Impression relaxation test, a new relaxation method to determine the time dependent characteristics of salt rock

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ABSTRACT: Relaxation impression technique is a novel relaxation test in which a cylindrical flat ended indenter penetrates into a small region of sample and after keeping the displacement at a certain point, the decrease in the stress level will be recorded. Conventional relaxation test is a time consuming and expensive technique when a number of samples are needed to be tested. In contrast, impression relaxation test requires only a small amount of sample which makes this method cheaper. In this study, the impression relaxation test will be carried out on salt rock using an apparatus, which is designed and fabricated for impression relaxation test, and the results will be compared to the results of conventional compression relaxation test.

1. INTRODUCTION

There is a strong demand for constructing deep underground spaces in many fields of rock engineering such as mining activities and petroleum production. As a result, defining characteristics of time-dependent deformations and failure around the underground openings are a major concern for stability and safety of structures. Creep under constant stress and relaxation under constant strain are two typical time-dependent phenomena of materials. In natural geological systems true creep or relaxation is, however, hard to be implemented, because a combination of creep and relaxation is commonly observed [1].

When a constant strain is applied to a viscoelastic material, which behaves in a nonlinear, and non-Hookean fashion, the force necessary to maintain that strain is not constant but decreases with time. This behavior is called “stress relaxation”. Conversely, when a viscoelastic material is subjected to a constant stress, an increase in the deformation takes place with time; this behavior is called “creep”. Figure 1(a) and (b) show typical schematic of relaxation and creep strain of material vs. time, respectively.

The processes causing stress relaxation may be physical or chemical in nature, and under all normal conditions, both types of processes will occur simultaneously. However, at normal or low temperatures and/or short times, stress relaxation is dominated by physical processes, while at high temperatures and/or long times, chemical processes are dominant [2, 3].

Fig. 1. Schematic of (a) stress relaxation, (b) creep behavior.
In rock mechanics, several researchers have studied the creep behavior, while a limited number of studies have been carried out on the relaxation behavior of rocks. With respect to Figure 1(a), the displacement of specimens during stress relaxation test increases to a certain value then the residual elastic stress in the system will be gradually converted to plastic strain. By keeping the strain rate of the sample constant, the stress level also decreases gradually. The load vs. time data attained from this test can be converted to a relation between applied stress and specimen strain rate by straightforward differentiation [4].

In this study some multi-step impression relaxation experiments were carried out on rock salt samples using three different diameters of cylindrical indenters, and the effects of relaxed stress in different diameter of indenters were compared. Furthermore, the effects of multi-step relaxation on rock salt was investigated which is like multi-step excavation of tunnels.

2. EXPERIMENTAL PROCEDURE

2.1. Rock Salt Composition Study

Because of having both elastic and viscous behavior, salt rock is capable of showing creep behavior. This property gives salt rock deformation the ability to expand as well as flow when enough time and space is given to do so [5]. Figure 2 shows the XRD result for the salt rock which was taken from a salt rock mine in the city of Garmsar in Iran, which shows that this sample is almost pure sodium chloride.

![Fig. 2. XRD result for Garmsar salt rock.](image)

**Fig. 2. XRD result for Garmsar salt rock.**

2.2. Impression Stress Relaxation

Impression method was applied for the first time on rocks by Moosavi et al. (2008) and Rassouli et al. (2009), to investigate the creep behavior of soft rocks [6, 7]. Impression stress relaxation is like impression creep except that the creep rate is measured by the rate of stress relaxation, so that the strain rate can be very small. Aydan et al. (2011) used this method to observe stress relaxation of Oya Tuff [8]. It is a convenient and time-saving way of collecting a lot of creep data from which a physical model can be thoroughly tested [9]. Larsson and Carlsson (1998) performed impression tests of viscoelastic materials, epoxy and PMMA, for stress relaxation and compared them with uniaxial tensile tests. They found that the effect of friction between the cylindrical indenter and the specimen was small. They prefer impression test from Brinell test because the contact area is a constant in the impression test. Furthermore, they prefer indentation tests from uniaxial tests because the latter have end effects [10].

To investigate the stressed relaxation behavior of rock salt, this new method was used, which its apparatus is shown schematically in Figure 3. Frame of this apparatus is made of two steel plates which have been connected to each other by four rods. The load is applied to the sample by three indenters with diameters of 2, 3 and 4 mm, through a screwed loading bar which has been passed through a leading bead by screwing a wheel which has been located at the top of the loading bar. The indenters are made out of hardened steel. The amount of the applied load is also measured by a load cell. For impression relaxation tests, some cubic specimens of rock salt with $3\times3\times3$ cm dimensions were prepared.

