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Research Paper

Stability and airtightness of a deep anhydrite cavern group used as an underground storage space: A case study

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ABSTRACT

This paper studies the usability of a deep mined-out anhydrite mine located in Anhui, China. The physical and mechanical parameters of the anhydrite intact rock and rock mass were determined through laboratory analysis and field investigation, and the stability of the cavern group was analyzed using the element safety factor method (ESFM) proposed in this paper. Moreover, the permeabilities of the anhydrite intact rock and rock mass were estimated based on laboratory and field tests. The results demonstrated that the stability and airtightness of the anhydrite cavern group are suitable for underground storage.

1. Introduction

Determination of the strength parameters of rock masses and analysis of rock stability are important topics in the field of rock mechanics [1,2]. Scientists have conducted substantial research to study the strength of rock masses. As an empirical failure criterion for rock, the Hoek-Brown (H-B) failure criterion, which was proposed by Hoek and Brown [3], describes the inherent nonlinearities in rock strength [4,5]. Since it was initially proposed, the H-B failure criterion has been extensively modified and improved. Notably, the generalized H-B failure criterion and the geological strength index (GSI) have been proposed and widely applied [5–9]. Sonmez and Ulusay [10] presented a quantificational method that determines the GSI to modify the generalized H-B failure criterion. Zhang et al. [11] proposed a method of calculating disturbance factor (D) via fuzzy comprehensive evaluation. In recent years, a three-dimensional Hoek-Brown failure criterion that accounts for the influence of the intermediate principal stress was proposed and developed [12,13]. The H-B failure criterion has been widely used in rock tunnel engineering, rock slope engineering and other fields [10,14–19]. Therefore, the use of the H-B failure criterion to calculate the strength of intact rock and rock masses is scientifically mature. In numerical analysis of cavern stability, researchers have generally focused on displacement, stress, strain the plastic zone distribution and other factors [20–22]. In general, displacement, stress, strain and plastic zone distribution are easy to obtain via numerical calculations. Displacement is an important parameter in engineering design and construction. By evaluating the stress and strain distribution, the stress and strain concentration can be easily determined [23]. The plastic zone can be assessed to determine whether elements yield [22]. However, through these indices, it is difficult and not intuitional to quantificationally determine the stability degree of the surrounding rock mass to some extent. Thus, it is necessary to develop a novel method to analyze stability degree of rock mass.

From the 1960s to 2000s, thousands of salt caverns around the world were exploited [24,25]. In addition, the number of utilized salt caverns has increased for more than 10 years. Salt cavern uses can be classified as either storage or disposal operations. Specifically, such caverns are mainly used to store liquid hydrocarbons, gaseous hydrocarbons and associated products [25]. The problems related to the use of salt caverns have been discussed for many years [26,27].

In China, gypsum rock reserves, which contain a considerable amount of anhydrite found at deep depths, are extremely abundant and have a wide distribution (Fig. 1). Some scientists have conducted tests of anhydrite rock and have found that a portion of the anhydrite has high engineering strength and stiffness [28,29]. And the use of abandoned anhydrite caverns as underground storage facilities has been proposed. Hangx et al. [30] present a study case that the mine-out anhydrite mine are used to store CO_2. Peng et al. [31] and Feng [32] discussed the feasibility of using abandoned anhydrite caverns of the An-hui Hengtai deep anhydrite mine to store oil. The use of abandoned caverns has the advantages of less land occupation and lower investment costs than traditional underground storage. Past research has shown that the intact anhydrite rock of the An-hui Hengtai deep anhydrite mine has high strength and stiffness properties.

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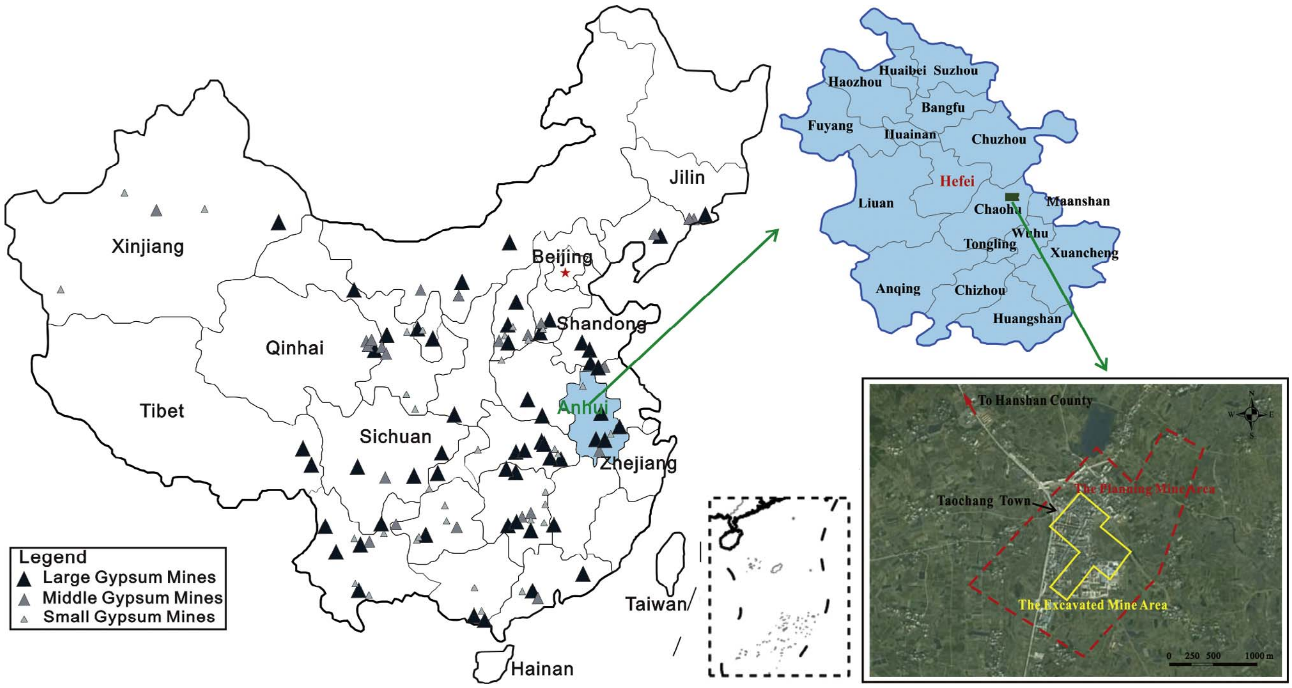

