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Investigation on the cavity evolution of underground salt cavern gas storages

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ABSTRACT

Because of their prominent advantages in strategic energy reserves and peacetime peak adjustment, underground salt cavern gas storages have drawn attention worldwide. Moreover, embedding wastes in the underground space of salt caverns complies with the global theme of ecological environmental protection. The creep properties of underground salt cavern gas storages directly impact the safety and stability of the long-term operation of gas storages. In this study, the physical model of the cavity in a selected gas storage was established based on the creep law and creep constitutive model of salt rocks. FLAC 3D software was adopted to simulate the rheological displacement and related plastic deformation of the surrounding rock under varying internal pressures. Safety indexes, such as the cavity volume shrinkage and safety factors of surrounding rocks, were calculated for different operating conditions. By controlling the cavity volume shrinkage, both the minimum and maximum operating internal pressure values were obtained. An optimized design scheme including optimized cavity shape and height-diameter ratio was proposed to ensure the long-term safe and stable operation of gas storages.

1. Introduction

Saturated multisource brine, a type of salt rock, undergoes three stages: salt crystallization, sedimentation, and accumulation. The underground formation of salt rock occurs over millions of years. Today, solution mining is widely applied in the construction of underground salt cavern gas storages. Solution mining consists in finding rock salt beds with suitable geological conditions, drilling through rock formations using conventional boring methods, and injecting fresh water into the underground area to wash out salt rock deposits by taking advantage of the water solubility of salt. Through a series of physical and chemical reactions, underground salt mines dissolve into fresh water, which is thereby collected and pumped out. Finally, the cavity formed can be utilized for energy storage (Hunsche, 1984). Compared with other rocks, salt rock exhibits excellent mechanical properties, such as good creep resistance, high thermal conductivity, a low permeability rate, low porosity, a strong plastic deformation capacity, and a good self-injury-recovery ability. Thus, underground salt caverns are unmatched with respect to the safe and closed storage of energy and are widely recognized as the ideal choice for energy reserves and waste embedment (Cristescu, 1993). Thousands of salt caverns, including 100 in France alone, are being used to store hydrocarbons (Weidinger et al., 1997). These caverns are the safest way to store large quantities of hydrocarbons, as salt formations are almost perfectly impermeable and fire or explosion is impossible underground.

With the wide application of underground salt cavern storages, great progress has been made in studying the variation in the regularity, security, and stability of underground cavities. Hunsche (Ladanyi and Gill, 1981) and Cristescu (Staudtmeister and Rokahr, 1997) et al. concentrated mainly on temperature, and they experimentally tested the features of salt rocks at multiple creep stages under both single-step and multiple-step loading conditions. These researchers concluded that creep was related to the temperature, stress and strain loading path at the initial creep stage of salt rocks. The creep rate varied little during steady creep when temperature and stress conditions remained constant. The rock salt entered the fracture stage as creep accelerated. One setback encountered in this type of research arises from differences in environments; the geological conditions in China differ greatly from those in other countries, where the majority of research on this topic has been conducted. Therefore, massive studies on the mechanical

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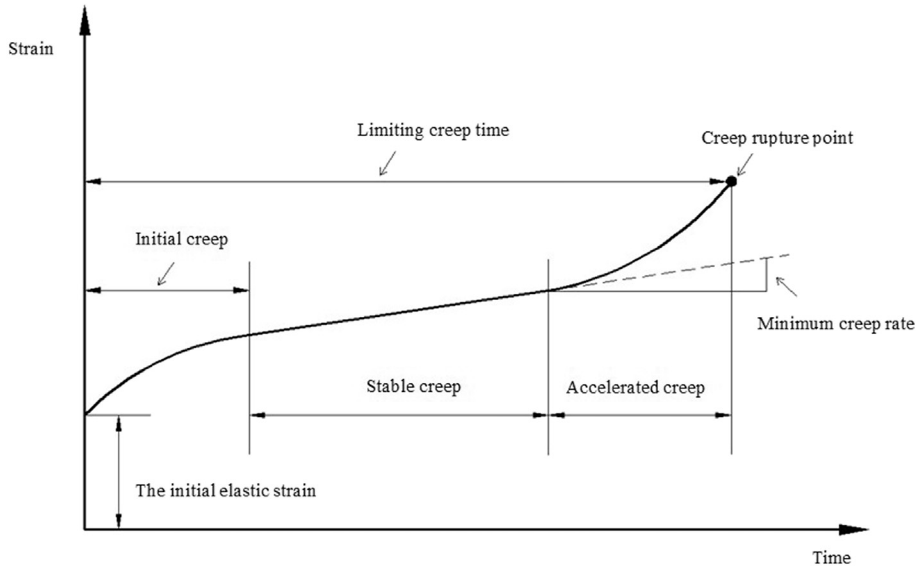

