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GEOMECHANICAL SUBSTANTIATION OF THE HYDRAULIC WASTE DISPOSALS STABILITY IN THE UNDERMINED AREAS OF COAL DEPOSITS

Speciality 25.00.20 – Geomechanics, rock destruction, mine aerogasdynamics and mining thermophysics

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GENERAL CHARACTERISTICS OF THE WORK

Relevance of the research. The intensification of the coal industry in the Kuzbass implies an increase in the coal recovery ratio due to the preserved reserves mining, including in the areas of coupling of open-pit and underground mining operations. The most complex cases of comprehensive exploitation of mineral resources are the coal-face works performance under the industrial hydraulic engineering facilities, among which a significant group is represented by hydraulic waste disposals of the stripping soils, formed during coal strip mining. Over the entire period of existence, 60 structures with an area of 50 to 900 ha and a height of 5 to 77 m have been washed in and deposited in the basin. They are composed mainly of "soft" dispersive, water-saturated, free-flowing and plastic soils. Hydraulic waste disposals undermining can lead to a stability violation of the retaining structures – levees and dams due to their involvement in the rocks subsidence processes a subsequent development of hydrodynamic accident. Domestic and world practice shows that accidents at industrial liquid waste accumulators almost always have serious material and environmental consequences, and sometimes reach the man-made disaster scale.

The degree of development of the research area:

The study of the subsidence process during the development of underground coal deposits described in numerous works of such authors as: H. Kratch, S.G. Avershin, D.A. Kazakovsky, V.N. Zemisev, A.G. Akimov, A.N. Medyantsev, I.A. Petukhov, M.A. Iophis, V.N. Gusev et al.

The use of geomechanical methods, including numerical modeling, in the development of mineral deposits is described in scientific papers of A.P. Gospodarikov, O. Zenkevich, O.V. Zoteev, M.A. Karasev, A.B. Makarov, A.G. Protosenya, A.B. Fadeev, B. Brady, W. Witke et al. In particular, an application of numerical methods for subsidence predicting is considered in papers of N.N. Grischenkov, V.V. Zubkov, V.P. Zubov, M.G. Mustafin, M.A. Coulthard, W. Keilich, A.M. Suchowerska, A. Vyazmensky et al.

The problems of ensuring the stability of mining facilities, including hydraulic waste disposals in coal and ore deposits, were dealt with by such scientists as G.L. Fisenko, A.M. Halperin, Yu.I. Kutepov, T.K. Pustovoitova, P.S. Shpakov, V.V. Cheskidov A.V. Zhabko, E.V. Sergina, A.V. Kiyanets and others. At the same time, issues related

to their undermining are considered by N.A. Kutepova, A.S. Yagunov, S.P. Bakhaeva, I.M. Gadymba, B.E. Bronsteim and others. These works consider only individual factors affecting the stability of undermining slopes. The lack of a systematic methodological approach to taking into account the impact of undermining on the stability of hydraulic dumps predetermined the **relevance** of this study.

Purpose of work: ensuring the stability of hydraulic waste disposals in the undermined areas in the underground mining of coal deposits.

The concept of the work is to take into account changes in the stress-strain state (SSS) of man-made and natural rock masses when assessing the stability of hydraulic waste disposals in the undermined areas of coal deposits.

The main research objectives:

1. Perform the analysis of mining-and-geological conditions of underground mining operations performance on coal deposits under hydraulic waste disposals of the stripping soils.
2. Develop a method of forecasting the parameters of the rock masses displacement process on the basis of numerical modeling.
3. Develop an evaluation method of the stability of water-saturated slopes of hydraulic waste disposals, taking into account their undermining.
4. Develop recommendations to ensure the stability of hydraulic waste disposals in the undermined areas.

The study objects are the stress-strain state of the undermined rock mass and the stability of hydraulic waste disposals in the undermined areas.

The study objects are hydraulic waste disposals of the stripping soils and geomechanical processes in the undermined rock masses.

Research design:

The paper uses a comprehensive approach, which includes an analysis of the works by domestic and foreign authors in the field of rock displacement and mine engineering structures stability, full-scale methods for studying the undermined solid mass deformations in field; numerical modeling of the rock displacement process during underground mining of coal deposits and the stability of hydraulic waste disposals.

Protected scientific provisions:

1. The forecast of the undermined rock mass deformations during the coal deposits mining must be performed using a medium elastic-plastic

model, the rock mass division into zones with different mechanical behavior and their parameters substantiation, taking into account the results of the field studies in the emerging subsidence trough.

