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# The effect of principal stress orientation on tunnel stability

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ABSTRACT

In order to investigate the effect of principal stress orientation on the stability of regular tunnels and cracked tunnels, experiments by using square specimens with a centralized small tunnel were conducted, and the corresponding numerical study as well as photoelastic study were implemented. Two kinds of materials, cement mortar and sandstone, were used to make tunnel models, and three types of tunnel models were studied, i.e. (1) regular tunnel models loaded by different orientation's principal stresses, (2) tunnel models with various orientation's radial cracks in the spandrel under compression, and (3) tunnel models with a fixed radial crack loaded by various orientation's principal stresses. In the numerical study, the stress intensity factors of the radial cracks were calculated, and the results agree well with the test results. For regular tunnels, when the angle $\theta$ between the major principal stress and the tunnel symmetrical axis is 45°, the corresponding tunnel is the most unfavorable; for tunnels with a radial crack in the spandrel, when the angle $\beta$ between the crack and the tunnel wall is 135°, the corresponding tunnel is the most unfavorable; for tunnels with a $\beta = 130°$ radial crack, when $\theta = 0°$ or $\theta = 70°$, the compressive strengths of the tunnel models are comparatively low, whereas when $\theta = 90°$, it is the highest.



## 1. Introduction

The stress states of underground rock mass may vary with different locations because except for the weight of the overlying rock mass, many factors are involved, such as the regional tectonic movement, the geological structure, the nearby volcanic eruptions or earthquakes (Brady and Brown, 1985; Roman et al., 2004; Bohnhoff et al., 2006; Zhu, 2013). This indicates that the principal stress orientation around a structure may not be in vertical plane or in horizontal plane, but has a certain angle with those planes. The stress states of rock mass could play an important role in underground structure stability, e.g. a tectonic movement or earthquake would produce stress state changing which could cause mass destruction, thus it is necessary to investigate the influence of stress states on structure's stability. The best approach to the study is to first generate an extensive experimental database on tunnel model failure properties, and then, based on these experimental database, to investigate the failure mechanism through numerical models so as to obtain a better understanding of the dominant parameters that control tunnel stability.

In this paper, the effect of principal stress orientation on the stability of tunnels and cracked tunnels will be focused. The issue of tunnel stability has been studied experimentally and numerically by many researchers, and accordingly many significant research results have been published, e.g. Song et al. (2001), Charpentier et al. (2003), Sterpi and Cividini (2004), Zhou and Qiu (2006), Chu et al. (2007), Wang et al. (2008), Lee and Schubert (2008), Seki et al. (2008), He et al. (2010), Li et al. (2010) and Li et al. (2012), etc. In the process of rock excavation, fragmentation by using explosive is a widely applied method in mining and quarrying due to its properties of easy operation, less cost, and high efficiency. Under the action of explosive detonation, blast-induced radial cracks will occur in the surrounding rock, which could largely affect tunnel stability (Zhu et al., 2007, 2008; Zhu, 2009a). About the effects of cracks or weak interlayers, many research results have been published. Suorineni et al. (1999) and Bruneau et al. (2003) pointed out that weak interlayers have a great influence on tunnel stability due to their low strength and stiffness. Many failures of underground openings were reported to be closely related to the occurrence of weak interlayers nearby. Jeon et al. (2004) investigated the effect of interlayer, weak plane, and grouting on the stability of a tunnel, through scaled model tests and numerical analysis. Huang et al. (2013) indicated that the weak interlayer affected the stability of tunnel by increasing the failure zones and causing asymmetrical stress distribution. The location, dip and thickness of the interlayer as well as the distance to tunnels were proved to be important factors influencing tunnel stability.

In numerical study, continuum-based and discontinuum-based numerical analyses are two major methods. The continuum-based methods include finite element method (FEM), finite difference

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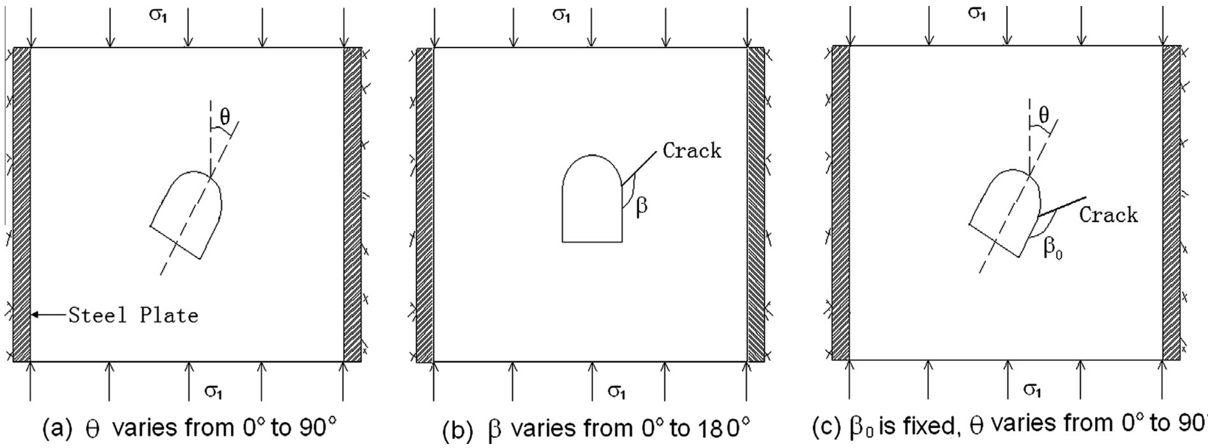


