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Salt Rock Deformation under Bulk Multiple-Stage Loading

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The paper presents experimental justification of the possibility to use bulk multiple-stage loading to study the process of salt rock deformation in the laboratory conditions. Results of comparative tests between bulk multiple-stage and single-stage loading of salt rock samples are demonstrated. The paper contains results of research on the rate of lateral pressure and its impact on strength limit and residual strength limit of sylvinite, estimated using single-stage and multiple-stage methods. Research results demonstrate how the rate of lateral pressure impacts dilatancy boundary of salt rocks. Analysis of how the loading method influences certificate parameters of Mohr-Coulomb strength of sylvinite has been carried out. The dynamics of elastic modulus in the process of salt rock deformation is analyzed depending on the rate of lateral pressure.

It is demonstrated how the method of multiple-stage loading adequately reflects the processes of salt rock deformation and decomposition, and facilitates not only lowering impact of sample's inner structure heterogeneities on the experimental results, but also significant reduction in the required amount of rock material.

Key words: salt rocks; bulk loading; multiple-stage method; elasticity model; strength limit; residual strength; dilatancy boundary

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Introduction. In the last decades there was a steady growth in the extraction of various mineral resources. It was achieved by means of raising the capacities of existing mines and construction of new plants. As a general rule, fields under development are characterized by difficult mining, geological and hydrological conditions, which increase the risk of industrial accidents. Despite meeting all the requirements stated in the regulatory documentation, in the course of time intensive deformation of mining tunnel contours can often occur, load-bearing elements of the mining system can fail. These events are accompanied by intensification of shifting processes in the overlying rocks, which eventually leads to the interruption of mineral resource extraction and to emergency conditions [17]. As mining industry belongs to the most difficult and dangerous human activities, the efficiency of its functioning is to a great extent defined by the quality of information support during mining operations. This is especially relevant for deposits of water-soluble ores, such as Upper Kama potash salt deposit. Its mining, geological and hydrological conditions are characterized by great difficulty and diversity, whereas its development is associated with the danger of catastrophic flooding in case of surface water inrush into underground mining tunnels.

According to B.V.Laptev [5], the worldwide practice of salt deposit development encompasses over 80 flooded mines, unfit for reconstruction. In the study [4] the author in great detail describes accidents that occurred at two mines of Upper Kama potash salt deposit. In June 1986 as a result of brine inrush into the tunnels one of the mines of the deposit was flooded. The amount of brines that flowed into the mining tunnels was around 15 million m^3. A sink formed on the surface above the water inrush, from 60 to 80 m long and from 40 to 50 m wide. In October 2006 the brine rushed into the mining tunnels of another mine. The attempts to save it from flooding failed. In July 2007 a sink appeared on the ground above the inrush, 55 m wide and 80 m long. The authors of publications [11, 12] study the problems associated with the flooding of potash mines in the area of Upper Kama potash salt deposit. Continuous processes associated with salt dissolution in the flooded mines, surface subsidence, the growth of old and formation of new sinks require close attention of

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experts in geomechanics and inflict irreparable damage on industrial and civil buildings and constructions, as well as on the environment.

The character of deformation and destruction in the structural elements of underground constructions depends on multiple factors: geometric dimensions and the shape of mining tunnels, specific characteristics of rock composition and properties, their behavior under stress load etc. To reduce the risk of emergency conditions there is a need for a flexible system of geomechanical control over the safety of mining operations, which will adequately reflect the diversity of processes occurring in the rock mass, and allow for a timely reaction to the local changes in mining, geological and engineering conditions in the process of decision making. Such system should assess the changes both in mechanical characteristics of the marginal rock mass and in its stress-strain state in the process of mining operations.

Up to this day a vast experience has been gathered in the solution of various problems associated with providing stability of structural elements in the underground constructions. For the analysis of geomechanical processes, occurring in the undermined salt massif, the authors of studies [10-12] widely apply methods of mineral rock mechanics. However, despite the complication of mathematical problem statement, the accuracy of their estimates depends on reliability of calculation parameters and adequacy of geomechanical models describing the process of changes in the stress-strain state of the rock mass, interchamber pillars, roof of the stopes. This brings about the necessity to examine the character of rock deformation and decomposition experimentally, in the laboratory conditions under various loading patterns associated with the stress state of rock mass edges.

