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Effects of loading rate on strength and deformability of Maha Sarakham salt

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ABSTRACT

Uniaxial and triaxial compression tests have been performed to assess the influence of loading rate on the compressive strength and deformability of the Maha Sarakham salt. The salt specimens with a nominal dimension of $5.4 \times 5.4 \times 5.4$ cm^3 are compressed to failure using a polyaxial load frame. The lateral confining pressures are maintained constant at 0, 3, 7, 12, 20 and 28 MPa while the axial stresses are increased at constant rates of 0.001, 0.01, 0.1, 1.0 and 10 MPa/s until failure occurs. The salt elasticity and strength increase with the loading rates. The elastic (tangent) modulus determined at about 40% of the failure stress varies from 15 to 25 GPa, and the Poisson's ratio from 0.23 to 0.43. The elastic parameters tend to be independent of the confining pressures. The strains induced at failure decrease as the loading rate increases. Various multi-axial formulations of loading rate dependent strength and deformability are derived. The variation of the octahedral shear stresses and strains induced at dilation and at failure with the applied shear stress rates can be best described by power relations. The distortional strain energy at dilation and at failure from various loading rates varies linearly with the mean normal stress. The proposed empirical criteria are applied to determine the safe maximum withdrawal rate of a compressed-air energy storage cavern in the Maha Sarakham salt formation. The strain energy criterion that considers both distortional and mean stress–strains at dilation tends to give the most conservative results.

1. Introduction

The effects of loading rate on the compressive strength and deformability of intact rocks have long been recognized (Kumar, 1968; Jaeger and Cook, 1979; Farmer, 1983; Cristescu and Hunsche, 1998). A primary concern of the rate-dependent effect arises when one applies the laboratory-determined properties of intact rock to the design and stability analysis of rock under in-situ conditions. The strength and elastic properties obtained from laboratory testing under a relatively high loading rate, normally about 0.5–1.0 MPa per second (e.g. ASTM D 7012-07, 2007) tend to be greater than those of in-situ rocks during excavations or constructions. This may lead to a non-conservative analysis and design of the relevant geologic structures. Okubo et al. (1992), Ishizuka et al. (1993), Ray et al. (1999), Li and Xia (2000) and Kohmura and Inada (2006) conclude from their experimental results that rock uniaxial compressive strengths tend to increase with strain and loading rates, respectively. The mechanisms governing the loading-rate dependency for brittle rocks have been related to the time-dependent initiation and propagation of the micro-cracks and fractures in the rock matrix (Costin, 1987; Zhang et al., 1999; Aubertin et al., 2000; Li and Xia, 2000). The loading rate effects on the elastic modulus remain inconclusive due to the insufficient test results (Blanton, 1981; Chong et al., 1987; Okubo et al., 2001, 2006; Wang, 2008).

For creeping rocks, such as rock salt, the loading rate strongly affects its mechanical responses. The main mechanisms governing the rate-dependent deformability and strength of rock salt involve the dislocation glide, dislocation climb, healing and fracture initiation and propagation (Munson and Fossum, 1984; Senseny and Pfeifle, 1985; Fuenkajorn and Daemen, 1988; Cristescu and Hunsche, 1998).

The loading rate effect plays a significant role on the stability analysis and design of the pressure schemes for compressed-air, LPG, and natural gas storage caverns in salt (Jeremic, 1994). Experimental and theoretical researches have long been performed, notably as part of nuclear waste disposal programs, to truly understand the time-dependent deformation (creep) of salt under the repository environments (e.g., elevated temperatures and pressures). Rare attempt, however, has been made to determine the rate-dependent strength of the salt, particularly under confined conditions. The strength criterion that can take the loading rate effects into consideration is also rare.

The objective of this research is to experimentally assess the influence of loading rate on the compressive strength and deformability of rock salt. Uniaxial and triaxial compression tests have been performed on Maha Sarakham salt using a polyaxial load frame (Fuenkajorn and Kenkhunthod, 2010) with applied loading rates from 0.001 to 10 MPa/s, and confining pressures from 0 to 28 MPa. Mathematical relationships between the salt strength, deformability,

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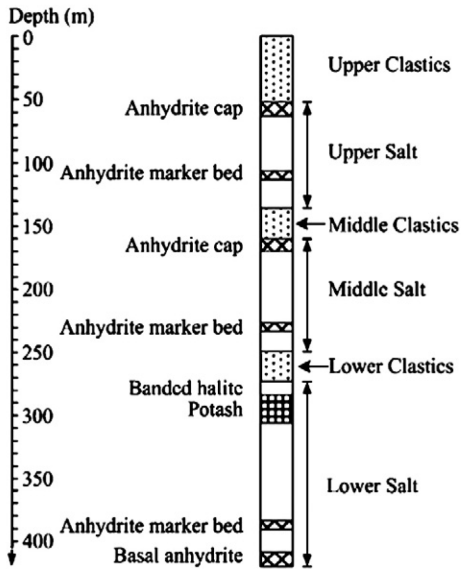

Fig. 1. A typical section of the Maha Sarakham formation (Suwanich, 1978).

loading rate and confining pressure are derived from the test data. Multi-axial empirical criteria that can take loading rate effect into consideration are proposed to describe the dilation and failure of the salt. Supported by numerical simulations, these criteria are applied to calculate the factors of safety of salt around a compressed-air energy storage cavern subjected to various rates of pressure reduction during retrieval periods.

