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Analysis of the behaviour of a novel support system in an anisotropically jointed rock mass

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ABSTRACT

When constructing an excavation, the segmental lining installed in an anisotropic rock mass is susceptible to asymmetrical pressure and substantial local instabilities. To promote liner stability in such cases, a support system that combines a segmental lining with a highly deformable expanded clay and rock bolts is proposed. A series of physical model tests were performed to study the effect of this support system. In the tests, different dip angles of the primary rock mass jointing, different thicknesses of the expanded clay and different lengths and spacings of rock bolts were considered. Variations in the internal forces and deformation of the segmental lining were recorded in each case. The distribution of the internal forces and deformation of the segmental lining were anisotropic due to the rock mass anisotropy; the maximum positive bending moment and positive deformation on the liner mainly developed in the direction normal to the stratification. By using a sufficiently thick deformable clay layer, the anisotropy of the load transferred to the segmental liner can be minimized. By adding rock bolts, the combined support system can take full advantage of the reinforcement effect of the rock bolts and the yielding effect of the deformable clay layer, and the effect of the rock bolts plus the yielding layer is greater than the sum of the two individual effects. Such a system can change the internal force and deformation distribution of the segmental lining to improve liner stability.

1. Introduction

In recent years, China has seen an increase in the construction of very long and deep tunnels. In many cases, the most cost-efficient means for constructing such tunnels has been to use tunnel boring machines (TBMs), which allow significant savings in construction time and costs for large-scale projects (Ramoni and Anagnostou, 2008). However, because squeezing conditions may vary over short distances due to rock heterogeneity and fluctuations in rock mass properties, the evaluation of the mechanical behaviour of tunnels in deep rock masses is an important part of ensuring efficient and safe construction (Wang et al., 2012). The main difficulties encountered by TBMs in hard rock are typically associated with jointed, blocky rock masses (Zheng et al., 2016). The configurations of discontinuities in the ground affect the TBM rock-cutting performance and the performance of tunnel supports. In anisotropically fractured rock masses, a segmental lining is susceptible to asymmetrical pressure and serious local instabilities, as shown Fig. 1. The stability of the liner and the surrounding rock is the key to ensure the safety of TBM tunnelling (Liu et al., 2016). Although many experts have studied support theory (Li et al., 2010; Li et al., 2014; Meng et al., 2014; Sun et al., 2008), there has been little research conducted on the influence of auxiliary support structures on segmental liner stability in highly stressed rock masses. There is a clear need to develop appropriate systems that will help ensure the safety of the segmental lining structure (Cantieni and Anagnostou, 2009).

Laboratory model tests, field tests and numerical approaches have been used to investigate ground-support interaction in highly stressed rock masses. Fortsakis et al., (2012) investigated tunnel excavation through stratified rock masses using numerical models. Their numerical analyses illustrate the mechanism of convergence development in stratified rock masses, and the differences between isotropic, anisotropic and transversely isotropic cases are demonstrated. Wang et al., (2012) conducted a series of numerical simulations to study the failure mechanism of a circular tunnel using the numerical code Realistic Failure Process Analysis (RFPA). Their results show two major failure modes around circular tunnels in transversely isotropic rock: tensile failure occurs when the stratification is perpendicular to the tunnel section, while shear failure occurs when the stratification is tangential to the tunnel section. Bonini and Barla (2012) studied the behaviour of a novel yield-support system with highly deformable concrete elements

