu$	1
Cohesion	$C_c = c_p/c_m$	$C_c = C_\mu$	50

Table 2
The mechanical parameters of material for rock mass.

Bulk weight γ (kN/m^3)	Elastic modulus E (MPa)	Poisson's ratio μ	Cohesion c (kPa)	Friction angle φ (°)	Uniaxial compressive strength σ_c (kPa)
20	50	0.32	10	31	150

Table 3
The mechanical parameters of the weak interlayer.

Bulk weight γ (kN/m^3)	Elastic modulus E (MPa)	Poisson's ratio (M)	Cohesion c (kPa)	Friction angle φ (°)	Uniaxial compressive strength σ_c (kPa)
23	28	0.35	2	26	50

The main advantage of this material is that various material strengths can be obtained by changing a mixing ratio, while the disadvantage is that the mixture will shrink after a very long time more than 3 months. The material can be reused by adding water according to the current water content to recover its original strength, and keep the permeability and freshness.

Various laboratory tests were carried out, including the conventional triaxial tests to determine the friction angel and cohesion, the dynamic triaxial tests to determine the elastic modulus, and the unconfined compression tests to achieve the uniaxial strength. The parameters of the simulated material are listed in Table 2.

It is generally recognized that the weak interlayer can be represented by an equivalent continuum material (Singh, 1973; Röchter et al., 2010). In the physical model tests, French chalk was adopted to simulate the weak interlayer in the surrounding rock mass. The relative mechanical parameters were also obtained by soil tests, as shown in Table 3.

2.2. Apparatus of model tests and measurement

If the weak interlayer is parallel to the intermediate principal stress and/or the intermediate stress is equal to the minimum principal stress, the three-dimensional model can be reduced to a two-dimensional model (Zhang, 2009), which was assumed in the present experimental study.

The model tests were conducted in a tank made of steel frame with dimensions of 1.6 m × 1.3 m in plane, and 0.4 m in thickness. As seen in Fig. 1a, the front and back sidewalls of the tank are constructed using transparent Plexiglas plates for observing ground movement patterns during testing. The transparent Plexiglas plate has a thickness of 10 mm, which is thick enough to constrain the ground strain in the normal direction of Plexiglas plate plane. PTFE films are attached on the inside of the left and right sidewalls to minimize the friction between the steel plane of the tank and the ground. The tunnel in the model test is a three-lane highway tunnel. The distances from the boundary of the tank to the side wall and the bottom of the tunnel are over two times of the tunnel span, so the boundary effect on the model tests can be ignored.

As seen in Fig. 2, the loading system at the top is used to reproduce an earth overburden load according to the unit weight of the overburden with a certain height, and the horizontal stress by the counteractive force on the steel frame of the right and left sidewalls. As it is known that the in situ stress state has significant effect on the tunnel stability, while the density of ground has influence on the in situ stress. Therefore, the process of simulating the model ground is very critical. The density and the horizontal in situ stress should be controlled strictly and kept in a rational range by careful operation.