Laboratory examinations of minerals' mechanical properties include a fair amount of various tests: studies of density properties, the character of deformation and decomposition under immediate and lasting loading for bulk and single-axis loading patterns. Examinations imply that the samples are tested for compression, tension, bending under various loading speed, level of lateral pressure, temperature etc., which requires a fair amount of identical samples. It often poses a problem to manufacture the right amount of samples, taking into account the scarcity of rock material. In this case the application of multiple-step bulk loading to examine the process of rock deformation in the laboratory conditions can significantly reduce required amount of rock material and lower the variation of mechanical characteristics associated with individual features of sample's internal structure.

This paper is dedicated to comparative analysis of application results for bulk multiple-stage loading and «conventional» (single-stage) standard method of bulk loading aimed at estimation of physical and mechanical properties of salt rocks in laboratory conditions. More detailed description of standard bulk loading methods is presented in GOST (National Standard) 21153.8-88 [3] or ASTM D7012-14e1 [9].

State of the matter. For the first time the method of multiple-stage bulk loading (multiple failure state test) was first proposed to estimate strength characteristics of the rocks by authors of the study [16]. Its main difference from single-stage loading lies in the fact that when axial stress reaches the limit (breaking point) of the first loading stage, lateral pressure is raised to the necessary level of the next stage, then the axial stress increases to reach the breaking point of the second loading stage. Thus one sample can be subject to several stages of loading. As a result of single-sample multiple-stage loading, it is possible to plot boundary envelope of rock strength. Using a known ratio between primary and shear stresses, one can transfer to coordinates «shear – normal stress», thus defining certificate parameters of Mohr-Coulomb strength: adhesion factor and internal friction angle.

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According to the data [16], for the rock types examined by the authors – limestone and marble – a multiple-stage method gives the values of breaking stress comparable to the ones obtained through a single-stage tests. Subsequent studies of the rocks and materials with similar properties under bulk loading demonstrate that in a number of cases multiple-stage method gives underestimated values of strength characteristics. In study [24] authors publish results of geomechanical tests on marcellus shale. They point out that multiple-stage and single-stage methods provide close values of breaking strength and elastic modulus. They explain this fact by a relatively small number of loading stages (three) and a transfer to the next step from the first two stages without reaching dilatancy boundary of the sample. Basing on comparative analysis of single-stage and multiple-stage tests on clay shale, authors of the study [8] conclude that the application of multiple-stage method for brittle rocks provides visibly underestimated values of strength properties. Moreover, the difference between results of multiple-stage and single-stage tests grows with increasing number of loading stages.

In the study [19] authors present results of comparison tests for red sandstone. Authors point out that significant differences between strength values of multiple-stage and single-stage experiments are related to the differences in loading history. Authors of the paper [15] demonstrated the possibility to use multiple-stage method to estimate strength and elasticity modulus of Newberry tuff under varying levels of lateral pressure. Comparative examinations of the possibility to use multiple-stage method to estimate strength characteristics of Edwards limestone, described in the publication [25], reveal that in case of transfer to the next loading stage without bringing the sample to intensive fracturing, a multiple-stage method provides results similar to single-stage tests.

In the study of argillite samples under natural conditions in the lower part of the well [22], it is stated that due to accumulation of damages in the samples under multiple-stage loading the strength of the rock can be seriously underestimated. In the paper [23] authors describe interesting research performed with multiple-stage experiments on large-size samples: 120 cm in height, 60 cm in diameter. The samples are represented by layers of argillite and sandstone, argillite and limestone. Authors of the paper [23] identify plastic behavior of the rock as a necessary condition, which allows to estimate strength limit of the rock under multiple-stage loading without destroying the sample. In the publication [14] authors demonstrate how multiple-stage method can be applied not only to minerals, but also to unconventional granular materials. The paper points out relatively good correspondence between results of multiple-stage tests and the data from single-stage ones.

The study [13] presents results of research on changes in adhesion and friction angle in the process of damage accumulation in the samples of argillaceous packsand rock. Damages in the samples were made using multiple-stage tests. Research results [19] clearly demonstrate that a multiple-stage method with a fair amount of loading stages provides results, significantly different from the ones obtained with single-stage tests. In the process of multiple-stage loading, when the transfer to the next stage occurs much earlier or after the sample reaches the breaking point, its strength characteristics can differ substantially from the data of single-stage tests [21]. Proceeding from the above, so far there is no conclusive opinion on the possibility to use multiple-stage method to examine behaviour of rock samples under bulk loading.

