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Effects of stress path on shear strength of a rock salt

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1. Introduction

The effect of intermediate principal stress on rock strengths have long been recognized.[1–6] It has been found that in a σ_1 - σ_2 diagram, for a given σ_3, σ_1 at failure initially increases with σ_2 to a certain magnitude, and then it gradually decreases as σ_2 increases. The effect of σ_2 is larger under higher σ_3. Cai[7] offers an explanation of how the intermediate principal stress affects the rock strength based on the results from numerical simulations on fracture initiation and propagation. He states that the intermediate principal stress confines the rock in such a way that fractures can only be initiated and propagated in the direction parallel to σ_1 and σ_2. The effect of σ_2 is related to the stress-induced anisotropic properties and behaviour of the rock and to the end effect at the interface between the rock surface and loading platen in the direction of the σ_2 application. The effect should be smaller in homogeneous and fine-grained rocks than in coarse-grained rocks where pre-existing micro-cracks are not uniformly distributed.

Several failure criteria have been developed to describe the rock strength under true triaxial stress states. Comprehensive reviews of these criteria have been given recently by Colmenares and Zoback,[2] Haimson,[5] Cai,[7] Yu et al.[8] Al-Ajmi and Zimmerman,[9] Liu et al.[10] and Meyer and Labuz.[11] Among several other criteria, the Mogi and modified Wiebols and Cook criteria are perhaps the most widely used to describe the rock compressive strengths under true triaxial stresses.

It has been recognized that rock strengths obtained from the conventional loading path with constant confining pressure (σ_3) may not truly represent the rocks strengths and deformation around underground openings where the mean stress (σ_m) remains constant and two or three principal stresses change after the opening has been excavated.[12–14] The effects of intermediate principal stress on such stress path has rarely been addressed or quantitatively determined. The representativeness of the multiaxial strength criteria mentioned above has never been experimentally investigated and verified under the loading path of constant mean stress.

The objective of this study is to experimentally determine the effects of stress paths on the compressive shear strengths of the Maha Sarakham salt. The effects of the two stress paths are assessed under three test (loading) conditions: triaxial compression, polyaxial compression and triaxial extension. Modes of failure are investigated. The modified Wiebols and Cook and Mogi criteria derived from constant σ_3 test data are used to predict the constant σ_m strength data. The predictive capability of these criteria is assessed and discussed.

2. Sample preparation

The specimens are prepared from 63 mm diameter salt cores drilled from depths ranging between 150 m and 250 m. The salt cores belong to the Middle Salt member of the Maha Sarakham formation. This salt member hosts several solution-mined caverns. The formation is also being considered as a host rock for compressed-air energy storage (CAES) caverns by the Thai Department of Energy, and for chemical waste disposal by the Office of Atomic Energy for Peace. Warren[15] gives the origin and geological description of the Maha Sarakham salt.

The salt specemens are virtually pure halite, with a slight amount of clay inclusions (less than 1%). The drilled cores are dry-cut to obtain rectangular specimens with nominal dimensions of $45 \times 45 \times 90\,\text{mm}^3$. Over 60 specimens have been prepared. No bedding plane is observed in the specimens. The average density is $2.16 \pm 0.09\,\text{g/cm}^3$. Sriapai et al.[16] determine the mechanical properties of the same salt, and report that the internal friction angle of the salt is 50° and the cohesion is 5.0 MPa. The elastic modulus and Poisson's ratio average as 21.5 ± 2.6 GPa and 0.40 ± 0.04.

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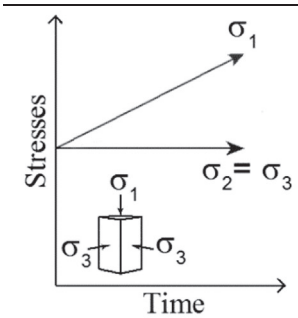
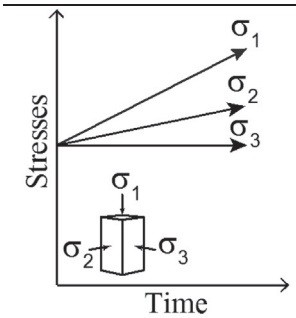
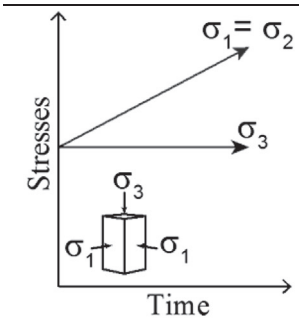
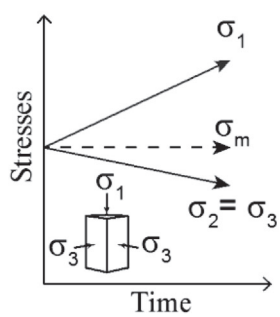
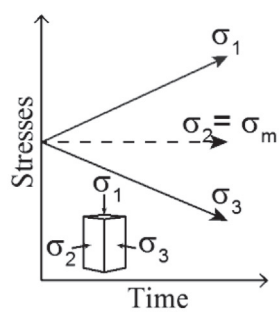
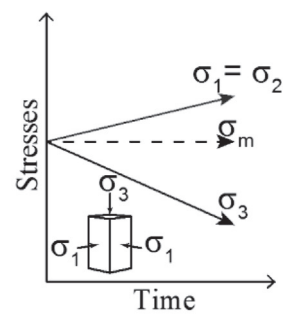
Table 1
Test plan