2. Assessment of the stability of the hydraulic waste disposal in the undermined areas must be performed on the basis of the developed method, taking into account the relative location of diverging levees and working face, direction of mining, subsidence parameters, magnitude and nature of the changes of rock strength properties and hydrodynamic regime of the man-made rock mass of the hydraulic waste disposal and its foundation in the area of deformations distribution.

3. Control of the stability of hydraulic waste disposals during undermining by longwall panels is achieved through organizational and technical measures, the optimal composition of which should be determined on the basis of the developed system of geomechanical provision of stability, including a package of works on the forecast and monitoring of the geomechanical processes in the "longwall panel – rock mass – hydraulic waste disposal" system.

The scientific novelty of the thesis research is as follows:

• the regularities of the change of the slope stability factor of the undermined hydraulic waste disposal, depending on its distance to the longwall face and the direction of mining operations relative to the structure are obtained;

• the conditions of possible formation of excessive pore pressure in the clay water-saturated soils of the washed-in rock mass and the natural foundation of the structure during their longwall undermining are revealed.

The obtained scientific results correspond to the specialty passport 25.00.20 – Geomechanics, rocks destruction, mine aerogasodynamics and rock thermophysics (cl. 1, 2, 4, 5, 13).

Practical significance of the research:

• the evaluation method of the stability of hydraulic waste disposal slopes in the undermined areas based on analytical calculations of subsidence and stability, as well as the SSS FEM numerical simulation of the rocks of the undermined rock masses;

• recommendations for controlling the stability and safety of the hydraulic waste disposals in the undermined areas, that include the requirements for underground mining operations, measures to improve the stability of dams and condition monitoring.

Implementation of the research results. The results were used at the mine named after A.D. Ruban of SUEK-Kuzbass JSC, during substantiation of the safe conditions of the hydraulic waste disposal undermining in the "Krasnogorsk II" open pit at the "Blagodatny-Glubokiy" section, where the coal reserves with an estimated volume of 60 million tons were depreserved in 2019.

Reliability and substantiation of the scientific provisions, conclusions and recommendations is confirmed by a satisfactory convergence of the results of field observations of surface deformations during undermining, analytical calculations and FEM numerical modeling of the rock subsidence process, by application of the modern methods of continuum mechanics to assess the stability of hydraulic waste disposals and forecast of the rock subsidence, methods of numerical analysis to perform geomechanics calculations.

The author's personal contribution consists in defining and formulating the goal and objectives of the research; substantiation of the possibility and necessity of numerical methods application to simulate the rock subsidence process; study of the factors affecting the stability of slopes of the protective structures of the hydraulic waste disposal during its undermining; development of an assessment method of the stability of hydraulic waste disposal, with tasking into account the factors; development of a numerical model for forecasting the stress-strain state of hydraulic waste disposal during undermining; obtaining the regularities of the changes in the structure slope stability factor for various combinations of impact factors; development of a system of geomechanics substantiation of the hydraulic waste disposal stability in the undermined areas.

Confirmation of the conducted research. The main provisions and research results were presented in the form of 11 reports at scientific conferences and other scientific events in 2016-2019.: *at the St. Petersburg Mining University*: The international forum-contest of students and young researchers “Topical issues of rational use of natural resources” (II degree diploma, 2017); VIII International scientific and practical conference "Innovative directions in the design of mining enterprises: geomechanical support for the design and maintenance of mining", 2017; International scientific-practical conference "Modern problems of geomechanics in the development of mineral deposits and underground space of megacities" 2017; International european scientific

Symposium EUROCK-2018 (2018); *on the basis of other universities:* international conference 11 Freiberg – St. Petersburger Kolloquium junger Wissenschaftler (Freiberg University of Mining and Technology, Germany, 2016); The international scientific symposium "Miner's Week" (National university of mining and technology "MISIS", Moscow) in 2016, 2017 and 2019.

Publications. 9 papers have been published on the thesis research topic, including 6 papers in publications, included in the list recommended by the State commission for academic degrees and titles of the Ministry of science and higher education of the Russian Federation, including 3 – in publications, indexed in the Scopus international database.

Volume and structure of the thesis research. The thesis research consists of the introduction, four chapters, conclusion, list of references, including 172 titles, is specified on 184 pages of typewritten text and contains 48 figures and 12 tables.

THE MAIN CONTENT OF THE RESEARCH

The relevance, main purpose and idea, scientific novelty and practical significance of the work are formulated in the **introduction**.

