Computers and Geotechnics 68 (2015) 147–160

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Stability evaluation and failure analysis of rock salt gas storage caverns based on deformation reinforcement theory

J.Q. Deng *, Q. Yang, Y.R. Liu, Y.W. Pan

State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form 9 March 2015
Accepted 30 March 2015
Available online 28 April 2015

Keywords:
Rock salt cavern
Nonlinear FEM
Stability evaluation
Failure analysis
Plastic complementary energy
Unbalanced force

ABSTRACT

To perform a stability evaluation of underground gas storage caverns, the strength reduction finite element method is introduced into deformation reinforcement theory (DRT). The stability criterion of gas storage in caverns is established based on the $K \sim \Delta E$ curve, where K is the strength reduction factor (SRF) and ΔE is plastic complementary energy (PCE). With respect to the state of instability, PCE quantitatively indicates the global stability of gas storage caverns, whereas the unbalanced force (UF) clearly specifies the local failure position and failure mode of gas storage caverns. A comparison between the results of geo-mechanical model testing and numerical simulation verifies the correlation between the UF and failure. DRT is applied to the stability evaluation and failure analysis of a gas storage double cavern, as well as the projected performance of rock salt gas storage caverns.

1. Introduction

Rock salt has become an ideal medium for energy reserves because of its notably low permeability and self-healing properties. Unlike the thick salt domes located outside of China that have been formed by marine deposits, rock salt in China possesses a stratified structure formed by lake deposits. Rock salt layers have a small thickness, a large number of insoluble intercalations and a shallow burial depth [1]. When intensive underground gas storage caverns are constructed in such rock salt, the global stability evaluation and control as well as failure analysis of such caverns arise as key problems that need to be solved.

The main problems associated with geotechnical stability include those pertaining to the stability of slopes, the bearing capacity of foundations and the stability of underground caverns. The theoretical basis for addressing these problems is limit analysis theory. With the development of numerical analysis methods in the second half of the 20th century, the finite element method (FEM) was introduced into limit analysis. The FEM overload method and the FEM strength reduction method were then developed to determine the ultimate load and stability safety factors [2,3]. It is argued that the finite element method of stability analysis has broad application prospects because of its simplicity and practicability and its widespread use should now be standard in geotechnical practice [4–6].

When the FEM strength reduction method is utilised to analyse stability, one critical problem that is faced is determining how to judge whether a rock mass has reached its ultimate failure state according to the results obtained by the FEM. For the stability analysis of a slope, the plastic zone connection, the divergence of the numerical results obtained by the FEM, and the variation in strain and displacement are typically utilised to determine whether the slope reaches its ultimate failure state.

To date, the traditional numerical method has typically been used to analyse the stability and failure of underground energy storage caverns.

Gnirk and Fossum [7] studied the stability and design criteria of underground caverns used for compressed gas storage in hard rock. Yoichi and Yamashita [8] utilised the elastic FEM to study the stability of side-by-side caverns and were the first to develop with the critical stability indicator as a stability criterion of caverns. Heusermann et al. [9] utilised the ADINA and LUBBY2 models to analyse the nonlinear stability of rock salt caverns. Yoshida and Horii [10] utilised the continuum method of micromechanics to study the stability of underground caverns in jointed rock masses. DeVries et al. [11] studied the roof stability of gas storage caverns in bedded rock salt. In summary, stability and failure criteria are mainly limited to the stress, displacement and plastic zones.

However, there are several critical problems that need to be solved when performing global stability evaluation and failure

* Corresponding author. Tel.: +86 10 62781760.
E-mail address: dengjq@aliyun.com (J.Q. Deng).

http://dx.doi.org/10.1016/j.compgeo.2015.03.013
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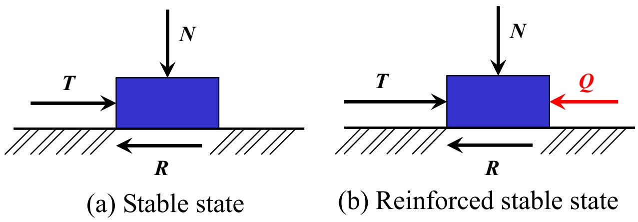

Fig. 1. Sketch of the stability of a single rigid block.

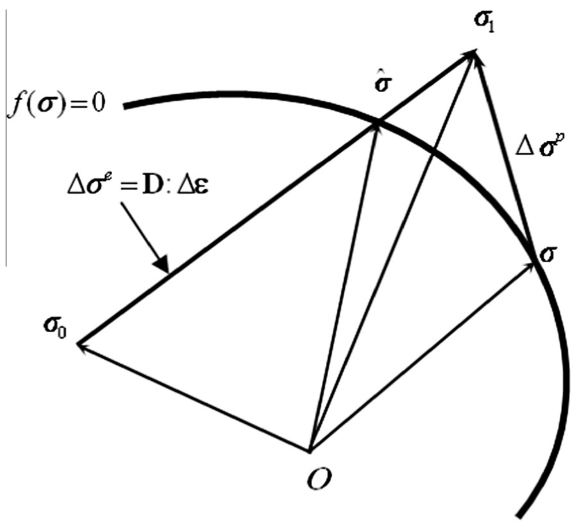

Fig. 2. Elastic–plastic stress adjustment.

