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Features of interrelations between acoustic quality factor and strength of rock salt during fatigue cyclic loadings

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ABSTRACT

This study considers the results of tested rock salt (halite) samples of the Novomoskovsk deposit (Tula Region, Russia) for cyclic loads. It was established that in uniaxial compression, the acoustic quality factor Q, dynamic elasticity modulus E, and strength σ_r undergo a non-monotonous change depending on the number of loads N in a stress range from 2 to 5% up to a maximum level of 40, 60, 80% of the initial strength σ_0. With $\gamma = 80\%$, a strength minimum was observed when $N = 15$, with 40, 60% strength minimum observed when $N = 20$. The smaller value of γ corresponds to the smaller value of σ_r. The minimum in the quality factor Q decreased compared to the initial value by 90, 92, 86% for stresses with $\gamma = 40$, 60 and 80% respectively. Strength decreased by 42.3, 31.1, 26.5% for $\gamma = 40$, 60, 80%. For a strength decrease section with $N = 20$, we obtained equations relating quality factor and strength: at $\gamma = 40\%$ $\sigma_r(Q) = 4.89\ln(Q) + 6.91$, determination coefficient $R^2 = 0.76$; at $\gamma = 60\%$ $\sigma_r(Q) = 6.70\ln(Q) + 7.51$, $R^2 = 0.83$; at $\gamma = 80\%$ $\sigma_r(Q) = 13.77\ln(Q) - 21.45$, $R^2 = 0.93$. Additional experiments were carried out to support the credibility of the obtained results.

1. Introduction

Research into rock salt fatigue in cyclic mechanical and thermal loading has been performed in order to use rock salt as a geomedium to construct underground storage of hydrocarbons [1] as well as compressed gases, air, and hydrogen as energy accumulators [2,3]. Issues of construction and exploitation of salt sediments as underground reservoirs are dealt with in [4–6], inter alia. The main suitability criteria for the construction of underground storage are thickness, salt body configuration and its depth of occurrence, ensuring sufficient reservoir storage space. Modern technologies allow the construction of underground reservoirs up to 2000 m deep. They are created by the solution of rock salt through boreholes, and are used as capital constructions aimed at long-term exploitation.

In the process of storage exploitation, salt arrays around the reservoir come under changeable loads with a period ranging from one day to one year [7]. These are connected with cyclic gas pumping in summer and its discharge in winter. The gas pressure of the reservoir in the process is limited from the top and bottom; the upper limit is estimated by equipment and rock massif strength if there is no gas leakage. Usually, it is 80–85% of the vertical stress in the massif [8]. The lower limit is estimated by the necessary value of gas pressure, which compensates for the rock overburden weight and prevents rock salt destruction. Residual gas is called buffer gas; its volume in storage is constant. The reservoir's pressure can change, ranging from 20 to 90% of the acting stress of the overlying rock weight. For example, in the design and construction of the Mogilino storage facility in Poland, the minimum preset pressure was 3.3 MPa and the maximum pressure was 21.3 MPa [9].

Thus, the rock salt surrounding the reservoir is under variable load conditions, ranging from a day to a year. The key factor here is the question of reservoir safety, breakage protection, and adequate strength of the surrounding rock salt massif [10].

Most relevant studies deal with physical mechanisms and changes in the properties of rock salt in fatigue mechanical impacts, such as elasticity, permeability, creeping, etc. Rock salt strength was considered over a long time period of fatigue change in tension or deformation. Its dependence on the number of fatigue cycles is not considered. Moreover, the dependencies between

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strength and acoustic quality factor were not considered either. However, these dependencies can be used to assess strength without any damage to the objects under test.

2. Objectives

The aim of this work is to study the dependence of changes in strength at uniaxial compression σ_r and acoustic quality factor Q of rock salt on the number of cyclic loads N, imitating pressure changes in the underground storage of hydrocarbons; and the dependencies $\sigma_r(Q)$ and comparisons of these dependencies to those obtained for different types of rock.

A previous study [11] has shown that the increase of N for sandstone, gabbro, travertine and gypsum leads to decreases in both strength and quality factor. At the same time, with marble, we observe a non-monotonous change in the strength and quality factor. They decrease initially then increase, accounted for by plastic strengthening. This study considers the peculiarities of similar dependencies for rock salt samples of the Novomoskovsk deposit, Tula Region, Russia. We show that their dependencies are similar to those obtained for marble.