Our previous research on the possibility to use bulk multiple-stage loading to estimate strength characteristics of salt rocks [6] demonstrated that compared to single-stage loading, multiple-stage method performed as in the study [16] provides underestimated values of strength characteristics. This fact is probably explained by the accumulation of damages in the sample. Analysis of quasi-plastic deformation of salt rocks in the process of bulk loading according to studies [1, 2, 6, 7] allows to conclude that a transfer to the next stage of deformation in the process of multiple-stage loading should occur before bringing the sample to the breaking point. To rule out early loss of the bearing capacity of the sample, studies [15, 21, 24] propose to implement transition to the next step

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of multiple-stage loading when the sample reaches its dilatancy boundary. From this point onward under dilatancy boundary we understand the level of axial stress, under which the sample densifies due to deformation and it volume reaches the minimum value. Subsequent loading of the sample above dilatancy boundary leads to accumulation of damages and decompaction of the sample due to breaking of bonds between structural elements of the rock.

Experimental part. This paper reviews two possible ways to transfer to the next stage of bulk multiple-stage loading: 1) at dilatancy boundary; 2) at the level of approximately 0.9 from the strength limit of the respective loading stage.

Study on the impact of lateral pressure level on salt rock dilatancy boundary. In order to study the possibility to transfer to the next stage of bulk multiple-stage loading at the dilatancy boundary, 12 cylindric samples (86 mm in height, 43 mm in diameter) were prepared – drilled without using flushing fluid from a rock salt monolith at Upper Kama potash salt deposit. To rule out humidity influence on research results, before the experiment all the samples were kept in a drying box until they reached constant mass. Laboratory experiments were performed using single-stage method on a testing system MTS 815 under the following levels of lateral pressure: 1; 4 and 10 MPa.

Experimental procedure:

1) the sample was packed in the elastic collar and located in a bulk loading chamber;

2) sensors of longitudinal and lateral deformation, MTS 632.90F-04 and MTS 632.92H-03, respectively, were adjusted;

3) after the bulk loading chamber had been filled with oil, hydrostatic pressure rose to 1; 4 or 10 MPa;

4) the sample was kept at a specified level of hydrostatic pressure until the system «sample – testing machine» reached equilibrium;

5) the sample was loaded at constant deformation speed of $5 \cdot 10^{-5}$ s^{-1};

6) the experiment ended after obtaining the steady decline area in the post-peak part of the plot «longitudinal stress σ_1 – longitudinal deformation ε_1» (Fig.1).

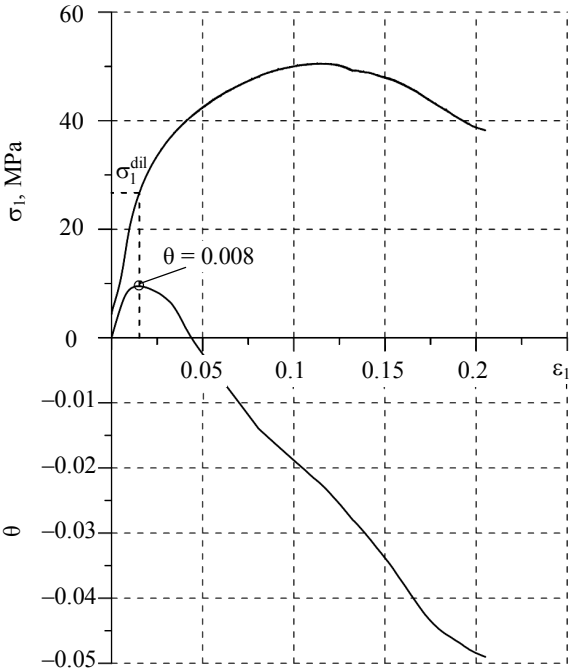


Fig.1. Deformation curve of a sample tested under lateral pressure 4 MPa

σ_1^{dil} – dilatancy boundary, $\theta = 0.008$ – respective bulk deformation of the sample

Tests were performed to assess the impact of lateral pressure level ($\sigma_2 = \sigma_3$) on dilatancy boundary of the rock salts from Upper Kama potash salt deposit (Fig.2). Each point on the curve was obtained as a result of tests on four samples.