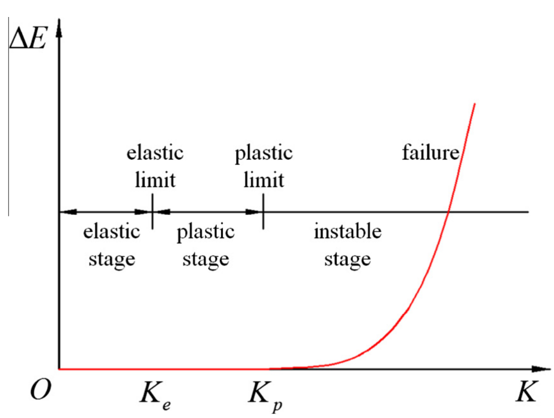

Fig. 3. $K \sim \Delta E$ curve of entire failure process.

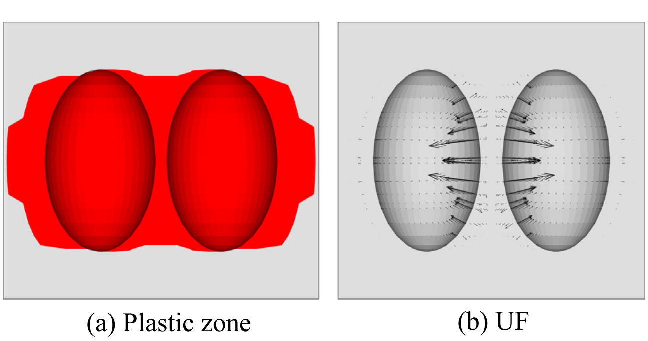

Fig. 4. Plastic zone and UF.

Table 1
Prototype material parameters.

Material	E (GPa)	ν	c (MPa)	θ (°)	ρ (kg m^{-3})
Rock salt	18	0.3	1.0	30	2150
Mudstone	4	0.3	0.5	30	2800

Table 2
Model equivalent material parameters.

Material	E (MPa)	v	c (MPa)	θ (°)	ρ (kg m^{-3})
Rock salt	45	0.3	2.50×10^{-3}	30	2150
Mudstone	10	0.3	1.25×10^{-3}	30	2800

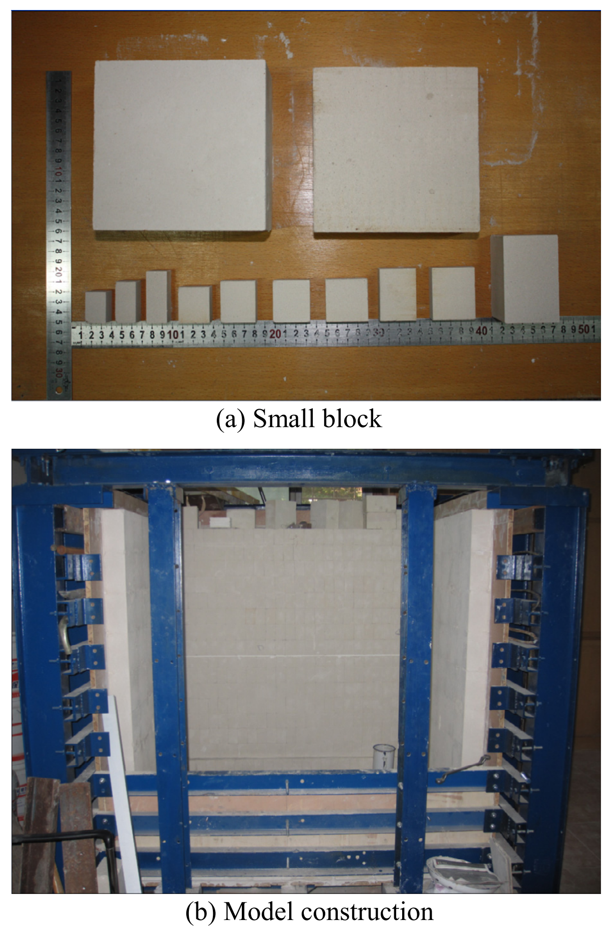

Fig. 5. The small block and model construction.

analysis of underground gas caverns. First, quantitatively evaluating the global stability of intensive gas storage caverns is essential to the optimisation of the arrangement and mode of operation of such caverns. However, using current conventional elastic–plasticity analysis, it is still too difficult to produce a quantitative stability criterion. Second, there is a wide range of plastic zones in gas caverns that are on the verge of failure; therefore, a more effective indicator in plastic zones is needed to better reflect the failure positions and failure modes of gas caverns.

Yang and Liu et al. [12,13] conceived of the concepts of plastic complementary energy (PCE) and unbalanced force (UF) and have conducted many studies to develop deformation reinforcement theory (DRT). DRT provides a good theory for solving the above-mentioned problems. DRT mainly addresses the post-failure