Tunnelling and Underground Space Technology 76 (2018) 48–63

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

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

Numerical modeling of the time-dependent development of the damage zone around a tunnel under high humidity conditions

Shibin Tang*, Chaoyun Yu, Chunan Tang

State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian 116024, China

ARTICLE INFO

Keywords:
Time-dependent deformation
Excavation damage zone
Humidity diffusion
Numerical simulation
Tunnel

ABSTRACT

A coupled mechanical and diffusion model is proposed to determine the instantaneous and time-dependent elastoplastic behaviors of rock under high humidity conditions and model the time-dependent development of an excavation damage zone (EDZ). Time-dependent deformation is a macroscopic consequence of the progressive damage caused by stress and the degradation of the elastic modulus and strength of rock. An experiment is designed to verify the numerical model, and good agreement is observed between the experimental and numerical results. The time-dependent deformation of specimens at different stress levels is simulated to study the sensitivity of the results to the stress level. The influence of joints on the development of an EDZ is studied based on the proposed numerical model. The application of this numerical model to the in situ development of an EDZ in the headrace tunnel of the Jinping II Hydropower Station indicated that the support system did not prevent the development of the EDZ but effectively prevented the deformation of the surrounding rock under high humidity conditions. The conclusions of this study provide some guidelines for designing underground openings under highly humidity conditions.

1. Introduction

The zone of damaged rock created around an underground opening is often called the excavation damage zone (EDZ). The characterization of this zone is very important when constructing underground spaces, such as subways, headrace tunnels, natural gas storage areas and nuclear waste repositories. Several authors have considered the development of EDZs by conducting laboratory and in situ experimental investigations in different underground research laboratories (Blümling et al., 2007; Martino and Chandler, 2004; Pellet, 2006). Many numerical models have been proposed to evaluate the development of EDZs, including those proposed by Boidy et al. (2002), Cantieni and Anagnostou (2009), Chen et al. (2004), Dhawan et al. (2002), Eberhardt (2001), Pellet and Zerfa (2005), and Zhu and Bruhns (2008).

Two types of EDZs exist. The first type involves the short-term development of cracks due to blasting, drilling and mechanical excavation. In this case, excavation disturbs the stress field around the surrounding rock and causes rock failure. This type of EDZ develops soon after excavation. The second type of EDZ involves the long-term deformation of the surrounding rock, which corresponds to the time-dependent deformation of the rock. When a stressed rock mass is excavated to form an underground opening, short-term instabilities can occur during or after operation. The underground opening can also collapse many days or years after excavation. Indeed, the time-dependent behavior of rock is an important underground construction issue, as summarized by Brantut et al. (2013). Thus, the time-dependent development of an EDZ must include the time-dependent crack growth and the evolution of the mechanical properties of the rock. Golshani et al. (2007) proposed a micromechanics-based damage model for analyzing the lengths of microcracks and the development of the EDZ with time. Pellet et al. (2009) presented a numerical simulation of the mechanical behavior of deep underground galleries that emphasized the time-dependent development of EDZs. Zhang et al. (2016) proposed a creep model based on thermodynamics and the internal state variables theory to simulate the complex time-dependent development of EDZs.

Viscoelasticity or viscoplasticity is often used to describe creep deformation. These terms provide a mathematical description of creep but do account for the internal physical mechanisms associated with creep deformation (Shao et al., 2003). However, scanning electron microscopy (SEM) results have suggested that creep deformation and creep failure result from the growth of microcracks originating at the locations of preexisting defects (Yoshida and Horii, 1992). Moreover, an overwhelming amount of experimental and observational evidence suggests that the growth of preexisting cracks and flaws via stress corrosion is the main mechanism of subcritical crack growth in rocks

* Corresponding author.
E-mail address: tang_shibin@dlut.edu.cn (S. Tang).

https://doi.org/10.1016/j.tust.2018.03.012
Received 30 May 2016; Received in revised form 24 January 2018; Accepted 8 March 2018

(Anderson and Grew, 1977; Atkinson, 1982, 1984; Atkinson and Meredith, 1987; Costin, 1987). Details of these processes were published by Potyondy (2007). Thus, stress corrosion is likely the main source of time-dependent rock deformation. In engineering, the moisture or humidity in the air serves as an important stress-corrosion agent that affects the growth of cracks in rocks and influences their long-term behaviors (Nara et al., 2008; Nara and Kaneko, 2005; Nara et al., 2009b). Using underground excavation as an example, if the relative humidity at the free surface is higher than that in the surrounding rock, the humidity gradient becomes a driving force for moisture diffusion from zones of high humidity to zones of low humidity, and this process subsequently results in the degradation of the mechanical properties of the surrounding rock and leads to the time-dependent development of an EDZ. Hoxha et al. (2005, 2006) found that relative humidity significantly affects the time-dependent deformation of gypsum. This effect is thought to result from the migration of water molecules in the crystalline structure of gypsum under stress. Auvray et al. (2008) investigated the time-dependent behavior of gypsum in the laboratory based on the relative humidity and obtained in situ measurements revealing that the relative humidity influences the convergence values. However, both studies assumed that the humidity in the rock remained constant or uniformly changed, and neither considered the diffusion of humidity (or moisture). When moisture penetrates rock, it weakens the interatomic bonds and accelerates the time-dependent development of the EDZ. For water-sensitive rocks such as mudstone, shale and chlorite schist, the time-dependent deformation caused by moisture/humidity is much larger than that caused by stress-induced damages.

