THE MODELING OF THE INTERACTION OF ROCK MASS AND COMPLIANT LINING WHILE IT IS EXPANDED

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Abstract

The bearing capacity of metal lining from a special interchangeable profile was studied under the conditions of its interaction with the rock mass both in expanding and in compliant modes. The purpose of research is the development of methods for managing the state of mine working by adapting its parameters to the rock pressure effects. The idea of the work is to numerically model the interaction of the rock mass and arched compliant lining during its expanding. In this case, the lining was imitated using a rod system of finite elements. As a result of the studies, the parameters of the lining are determined, which ensure the reliable functioning of the mine working throughout its entire service life. In order for the lining to work efficiently, the filling of voids beyond it is needed. In this case, however, the compliant elements must have the strength of resistance that higher than that of existing lining structures. The results of studies can be used in the construction of tunnel-like mine workings.

Introduction

Reducing the cost of coal is related to the problem of increasing the sustainability of mine workings, since the cost of their maintenance varies at different mines in the range of 25% to 45%. Basically, the Donbass mines use arch compliant lining. It is mounted with a large mounting gap, usually without filling the voids beyond the arch, so the lining does not come in contact with the rock outcrop for a long time and does not prevent the rock from exfoliation and loosening. From the point of view of resource conservation, the main bearing element in ensuring the sustainability of mine workings should not be lining, but its own bearing capacity of rocks. The lining of mine working should be used, first of all, as a means of controlling the deformation processes and increasing the strength of resistance to the destruction of rocks. The study of the possibility managing the condition of mine working by means of compliant lining that is able to expand is relevant, because it is of great scientific and practical importance.

Analysis of ways to manage the condition of mine working

Ways to manage the condition of tunnel-like mine working should provide [1]:

– continuous monitoring of the state of the rock mass throughout the life of mine working;

– rational management of the interaction of the lining and the rock mass in accordance with the form of loss of its firmness;

– workability, which is the ease of implementation;

– efficiency of impact on the rock mass;

– resource conservation, i.e. the economical use of materials.

Depending on the object of the control impact application, all methods for managing the state of the surrounding rock mass can be divided into four groups:

– methods of influencing upon the rock mass by the expanding of lining;

– methods of influencing upon the lining to regulate its parameters;

– methods of managing the contact conditions of interaction of rock mass and lining;

– complex methods of adaptive management of the mine working condition.

The principles stated earlier correspond to the method of forceful influence of a compliant lining upon the rock mass, which is carried out by the active expanding. The idea of this method was probably first expressed in DonNTU [2]. The idea was brought to the practical realization by prof. I.L. Chernyak [3], who checked it at a number of Donbass coal mines. With the help of mine experiments he proved the possibility of compaction of the destroyed rocks in the zone of inelastic deformation. However, while frame of lining is being expanded with hydraulic props it does not participate in the process of creating the packing force. Therefore, after the dismantling of the hydraulic props, the rocks will be exfoliated, i.e. the desired effect, which is only possible with the proper interaction of rock mass and lining, is not achieved. More effective are the methods of two-stage influence upon rock outcrop, proposed in DonSTU [4, 5, 6].

However, the problem of adequate calculation of the metal frame lining remains unresolved. Methods of calculation proposed in the past based on the methods of construction mechanics and solid-state mechanics have not been widely used in practice. The main reason for this is that the complex and specific conditions of interaction the lining with the rock mass are still insufficiently studied, forcing the use of simplified hypotheses and numerous idealizations, which negate the practical value of such onerous calculation methods.

Known methods for determining the parameters of metal frame lining include, as a rule, three separate steps:

– determination of loads for lining and drawing up of the calculation scheme;

– calculation of internal forces and stresses, displacements and deformations in the structure of lining;

– design calculation of the lining, including the verification of its bearing capacity.

It should be noted that none of the known methods of calculating the lining does not allow for the active influence of arched lining upon the destroyed rocks in order to create the buffer zone of compacted rocks in the zone of inelastic deformation. Improvement of calculation methods should be aimed, first, at ensuring the mode of operation of the lining in its interaction with the rock mass; secondly, to take more fully into account the factors that determine the physical and mechanical properties of the rock mass, especially the formation of the zone of inelastic deformations; third, the widespread use of PCs, which allow the implementation of modern methods of computer simulation.