The **first chapter** contains the analysis of the methods of the subsidence processes prediction and the stability evaluation of the hydraulic waste disposal slopes, experience of researching the Kuzbass hydraulic waste disposals, including the examples of their undermining; formulates the goals and objectives of the research.

The **second chapter** presents the experience analysis of numerical modeling of the rock masses subsidence, on the basis of which an own subsidence modeling technique is presented. The description and results of the scientific and industrial experiment on determination of actual parameters of the subsidence process at the mine "Named after A.D. Ruban". The application results of the developed method for the ground surface subsidence prediction on the "Maghistralniy" section are presented in the chapter end.

The analysis of the factors, determining stability of slopes of the protective structures of hydraulic waste disposals in the course of their undermining is performed in the **third chapter**. The forecast method of the changes in the stress-strain state of the hydraulic waste disposal rocks during undermining and method of assessing its stability, taking into account the selected impact factors. Various scenarios of undermining of

hydraulic waste disposal on the Elovka river of "UK "Kuzbassrazrezugol" JSC are considered.

The **fourth chapter** presents the geomechanics providing system of stability of the hydraulic waste disposals in the undermined areas, describes its components and proposes a package of measures to control the stability of the undermined slopes of the structure.

The **conclusion** formulates the main scientific and practical conclusions of the research.

The main results of the research are reflected in the following protected provisions:

1. The forecast of the undermined rock mass deformations during the coal deposits mining must be performed using a medium elastic-plastic model, the rock mass division into zones with different mechanical behavior and their parameters substantiation, taking into account the results of the field studies in the emerging subsidence trough.

The research considers the mining and geological conditions of the Krasnoyarsk and Maghistralniy sections of the mine "Named after A.D. Ruban", developing the Egozovo-Krasnoyarsk coal deposit of the Leninsky geological and economic district of the Kuzbass. The mine undermines seams of flat bedding (2-15°) Polysaevsky II, Nadbaikaimsky and Baykaimsky average capacity of 4.5, 2.4 and 2.8 m, respectively. The rock mass is represented in the geological sheet by a thickness of alternating sandstones, siltstones and coals, overlaid at the top of the section by Neogene-Quaternary loams with a width of up to 50 m.

Full-scale study of the process of displacement in field was performed on the Maghistralniy section during the undermining of the Polysaevsky II bank by pioneer longwall panel No. 812 in 2018. The longwall panel had a length of 300 m and an average excavated depth of 191 m. The industrial experiment included observations of deformations of the ground surface and rock mass by ground and deep bench marks. According to the results of the experiment, the deformations on the ground surface and in the rock mass during the subsidence trough formation established, that allowed to calculate this process parameters. Their comparison with the calculated values obtained according to the regulatory document allowed to establish a good coincidence of the maximum subsidence of 3.18 m at the forecast of 3.01 m, as well as a 40-meter trough center shift relative to the calculated one. The actual width

of the formed subsidence trough transversely to the strike was 533 m with an estimated value of 496 m. The actual values of the boundary angles obtained by the reverse construction of the boundaries of the longwall panel impact zone were: β_0 = 63.5°; γ_0 = 66.2°, and the maximum subsidence angle is – θ = 77.2°. The comparative analysis of the calculated and actual subsidence trough on the strike shows that the results of the experiment quantitatively repeat the typical distribution, but in the active stage of the deformation process there is a lag of the actual subsidence against the calculated one with a shift to the side by about 40 m. Therefore, the dynamic trough is wider at a constant angle of subsidence (δ_0), and the maximum subsidence angle ψ_3 becomes equal to 44°, which is 6° less than the standard value of 50° for the Kuzbass.

The rock subsidence forecast during sinking of longwall panel No. 812 was performed with the use of the developed method of FEM numerical modeling. Its development was preceded by an analysis of existing methods and programs. This method essence is as follows: the longwall panel is modeled in the form of a cavity by removing the corresponding elements at a model step, after what there is a redistribution of stresses in the rock mass and the excavation contour is deformed under the influence of gravity, approaching itself until it comes into contact.

The undermined rock mass is divided into three zones: "collapses", "cracks" and "undisturbed" ones, the position of which depends on the panel size (figure 1). The mechanical properties of the rocks of the cracks and collapses zones were characterized by reduced cohesion parameters and deformation module. Two medium models were considered to describe the rock mass deformation behavior: elastic and perfectly elastic-plastic ones. The modeling was performed in a plane-strain scenario within the continuum mechanics.