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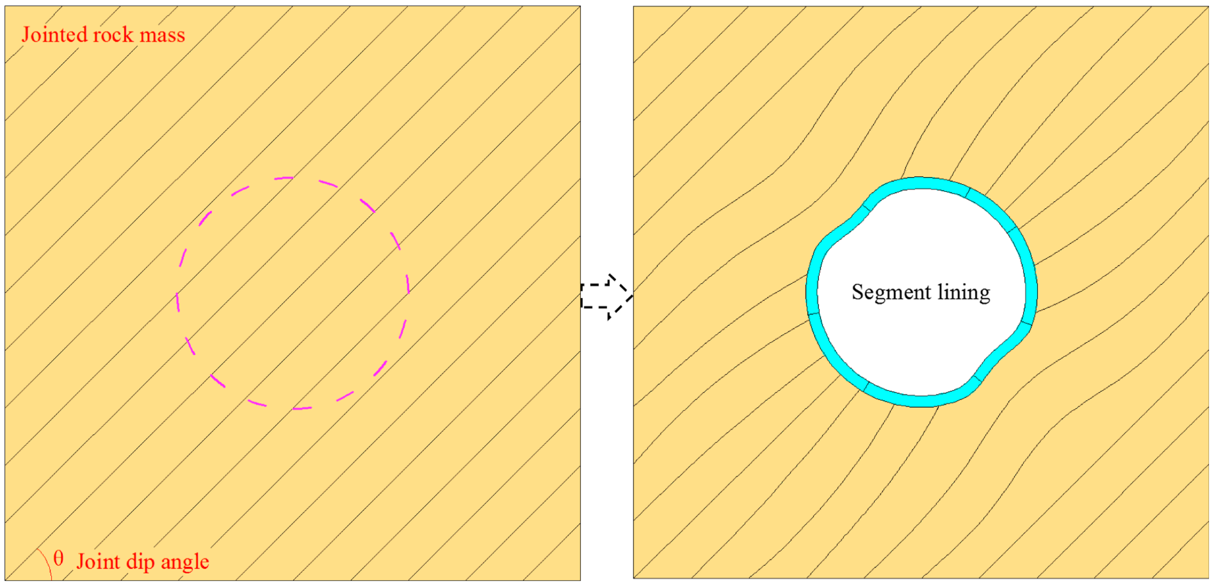

(a) Before excavation (b) After excavation

Fig. 1. Segmental lining deformation in a jointed rock.

Fig. 2. Synthetic rock-like model.

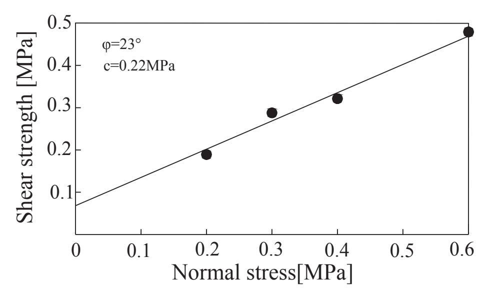

Fig. 3. Frictional features of the artificial joint surface.

Table 1
Segmental lining and modelled rock properties.

Item	Prototype	Model	Similarity ratio
Segmental lining			
Outer diameter (m)	7.3	0.52	12
Ring thickness (m)	0.35	0.027	12
Transverse effective stiffness ratio (η)	0.8	0.8	1
Elastic modulus (GPa)	32.5	2.3	12
Uniaxial compression strength (MPa)	26.8	2.2	12
Rock-like model			
Tensile strength – σ_t (MPa)	2.6	0.25	12
Uniaxial compression strength – σ_c (MPa)	42.5	3.2	12
Elastic modulus – E (GPa)	18.2	1.2	12
Cohesion – c (MPa)	2.2	0.15	12
Friction angle – φ (°)	40	36	1
Poisson's ratio – υ	0.3	0.34	1

incorporated in the primary lining. This method has been successfully adopted in the Saint Martin La Porte access adit (Lyon-Turin Base Tunnel), when excavating through a highly heterogeneous, overstressed and anisotropic rock mass exhibiting squeezing behaviour. Yang et al., (2014) proposed a high-resistance controlled yielding support concept that allows the tunnel support to resist deformation through high pre-tensioning force and high stiffness at low deformations, making use of a yielding tube at moderate deformations, and resisting deformation beyond a certain point by applying total-section Gunite after initiation of deformation. The practical results show that the high-resistance controlled yielding support technique can effectively control large deformation and long-time rheology of deep-well oil shale roadways. Meng et al. (2015) monitored large deformation and failure of the rock surrounding an extraction roadway within weakly cemented strata and showed that these can be effectively controlled by a combined bolt-cable support technology that ensures the long-term stability and safety of the surrounding rock and supporting structure.

Previous studies on this topic area have mainly focused on the failure mechanism of jointed rock masses by testing an individual support type usually associated with conventional excavation methods. The authors are not aware of any studies focused on physical tests that demonstrate the interaction between a jointed rock mass and multiple support system elements, including the segmental lining. This study investigates the effect of different dip angles of the joints (dip angle of the joint to the horizontal) on the bending moment, thrust force and deformation of a segmental lining and proposes an innovative support system of segmental lining combined with the use of highly deformable