**Fig. 1.** Three test models of tunnels.

**Table 1**
Material parameters of cement mortar and sandstone.

| Material | Young's modulus $E$ (GPa) | Poisson's ratio $v$ | Density $\rho$ (kg/m$^3$) | Cohesion $c$ (MPa) | Internal friction angle $\psi$ (°) | UCS (MPa) |
|---|---|---|---|---|---|---|
| Cement mortar | 2.7 | 0.2 | 2375 | 1.2 | 15 | 8.25 |
| Sandstone | 12.1 | 0.2 | 2280 | 2.01 | 38 38 | 11.7 |

method (FDM), boundary element method (BEM) and meshless method (MM), etc. Dhawan et al. (2002) analyzed the effects of weak zones in rock mass and creation of multiple cavities in the inhomogeneous rock mass by using FEM. Lee and Kim (2003) assessed the effect of fault zones under different in-situ stresses by using hybrid method of FEM and BEM. Jia and Tang (2008) used a FEM based code RFPA to study the influence of different dip angle of layered joints and the lateral pressure coefficient on the stability of tunnel in jointed rock mass. Huang and Xiao (2010) simulated the construction of a double arch tunnel through a weak interlayer based on Mohr–Coulomb yield criterion by FLAC3D code. Zheng et al. (2011) used strength reduction FEM to analyze tunnel damage and safety coefficient.

Although many significant results have been published, less attention has been paid to the effect of principal stress orientation on the stability of tunnels and cracked tunnels. The objective of this study is to experimentally and numerically investigate the relationship between principal stress orientations and tunnel stabilities. Two typical tunnels, i.e. regular tunnels and cracked tunnels will be considered. In the experimental study, the cement mortar and sandstone will be used to make tunnel models. In the numerical study, the finite element code ABAQUS will be applied in the analysis of tunnel stability. The numerical results are compared with the test data, and some conclusions are presented.

## 2. Test models and materials

Principal stress orientations may have a large effect on tunnel stability, and therefore, it is necessary to study tunnel failure property experimentally and numerically. In this paper, three typical tunnel models are studied, the first one is a regular tunnel loaded by various orientation's principal stresses as shown in Fig. 1(a), the second one is a tunnel with various inclination $\beta$ cracks as shown in Fig. 1(b); and the third one is a tunnel with a fixed angle crack loaded by various orientation's principal stresses as shown in Fig. 1(c).

Considering the action of lateral pressures in the reality of tunnels, the tunnel models in Fig. 1 are confined by two steel plates during vertical loading, which has the function of limiting the

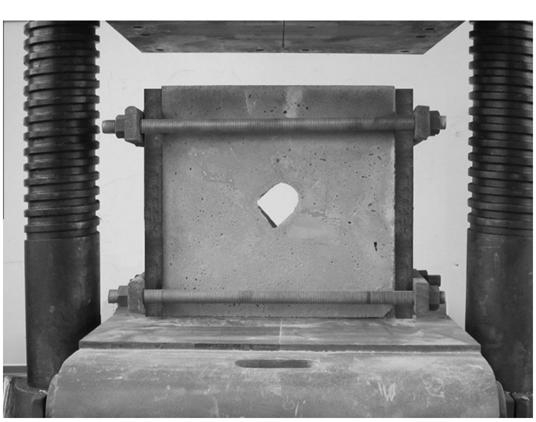

**Fig. 2.** A cement mortar tunnel model and its loading device.

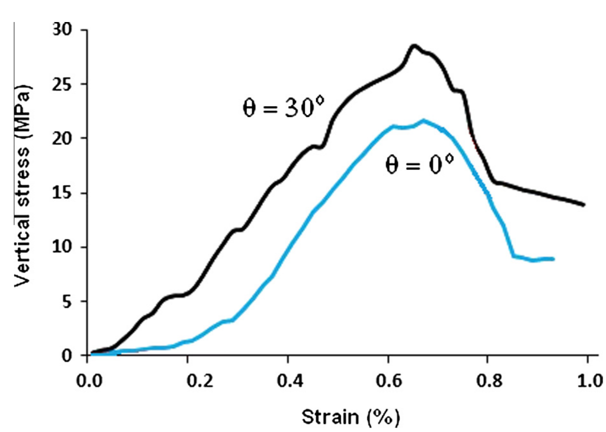


**Fig. 3.** The typical vertical stress–strain curves obtained from the model tests.