Comparison of the subsidence troughs, obtained in modeling with the full-scale data and the reference curve (figure 2), allowed to establish that the convergence between the results of numerical modeling and the actual measurements is achieved when an elastic-plastic model based on the Coulomb-Mohr plasticity condition is applied, with the rock mass division into zones with different mechanical behavior. The obtained subsidence troughs showed a satisfactory convergence between the modeling results and field data, what allows to recommend the use of this method for the rocks subsidence forecast along with the standard methods.

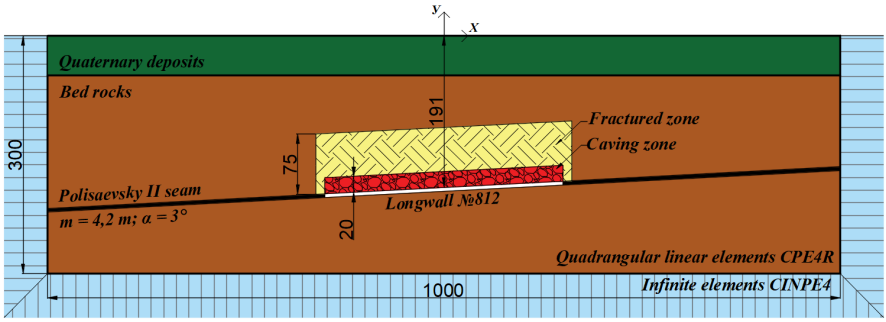

Figure 1 – Computational pattern for the simulation of the movement process.

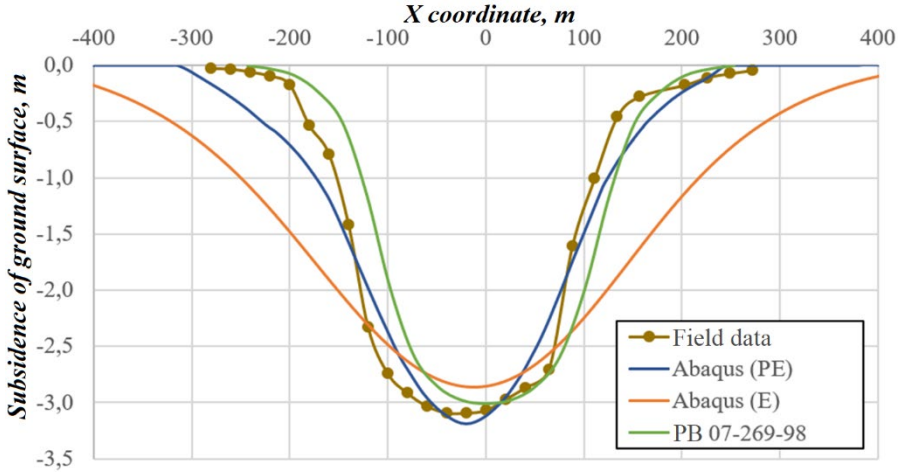

Figure 2 – Comparison of subsidence troughs, obtained during simulation and by reference with field data: *E* – elastic and *PE* – elastoplastic model.

2. Assessment of the stability of the hydraulic waste disposal in the undermined areas must be performed on the basis of the developed method, taking into account the relative location of diverging levees and working face, direction of mining, subsidence parameters, magnitude and nature of the changes of rock strength properties and hydrodynamic regime of the man-made rock mass of the hydraulic waste disposal and its foundation in the area of deformations distribution.

Study on the undermining impact to the stability of diverging levees was performed for the conditions of hydraulic waste disposal on the Elovka river of the "Mokhovskiy" open pit, characterized by an area of

900 hectares, height of 55 m and a length of levees (dams) of more than 6,000 m. Undermining of the water drainage channel and downstream slope of the hydraulic waste disposal dam was performed in the South-Western part on the interface section of the main dam and diverging levees by three longwall panels Nos. 5, 13 and 14 along Polysayevskiy II seam. Excavation of longwall panel No. 14 was accompanied by surveying observations of the surface during the subsidence trough formation. The average extracting seam thickness was 4.9 m; the dimensions of the longwall panel transversely to and on the strike were respectively 220 and 910 m, the undermining depth varied from 220 to 310 m. According to the results of surveying observations within the subsidence trough, different values of subsidence of 0.2 and 1 m on the slope of the hydraulic waste disposal and in the area of the drainage channel were established. In this case, the maximum value of subsidence reached 2.39 m with the length of the half-trough on the strike of 337 m.