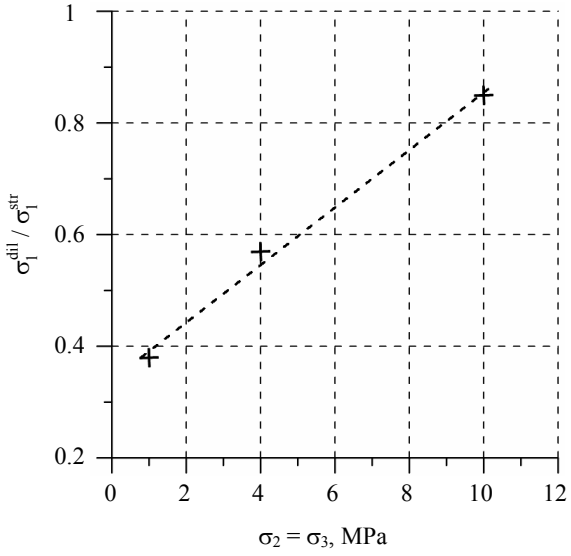


Fig.2. Influence of lateral pressure on rock salt dilatancy boundary

$\sigma_1^{dil} / \sigma_1^{str}$ – ratio of dilatancy boundary to sample's strength limit

According to Fig.2, it is visible that rock salt dilatancy boundary under lateral pressure around 5 MPa does not exceed 0.6 of the strength limit. Low value relative to dilatancy boundary ($\sigma_1^{dil} / \sigma_1^{str}$) under low

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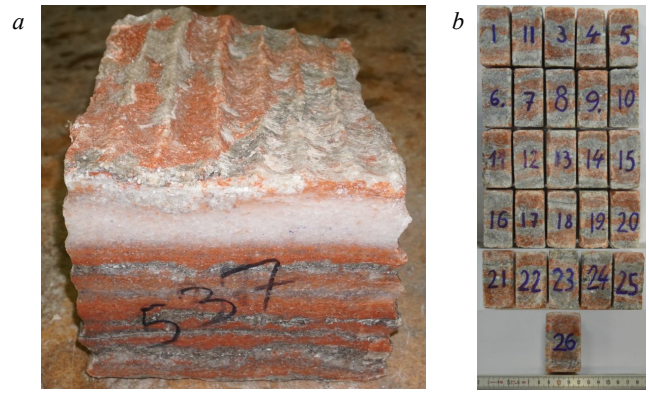


Fig.3. Photograph of a banded sylvinite monolith (*a*) and test samples (*b*)

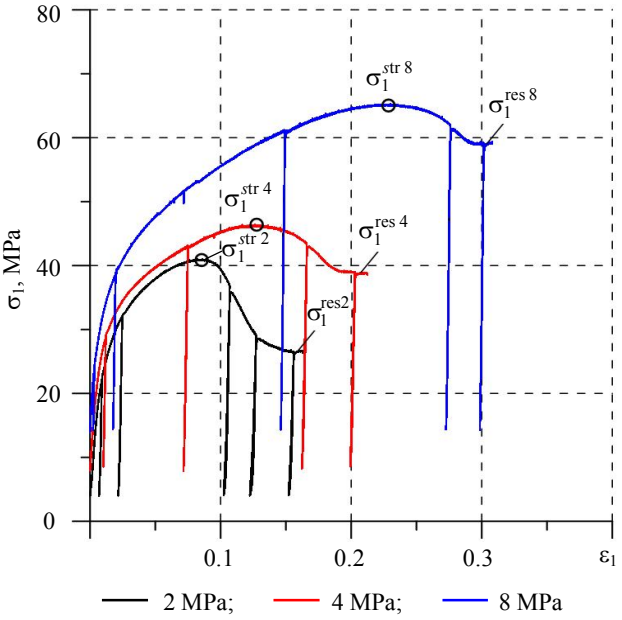


Fig.4. Dependency between longitudinal stresses and relative longitudinal deformations, obtained with single-stage tests of sylvinite samples under varying lateral pressure

levels of lateral pressure does not allow to predict the strength limit of rock salt from Upper Kama deposit at the first stages of multiple-stage loading. It should be noted that obtained value of relative dilatancy boundary of rock salt agrees quite well with the data from study [7]. Authors [7] associate the existence of dilatancy boundary in mineral rocks with structural changes, occurring inside the sample in the process of loading. Before dilatancy boundary occurs a partial closing of fractured-porous space of the sample. After longitudinal stresses exceed dilatancy boundary, a reopening of earlier closed fractures and (or) emergence of new ones take place. Low value of relative dilatancy boundary in salt rocks is explained by their very low porosity and practically total absence of intergrain fractures. According to the study [18], salt rock porosity amounts to 0.5-1 %, in separate cases it can be lower than 0.1 %. According to authors of the paper [20], naturally low fracturing of saline deposits is associated with the inclination of salt rocks to heal fissures in the creep process.

