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Weakening mechanisms of gypsum interlayers from Yunying salt cavern subjected to a coupled thermo-hydro-chemical environment

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ABSTRACT

China's rock salt deposits in the Yunying area are typically characterized by interlayers. When forming salt caverns, the gypsum interlayers are soaked in saline brines of different concentrations at various temperatures, which damage and weaken them. Moreover, the suspended gypsum interlayers periodically collapse as the size of the salt cavern increases. This can seriously damage the pipeline and influence the shape of the salt cavern. To predict the critical caving pace of a suspended gypsum interlayer and investigate the weakening mechanism and damage law of gypsum interlayers under corrosive environments, a series of laboratory tests were conducted, including scanning electron microscopy (SEM), micro-computed tomography (MCT) scanning, and indentation tests. In these tests, more than four hundred specimens were prepared and then soaked in 3 types of liquid and at 3 different temperatures. The results have demonstrated that deterioration increases with increasing temperature following soaking in water. More prominent steps on the surface of gypsum were noticed when soaked in high saturation brine, as compared with those in distilled water. The fitting parameters, critical transition force (CTF) and indentation modulus (IM) increased with increasing temperature but remained approximately identical with increasing brine concentration. Additionally, to study the effect of each factor, as well as the effects of interactions between factors, on the response variable (i.e., the CTF and IM), a 2 × 2 factorial design was employed to assess the brine concentrations and temperatures. It verifies that water-temperature has a significant weakening effect on the gypsum, while a much weaker effect from the chlorine ions. Based on these results, a damage law that includes time-dependent behaviour is proposed for describing the thermo-hydro-chemical process, which can be implemented in the Particle Flow Code (PFC). Consequently, this study has important implications for the control of the shape and size of salt caverns, as well as their stability and safety.

1. Introduction

Hydrogen, which constitutes approximately 93% of all atoms, is one of the most abundant elements on Earth. Hydrogen gas is stored in salt rock formations to enable the use of large quantities of hydrogen and to smooth out fluctuations in hydrogen demand. Compared with natural gas, the likelihood of hydrogen seepage is higher because of its greater mobility, smaller dynamic viscosity and smaller molecular radius. Moreover, for efficient storage, the inner pressure caused by compressed hydrogen gas should be higher because of its smaller molecular weight. Consequently, due to the greater mobility and higher compression requirements, the size and shape of salt caverns for hydrogen storage are strictly regulated.

China's rock salt deposits are typically composed of layered rock, unlike those of other countries that contain many thick salt dome caverns (Gao et al., 2011; Liang et al., 2012; Meng et al., 2013; Wang et al., 2013; Wang et al., 2015; Zhang et al., 2015a,b). Gypsum is one of the more common interlayer compositions in bedded salt formations (Fig. 1a). The depth of most salt caverns is 500–2000 m, and the ground temperature is 20–80 °C. A pilot well for a potential hydrogen storage cluster is located in a bedded salt formation in Yunying, a city located between Hubei Province, Zhejiang Province and Shanghai City (Liu et al., 2015). According to the pilot well and