Stress path	Test conditions		
	Compression ($\sigma_1 \neq \sigma_2 = \sigma_3$) $\mu = 1$	Polyaxial ($\sigma_1 \neq \sigma_2 \neq \sigma_3$) $-1 < \mu < 1$	Extension ($\sigma_1 = \sigma_2 \neq \sigma_3$) $\mu = -1$
Constant σ_3			
	σ_3 = 1 - 28 MPa	σ_3 = 0 - 10 MPa	σ_3 = 0 - 10 MPa
Constant σ_m			
	σ_m = 8 - 70 MPa	σ_m = 20 - 80 MPa	σ_m = 21 - 85 MPa

3. Apparatus and test method

A true triaxial load frame[17] is used to apply axial stress (σ_1) and lateral stresses (σ_2 and σ_3) to the specimen. The frame comprises four main components: three mutually perpendicular load frames, six 100-ton hydraulic cylinders, measurement system and three hydraulic pumps. The measurement system includes pressure transducers, displacement transducers, switching box, and data logger. Neoprene sheets are placed at all interfaces between the loading platens and specimen surfaces to minimize the friction.

The tests are performed under two stress paths; constant confining stress (σ_3 from 0 to 28 MPa) and constant mean stresses (σ_m from 8 to 85 MPa). Three test conditions are applied for each stress path; triaxial compression ($\sigma_1 \ddagger \sigma_2 = \sigma_3$), polyaxial compression ($\sigma_1 \ddagger \sigma_2 \ddagger \sigma_3$) and triaxial extension ($\sigma_1 = \sigma_2 \ddagger \sigma_3$). Table 1 summarizes the test plan showing the three test conditions with the Lode parameter,[18] $\mu = 1$ for compression, $-1 < \mu < 1$ for polyaxial and $\mu = -1$ for extension loading where $\mu = (2\sigma_2 - \sigma_3 - \sigma_1) / (\sigma_3 - \sigma_1)$. All stresses are increased or decreased monotonically under constant rates until failure occurs (drop of σ_1). It is recognized that infinite stress paths can be taken to obtain constant σ_3 and constant σ_m conditions. The monotonic loading conditions under constant rates are used here mainly to simplify and limit the numbers of test variables.

After installing the salt specimen into the load frame, the vertical and lateral stresses are simultaneously increased to the predefined σ_3 (for constant σ_3 testing) or σ_m (for constant σ_m testing). This uniform stress is maintained for a minimum of one hour, primarily to ensure that the salt specimen is under isostatic condition.

For the constant σ_3 path the triaxial compression test is started by increasing σ_1 at the rate of 0.1 MPa/s while σ_2 and σ_3 are equal and maintained constant (between 1 and 28 MPa) until failure occurs. The polyaxial compression tests are performed by increasing σ_1 and σ_2 at different rates while σ_3 is maintained constant between 0 and 10 MPa. For the triaxial extension testing σ_1 and σ_2 are simultaneously increased under the rate of 0.1 MPa/s while σ_3 is maintained constant between 0 and 10 MPa until failure.

Under constant σ_m path, the triaxial compression tests are performed by increasing σ_1 at the rate of 0.1 MPa/s while σ_2 and σ_3 are decreased at the rate of 0.05 MPa/s. The polyaxial compression testing is performed under σ_m ranging between 20 and 80 MPa. The increase of σ_1 and the decrease of σ_3 are under the same rate of 0.1 MPa/s while σ_2 is maintained constant. The triaxial extension tests are performed under σ_m ranging between 21 and 85 MPa. The increases of σ_1 and σ_2 are made under the same rate of 0.1 MPa/s while decreasing σ_3 at the rate of 0.05 MPa/s. Photographs are taken of the post-test specimens. The modes of failure are identified.

4. Test results

The stress-strain curves for both stress paths are given in Fig. 1. Both stress paths show that the triaxial compression loading provides a higher strength than the polyaxial compression and triaxial extension

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