Computers and Geotechnics 61 (2014) 292–307

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

A physical and numerical investigation of the failure mechanism of weak rocks surrounding tunnels

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ARTICLE INFO

Article history:
Received 23 December 2013
Received in revised form 24 May 2014
Accepted 25 May 2014
Available online 3 July 2014

Keywords:
Physical model test
Digital speckle correlation method
Weak rocks surrounding a tunnel
Failure mechanism
FLAC^{3D} secondary development
Deformation modulus degradation

ABSTRACT

The large-scale construction of railway tunnels in China is hindered by several challenges, including large depths, large tunnel cross-sections, and fragile geological conditions. In this paper, we explored a new physical and numerical simulation method that improves upon the currently used methods to investigate the deformation and failure modes of weak rocks surrounding a tunnel. We also compared the results from physical tests and numerical simulations with the field measurements to demonstrate the effectiveness of the proposed numerical simulation method. In the physical model test, an artificial speckle field was developed by staining quartz sand particles and mixing the particles with barite powder and petroleum jelly in preset proportions. The artificial speckle field was employed in the digital speckle correlation method (DSCM) to monitor the evolution of the strain field on the surface of the plain strain model for tunneling during loading. A secondary strain-softening constitutive model using the numerical modeling code FLAC^{3D} was developed (degradation constitutive model) by considering the deformation modulus degradation in the numerical simulation. The failure mode of weak rocks surrounding a tunnel in the physical model test was examined using the developed degradation constitutive model. Both the physical and numerical results revealed that the least stable area was the shear wedge along the minimum principal stress, which was confirmed in the damage zone of the surrounding rocks. The results were consistent with previous research findings. The results of the DSCM in the physical model test indicated that the shear wedge in the middle part of the tunnel and the cracks around the arch of the tunnel were induced by shear strain, whereas the collapse of the arch was attributed to a combination of tensile strain and shear strain. A comparison of the physical and numerical simulation results demonstrated that the degradation constitutive model can be used to describe the extent and depth of the excavation damage zone of tunneling. A comparison of the displacements from the numerical simulation and field measurements indicated that the degradation model can be used to capture the displacement of weak rocks surrounding tunnels.

1. Introduction

Approximately 5000 railway tunnels are currently set to be constructed in China over the next 10 years; the total length of these proposed tunnels (9000 km) exceeds the total length of the existing railway tunnels in China. Currently, tunnel construction is hindered by several challenges, including large depths, large tunnel cross-sections, and fragile geological conditions. In the next stage of large-scale railway tunnel construction in China, the deformation failure mechanism of weak rocks surrounding a tunnel will be systematically investigated to provide additional information to tunnel designers and engineers and satisfy the urgent requirement of modern tunnel construction.

Tunnel excavation causes the stress in the rock mass surrounding the tunnel to be redistributed. When the secondary stress exceeds the strength of the surrounding rock, damage or local failure will occur at a specific distance from the tunnel walls. However, the extent of the mechanical effect of the excavation on the rock mass is limited due to the effect of pressure arching. The deformation and failure mechanism of tunnels has been extensively investigated in recent years. Huang et al. [11] and Lee et al. [21] explored tunnel stability and arching effects. Mollon et al. [30] and Wonga et al. [35] conducted an analysis of the passive failure mechanism of tunnel faces. Sterpi and Cividini [33], Kentaro et al. [19], and Huang and Xiao [13] determined that shear

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http://dx.doi.org/10.1016/j.compgeo.2014.05.017
0266-352X/

strain localization is the main type of failure for shallow tunnels in strain-softening media. The concept of "wedge shear" was introduced by Zhu et al. [42]. Hajiabdolmajida et al. [12], Corkum and Martin [3], and Chang et al. [4] determined that the failure mechanism of hard rocks around deep buried tunnels includes spalling and "wedge-shear" failure. Huang et al. [15] and Fraldi and Guarracino [9] concluded that collapse is the main failure mode in tunnels at a specific depth. Li et al. [24] adopted a 3D physical model and numerical simulation with field measurements to analyze the deformation mechanism for tunnels in dipping layered formation. Despite recent advancements in tunnel failure research, investigation of the failure mechanism of weak rocks surrounding tunnels remains challenging [19]. Additional studies are required to obtain improved physical and numerical simulation methods.

Use of physical model testing to investigate the progressive failure mechanism of tunnels [15] requires an effective observation method to monitor and record the evolution of the deformation field. The digital speckle correlation method (DSCM) has been employed for observations during tests of rock specimens on various scales [27,29,31] due to its merits as a full-field, noncontact, high-precision, and accessible measurement system and data-processing tool. Few researchers have used the DSCM in physical model material experiments because of the difficulty associated with forming speckles on the model surface. Researchers have used punctuation embedded surfaces [25] or created grid lines [21,15,36] to observe the deformation of the surrounding wall. However, the number of measurement points in these methods is limited, and advanced measurements of the deformation are not feasible. In our experiments, we used stained quartz sand mixed with barite and petroleum jelly to prepare the observed material and create an artificial speckle field on the model surface using chromatic aberration of the material, which was applied to the DSCM.