A complex of computational studies on the stability of the hydraulic waste disposal slope, undermined by longwall panels with the use of methods of limit equilibrium method and FEM numerical simulation, has been perform for the conditions of this section. The calculations were performed for various situations of the hydraulic waste disposal slope undermining depending on the location of diverging levees relative to the working face, direction of mining, the subsidence parameters, magnitude and character of change of the rock strength properties and hydrodynamic regime of the man-made solid mass of the hydraulic waste disposal and its foundation in the area of deformations distribution. In particular, three scenarios of undermining were considered: in the direction "to the slope" (actual), "from under the slope" and parallel to the slope. Figure 3 shows the design scheme of undermining in the area of the profile of hydraulic waste disposal No. 8.

Computational studies of the undermining impact on the hydraulic waste disposal stability were performed with the use of the method of Spencer's limit equilibrium with a step of 50-100 m of the longwall face advancing relative to the slope. The “*Z*” coordinate is equal to the distance from the working face to the foot slope of the hydraulic waste disposal. For each of them, a separate model was built with a modified slope geometry in accordance with the slope position in the subsidence trough. The selected engineering-geological elements in the slope were characterized by physical and mechanical properties of the rocks; in

certain areas of the rock mass, involved in the subsidence process, a decrease in cohesion parameters by the value of structural strength was done. For each of the positions, the safety factor (FoS) was calculated (figure 4).

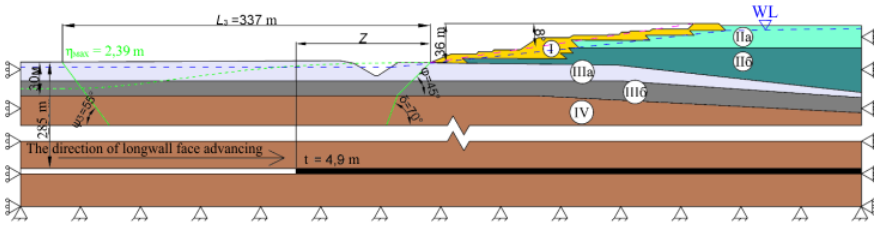

Figure 3 – The design scheme of undermining in the area of the profile of hydraulic waste disposal No. 8: I – debris rock, tail of the embankment; II – hydraulic soils; III – natural foundation; IV – Bed rocks; WL – water level

As a result of computational studies, the regularities of changes of the structure FoS at all stages of its undermining with a different combination of impact factors, as well as possible directions of mining operations. In the case of the hydraulic waste disposal undermining in the direction "to the slope" a tendency of the FoS reduction below the creterian value is observed at the initial stages of undermining, and then its increase happens to a certain value. This means that the hydraulic waste disposal exploitation under such conditions may not meet the established requirements of stability and predetermines the need for measures to improve it. In the case of the hydraulic waste disposal undermining in the direction "from under the slope", the opposite trend is observed.

The FEM numerical simulation was performed to assess the impact of the subsidence process to the SSS of the undermined water-saturated rock masses of the hydraulic waste disposals. Under certain conditions of the coal seam undermining under the hydraulic waste disposal in its slope and foundation, the fact of formation of an excess pore pressure is established. Its localization zone has a length of about 100 m (figure 5), the obtained maximum value of excess pore pressure is 33 kPa.

The excess pressure zone constantly moves forward together with the working face, and behind it there a gradual dispersion happens. The dispersion rate within this task depends on the performance rate of mining operations and the soil permeability.

