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Time-dependent behaviour and stability evaluation of gas storage caverns in salt rock based on deformation reinforcement theory

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ABSTRACT

To simulate the time-dependent deformation and quantitatively evaluate the global stability of gas storage caverns in salt rock, the nonlinear viscoelastic, viscoplastic and viscodamage models are incorporated into the deformation reinforcement theory (DRT). A quantitative criterion for the long-term stability evaluation of gas storage caverns is established during the non-equilibrium evolution process based on a T–ΔE curve, where T is time and ΔE is plastic complementary energy (PCE). PCE quantitatively indicates the global stability of gas storage caverns. Over force clearly exhibits the local failure position and mode of gas storage caverns, determines the internal effective driving force of unrecoverable time-dependent deformation or damage evolution, and is also the required optimal reinforcement force. DRT is applied to analyse the time-dependent deformation, global stability and local failure of a double-cavern of gas storage in salt rock.

1. Introduction

Salt rock has very low permeability, high ductility and is able to self-heal damage. Moreover, underground salt caverns can be constructed by solution mining techniques, which are less expensive than other conventional excavation techniques. These advantages make salt deposits an ideal media for the construction of underground cavities for natural gas, hydrocarbons and other radioactive waste (Nazary Moghadam et al., 2013).

Numerous test studies have shown that the mechanical response of salt rock is time-dependent and exhibits both recoverable (viscoelastic) and irrecoverable (viscoplastic) deformations, and acceleration deformations of a tertiary creep phase due to damage evolution (Cristescu, 1993; Chan et al., 1994; Jin and Cristescu, 1998; Yahya et al., 2000; Hou, 2003). As shown in Fig. 1, the red curve represents a typical creep process of rock salt that consists of a primary creep phase, a steady creep phase and an accelerated creep phase. In the primary creep phase, the creep deformation rate continuously decreases in time until a steady creep deformation rate is reached. In the steady creep phase creep deformation continues with a constant or nearly constant creep deformation state until the failure in the accelerated creep phase.

The viscoelastic and viscoplastic constitutive models are usually used to describe the time-dependent behaviour of rock salt. Zienkiewicz et al. (1968) used a number of Kelvin models connected in series to represent the viscoelastic behaviour of a material and developed a completely general method of numerical viscoelastic stress analysis. Perzyna (1966) first utilised the overstress concept in viscoplasticity theory to describe the time-dependent inelastic behaviour. Zienkiewicz and Cormeau (1974) then presented a numerical procedure to address a general elastic/viscoplastic material when the plastic flue rule and yield condition were not associated. In the procedure, if the stress state exceeds the yield condition after an elastic prediction of stress increment, viscoplastic strain is assumed to develop in time until the yield condition is satisfied within an acceptable tolerance. There are two viscoplastic models based on the overstress concept: the Perzyna model (Perzyna, 1966) and the Duvaut-Lions model (Duvaut et al., 1976). They have the same constitutive formulations in a one-dimensional stress state but different constitutive formulations when extended to a three-dimensional stress state.

The change of microstructure in salt rock during deformation usually causes micro-damage (micro-cracks and micro-voids) under a variety of loading stress levels and strain rates. The growth of deformation and damage over time is of vital importance for the global stability and local failure of gas storage caverns in salt rock. Specific phenomena such as tertiary creep, post-peak behaviour of the stress–strain response and degradation in the mechanical properties of salt rock are mostly due to damage and cannot be explained only by viscoelasticity or viscoplasticity constitutive models. Models based on continuum damage mechanics are

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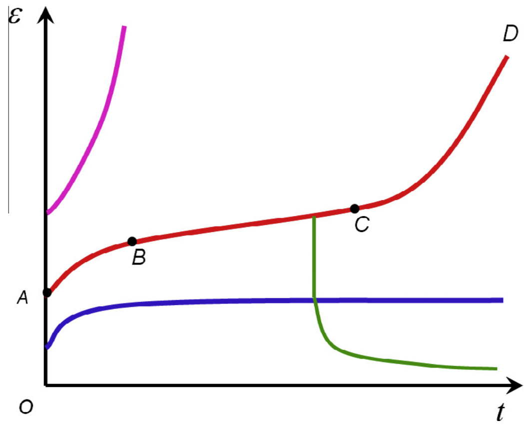

Fig. 1. Creep curves of rock salt.

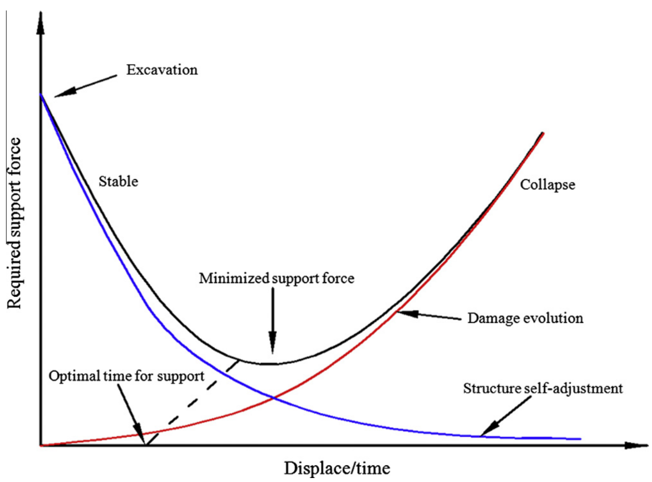

Fig. 2. Relation between support force and tunnel convergence in NATM.

effective to model the degradations in salt rock due to micro-cracks and micro-voids.