Previous studies focused on the effect of moisture or humidity on the mechanical behavior of rock, e.g., subcritical cracking (Auvray et al., 2008; Jeong et al., 2007; Nara et al., 2008, 2009a, 2009b). However, the time-dependent development of underground EDZs under high humidity conditions has not been studied. In this study, a coupled mechanical and diffusion model is proposed to simulate the instantaneous and time-dependent elastoplastic behaviors of rock under high humidity conditions, as well as the time-dependent development of the EDZ. Time-dependent deformation is a macroscopic consequence of the progressive damage/degradation of the properties of a material caused by a force or multiple forces and water. The damage is caused by both humidity diffusion and stress or strain forces, which are functions of the deformation process and humidity content. In our numerical model, the moisture content of the rock is dynamic rather than static and is related to the humidity diffusion process.

2. Numerical methodology

2.1. The diffusion of humidity in rock

The capillary pressure gradient (Darcian transport) of pore water and the moisture concentration gradient (Fickian transport) of water vapor are the two basic driving forces behind the drying and wetting processes that occur in partially saturated porous media (Zeng et al., 2013). Fickian transport is more convenient and suitable for studying the movement of moisture when a rock-like material is predominantly unsaturated, and moisture mainly moves through the material via a vapor flux and when the relative humidity (RH) in the pores of the material is between 15 and 100% (Bažant and Najjar, 1972). The moisture flux, J, can be defined in terms of the pore RH gradient as follows:

$$J = -D_h grad(RH) \tag{1}$$

where J is the moisture flux in m/s and is the mass of water that passes through an area perpendicular to J per unit time; RH is the relative humidity in the pores or the water content; D_h is the humidity diffusion coefficient and is a function of the pore RH; and $grad$ is the gradient function. The pore RH is the ratio of the current vapor pressure to the vapor pressure at saturation, which is difficult to measure and typically determined based on its relationship with the degree of saturation obtained from a humidity isotherm test.

According to Bažant and Najjar (1971, 1972), who used Fick's diffusion laws for RH, the moisture potential can be represented using the Kelvin-Laplace equation. If the temperature is assumed to be constant, Eq. (1) can be expressed as follows:

$$\frac{\partial RH}{\partial t} = D_h \nabla^2 RH \tag{2}$$

where t is the time in seconds; div is the derivative function; and D_h is the diffusion coefficient, which is a function of RH.

The initial conditions within a rock can be regarded as the initial RH at the beginning of moisture diffusion, which can be written as follows:

$$RH(p, t_0) = RH_0(p) \tag{3}$$

where p denotes the coordinates (expressed as x and y) in two dimensions; t_0 is the initial time; and h_0 is the initial RH in the rock.

The humidity at the surface boundary can be characterized using the following equation:

$$RH_s = RH_{en} \tag{4}$$

where RH_{en} and RH_s are the relative humidity of the environment and the pore relative humidity at the material surface, respectively.

2.2. The relationship between the strength/elastic modulus and humidity

The moisture content is one of the most important factors that decreases the strength of a rock. A small increase in the moisture content may result in significant reductions in both strength and deformability (Hawkins and McConnell, 1992). Decreases in the strength and deformability of rocks with increasing moisture content are important in studies of the mechanical behaviors of rock. The sensitivities of different types of rock to moisture are highly variable. Several investigations of the influences of the moisture content on the mechanical properties of rock materials have been conducted. Colback and Wild (1965) studied the influences of moisture on the strength and deformability of rocks with shale lithologies and a quartzitic sandstone and found that these rocks experienced a 50% loss in uniaxial compressive strength (UCS) when dried from their saturated condition. Dyke and Dobereiner (1991) demonstrated the variations in UCS with the moisture content for three quartz arenites with dry strengths ranging from approximately 34 to 70 MPa. Hawkins and McConnell (1992) discussed the loss of UCS between dry and saturated conditions for 35 types of British sandstone and observed the greatest loss of strength in greensand from Wiltshire (78%) and the smallest loss of strength (8%) in siliceous sandstone from the Bristol area. The results of several experiments involving coal mining rocks, such as shale, mudstone and siltstone, indicated that the UCS and elastic modulus decrease linearly with increasing water content (Chugh and Missavage, 1981). Vásárhelyi (2003) analyzed published data and showed that the UCS values under dry and fully saturated conditions are linearly correlated. Based on the results of Chugh and Missavage (1981) and Vásárhelyi (2003), this paper assumes that the impacts of the humidity on the strength and elastic modulus can be described by the following relationships:

$$\sigma_c = \begin{cases} \sigma_{c0} & h < h_{cri} \\ \sigma_{c0}\left(1, -, \frac{h - h_{cri}}{1 - h_{cri}}, \omega\right) & h \geq h_{cri} \end{cases} \tag{5}$$

$$E = \begin{cases} E_0 & h < h_{cri} \\ E_0\left(1, -, \frac{h - h_{cri}}{1 - h_{cri}}, \xi\right) & h \geq h_{cri} \end{cases} \tag{6}$$

where σ_c and σ_{c0} represent the current and initial uniaxial strengths of rock, respectively; E and E_0 represent the current and initial elastic moduli of rock, respectively; h is the current RH; and h_{cri} is a critical