Beginning in the mid-1970s, the finite element method (FEM) has become the leading method of numerical solution of various geomechanical problems. Versatility and constancy of computational algorithms are the features inherent in the FEM that provided it a leading position in geomechanics. The approximation of the object being examined by a finite number of elements has a strongly marked physical nature, which increases the ease of perception of the calculation results. FEM allows modeling of plastic deformation and brittle fracture.

Setting of research objectives

The analysis showed that the problem of the mine workings is far from being finally resolved. Past studies on improving the stability of the mine workings have usually been limited to considering a separate period of their existence and a particular method adapted to the particular form of the rock pressure effects. The overall purpose of this work is to develop a methodology for managing the condition of mine working and ensure their reliable functioning by adapting metal arch lining to the rock pressure effects. To achieve this goal, it is necessary to analyze the geomechanics of management of mine working condition by means of compliant lining that allow the expanding, than to perform theoretical studies on this basis to determine the patterns of joint deformation of rocks and compliant lining by FEM numerical modeling on the PC.

General methodological proposition of modeling

On the basis of testing different methods for calculating mounting as a core system for a given load, the licensed ЛИРА software was selected. The experience of its use in underground construction proved the prospect of its application [7, 8].

The basic design scheme is a two-hinged circular arch fixed with immobile hinges at the lower nodes (1 and 98). The width of the arch is 5154 mm and the height – 3477 mm, which corresponds to the typical cross-section of the tunnel-like mine working (Fig. 1). For modeling the frame of lining, a linear universal spatial-rod finite element КЭ-10 is used, the length of which is chosen to be about 10 cm. Thus, the frame of lining model consisted of 97 identical rod elements and 98 nodes. The parameters of the elements of the КЭ-10 are set corresponding to the parameters of the special interchangeable profile of the СВП-22 (F = 27,91 cm^2, I_y = 428,6 cm^4, I_z = 566,3 cm^4, I_k = 15,54 cm^4). Physically the rod elements is reproduced of ideally elastic material with Young's modulus $E = 2 \cdot 10^5$ MPa, which corresponds to the modulus of elasticity of structural steel.

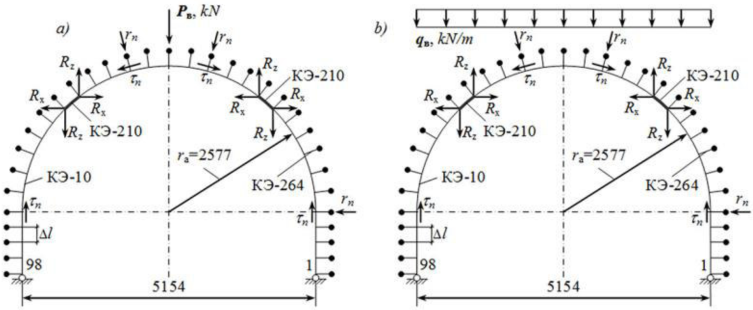


Fig. 1. Design scheme of arch lining loaded with concentrated force $P_в$ = 326 *kN* (*a*) and distributed force $q_в$ = 63,25 *kN/m* (*b*)

The presence of passive reaction of rock is the feature of the interaction of underground structures with rock mass that is surrounding their. For the simulation of rock reaction 98 physically bilinear two-node finite elements КЭ-264 are used. They have one-sided elastic bond of a given stiffness that is given taking into account the tangent displacements and friction. The resulting friction force is given as a parameter of the element КЭ-264, namely the coefficient of friction, which in the calculation is taken to be f = 0.3. The stiffness of the finite elements КЭ-264, mounted on the contour of the model of lining, is determined on the basis of the bedding value of the medium, which is equal to the ratio of pressure on its surface to displacement of the surface of the loaded area. In [9] it is stated that the bedding value depends on the displacement of the structure, and if displacements U > 2 cm then the bedding value is less than 20 MN/m^3. For loose filling, this factor can be up to 10 MN/m^3.

In the simulation, it was considered that the filling is present only in the sides of the mine working, and that filling is performed by the workers of the tunneling crew at human height (2 m). The mounting gap as a property of the element КЭ-264 is set equal to zero in the sides of the mine working, and equal to 50 mm in the roof.

The expanding of the lining is simulated with nonlinear rod finite elements КЭ-210 placed to the structure of lining frame (instead of elements КЭ-10) at the two areas that are correspond to the clamps of lining (four elements in each clamp, so the length of each clamp is 400 mm).