Multiple-stage tests of salt rocks. In order to investigate salt rock deformations under bulk multiple-stage loading, a block of banded sylvinite with dimensions of 400 × 400 × 400 mm (Fig.3, *a*) was picked at the 4th Berezniki potash salt mine of Upper Kama potash salt deposit. A series of prismatic samples with dimensions of 35 × 35 × 70 mm were madefrom it. The samples were manufactured on a cutoff machine with a diamond blade without using flushing fluid. Prismatic shape of the samples in this part of the experiment is associated with existing difficulties, which we encountered trying to drill cylindrical samples from the blocks of banded sylvinite.

In total 26 samples were tested (Fig.3, *b*), including 21 samples tested with a single-stage method and 5 samples – with a multiple-stage loading. The tests were performed under three levels of lateral pressure: 2; 4 and 8 MPa. Before performing the experiments, the samples were kept in a drying box until they reached constant mass.

Single-stage experiments were carried out following the same procedure, described in the previous section. The difference lay in the fact that to track the changes of elasticity modulus at various deformation stages a series of unloadings with subsequent loading was performed. Elasticity modulus was estimated using linear part slope of the unloading leg from the diagram «longitudinal stress – relative longitudinal deformation». Basing on the results of single-stage tests, the strength limit σ_1^{str} and residual strength σ_1^{res} of banded sylvinite samples were estimated (Fig.4).

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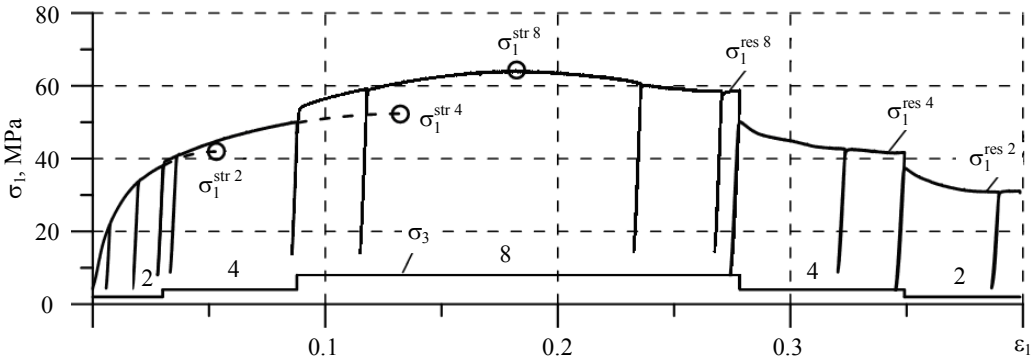


Fig.5. Dependency «longitudinal stresses – relative longitudinal deformations», obtained for one of the samples with a «modified» multiple-stage loading method

The principal difference of the applied multiple-stage loading from the method used by the authors [6, 16, 19, 22, 29] lies in the fact that in our experiments the transfer to the next loading stage occurred at the loading level of approximately 0.9 of the strength limit ($0.9\,\sigma_1^{str}$) of the respective loading stage. To track the changes of elasticity modulus in the process of multiple-stage loading, at each stage a series of unloadings with subsequent loading was performed (similar to single-stage tests). The loading during multiple-stage tests was performed at constant speed of longitudinal deformation $5\cdot10^{-5}$ s^{-1}. The breaking point at lateral pressure values of 2 and 4 MPa was estimated by means of graphical extrapolation of pre-peak part of the diagram «longitudinal stress – relative longitudinal deformation» (Fig.5). After the sample reached residual strength $\sigma_1^{res\,8}$ at lateral pressure of 8Mpa, step-down reduction of lateral pressure took place – a transfer to the following stage with lateral pressure 4 MPa, the speed of longitudinal deformation remained constant, residual strength $\sigma_1^{res\,4}$ was estimated. In a similar fashion, residual strength $\sigma_1^{res\,2}$ was assessed at lateral pressure 2 MPa.

On a qualitative level, Fig.6 demonstrates how much the sample loses its shape as a result of compression tests under varying levels of lateral pressure and loading patterns (single- and multiple-stage). Samples 1, 20, 9 were examined by means of a single-stage loading, sample 6 – by means of a multiple-stage one.

