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A coupled hydro-mechanical creep damage model for clayey rock and its application to nuclear waste repository

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ABSTRACT

In this paper we propose a new nonlinear elasto-viscoplastic damage model, based on a modified Mohr-Coulomb criterion, to study the creep and seepage in clayey rock during construction of a high-level radioactive waste repository through laboratory experiments and field tests. First, three types of damage evolution equations are constructed by using the relationship between the damage variable and the strain. Then, a self-healing model is investigated for the clayey rock by considering the damage, confining pressure, pore water, and duration of saturated state. By introducing the damage, permeability evolution and self-healing as the key factors, a fully coupled hydro-mechanical model for clayey rock is developed with the commercial software ABAQUS. The hydro-mechanical behaviour in the surrounding rock is simulated with the proposed model considering the actual construction of the repository. The numerical results show that the construction quality has a significant effect on the stability of the rock formation, and that the extent of the horizontal gallery disturbed by shield tunnelling is less than that of the test drift disturbed by using jackhammers method. The creep damage of the surrounding rock increases rapidly at the early stage and tends to stabilize gradually after 15 years, and the damage in the middle part of the surrounding rock is larger than that in the bottom and top parts. In addition, due to the self-healing effect of clayey rock, around three years later, the permeability of the excavation disturbed zone (EDZ) is close to that of the original clayey rock with an order of magnitude 10^{-19} m^2. The present model can also be used to predict the long-term stability of tunnels.

1. Introduction

Characterization of hydro-mechanical coupling of rocks has become one of the most important topics in underground engineering (Kolditz et al., 2015) such as resource extraction, nuclear waste disposal and deep storage of natural gas or oil. Clayey rock, a class of soft rock that often causes instability problems in many underground engineering projects (Zhang and Rothfuchs, 2004; Fan et al., 2010; Yang et al., 2014; Liu et al., 2015), also involves this coupling process and particularly its creep properties are affected by the hydro-mechanical interaction. As underground engineering activities go deeper and deeper, the hydro-mechanical behaviours of clayey rock become more complicated because of damage evolution and pore fluid flowing in the disturbed rock mass (Wileveau and Bernier, 2008; Pardoen et al., 2015; Lisjak et al., 2015). Furthermore, the permeability and fracture self-healing of disturbed rock are significantly affected by damage (Bastiaens et al., 2007; Zhang and Rothfuchs, 2008; Elkhoury et al., 2015). Therefore, study on the hydro-mechanical coupling and time-dependent creep characteristics of clayey rock is of great interest and importance for physical repository design.

As one of the major soft rocks, clayey rock has obvious creep behaviour, which usually causes surrounding rock instability and supports structure failure in the tunnel, thus leading to high economic and environmental costs. Many researchers have investigated the creep characteristics of clayey rock through triaxial creep tests. It is found that there exist stress thresholds when the creep deformation occurs, and that different creep stages such as steady-state creep and accelerating creep have different stress thresholds. Although the creep behaviour of clayey rock has been widely investigated (Rejeb, 2003; Gasc-Barbier et al., 2004; Fabre and Pellet, 2006; Fan et al., 2010), there are few experimental studies under hydro-mechanical (HM) coupling conditions. Drained and undrained triaxial creep tests are most widely used for clayey rock. Extensive work has been conducted by the Belgian Agency for radioactive wastes management to characterize the creep behaviour

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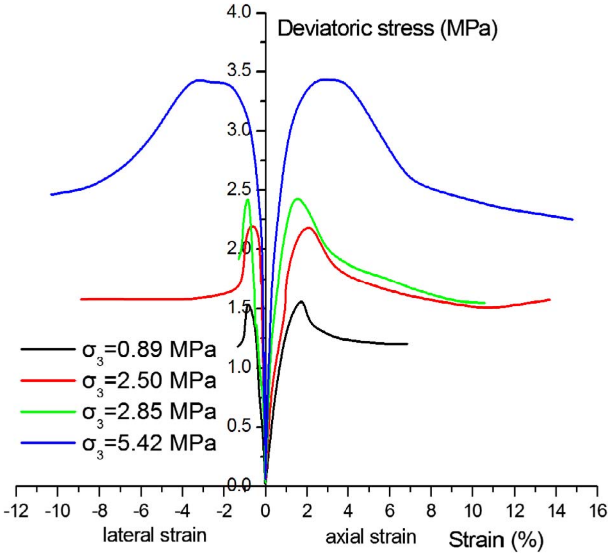

Fig. 1. Stress-strain curves of clayey rock under various confining pressures.

of Boom clay considering the HM interaction. Giraud and Rousset (1996) studied the creep behaviour under complex stress paths, and found that the creep deformation was significant under undrained conditions. Gong (2015) stated that the creep rate of clayey rock under drained condition was smaller than that under undrained condition. From the triaxial creep tests under HM coupling, Jia (2009) and Yu et al. (2015) found that there existed a deviatoric stress threshold below which no obvious creep was observed. When the deviatoric stress exceeds the threshold value, the creep deformation increases gradually with time, and the creep behaviour becomes more and more significant when the deviatoric stress increases. In addition, the mechanical properties of clayey rock are deteriorated by creep deformation and are nonlinearly dependent on the coupling of damage and hardening (Renner et al., 2000; Gasc-Barbier et al., 2004; Fabre and Pellet, 2006; Fan et al., 2010; Yu et al., 2015).