Nonlinearity was taken into account by setting the elements of the piecewise linear deformation law. The deformation diagram in the compression region was given by two segments: in the range $\varepsilon =$ 0…0,0875 – $\sigma =$ 0…90 MPa, which corresponds to the bearing capacity of the clamp 260 kN; in the range $\varepsilon =$ 0.0875… 0.75 – $\sigma =$ 90…92 MPa. In the stretching range, the deformation diagram was given by one segment in the range $\varepsilon =$ 0… −0.75 – $\sigma =$ 0… −10 MPa.

When calculating the mounting loads acting in the frame of the lining, which is mounted with the previous expanding, it was considered that due to the sliding of the frame by means of hydraulic jacks installed on the clamps of the lining, the top of arch interacts with the destroyed rocks of the roof, so the stiffness of the finite elements КЭ-264 of the working roof is taken to be equal to 2.5 MN/m, and the mounting gap is set at zero. The expanding force was assumed to be equal to 1000 kN and was modeled by the adding of concentrated forces to the nodes of the lining frame that correspond to the jacking points.

In the design schemas, the rock pressure iss set with different distribution laws (vertical concentrated force applied to the top of the arch, and vertically uniformly distributed load). The value of the load is set equal to $P_{в}$ =326 kN, which corresponds to the specific load $q_{в}$ = 63.25 kN/m.

Bearing capacity of the lining

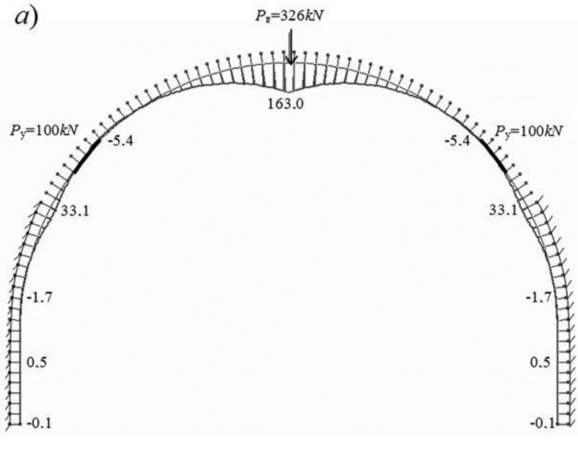
The passive reaction of the rocks during the expanding of the lining is very unevenly distributed along the perimeter of the arch. Maximum normal $r_{п}$ and tangent force $\tau_{п}$ are observed directly at the point where the hydraulic jack is applied. With distance from the point of the application of the force, the tensile forces are reduced, reaching a minimum in the lower hinges and the top of arch. The higher the expanding force *R*, the greater the passive reaction of the rocks in the nodal elements, the value of which is proportional to the mounting load and is determined by the bedding value *c*. With the exception of local areas at load sites and end portions of lining legs, the expanding force is transmitted to the rocks relatively evenly and at the expanding force of 1000 *kN* the distributed normal load is approximately 300 *kN/m*.

Figures of internal forces in a compliant arch with a minimum reaction of the node of compliance (100 *kN*) under the action of concentrated force are shown in Fig. 2 ($P_в$=326 *kN*). The maximum positive bending moments are concentrated at the point of application of the vertical concentrated force and at the sites of action of the maximum load from the reaction of the rocks in the sides of the mine working. The longitudinal force is distributed almost evenly over the perimeter of the arch.

The internal forces in the arch of lining when the reaction of compliant nodes is 100 *kN* under the action of distributed load are presented in Fig. 3 ($q_в$ = 63.25 *kN/m*). The highest bending moment is observed in the roof of the mine working. The second unsafe area is located at the point where the peak of rock reaction is exposed, which is distributed unevenly at the contact area with the filling, especially under concentrated loading. The maximums of the lining reaction correspond to the points where filling ends.

The computational experiment showed that the load of arched lining with concentrated force without filling the voids outside the lining is the worst case of its work, but it is common in practice. The lining works as a rigid structure and collapses from bending moments at the top. In this case, the lining operation in the compliant mode is prevented by the negative moment at the location of the compliant node with the low value of the longitudinal forces, which remain much less than the bearing capacity. Therefore, in such conditions, the load of lining arches often does not work in the normal mode and fails before entering the compliant stage of work. In this case, the limit load at which the lining is destroyed is an order of much lower than the standard bearing capacity of the lining.