Discussion of examination results. Results of examinations are summarized in the table. Analysis of the influence that lateral pressure exerts on the strength limit of banded sylvinite samples reveals that results of multiple-stage tests are similar to the ones of single-stage examinations. Relative error of breaking point estimation using multiple-stage method as compared to the single-stage approach lies within the range from 3.4 to 9.5 %. This being said, there is a clear trend of strength limit rising with the growth of lateral pressure. Thus, e.g., as lateral pressure rises from 2 to 8 MPa, the strength limit of sylvinite increases more than by 1.5. Same results were obtained for the residual strength as well (see the Table). Slightly overestimated limit of residual strength ($\delta^{res} = 19.8$ %), obtained with the multiple-stage method under lateral pressure of 2 MPa, can be explained by strong deformation of the samples in the course of examinations, which lead to indentation of loading hobs into the sides of the samples (Fig.6). This

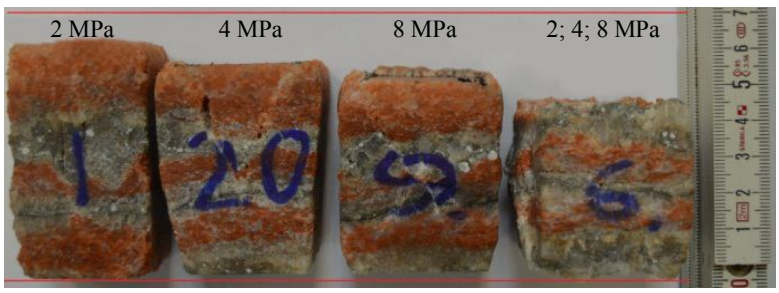


Fig.6. Photograph of samples after the test

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problem can be solved by using larger hobs: the size of loading hob's edge should be 1-2 mm longer than the respective side of the sample.

Strength limit σ_1^{str} and residual strength σ_1^{res} of banded sylvinite, obtained by means of single- and multiple-stage tests

Lateral pressure $\sigma_2 = \sigma_3$, MPa	Single-stage method, 21 samples		Multiple-stage method, 5 samples			
	σ_1^{str}, MPa	σ_1^{res}, MPa	σ_1^{str}, MPa	δ^{str}, %	σ_1^{res}, MPa	δ^{res},%
2	41.9 ± 2.0	26.8 ± 1.2	37.9 ± 1.7	9.5	32.1 ± 1.5	19.8
4	49.8 ± 2.0	38.8 ± 4.1	48.1 ± 1.9	3.4	42.1 ± 2.4	8.5
8	65.1 ± 1.3	58.0 ± 6.3	61.9 ± 4.1	4.9	56.4 ± 2.6	2.7

Note. Reliability 0.9; values δ^{str} and δ^{res} – relative error of strength limit and residual strength estimation by means of a multiple-stage method as compared to single-stage method results.

According to examination results, certificate parameters of Mohr-Coulomb strength were defined for banded sylvinite: adhesion coefficient C, angle of internal friction φ at the strength limit, adhesion coefficient C^{res} and angle of internal friction φ^{res} at the residual strength limit (Fig.7). Analysis of calculated values of adhesion coefficients and internal friction angles for banded sylvinite samples (Fig.7, *a*, *c*) demonstrates that multiple-stage method of bulk loading provides values of mechanical indicators, which take into account dispersion of experimental data in the process of strength limit estimation (see the Table), comparable to single-stage test results. Values of adhesion coefficient and internal friction angle at the residual strength limit, obtained by means of multiple-stage method, significantly differ from the ones calculated using single-stage approach (Fig.7, *b*, *d*). This fact is explained by overestimated residual strength,