![Fig. 3. Schematic of impression relaxation apparatus](image)

**Fig. 3. Schematic of impression relaxation apparatus**

Table 1 shows the test schedule for impression relaxation experiments. To investigate the multi-step relaxation like what happens in multi-step excavation in tunnels, some multi-step impression relaxation tests were carried out on rock salt samples. For this purpose, six levels of stress, 39, 58.5, 78, 97.5, 117 and 136.5 MPa, were applied on the samples using three diameters of indenter. Furthermore, to investigate the effects of different stress levels on relaxation behavior of rock salt, five different multi-step experimental manners were applied to the specimens for each of the indenters.
In this experimental manner, the first multi-step relaxation test included all six levels of stress. For the next multi-step test, the first level of stress was eliminated, and the test started with the second level of stress. As an illustration, let’s consider the test number “2-6”. In this experiment, the test includes 6 levels of stress and starts with stress level of 39 MPa using the indenter with diameter of 2 mm. The next experiment for this diameter of indenter, test number “2-5”, includes 5 levels of stress and starts with stress level of 58.5 MPa, and so on. It can be implied that the impression relaxation behavior of rock salt can be compared by the first step of each experiment.

Table 1. Impression relaxation tests schedule

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Indenter Diameter (mm)</th>
<th>Stress Levels (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-6</td>
<td>2</td>
<td>39, 58.5, 78, 97.5, 117, 136.5</td>
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<td>2-5</td>
<td>2</td>
<td>58.5, 78, 97.5, 117, 136.5</td>
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<tr>
<td>2-4</td>
<td>2</td>
<td>78, 97.5, 117, 136.5</td>
</tr>
<tr>
<td>2-3</td>
<td>2</td>
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</tr>
<tr>
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<td>2</td>
<td>117, 136.5</td>
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<td>58.5, 78, 97.5, 117, 136.5</td>
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<tr>
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<td>3</td>
<td>78, 97.5, 117, 136.5</td>
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<tr>
<td>4-2</td>
<td>4</td>
<td>117, 136.5</td>
</tr>
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</table>

3. RESULTS AND CONCLUSION

3.1. Maxwell Model

A Maxwell material is a viscoelastic material. The Maxwell model can be represented by a purely viscous damper and a purely elastic spring connected in series.

The general form of Maxwell model under constant strain is described as follow [11]:

$$
\sigma = E\varepsilon_0 e^{-\mu t}
$$

(1)

Where σ is the stress level, E is the Young’s modulus, µ is the viscosity modulus, ε0 is the initial strain and t is time.

By dividing the stress to the initial strain, the following equation could be attained as the Maxwell function:

$$
G(t) = Ee^{-\mu t}
$$

(2)

This function shows the stress relaxation for Maxwell materials.

In this study, the Maxwell model was used to calculate the relaxation parameters of rock salt.

3.2. Impression Relaxation Experiments

All tests with stress impression relaxation were done in the laboratory on rock salt samples. The specimens were deformed up to a certain value during a continuous growth of the strain using cylindrical indenters; the loading was then stopped, and a condition was created that precluded spontaneous development of deformations in the sample.

From the point the loading was measured continuously during the tests and when the sample deformation was stopped, the drop of the stress level in the sample was measured in time as the remained stress in rock salt, and all the comparisons were made based on these remained stresses. The stress drop over time was recorded until the relaxation curves plateaued out and the stresses no longer depended on time, or until the curves arrived at a segment of low stress relaxation with a constant rate of stress drop. After this, the sample was again deformed until the next point, where the stress relaxation was measured.

Figure 5 shows an example of multi-step impression relaxation experiment for test number “2-6”. It can be seen in this graph that in each level of relaxation, after relaxation of the sample, when the stress and the relaxed stress rate achieved to a constant value, the stress level was increased to the next step of relaxation stress level.

Figure 6 shows the stress levels of all test numbers in which the first step of each experiment achieves after relaxation process. The first step of all experiments was chosen for this comparison because the specimen did not have previous loading history. The amounts of stress...
level after relaxation process are mentioned in Table 2. As it can be seen in Table 2, the stress level after relaxation, for the first step of experiments, increases as the diameter of indenter increases. Also, it was predictable that by increasing the applied stress level, the stress level after relaxation will increase.