Fig. 1. Typical salt rock creep curve.

properties, damage mechanism, and creep features of salt rocks are necessary to summarize the mechanical damage properties of the interbedded thin stratified salt rocks in China.

Over the years, much research has been performed regarding the various properties and applications of rock salts. Cristescu (Asanov and Pan'kov, 2004) proposed a model to describe the initial and steady creep state of salt rocks. Szczepanik (Stead and Szczepanik, 1991) discussed the creep phenomena from the perspective of damage mechanics. Chen Feng (Chen et al., 2006) et al. conducted creep tests under varying surrounding pressures and axial pressures, and the team researched the creep properties of salt rocks and laminated salt rocks containing mudstone from the Yunying Salt Mine in Hubei. Based on the test results, the authors constructed corresponding creep constitutive relations. Cundaal, Bergeron and Passaris (Wang et al., 2011) et al. adopted viscoelastic plasticity theory in investigations on the initial creep constitutive relationships. However, the model was only applicable within the linear elastic deformation range according to engineering testing, as the model was unable to accurately describe the non-linear features of salt rock creep. Most creep constitutive models presently used are original or improved classical constitutive models from abroad. A series of deformation constitutive model equations with limited, easy-to-access parameters and definite physical meanings suitable for the special features of Chinese salt rocks have yet to be developed.

Lux, from Germany, proposed three criteria for gas storage stability in his first monograph published on the mechanical design of salt cavern storages, and these criteria are still used today (Dreyer, 1973). The three principles are the wall caving failure criterion, the jamb safety criterion, and the creep fracture criterion. Dreyer (Tillerson, 1979a) et al. conducted intensive studies on the mechanical performance and stability of salt rocks under different stress conditions and obtained the mechanical parameters of salt rocks suitable for energy storage. Tillerson (Liu et al., 2006) et al. carried out a stability analysis on the underground salt cavern storages along the US Gulf Coast, and they determined the creep law of salt rocks. By combining this law and finite element software, they simulated and predicted the long-term operation stability of the storages.

Despite the extensive research mentioned above, systematic and comprehensive investigations on the factors influencing stability and on the evaluation criteria that are relevant during the long-term operation of underground salt cavern gas storages under the unique conditions of salt rock deposits in China are still lacking. These studies hold great significance for the operational safety and service life of salt cavern storages in China. This paper analyses the morphology evolution regularity of cavities using numerical simulation software in combination with the unique conditions of salt cavern gas storages in China based on studies regarding the mechanism and features of creep mechanics. The design parameters are optimized to ensure the safe and stable long-term operation of salt cavern gas storages.

2. Basic theory

2.1. Creep curve of salt rocks

The creep deformation of salt rocks is the macroscopic deformation of the rock body caused by microcrystal deformation or intergranular mass transfer. Multiple creep mechanisms exist concurrently during the process of rock salt creep. 1 The condition in which the rate of vacancy diffusion (dislocation migration) is equal to the rate of recovery (self-healing) is referred to as steady-state creep. Accelerated creep arises when the dislocation migration rate is greater than the self-healing rate. Fig. 1 demonstrates a typical rock salt creep curve (King, 1973).

Table 1
Statics parameters of the rock body.

Rock nature	Elastic modulus (GPa)	Poisson's ratio	Cohesive force (MPa)	Tensile strength (MPa)	Internal friction angle (°)	Rock body density (kg/m^3)
Mudstone	15.00	0.27	1.00	1.00	35	2600
Salt rock	18.50	0.30	1.25	1.00	40	2200
Mudstone interlayer	10.00	0.30	0.50	0.50	30	2300