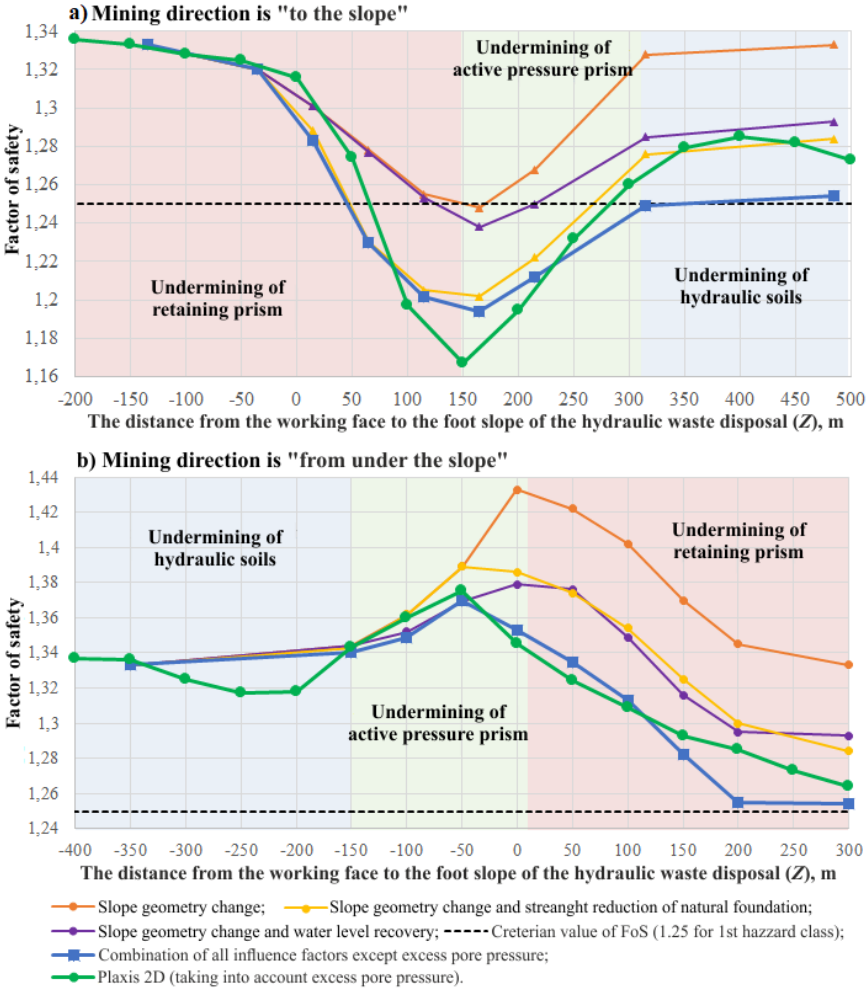

Рисунок 4 – Schedule of safety factor change depending on the distance between the working face and the slope foot during mining operations in the direction: а) to the slope; б) from-under the slope

Summing up the calculation results analysis, it should be noted that the greatest influence on the stability of hydraulic waste disposals is performed by the geometry change factor of the slope being undermined, associated with the subsidence parameters. Other factors deteriorate the FoS approximately to the same degree. The most unfavorable stability

conditions in both cases are observed when the retaining prism is undermined. On the contrary, the active pressure prism undermining leads to a positive result. However, under a combined influence of all the factors, in most cases, when the hydraulic waste disposal is undermined, a deterioration in the conditions of its stability is observed.

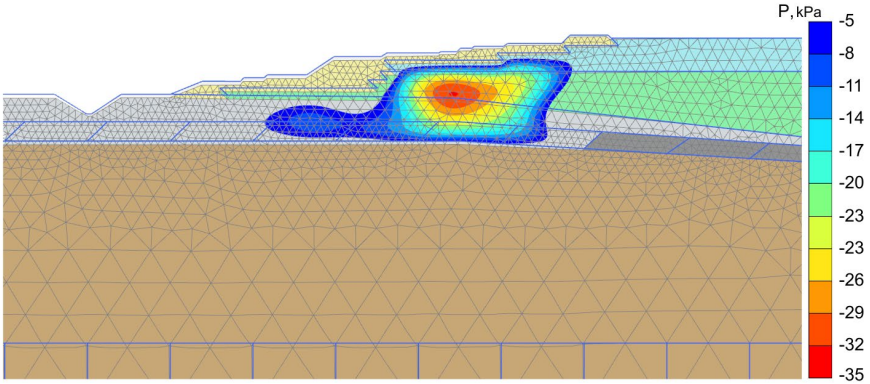

Figure 5 – Excessive pore pressure distribution, Z = 250 m

3. Control of the stability of hydraulic waste disposals during undermining by longwall panels is achieved through organizational and technical measures, the optimal composition of which should be determined on the basis of the developed system of geomechanical provision of stability, including a package of works on the forecast and monitoring of the geomechanical processes in the "longwall panel – rock mass – hydraulic waste disposal" system.

The system of geomechanical provision of stability is a complex of works and researches on studying, substantiation, control and monitoring of the rocks of man-made masses which are performed during the whole period of the hydraulic waste disposal undermining. It includes: study of mining and geological conditions of the natural-technical system (NTS) "longwall panel - rock mass - hydraulic waste disposal"; development of hydrogeomechanical model (numerical model); design substantiation; development of measures for stability control; safety monitoring.

Figure 6 schematically shows the system components and the interdependencies between them. The system key element is the design substantiation, which can be divided into two consecutively performed tasks: ground surface and structure subsidence forecast; undermined structure stability assessment. According to the calculation results, the

conclusion is made about the structure stability for the undermining period and the necessity of special measures undertaking.