This phenomenon was predictable because of dislocations movement. As the diameter of indenter increases, the amount of material beneath the indenter inclines so the movement of this material will be restricted. As the material displacement decrease, the amount of relaxed stress will also decrease; as a result, for the same level of applied stress, the remained stress after relaxation process will be higher for the experiments which are done by indenters with bigger flat end area.

![Fig. 5. Multi-step impression relaxation test for the indenter with diameter of 2 mm.](image)

Figure 7 to 9 show the effects of multistage loading on remained stress after relaxation for each step in multi-step relaxation tests for three different diameters of indenters. The test numbers in these graphs are those mentioned in the Table 2.

![Fig. 6. Applied stress vs. its related stress after relaxation for the first step of each experiment.](image)

It can be implied from these curves that at the same level of applied stress, the higher number of applied loading cycles the less amount of sample relaxation. This may be caused by the history of applied loading on samples. In those samples that tolerate more loading cycles, the material beneath the indenter has become dense. As a result, when the number of loading cycles increases the samples deformation decreases, and consequently the relaxed stress will also decreases.

For the first step of all impression relaxation experiments, Maxwell model was fitted to the curves. Figure 10 shows an example of Maxwell models fitted to the first step of impression relaxation test for indenter with diameter of 3 mm. The equations of exponential model which were fitted to the curves are presented in Table 3.

![Fig. 7. The effect of multistage loading on the remained stress after each step of relaxation for the test carried out by indenter with 2 mm diameter (the amount above the curves show the stress applied at each stage of loading).](image)

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Indenter Diameter (mm)</th>
<th>Applied Stress (MPa)</th>
<th>Stress level after relaxation (MPa)</th>
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<tbody>
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<td>2-6</td>
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<td>25.4</td>
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<td>117</td>
<td>81.73</td>
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</table>

Table 2. Applied and remained stress for impression relaxation experiments
The effect of multistage loading on the remained stress after each step of relaxation for the test carried out by indenter with 3 mm diameter (the amount above the curves show the stress applied at each stage of loading).

With respect to equation 1, this equation can also be rewritten more general as follow:

\[ \sigma = C \sigma_0 e^{-\frac{E}{\mu}} \]

where \( \sigma_0 \) is the initial applied stress and \( C \) is a material constant.

Dividing equation 3 by the initial applied stress results in the following equation:

\[ \frac{\sigma}{\sigma_0} = C e^{-\frac{E}{\mu}} \]

As it can be seen in the Table 3, the material constant of “C” is calculated for the first step of all relaxation experiments. It can be implied that this amount is almost the same for all the tests, and the rock salt is following the same trend of relaxation behavior under different conditions of stress level and indenter diameter.

Furthermore, the coefficient of time in the power term is almost the same for the first step of all impression relaxation experiments. This is because the “E” and “\( \mu \)” modulus are constant for a kind of material, so the attained results are following the correct trend.

4. CONCLUSION

This empirical study was undertaken to make further contributions to the understanding of impression stress relaxation of salt rock (keeping the strain constant and recording the loss of stress using impression method).

To investigate this new relaxation method, some multi-step impression relaxation tests were carried out on rock...
salt samples using three different diameters of indenter. By performing multi-step relaxation test the effect of multi-step loading on rock like what happens in multi-step excavation was investigated. It was attained from these experiments that at the same level of applied stress, the amount of released stress in those samples with longer and several history of loading is less than those ones with short history and less steps of previous loading. This may be caused by density of the sample beneath the indenter in which the displacement of samples with longer history of loading is less than those with shorter loading history, and as a result, the amount of released stress is less in the former ones.

The impression relaxation tests were also followed in another manner. In this manner, the first multi-step experiments were repeated by removing the first stress level of previous test. At the end 15 different experiments were carried out with different first step level of stress. All of these experiments were following the same trend of relaxation behavior, and the amount of material constant and coefficient of time in power of Maxwell equation were almost the same for all experiments. This result is due to the fact that these parameters are related to the nature of materials and are independent from the test procedure.

It was also inferred from the experimental results that by increasing the diameter of indenters, the amount of released stress decreases. This may be caused by the displacement of dislocation in which under bigger flat end of indenters the material is more restricted than that under smaller indenters.

REFERENCES