Ghorbani and Sharifzadeh (2009) assessed the long-term stability of powerhouse cavern based on displacement back analysis method. Sharifzadeh et al. (2013) adopted Burger-creep viscoplastic model (CVISC) to simulate numerically the time-dependent behaviour of tunnel lining in weak rock mass based on displacement back analysis method. Golshani et al. (2007) extended the micromechanics-based damage model proposed by Golshani et al. so that time-dependent behaviours of brittle material could be taken into account, with special attention to the numerical analysis of an Excavation Damage Zone (EDZ) around an opening, which is a major concern in assessing the safety of underground repositories.

Pellet et al. (2005) presented a new constitutive model for the time dependent mechanical behaviour of rock which takes into account both viscoplastic behaviour and evolution of damage with respect to time by associating a viscoplastic constitutive law to the damage theory. Afterwards, Pellet et al. (2009) utilised Lemaitre's viscoplastic damageable model in which both viscous and damage parameters are taken into account to model the rock mass behaviour, and presented a 3D numerical simulation of the mechanical behaviour of deep underground galleries with a special emphasis on time-dependent development of the Excavation Damage Zone (EDZ).

Darabi et al. (2011) developed a thermo-viscoelastic–viscoplastic–viscodamage constitutive model for asphaltic materials. They proposed a temperature-dependent viscodamage model whose damage evolution law is a product of a power law function of stress level and an exponential function of effective total strain including both viscoelastic and viscoplastic components, and coupled it to the temperature-dependent Schapery's nonlinear viscoelasticity and the temperature-dependent Perzyna's viscoplasticity constitutive model. Wang (2004) presented a new constitutive creep-damage model for salt rock by introducing damage and a concept of "damage accelerating limit" into Carter's creep model to investigate the characteristics of the long-term stability and deformation of rock salt surrounding a cavity for gas storage. The model involves the transient-creep stage, steady-creep stage described by Carter's equation, and a term of creep induced by damage. The damage evolution equation takes the form of Lemaitre/Chaboche's equation by introducing a concept of damage accelerative limit.

Pre-loaded by tectonic and gravitational forces for many millions of years, the rock structure is in a state of pre-loaded equilibrium. In some locations, it is in a state of critical equilibrium. In other locations, the equilibrium is far from critical. Any engineering activity will disturb this pre-existing equilibrium. Excavation unloading is the essential cause for the deformation and failure of rock structures. Failures caused by excavation unloading include damage and fracture, disintegration and rock-burst, etc. Excavation unloading can be viewed as a non-equilibrium evolution process. It is very important and necessary to reveal the driving force behind the non-equilibrium evolution processes, and demonstrate its engineering values, especially for reinforcement design.

The relation between time-dependent deformation, damage evolution and reinforcement force during excavation unloading process can be well shown by the ground reaction or response curve (GRC) in the New Austria Tunneling Method (NATM) (Rabcewicz, 1964; Brown et al., 1983; Alonso et al., 2003; Alejano et al., 2009). The typical relation between the required support force and the convergence of the tunnel wall after excavation is indicated by the GRC in Fig. 2. This NATM support force curve also reflects the variation of driving force during excavation unloading process.

The stability of underground gas caverns is essentially a deformation-related issue. Numerical analysis method such as the three-dimensional nonlinear finite element method (FEM), have significant advantages in structural response analysis, but they are not easily used to quantitatively evaluate the global stability of gas caverns and determine the failure position and mode through responses such as displacement, stress fields and plastic regions, let alone the reinforcement design. To overcome the deficiency of FEM in stability evaluation and reinforcement analysis, Yang et al. (2008b) developed the deformation reinforcement theory (DRT) and presented the concepts of Plastic complementary energy (PCE) and Unbalanced force. PCE is utilised to quantitatively evaluate the global stability of structures. Unbalanced force clearly exhibits the local failure position and failure mode of structures and determines the optimal reinforcement force. DRT has been applied to stability evaluation, failure analysis and reinforcement analysis in significant geotechnical engineering such as high arch dam (Yang et al., 2008b) and high slope (Liu et al., 2012). However, this previous work is based on the time-independent elasto-plasticity theory and the time-dependent behaviour of material is not taken into account.

The main objective of this paper is to incorporate the nonlinear viscoelastic, viscoplastic and viscodamage models into deformation reinforcement theory (DRT), which unifies global stability evaluation, failure analysis, reinforcement design and safety monitoring. Based on the T–ΔE curve, a more effective and unified quantitative stability criterion for gas storage caverns in salt rock under various factors is developed. The outline of this paper is as follows: In Section 2, the coupled nonlinear viscoelastic,