The filling of the voids outside the lining has significant influence on its work that as a result of the interaction rock mass and lining leads to the appearance of rocks reaction, which is very rarely taken into account in existing methods of designing lining. If the filling is carried out in part, only in the sides of the mine working, then at the end of its formation a second danger zone is formed as a result of the action of the peak reaction of the rocks, the value of which largely depends on the rigidity of the filling and the height of its area.



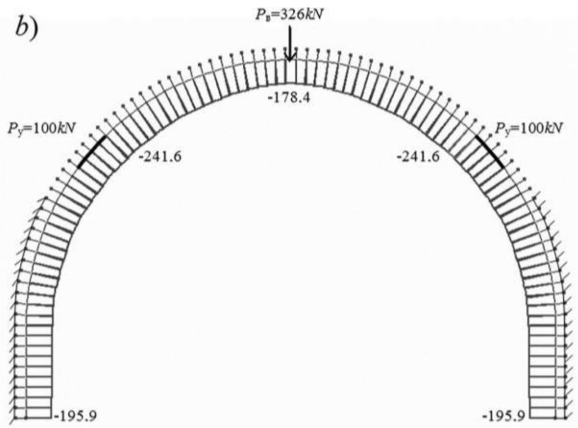
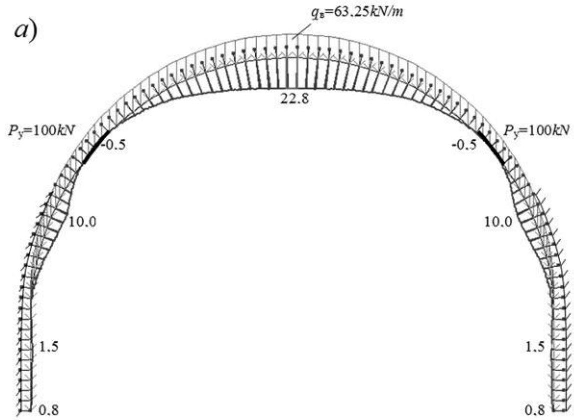


Fig. 2. Distribution of bending moments M, *kN/m* (*a*), longitudinal forces N, *kN* (*b*) in a compliant arch with a bearing capability of 100 *kN* under the influence of a concentrated force of 326 *kN*



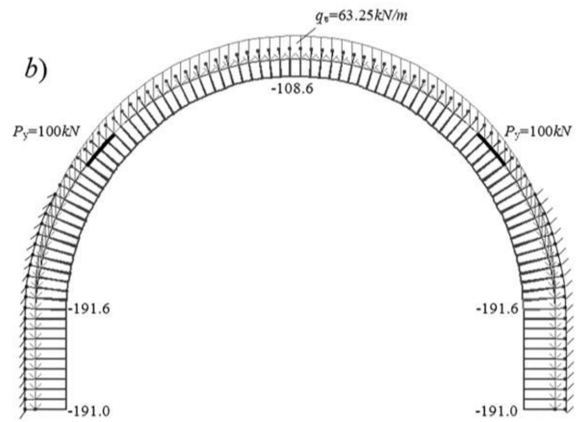


Fig. 3. Distribution of bending moments M, *kN/m* (*a*), longitudinal forces N, *kN* (*b*) in a compliant arch with a bearing capability of 100 *kN* under the influence of distributed load 63.25 *kN/m*

When the load is distributed, the bending moment in the clamps of lining decreases considerably, however, there is another dangerous cross section in the arch legs, where, in case of the absence of filling, the lining may be destroyed even before the implementation of the compliant operating mode. In order for the lining to work effectively, filling the voids beyond the lining is a prerequisite; however, the resistance of the compliant nodes must be significantly higher than that of existing structures.

The calculation of the joint action of the load from the rock pressure and from the expanding (Fig. 4) is carried out only for the distributed vertical load $q_в$ = 63,25*kN/m* when the expanding force is of 500 *kN*. Effect of concentrated force is not taken into account, since the purpose of expanding is, first and foremost, in the bringing of lining in contact with the rock mass overall the perimeter, and only then in the compaction of the destroyed rocks.

Under distributed load, the rocks are in contact with the lining over the entire length of the top, so when the arch is expanded by hydraulic jacks, the rock reaction will be more evenly distributed, and its value is determined by the amount of movement of the arch toward the rock mass and by the rigidity of the bonds, which for the destroyed rocks is 2.5 *MN/m.* An additional factor that causes the uneven distribution of the rocks reaction is the transition from the contact with the filling to the contact with destroyed rocks.