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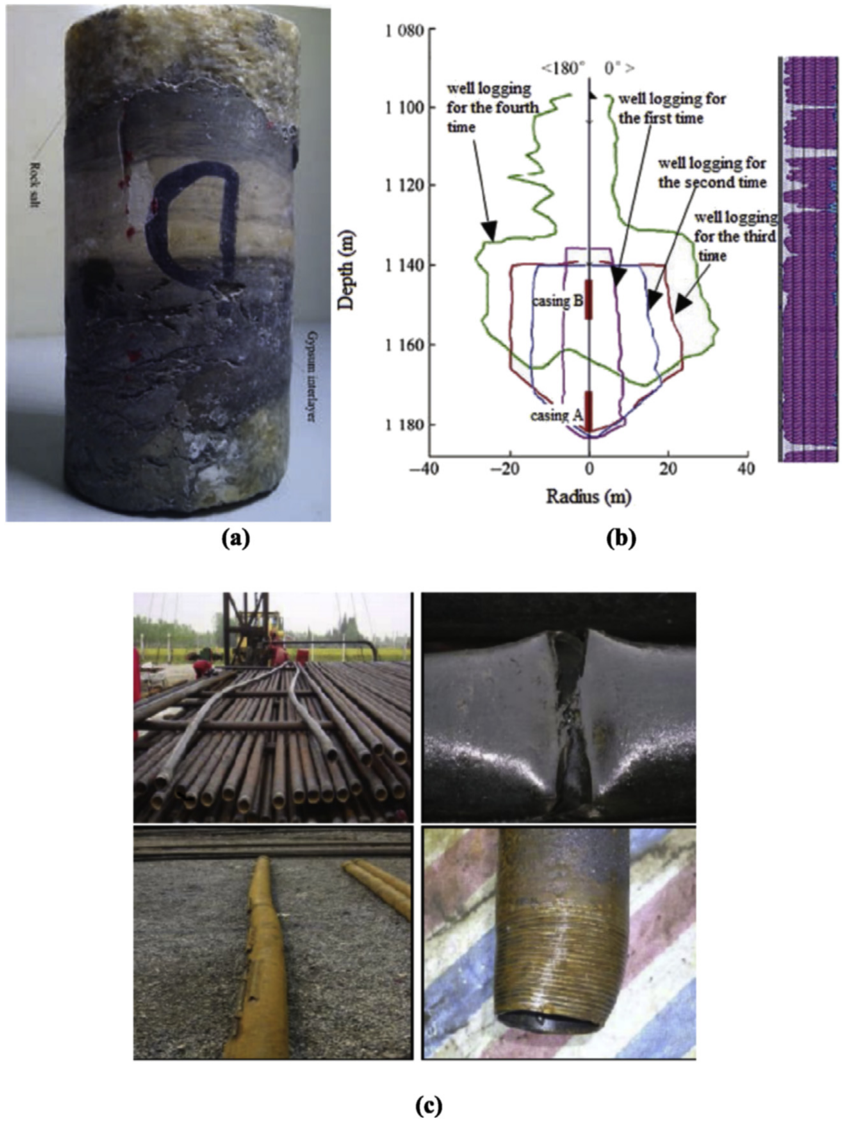

Fig. 1. (a) Salt deposits in Yunying, China. (b) Irregular cavern shape caused by the collapse of gypsum interlayers. (c) Leaching tubing damage in a salt cavern.

geophysical data, several typical gypsum interlayers intersect the cavern's vertical section. When forming salt caverns, rock salt around the cavity is dissolved in water or unsaturated brine, which results in suspended gypsum interlayers soaked in hot brine. The concentration of the brine varies with spatial position due to the effects of dissolution, gravity circulation. Specifically, the brine concentration is higher at the bottom while lower at the top of the salt cavern (Liang et al., 2012). Hence, the gypsum interlayers are exposed to saline brines with different concentrations and different temperatures, and these brines damage and weaken the gypsum interlayers. The insoluble gypsum interlayers influence the flow field and impact the flow velocity. This has a pronounced impact on the rate of rock salt dissolution and makes it hard to control the shape and size of the salt cavern (Fig. 1b). Moreover, during the leaching process, a sudden collapse of a thick interlayer may smash or cut the pipe (Fig. 1c). Damaged leaching pipes would change the depth of the water outlet and the brine inlet, which causes an irregular cavern shape (Wang et al., 2015). Shi et al. (2011) proposed a circular plate model for predicting the caving pace of a suspended interlayer. They analysed the collapse mechanism caused by partial failure and integral instability. However, due to the corrosion of hot brine and the huge volume of a salt cavern, gypsum interlayers will periodically collapse with increases in cavern size. The weakening mechanism and damage law of gypsum interlayers under coupled thermo-hydro-chemical processes are not well understood, and few relevant data are available. Therefore, to precisely predict the critical caving pace of a suspended gypsum interlayer and to obtain the optimum size and shape of a salt cavern, it is necessary to study the weakening mechanism and damage law of gypsum interlayers under different brine/temperature conditions.

Most of previous research on the weakening mechanisms and damage laws of rocks features qualitative analyses based on experimental results rather than quantitative descriptions (Khilar et al., 1983; Aquilina et al., 1997; Huang et al., 1998; Zhang and Lampe, 1999; Webb and Zhang, 1999; Changwu and Shiliang, 2000; De Bressser et al., 2005; Yilmaz, 2010; Zhao et al., 2015). To quantitatively investigate the weakening mechanism and damage law of gypsum interlayers, we performed this study using scanning electron microscopy (SEM) and micro-computed tomography (MCT). Moreover, conventional standard laboratory tests are necessary for measuring rock mechanical strength. However, practical limitations, such as the costs involved, insufficiency of the