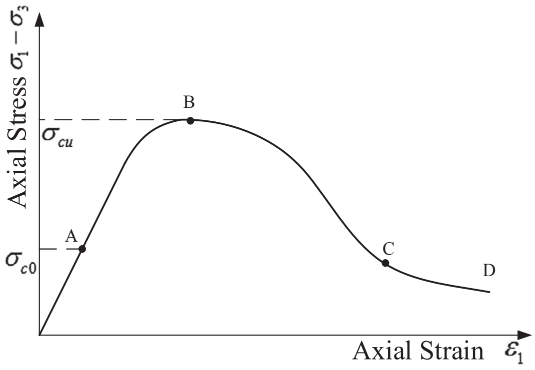

Fig. 2. Stress-strain curve of clayey rock in different stages.

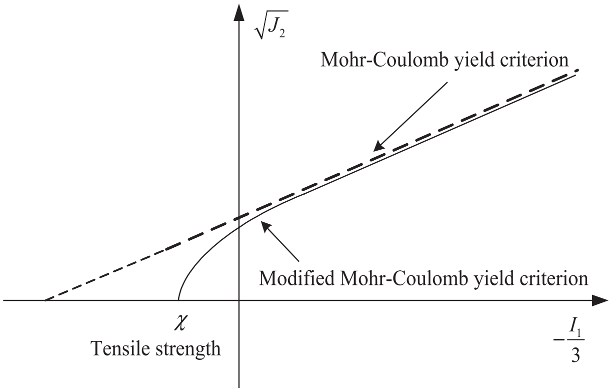

Fig. 3. Modified Mohr–Coulomb yield criterion.

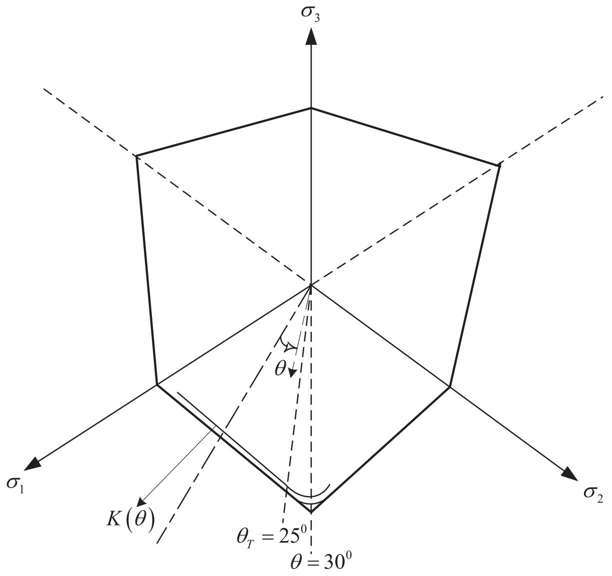

Fig. 4. Smooth treatment of Mohr-Coulomb criterion in the π plane.

A proper creep constitutive model, which is capable of describing precisely the time-dependent deformation behaviours, is the key to the stability analysis of the clayey rock. Because the underground space has safety and environmental issues, a deep understanding of the rheological behaviours of clayey rock becomes vitally inportant. Existing time-dependent constitutive models include mainly the component rheological (CR) model, yield surface rheological (YSR) model, empirical rheological (ER) model, and endochronic rheological constitutive (ERC) model (Cristescu and Hunsche, 1998; Rejeb, 2003; Jia, 2009; Rutenberg and Lux, 2011). The CR model is the most popular one due to its simple concept and capability of revealing the rheological properties of rock. However, the predicted yield surface is static in the CR model, which has the deficiency of fast creep convergence or accelerating creep. Compared to the CR model, the YSR model is more reasonable because the predicted yield surface changes dynamically with time. The ER model is able to explain the actual rheological behaviours under different stress paths, but it requires many creep tests to build. The ERC model can deal with not only static rheological behaviour, but also dynamic one under cyclic loading and unloading and

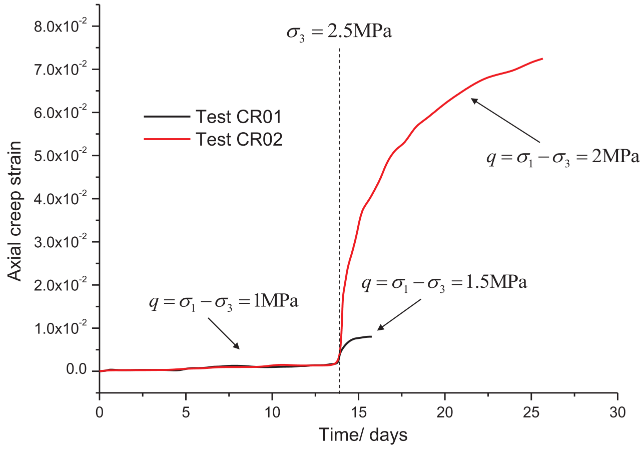

Fig. 5. Drained triaxial creep tests of clayey rock.