2. Salt specimens

The tested specimens were prepared from 60 mm diameter salt cores drilled from depths ranging between 140 m and 250 m by Pimai Salt Co. in the northeast of Thailand. The salt cores belong to the Middle Salt member of the Maha Sarakham formation. Fig. 1 shows the typical geological section of the formation. This salt member hosts several solution-mined caverns in the basin. The Maha Sarakham formation is also being considered as a host rock for compressed-air energy storage caverns by the Thai Department of Energy, and for chemical waste disposal by the Office of Atomic Energy for Peace. Warren (1999) gives the origin and geological description of the Maha Sarakham salt. The tested salt is virtually pure halite, with a slight amount of clay inclusions (less than 1%). The drilled cores were dry-cut to obtain cubical shaped specimens with nominal dimensions of $5.4\times5.4\times5.4$ cm^3. Over 40 specimens were prepared. No bedding plane was observed in the specimens. The average density is 2.19 ± 0.09 g/cm^3. Sriapai and Fuenkajorn (2010) determine the mechanical properties of the same salt under triaxial and polyaxial conditions, and report according to the Coulomb strength criterion that the internal friction angle of the rock is 50° and the cohesion is 5.0 MPa. They are determined from the failure stresses. The elastic modulus and Poisson's ratio average as $21.5\pm$ 2.6 GPa and $0.40\pm.04$.

3. Polyaxial load frame

A polyaxial load frame has been developed to apply constant lateral and axial stresses to cubical or rectangular rock specimens (Fig. 2). Two pairs of 152 cm long cantilever beams are used to apply the lateral loads in mutually perpendicular directions. The outer end of each beam is pulled down by a dead weight placed on a lower steel bar linking the two opposite beams underneath. The beam inner end is hinged by a pin mounted between vertical bars on each side of the frame. During testing all beams are arranged nearly horizontally, and hence a lateral compressive load results on the specimen placed at the center of the frame. Using different distances from the pin to the outer weighting point and to the inner loading point, a load magnification of 17 to 1 is obtained. This loading ratio is also used to determine the lateral deformation of the specimen by monitoring the vertical movement of the two steel bars below. The maximum lateral load is designed for 100 kN. The axial load is applied by a 1000-kN hydraulic load cell connected to an electric oil pump via a pressure regulator. The load frame can accommodate specimen sizes from $2.5\times2.5\times2.5$ cm to $10\times10\times20$ cm.

The polyaxial load frame has been used in this study because the cantilever beams with pre-calibrated dead weight can apply a truly constant lateral stress to the specimen. These lateral confining mechanism and deformation measurements are isolated from the axial loading system. Such arrangement is necessary particularly for the triaxial testing under very high axial loading rates. For example at the loading rate of 10 MPa/s the salt specimens can fail within 5–10 s. The induced specimen dilation is too rapid for standard Hoek cell or triaxial cell to release the pressurized oil and maintain a constant confining pressure during loading.

4. Test method

The polyaxial load frame applies constant and uniform lateral stresses (confining pressures) to the salt specimen while the vertical stress is increased at a constant rate until failure occurs. Prior to testing both lateral loads are calibrated to obtain a desired confining pressure using an electronic load cell. The vertical stress is applied along the original axial direction of the salt core. The uniform lateral confining pressures ($\sigma_2=\sigma$) on the salt specimens range from 0, 3, 7, 12, 20 to 28 MPa, and the constant vertical stress rates ($\partial\sigma_1/\partial t$) from 0.001, 0.01, 0.1, 1.0 to 10 MPa/s.

After installing the cubical salt specimen into the load frame, dead weights are placed on the two lower bars to obtain the pre-defined magnitude of the uniform lateral stress (σ_3) on the specimen. Simultaneously the vertical stress is increased to the pre-defined σ_3 value. Neoprene sheets have been placed at the interface between loading platens and rock surfaces to minimize the friction. This uniform stress is maintained for a minimum of one hour, primarily to ensure that the salt specimen is under isostatic condition. This process is not intended to heal or compress the salt specimen to the original in-situ stress state. The test is started by increasing the vertical stress at the pre-defined rate using the electric pump. The specimen deformations are monitored in the three loading directions and are used to calculate the principal strains during loading. The readings are recorded every 10 kN (or about 3.43 MPa) of load increment until failure. The failure loads are recorded and the mode of failure is examined.

5. Test results

Figs. 3–5 show the stress–strain curves of some salt specimens. Each salt specimen shows virtually identical lateral strains measured from the two mutually perpendicular directions ($\varepsilon_2=\varepsilon_3$). The specimens tend to show nonlinear behavior, particularly under high confining pressures. All post-test specimens show combinations of shear failure and extension cracks (Figure 6). No distinctive difference of the failure modes is observed among the specimens.

Table 1 summarizes the results from all specimens, listing the major principal (vertical) stresses (σ_1) at failure for each lateral confining pressure (σ_3). The elastic modulus (E) and Poisson's ratio (ν) are determined from the tangent at about 40% of the failure stress for each specimen. The mean stresses (σ_m) and strains (ε_m) and the octahedral shear stresses ($\tau_{oct,f}$) and shear strains ($\gamma_{oct,f}$) at failure are also determined using the following relations (Jaeger et al., 2007):

$$\sigma_m=(\sigma_1+2\sigma_3)/3 \quad (1)$$