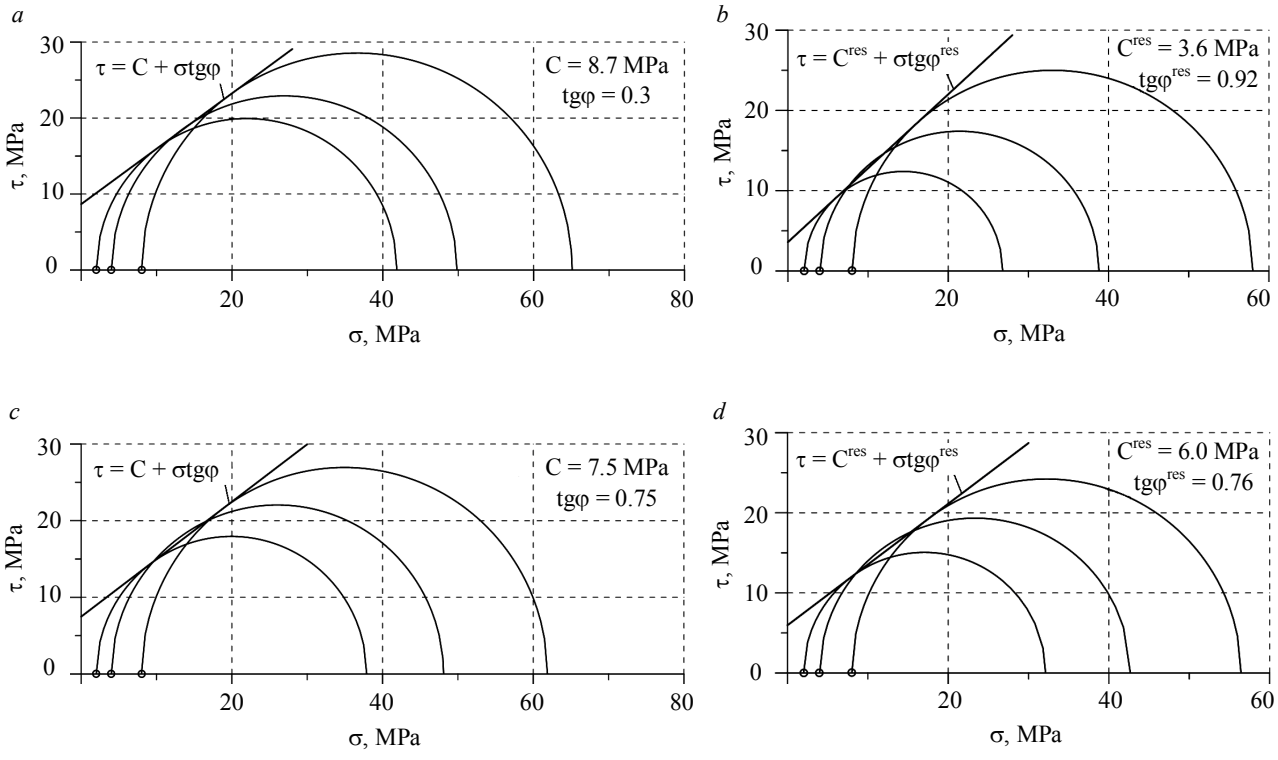


Fig.7. Certificate of strength (*a*, *c*) and residual strength (*b*, *d*) of banded sylvinite, obtained by means of single-stage (*a*, *b*) and multiple-stage (*c*, *d*) tests

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obtained by means of multiple-stage method under lateral pressure of 2 MPa (see Table). As mentioned earlier, this problem can be solved by using slightly larger loading hobs.

Estimation of elasticity modulus E of banded sylvinite in the process of deformation (σ_1/σ^{str}) depending on the level of lateral pressure ($\sigma_2 = \sigma_3$) and examination type is reflected in Fig.8. X-axis represents the process of deformation relative to the strength limit of corresponding samples. Y-axis is divided into two parts: pre-peak and post-peak. Subvertical dash-dot line is a conventional border between post-peak decompaction of the rock and sample's achievement of residual strength level.

Data of single-stage tests (Fig.8) show that with growing lateral pressure sylvinite elasticity modulus increases at all stages of deformation. Under lateral pressure of 2 MPa (Fig.8, *a*), 4 MPa (Fig.8, *b*) in the process of deformation there is a clear trend of decreasing elastic characteristics. The most intensive reduction of elasticity modulus under constant lateral pressure takes place at the deformation stage of 0.8-1.0 from the strength limit of respective samples. At the same time, the process of samples reaching residual strength is accompanied by the elasticity modulus approaching a constant value, which indirectly hints at the fact that formation of the material with the new structure has ended [1]. It should be noted that the intensity of Young modulus reduction in the deformation process significantly drops with rising lateral pressure.