Fig. 1. Distribution of gypsum mines in China and geographic location of the An-hui Hengtai anhydrite mine.

This paper explores the An-hui Hengtai deep anhydrite mine located in Anhui Province, China, as an engineering case study. Based on engineering lab tests and field investigations, the H-B failure criterion parameters of the deep anhydrite intact rock and rock mass were obtained. And a numerical simulation model was built in FLAC^{3D}5.0. Furthermore, based on the generalized H-B failure criterion and stress distribution of numerical calculation, the element safety factor method (ESFM) was proposed in this paper and used to estimate the stability of the anhydrite cavern group. Moreover, the permeabilities of the anhydrite intact rock and rock mass were analyzed through micro measurements of the intact rock and high-pressure water injection tests of the rock mass conducted in the field. The systematic method used in this paper to calculate the parameters of the H-B failure criterion and to estimate the stabilities of various geotechnical engineering can be used as references for other analysis.

2. Element safety factor method

In numerical analysis, the traditional methods of evaluating the stability of a cavern is based on displacement, stress, strain and plastic zone analysis [20–22]. However, these analysis are uneasy to quantificationally determine the stability degree of element in numerical model describing the surrounding rock mass. The element is defined as the basic component of whole model mesh. Therefore, based on the generalized H-B failure criterion and stress distribution of numerical calculation, this paper proposes a complementary calculation method, the ESFM, to evaluate the stability of the cavern group. The method is quantitative and intuitional, and supplies the stability analysis measures.

Based on the generalized H-B failure criterion, the element safety factor E_{fos} was defined as follows.

$$\text{while } \sigma_1 > 0, \sigma_1 = \frac{\sigma_3 + \sigma_c\left[m_b\frac{\sigma_3}{\sigma_c} + s\right]^a}{E_{fos}} \tag{1}$$

$$E_{fos} = \frac{\sigma_3 + \sigma_c\left[m_b\frac{\sigma_3}{\sigma_c} + s\right]^a}{\sigma_1} \tag{2}$$

$$\text{while } \sigma_1 = 0, E_{fos} = -\frac{\sigma_{tRM}}{\sigma_3} \tag{3}$$

where

σ_1 and σ_3 are the major and minor principal stresses (MPa), respectively;
σ_c is the UCS of the rock (MPa);
m_b, s and a are the material constants ($a = 0.5$ and $s = 1$ for intact rock);
σ_{tRM} is the tensile strength of the rock mass;
E_{fos} is the element safety factor.

Then, Eqs. (2) and (3) were incorporated into FLAC^{3D} using Fish language, and the element safety factor of each element. According to the calculation results, it is convenient and easy to determine the zones of poor stability, or the zone with the lowest safety factor. Moreover, the Fig. 2 shows the principle of the ESFM. Furthermore, we can define the stability classes as follows.

When $E_{fos} \geqslant 1.3$, the elements are stable and the safety factor is sufficiently high. This class is called 'high stability'.

When $1.0 \leqslant E_{fos} > 1.3$, the elements are stable, but the safety factor is insufficient. This class is called 'poor stability'.

When $E_{fos} < 1.0$, the elements are unstable and plastic failure is

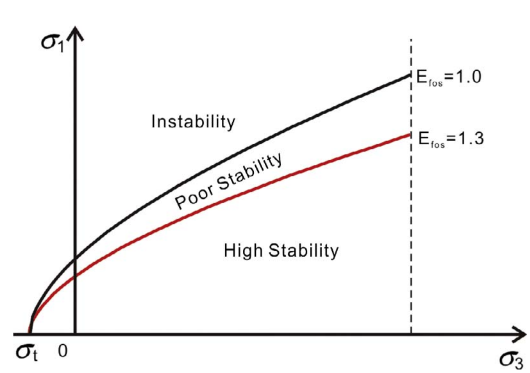

Fig. 2. Principle of the ESFM.