It should be noted that in the area of positive bending moments as a result of the lining deformation in the place of its contact with the rock will form a zone of exfoliation, i.e. special elements КЭ-264 should work only on shrinking. However, despite the declared properties of the one-sided operation of the finite element КЭ-264, the results of the test calculations did not confirm this possibility of ЛІ-РА software. Therefore, the action of the expanding force in the calculation was given in the form of reactive nodal loads of the rocks reaction r_n and τ_n that act simultaneously with the distributed load from the rock pressure and passive rock reaction formed at the location of the filling.

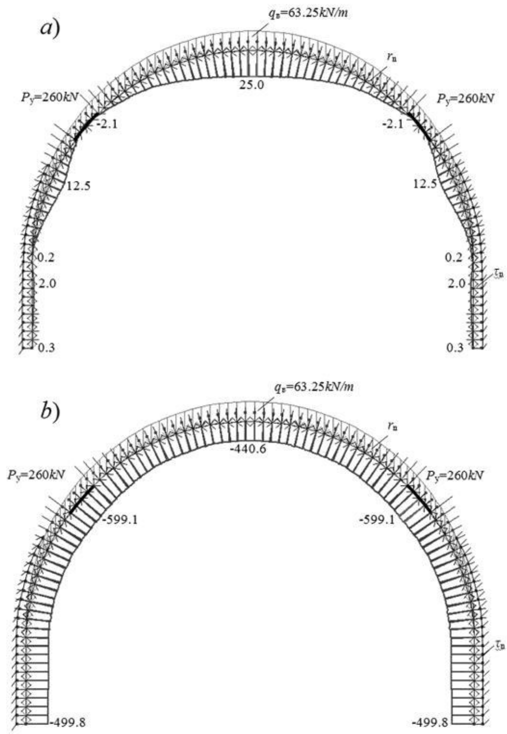


Fig. 4. Distribution of bending moments M, *kN/m* (*a*), longitudinal forces N, *kN* (*b*) in a compliant arch with a bearing capability 260 *kN* under the action of distributed force 63.25 *kN/m* and force of expanding of 500 *kN*

When the lining is expanded with the force of the 500 *kN*, the positive moments at the dangerous points (at the end of the filling) increase by a maximum of 10%, and the longitudinal force increases in the arch approximately 3 times. Therefore, the active expanding of the lining leads to an increase in bending moments and longitudinal forces in the arch, with the maximum load due to the joint action of the rock pressure and the expanding of lining is limited by the approach of the stage of steel yielding at the most dangerous point. However, the increase in internal forces in the lining during the arch expanding should be compensated by ensuring a more uniform application of the load from the rock pressure, as well as by the compacting of destroyed rocks in the zone of inelastic deformation. In order to evaluate the observed effects, the calculation of the compliant lining must be performed taking into account the actual stress-strain state of the rock mass that interacts with the lining during its expanding.

The stress-strain state of the rock mass

The calculation of the stress distribution around the tunnel-like mine working with lining is performed using the ЛІРА software on an elastic spatial model consisting of 20120 finite elements and 11578 nodes. Due to the symmetry with respect to the vertical plane in which the line of mine working lies, the fragment of the rock mass is limited to half-space. The thickness of the model in the direction of mine working development is accepted equal to 4 m that allowed to place in the model 5 frames of lining with a step of 1 m. The dimensions of the model, 28.8 m wide and 57.6 m high, ensure that the initial conditions at the model boundary are met.

The rock mass was represented using prismatic finite elements of type КЭ-34 (spatial six-node finite element). In the simulation, six layers of rocks are simulated in accordance with their real occurrence. The Poisson coefficient for all rock layers except the sandstone underlying the mine working soil was taken to be 0.3. The properties of finite elements within the sandstone layer are set taking into account its deformation anisotropy; in the vertical direction, the Poisson coefficient is set equal to 0.3, and in the horizontal direction - 0.25. This achieves an additional concentration of stresses in this rock layer and its destruction, which is observed in natural conditions in the form of exfoliation and sudden lifting of the soil of the mine working. Young's modulus of longitudinal elasticity for the mudstone and siltstone are assumed E = 5000 MPa, for limestone E = 15000 MPa, for coal E = 1200 MPa. The zone of rock destruction is set artificially by reducing the Young's modulus for coal to 60 MPa and for sandstone to 200 MPa.

The hydrostatic load on the mine working is modeled outside the area where its face impacts. The value of the load is calculated based on the average depth of the mine working site (655 m) and the average value of the specific gravity of the rocks (2050 kgf/m^3), which is 13.16 MPa.