Numerical simulation methods, such as the discrete element method [5,18], coupling FEM and DEM strategies [28,7], and the FEM software RFPA [14,42], have been employed to model the fracture of geological material. Huang et al. [15] described the damage zone around a tunnel in strain-softening media using the FEM software ABQUES. The selection of the geotechnical constitutive model was an important consideration in the numerical simulation. The strain-softening model is extensively used to describe the nonlinear mechanical properties of weak rock around a tunnel [1,10,41,34,22,17]. An extensive range of closed-form solutions that are related to the strain-softening model, such as the models by Kyung-Ho et al. [20], Youn-Kyou and Pietruszczak [37], and Zhao and Cai [38], Zhao and Cai [39], have considered the effect of variable dilation within the softening zone and have been applied to calculate the excavation-induced damage zone and displacement around tunnels. However, these models disregard the notion that the deformation modulus also deteriorates within the softening zone. The degradation of the deformation modulus can have a considerable effect on the deformation properties [43,40], especially for the weak rock surrounding a tunnel. Because the strain-softening constitutive model FLAC^{3D} [16] also disregards deformation modulus degradation, it cannot be used to precisely analyze rock damage problems around tunnels. FLAC^{3D} provides a relatively convenient development environment in which the user can easily perform secondary development work in the VC++ environment. Here, we perform secondary development of the strain softening constitutive model, in which deformation modulus degradation (the degradation constitutive model) in FLAC^{3D} is considered.

In this paper, an exploratory physical model, a numerical simulation method and field measurements were used to evaluate the deformation and failure modes of tunneling in weak rocks. In the physical model testing, a mixture of barite powder, quartz sand, and petroleum jelly in preset proportions were used as the simulating model material and the artificial speckle field was created by staining quartz sand particles and mixing them with other materials. The artificial speckle was used in the DSCM to monitor the evolution of the strain field on the specimen surface during loading. In the numerical simulation, the degradation constitutive model was subsequently developed in the FLAC^{3D} code in a VC++ environment and the degradation constitutive model was employed to study the failure mechanism and deformation law of weak rocks surrounding a tunnel. The physical, numerical simulation and field measurement results were compared to demonstrate the effectiveness of the developed degradation constitutive model.

2. Physical model test

2.1. Apparatus and loading system

In the plane strain model, we used an experimental table that simulated tunnel construction in the experiment (Fig. 1). The experimental table, which had dimensions of $1000 \times 300 \times 1620$ mm, was created in the Beijing Jiaotong University Laboratory of the Tunnel Engineering Center. A plexiglass plate was bolted to the front of the apparatus to enable the simulation of the plane strain and observation of the deformation process. A 200-mm-diameter circular hole located 750 mm from the top of the glass plate simulated the excavation of the tunnel structure. The maximum loading of the experimental table is 0.3 MPa; this loading consists of vertically uniform pressure that simulates the self-weight stress σ_z. Because the plane strain model is fixed horizontally, the horizontal stress σ_x is approximately $[\mu/(1-\mu)]\sigma_z$. The local deformation of the structure system under pressure is less than 3 mm, with a machining precision of 0.5‰.

Two types of loading systems (gasbag loading and lifting loading) were employed in the physical model testing to observe the variations in failure caused by different loading systems. For gasbag loading, the initial loading was 0.04 MPa and the overlying load was gradually increased in 0.02 MPa intervals until the tunnel failed. Each loading was conducted after the model achieved deformation stability. In the lifting-loading mode, the overlying load comprised 1 kN per step and gradually increased until the tunnel failed.

2.2. DSCM monitoring system

The DSCM was first presented by I. Yamaguchi and co-workers in the 1980s [2]. In this method, the image of the speckle field on the surface of the object before and after deformation is recorded

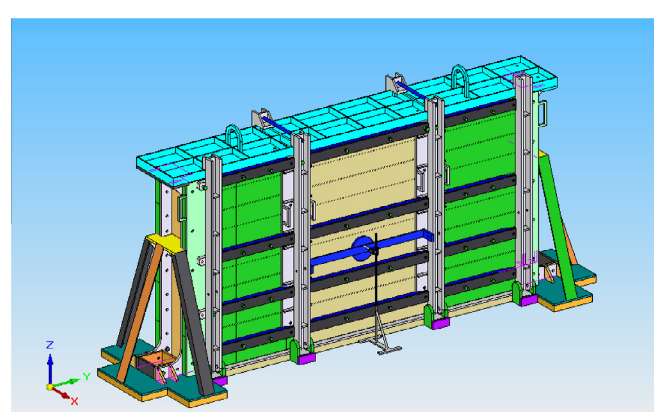

Fig. 1. Apparatus used in the physical model test.