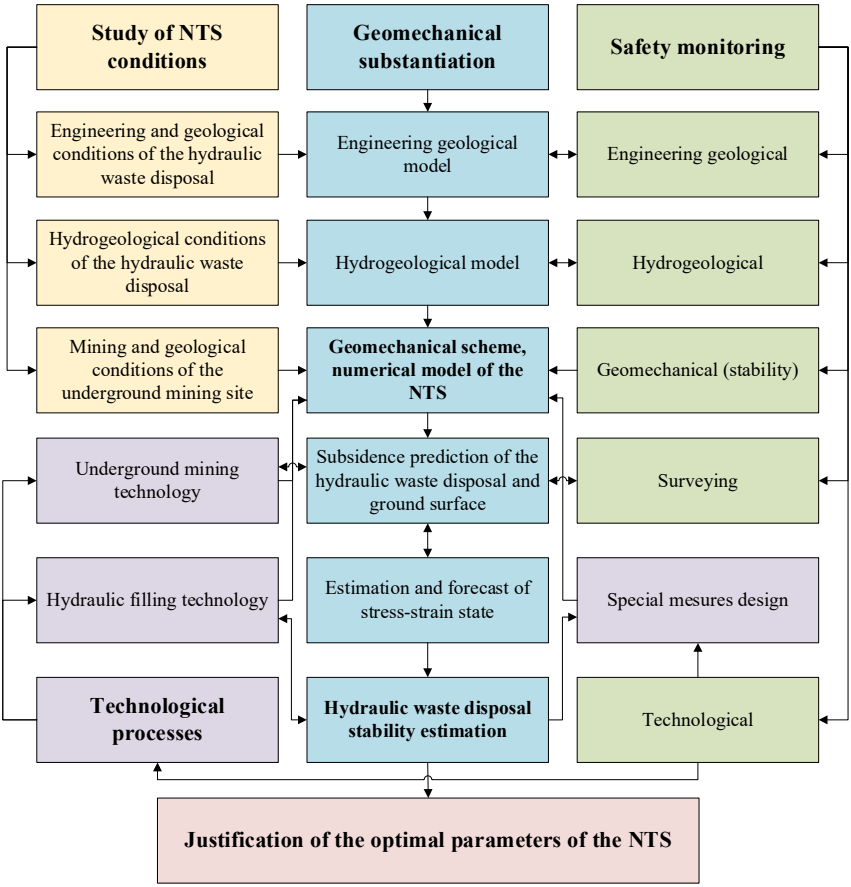

Figure 6 – The system of geomechanical provision of hydraulic waste disposals stability in the undermined areas

The hydraulic waste disposal stability control is performed by changing the process parameters of underground mining and hydraulic filling operations. During the underground mining of the coal deposits, reduction of the negative impact of mining operations on the hydraulic waste disposal stability can be performed by reducing the excavated seam thickness, speed and direction of longwall panel undermining, change in the mine layout, leaving protective pillars under the dams, and etc.

Among the controlled factors, affecting the hydraulic waste disposal stability there are the process parameters of hydraulic filling, and namely: the direction, filling method and intensity, as well as repeatability of the flow of materials of different grading coarseness to the hydraulic waste disposal. In particular, the hydraulic waste disposal filling is recommended to be performed in the direction from the bund walls, which are planned to be undermined.

The arrangement of drains that prevent filtration deformations of the slopes or improve the consolidation conditions of filled-up soils to ensure stability of the hydraulic waste disposals at the stages of their construction. Improving the stability of dams of the hydraulic waste disposals is also achieved by creating buttresses (counterweight) at the structure foundation or elsewhere.

One of the possible ways to improve the stability conditions of the hydraulic waste disposal at the stage of its liquidation, conservation and reclamation is the "dry" stockpile filling on the inwash rock mass surface. As a result of this measure undertaking it is possible to achieve extrusion of soft water-saturated rocks from the bund walls and replacement of them by stronger dump masses, and also to accelerate consolidation of the inwash soils. The process of "extrusion-substitution" forecast is recommended to be performed according to the developed method of the FEM numerical modeling.

The stability provision of the hydraulic waste disposal at all stages of its undermining is achieved through arrangement and implementation of the safety monitoring with the use of instrumental procedure of observations for deformations and hydrodynamic regime in the structure slope parts, monitoring compliance with the adopted project technology of the hydraulic waste disposal formation and changes in the engineering and geological conditions. The monitoring geomechanical component is aimed at monitoring the current stability reserve factor of the hydraulic waste disposal slopes for its compliance with the standard values, regulated by the project.

