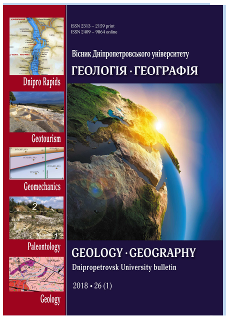

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Определение параметров описания неоднородного трещиноватого породного массива в вычислительном эксперименте

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Аннотация. Целью работы является построение вычислительной модели, основанной на классификаторах описываемых элементов геомеханической системы, имеющих нелинейную физическую природу. Разработана методика проведения вычислительного эксперимента, основанного на применении сеточных численных методов, с определением допустимого порога точности для различных схем описания механического состояния среды. Получена трехуровневая система описания механических характеристик геотехнической системы, управляющая многопараметрической сетью классификаторов описания элементов расчетной области. Качественно улучшены параметры расчетов контактных задач в сложноструктурированных геомеханических моделях, что обеспечивается повышением точности описания элементов геотехнической системы. Учет нелинейных характеристик позволяет проводить оптимизацию схем крепежных систем для различных шахтных условий на основе вычислительного эксперимента. В результате сохранение эксплуатационных характеристик выемочных выработок Западного Донбасса, пройденных в сложных горно-геологических условиях, достигается путем выбора оптимальных параметров крепежных систем, позволяющих минимизировать производственные затраты.

Ключевые слова: породный массива, трещиноватость, МКЭ, слоистый породный массива, угол падения.

Determination of parameters of non-uniform fractured rock massif in computing experiment

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Abstract. The purpose of work is creation of the computing model that based on qualifiers of described elements of geomechanical system that having the nonlinear physical nature. The procedure of computing experiment conducting that based on application of net numerical methods with determination of admissible precision limit is developed for various description schemes of mechanical condition of the environment. The iterative computing experiment under control of the system of the external estimated indicators that defining structure and a format of the description of computing area of finite element method during rock massif modeling is conducted. The area of admissible values of parameters of the elements description of geomechanical system during solution of multiple parameter problem of optimization for implicitly set entry conditions is determined. Application limits in computing models of the following groups of characteristics of description elements of computing model are defined: macro -, mini- and mixed. The three-level system of the description of mechanical characteristics of geotechnical system that managing of multiple parameter network of qualifiers of the elements description of computing area is received. Parameters of calculations of contact tasks in difficult structured geomechanical models are qualitatively improved that is provided by increasing in accuracy of the description of geotechnical system elements. Accounting of nonlinear characteristics allows performing optimization of schemes of bolting systems for various mine conditions that based on a computing experiment. The presented studies were carried out on example of conditions of the «Almaznaya" mine, southern conveyor drift, coal seam l1, depth 550m. As a result, preservation of operational characteristics of extraction mine workings of Western Donbas that were drived in complicated mining-and-geological conditions is reached by the choice of optimum parameters of bolting systems that allowing to minimize production expenses. Results that based on the executed computing experiments using the considered procedure allowed to keep operational characteristics of extraction workings with economy of materials and labor costs at the level of 9 – 17%.

Keywords: Rock massif, fracturing, FEM, layered rock massif, angle of slope.

Relevance. The choice at the design stage of bedded extraction mine working of optimum parameters of bolting and protection designs allows to minimize production expenses that reduces cost value of coal mining. Nowadays, the most available way of determination of optimum parameters of geomechanical system is the computing experiment that based on application of finite-difference numerical methods. The created rated area has to describe geomechanical system at the acceptable level of detailing. It guarantees receiving results of calculations, which with the specified accuracy will correspond to stress and deformations distribution in real mining-and-geological conditions (Bondarenko et.al., 2016).

There is the question how to implement the choice of description of elements of real object in computing model to provide the chosen precision limit with minimization of the general complexity of rated model structure.

