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Time and technique of rehabilitation for large deformation of tunnels in jointed rock masses based on FDM and DEM numerical modeling

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ABSTRACT

When large deformation occurs in a tunnel, resulting in the primary lining intruding into the tunnel clearance, an appropriate treatment method is critically important to ensure that the tunnel can be completed on time and safely. This paper investigates the optimal treatment timing and technique for replacing the deformed primary lining. For this purpose, a two-stage numerical approach is employed for a severe tunnel collapse accident occurring on the Jinhong Highway. In the first stage, a global tunnel model is constructed using the finite difference method (FDM). The parameters are calibrated by the synthetic rock mass (SRM) approach, laboratory testing and field data. The continuously yielding (CY) joint model is used in the SRM, and its parameters are derived by the joint direct shear test. In the second stage, a local model encompassing the discrete fracture network (DFN) is constructed using the discrete element method (DEM) in the collapsed zone. Based on the DEM, the influence of the primary lining rehabilitation on the failure of the rock masses is analyzed. The local model is used to study the optimal rehabilitation timing, the optimum rehabilitation duration and the reasonable length of each replacement cycle. The following three conclusions are drawn. (1) The optimal rehabilitation timing is when the deformation of the rock masses reaches 90% of the total deformation. (2) There is a time threshold for the duration of the rehabilitation; if the duration is less than this value, the impact on the surrounding rock is small and almost the same. However, if the duration exceeds this value, the damage to the rock mass will increase as the duration increases. (3) The reasonable length of every replacement cycle should be less than the steel support spacing.

1. Introduction

Tunneling in mountainous areas often encounters complex geological conditions, e.g., high stress and jointed rock masses. As a discontinuous medium, the jointed rock mass is generally considered to be composed of intact rock blocks and joints. Shear failure may occur due to the low strength of the rock block or the weak joint (Hudson and Harrison, 2000). If the stress exceeds either the strength of the rock block or the joint, large deformations may occur, which will lead to the deformed primary lining intruding into the tunnel clearance. Large deformation is a concept relative to normal deformation, and there is still no uniform definition and criterion for it. In this study, the large deformation is defined as the deformation exceeding the design allowance value and the deformed rock mass or lining intruding into the tunnel clearance. To avoid the large deformation of the tunnel, one useful method is to provide a deformation allowance for various levels of the surrounding rock. However, if the surrounding rock is too weak and the support cannot bear the huge pressure from the rock mass, a large deformation of the tunnel is still possible.

In view of the large deformation, many researchers have studied many areas such as the influence factors, mechanisms and preventive measures. Anagnostou (1993) thought that the large deformation was due to the redistributed stress after excavation exceeding the strength of the surrounding rock. According to the stress-strain curves from uniaxial compression, Aydan et al. (1993) considered that the large deformation in discontinuous rock mass is due completely to shear failure. Based on this consideration, a method of predicting the extrusion potential of surrounding rock by tangential strain was proposed. The Terzaghi and Platts theory represented the collapse arch theory. They argued that the weight of the overlying strata is the pressure acting on the support structure, through which the corresponding strength support can be designed to prevent large deformation (Goodman, 1999; Karl, 1960). Subsequently, Salamon (1984) put forward the theory of energy support. Rabcewicz (2008) proposed the New Austrian Tunneling Method for dynamic design support based on the monitoring feedback data, which had become one of the main design and construction methods in tunnel engineering. These

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Fig. 1. Geographical location of the Jinhong Highway.

achievements are valuable to prevent the large deformation of the tunnel. However, in jointed rock masses, a great number of joints fundamentally change the performance of the rock masses. From the engineering point of view, Terzaghi (1946) and Goodman (1989) noted that the nature of the fracture network is as important and even decisive as the mineral composition. Therefore, large deformation is still an important disaster in tunnel.

For those tunnels that already experienced large deformation, how to replace the deformed primary lining, and when and how to expand the tunnel section to ensure the enough section tunnel clearance are still important problems that need to be solved urgently. However, there is little research about it (Liu et al., 2008). The conventional measure is to set up the temporary support until the tunnel becomes stable again, remove the deformed primary lining to expand the tunnel section to ensure the tunnel clearance, and finally re-install the strengthened primary lining. Unfortunately, in the process of replacement, due to the multiple disturbances to the surrounding rock, if the timing and approach are not appropriate, it is easy to cause tunnel large deformation again or even collapse. For example, a tunnel collapse accident occurred in a tunnel in the Jinhong Highway on April 29 in 2015, induced by the replacement of a deformed primary lining.

Tunnel deformation is caused by multiple factors. It is difficult to theoretically describe the support and destruction of tunnels. Many tunnels in China are constructed under complex and varied geological conditions, which implies that the engineering analogy method cannot be used effectively. Therefore, numerical analysis becomes a crucial tool for dealing with the large deformation problem. The finite element method (FEM) has become a very mature numerical simulation method since Blake (1966) first used it to solve the underground engineering in 1966. However, in a jointed rock mass, the existence of discontinuities makes the rock mass deformation and failure modes distinct from the continuous medium. The FEM and Finite Difference Method (FLAC) that have been used by many researchers have disadvantages in simulating large deformation or displacement of jointed rock masses (Yang et al., 2013). Therefore, the discontinuous method is considered a better method to address the large deformation in a jointed rock mass such as the distinct element method (DEM), the particle flow code (PFC) that is proposed by Cundall (1971) and Cundall and Strack (1979) and the discontinuous deformation analysis (DDA) that is proposed Shi and Goodman (2010). Among them, the discrete element software 3DEC, which has been developed to simulate the large displacement of discontinuous jointed rock masses, can effectively overcome these shortcomings above (Yang et al., 2013). At present, the 3DEC has been widely used in many fields. Nadimi et al. (2011) studied the time-dependent behavior of a pumped storage powerhouse cavern in a broken rock mass. Gao and Stead (2013) captured the cutter roof failure and a brittle fracture process with PFC3D and 3DEC without assumption of the identification of the fractured zone. Wang et al. (2012) analyzed the stress and stability of a mine tunnel in an underground iron ore mine coupled with an equivalent continuum analysis. Kulatilake and Biao (2015) built a 3DEC numerical model including the main faults to study the effect of a lateral pressure coefficient on the stability of the slope. Urli and Esmaieli (2016) successfully employed the DEM-DFN model to study the stability of an underground mine with different ore-skin thicknesses, determining the optimum thickness of the ore-skin. Karampinos et al. (2015, 2016) studied the squeeze deformation mechanism and the influence of the different support structures on the squeeze of the tunnel edge in hard rock.

Although the discrete element code 3DEC has congenital advantages in solving tunnel stability problems in jointed rock masses, the computing time will greatly increase if the number of discrete blocks increases, particularly when the DFN is incorporated into the model. Therefore, it is not practical to use only discrete element software to address the large and complex numerical models. In this paper, we combine the advantages of finite difference method FLAC 3D with the discrete element method 3DEC to improve research efficiency.