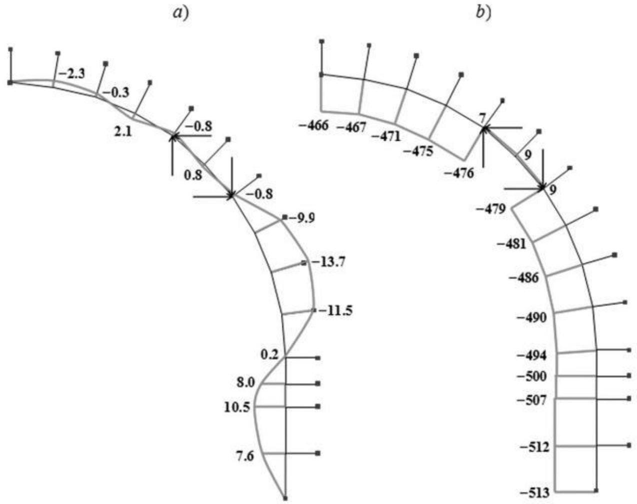


Fig. 5. Plots of distribution of bending moments (*a*), longitudinal forces (*b*) in the arched lining that interacts with rock mass during its expanding with force of 500 *kN*

The frame lining is modeled using the КЭ-10 universal space rod elements. The compliant of the lining frames is ensured by the putting into operation the physically nonlinear rod finite elements of the type КЭ-210, which simulates the clamps of lining. The load from the rock mass is transmitted to the lining frame by special finite element of the type КЭ-264 with single-sided elastic bond. The properties of the elements КЭ-10 and КЭ-264 are specified in the same way as in the previous calculations.

The expanding force from the hydraulic jacks is equal to 500 *kN*, is decomposed into vertical and horizontal components and applied in the form of concentrated forces to the extreme nodes of the lining clamps.

The analysis of the stress-strain state of the rock mass indicates that the stress distribution in the spatial problem is almost identical to the stress distribution in the flat model. As for the internal efforts, they do not correspond to those obtained in the previous calculations. This is due to the presence of a bond to the rock mass in the area of positive bending moments, which in reality is absent in the exfoliation zone.

Conclusions

As a result of the work the following results are obtained:

1) The FEM numerical modeling algorithms for the study of the stress-strain state of the rock mass around the tunnel-like mine working with the help of a flat model of the rock mass taking into account the extrinsic behavior of the rocks and their compaction during the expanding of the lining are substantiated.

2) By calculating the compliant lining allowed its expanding on the load from the rock pressure and the joint effect of the rock pressure and the expanding of the lining, the distribution of normal and tangential forces of rocks reaction along the perimeter of lining and the distribution of normal reactive resistance of the rocks in the sides of the mine working evoked by load from concentrated force and from uniformly distributed load depending on rigidity of filling, also the distribution of internal efforts, taking into account the load from expanding force and rock reaction in operating mode are investigated.

3) Based on the research it is found out that due to the distribution of vertical load of the lining, the bending moment in the lining clamps is reduced significantly, however, there is another dangerous section in the lining lags, where the destruction is possible in case of the absence of filling the voids outside lining.

4) In order for the lining to work effectively, filling the voids outside it is surely a prerequisite. Moreover, in this case, the resistance of the compliant nodes must be substantially higher than that of existing structures.

5) Based on the research, it is found out that the expanding force of 1000 kN corresponds to the maximum level of load on lining in order to not exceed the yield strength of the steels used for the production of special interchangeable profiles.

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COMPLEX APPROACH TO RESEARCH AND SELECTION OF HYDROCARBON SOLVENTS FOR ASPHALTENE-RESIN-PARAFFIN-HYDRATE DEPOSITS CONTROL

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Abstract
The article deals with the chemical methods of combating asphalt-resin-paraffin-hydrate deposits, in particular, the use of solvents. The influence of different chemicals on the dissolution of hydrates in the laboratory installation at different temperature-bar modes was carried out: the temperature varied discretely from -10 to + 40 ° C, the pressure from 0 to 10 MPa. To study the effect of hydrocarbon solvents on the process of removal of hydrate formations, we used the methods of regression analysis and mathematical planning of the experiment – simplex-lattice planning. The G-optimality criterion of the plan, including 22 experiments, was used. The measurement results are shown in the diagrams for each solvent separately. The