CONCLUSION

The research results are a complete scientific and qualification work, in which the solution of the urgent problem is given – the geomechanical substantiation of the stability of the hydraulic waste disposals in the undermined areas.

Main scientific and practical results:

1. The analysis of geomechanical processes in man-made and natural rock masses during a joint exploitation of the hydraulic waste disposals and underground coal mining has been performed. The experience of studying the rocks subsidence and slopes stability of the inwash structures is generalized. Follow-up on the issue of study of the hydraulic waste disposal stability in the undermined areas has been considered. It has been established that at the present stage there is no substantiated methods that allows to analyze the undermining impact on the hydraulic waste disposals stability.

2. The methods for the rocks subsidence forecast have been analyzed and a method based on the FEM numerical modeling with taking into account the results of field observations of deformations in the emerging subsidence trough has been proposed. The best convergence of modeling results with full-scale data is achieved with the use of the elastic-plastic model of the rocks and dividing the rock mass into zones with different mechanical behavior.

3. The factors determining the hydraulic waste disposals stability in the undermined areas have been identified, computational experiments have been performed to assess the impact of each of them on the slope safety factor for specific conditions of the hydraulic waste disposal undermining. It has been established that the stability in this case depends on position of the slope relative to the longwall panel and direction of its undermining; changes of the geometrical parameters of the slope during the rock mass subsidence; strength reduction in the natural foundation; changes in hydrodynamic regime in the undermined rock mass.

4. Computational experiments have established the worst conditions for the slope stability during its lower part - the retaining prism - undermining. With orientation of the stopes transversely to the strike to a slope, development of mining operations "from-under the slope" is preferable, as during the deformation first stage they are performed in the active pressure prism, and only then in the retaining prism.

5. The FEM numerical modelling technique of the stress state of a water-saturated rock mass falling into the subsidence zone with volumetric compression has been developed. In this case, conditions for the formation of a significant amount of excess pore pressure are created in the soils, reducing their strength and, accordingly, the stability of the hydraulic waste disposal slopes.

6. The control system of the hydraulic waste disposal stability on the undermined areas has been developed, consisting of works and researches of geomechanics, engineering-geological and process orientation. Its main elements are models of the stress-strain state of the undermined solid masses, which allow to predict the rocks subsidence and the stability of the hydraulic waste disposal slopes. Stability control of the hydraulic waste disposal during its undermining is performed by means of the underground mining technology, technology of operation of the hydraulic waste disposal, as well as undertaking of special measures to improve the stability state and safety monitoring.

7. The developed geomechanical provision can be used by scientific, design and production organizations during the research, design and production of the underground mining operations under the hydraulic structures.

On the thesis research topic 9 papers have been published, including 6 papers in publications, included in the list recommended by the State commission for academic degrees and titles of the Ministry of science and higher education of the Russian Federation, including 3 – in publications, indexed in the Scopus international database:

1. Kutepov, Y.Y. Geomechanical problems during the hydraulic fills operation in the areas of influence of open pit and underground mining / Y.Y. Kutepov, A.G. Protosenya // Scientific Reports on Resource Issues 2016: Proc. of Freiberg – St. Petersburg Colloquium of young scientists. – 2016. – № 11. – pp. 99-103.

2. Kutepov, Yu.I. Prediction of deformation of hydraulic-mine dumps overlaid with dump embankment / Yu.I. Kutepov, N.A. Kutepova, M.A. Karasev, Yu.Yu. Kutepov // Gornyy zhurnal – 2016, – № 12, – pp. 23-27.

3. Kutepov, Yu.Yu. Numerical modeling of the rock mass subsidence applied to geological conditions of the mine named after Ruban in Kuzbass / Yu.Yu. Kutepov, E.B. Borger // *Mining informational and analytical bulletin* – 2017, – № 5, – pp. 66-75.

4. Zelentsov, S.N. Investigation of surface failures and mechanism of their formation on undermined earth surface of the mine named after Ruban / S.N. Zelentsov, Yu.Yu. Kutepov, E.B. Borger // *Mining informational and analytical bulletin* – 2017, – № 5, – pp. 271–280.

5. Kutepov, Y.Y. The study of formation mechanism of earth surface failures due to longwall coal mining / Y.Y. Kutepov // Geomechanics and

Geodynamics of Rock Masses: Proc. of the 2018 European Rock Mechanics Symposium. – 2018. – Vol. 2. – pp. 1615-1619.

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