We carry out a series of experiments to establish the interdependencies between mechanical strength and acoustic quality factor undergoing changes as a result of adverse factors [12,13]. Application of this technique for assessment of durability of objects in natural mine conditions was discussed in [14]. Our objective is to develop methods of non-destructive strength control for different types of rock and service life assessment of underground constructions. It should be noted that our aim methodology of conducting experiments differ from traditional fatigue experiments; in particular those described in [15].

3. Materials and methods

3.1. Rock samples

The dependencies $\sigma_r(N)$, $Q(N)$, and $\sigma_r(Q)$ are discussed as an example of tested rock samples of the Novomoskovsk rock salt deposit.

According to the size and morphology of the salt deposit, complex internal structure, consistency of thickness, mode of occurrence, quality and technological properties of salt, this deposit belongs to the bedded type [16]. It is practically horizontal and is 870–890 m below ground level. The rock salt thickness at the site of the exploration boreholes varies from 30 to 44.7 m. Devonian Period coal, chalk and Quaternary sediments represent the stratigraphic cross section of the deposit [17]. The salt bend is securely isolated from underground water ingress into the workings from both the bottom and top. The deposit is exploited by the Novomoskovsk salt extraction enterprise, which extracts rock salt by underground solution through the boreholes. At present, the usage of abandoned chambers as underground gas storage (UGS) is under consideration.

Rock salt samples were extracted from exploration borehole 3P, drilled in 1996–1997 by obtaining core samples in salt sediments and non-solvent inclusive rock of the estimated operating thickness of UGS. These are Devonian clastic sea and lagoonal sediments occurring in the Upper Proterozoic crystalline rocks, in particular those of the Ryazhsky, Morse and Mosolovsky horizons. They are distributed throughout the salt-bearing basin and constitute rock salt in the depth range of 835.6–887.7 m, and the enclosing rock at intervals of 775.0–835.6 m and 887.7–949 m. The salt from the well has an inequigranular structure and layered texture. The cores extracted from the wells were used to create samples of cylindrical shape, 36.6 mm in diameter and 73.2 mm in height, with a height to diameter ratio of 2:1, according to standard GOST 21153.2-84. Rock salt density was in the range of 2.15...2.36 kg/m^3.

Figs. 1–3 present a series of photographs of the rock salt samples before and after cyclic loading. Three groups that differ in their structure can be distinguished. Samples of group *A* (Fig. 1) have a uniform halite structure with average fracture and no impurities. After the cyclic loadings, fracturing of the sample increased, but it was not destroyed. Samples of group *B* (Fig. 2) contain layers with impurities violating the uniform structure. Samples of group *C* (Fig. 3) contain interlayers, differing from each other by jointing. The upper and lower parts of the samples, even in the initial state, were already disturbed more than the average one. This was clear from the significantly lighter shade of these parts compared to the middle part.

A polished section of the cylindrical specimen's surface indicating the scale is shown in Fig. 4. The halite grain sizes are 0.4–20 mm.

The samples of groups *B* and *C* in the cyclic fatigue loadings suffered a monotonous reduction in strength, and collapsed. Therefore, the experiments conducted on them have not been taken into account. Further results relate exclusively to the samples of group *A*, consisting of halite. Their strength and other properties in the process of loading varied non-monotonously.

3.2. Testing: general procedure

Fatigue tests and the study of the relationship between strength and the acoustic quality factor $\sigma_r(Q)$ in rock salt were conducted in the following sequence:

1. To obtain the relationship between the acoustic quality factor and residual strength, a group of samples consisting of 10–12 units was selected. For each group of samples, the quality factor Q was measured in its initial state.
2. By loading the sample until failure, measuring maximum load and averaging 3–5 samples, the initial strength σ_0 was determined.
3. In the load range from 2 to 5% up to a maximum level γ, forming part of the initial strength σ_0 and set in advance of the conditions of the experiment, fatigue cyclic loading of the remaining samples was performed. The number of cycles N for each sam-

Fig. 1. Sample of group *A*: uniform structure and fracturing prior to (a) and after (b) testing; the area indicated by an arrow shows germinating micro-cracks.