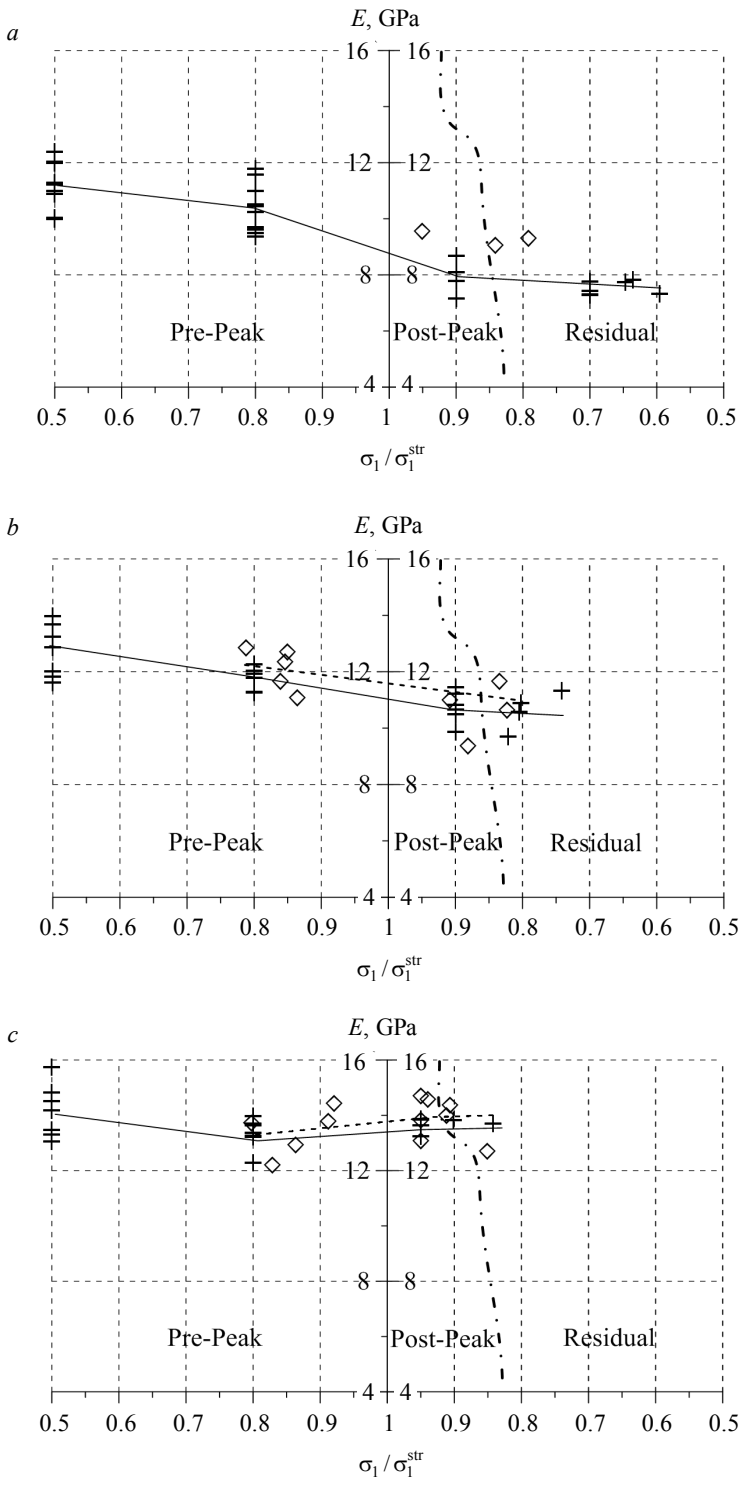


Fig.8. Changes in elasticity modulus in the deformation process depending on the level of lateral pressure (*a* – 2 MPa, *b* – 4 MPa, *c* – 8 MPa) and examination type
«–», «+» – result of single-stage tests;
«---», «◊» – result of multiple-stage tests

Results of elasticity modulus estimation in the process of multiple-stage loading are similar to the ones obtained by means of single-stage tests (Fig.8). Changes in elasticity modulus in the process of multiple-stage loading (Fig.8, *b*, *c*) are similar to the results of single-stage examinations. This fact can bear the evidence that described loading patterns cause similar deformation processes in the samples.

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Conclusion. The study of the influence that lateral pressure level exerts on the dilatancy boundary of salt rocks showed that it is inefficient to use dilatancy boundary to estimate the breaking point of salt rocks at Upper Kama potash salt deposit under bulk multiple-stage loading.

In order to analyze deformation processes occurring in salt rocks in the laboratory conditions, it is recommended to use bulk multiple-stage loading and to transfer to the next deformation stage at the point, corresponding to 0.9 of the sample's strength limit. As the sample reaches residual strength under maximum lateral pressure, it is feasible to transfer to the lower level of lateral pressure, which allows to obtain residual strength value, corresponding to current lateral pressure.

Performed research demonstrated that a multiple-stage method of bulk loading adequately reflects the processes of deformation and destruction, taking place in the samples, and can be utilized to assess not only strength, but also elastic characteristics of salt rocks.

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