The choice of procedure of the description of non-uniform rock massif, at the geomechanics problem definition, defines degree of accuracy of the received results. Therefore, during specific computing experiments conducting, the same characteristics of the massif can be described variously. Definition of variant description of separate characteristics of object is performed from conditions of necessary detailing at minimization of rated expenses (Majcherczyk, et. al., 2014). Three groups of indicators (characteristics) of rated model elements are detached: macro-, mini- and mixed characteristics. Macrocharacteristics are the set of the indicators that described explicitly with the maximum compliance to real (natural) indicators of the modelled object. Influence on result of calculation of such characteristics is maximum. The wrong description at least of one macrocharacteristic leads to loss of quality of rated model (Liu Fei et. al., 2015). Microcharacteristics are the set of the indicators that described in the implicit way. Substantially, such indicators do not influenced on the received result. However, they can displace area of possible decisions, therefore, that in some cases the received decisions will not correspond to the real condition of physical object. The mixed characteristics are the set of indicators which at the description in rated model using the approach that chosen for microcharacteristics at the same time influence on the received result at the level of macrocharacteristics (Elsoufiev, 2010).

The geometry of the rock layer and its main mechanical properties (elastic modulus, ultimate strengths, etc.) are detached to macrocharacteristics during modeling of layered rock massif conducting. Water content, geological non-uniformity of rock are detached to microcharacteristics. The fracturing is an example of the mixed characteristic (Sotskov et. al, 2014, 2017).

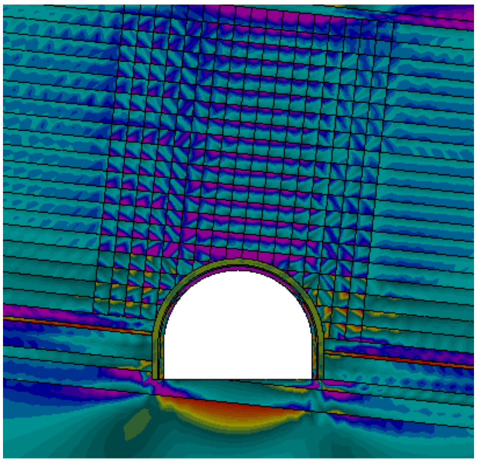
Performance of research. The stress-strain state of the rock massif nearby underground mine workings substantially depends on its structural complexity. Foliation is the macrocharacteristic and modelling with high degree of adequacy in following cases. Firstly, height of rock layers is commensurable with the general height of rated model; secondly, mechanical properties of rocks that modelling in rated model belong to the broad range of values; thirdly, the border of rock layers passes through the contour of mine working or at distance from it in two heights of working (Fomychov et al., 2017).

In all these cases, foliation substantially changes stress distribution, both nearby the contour of working, and in the zones that adjoining to borders the of rock layers. At the same time, extent of influence on stress fields for different components of geomechanical system can fluctuate ranging from 10 up to 270% (Fomichov et al., 2014).

For descriptive reasons, let’s consider stress fields of that presented on Fig 1. Here and elsewhere, we will consider only qualitative features of stress distribution that allows not specifying volume diagrams on legend figures. The presented studies were carried out for the conditions of the «Almaznaya” mine, southern conveyor drift, coal seam l_1, depth 550m.

Let’s execute simple visual comparison. Both diagrams are received for close mining-and-geological conditions, but for the different form and cross-sectional area of bedded working.

From provided it is visible that changes in the field of stress in both cases are considerable not only around development, but also on bedding surfaces. If the rock layer is crossed by development cross-sectional area, change of its SSS is observed at considerable distance from the development contour. At the same time, the less height of the layer, that changes are shown more considerably. With growth of distance from the working’s arch to border of the rock layers which are located in its roof, influence of technical characteristics fix developments on the SSS of rated model. In principle, modeling of foliation in the upper of this rated area can be neglected. The basic reason of the foliation, which is so clearly demonstrating influence in this rated model is the difference in strength characteristics of rock layers. Rock layers forming the soil and sides of working possess the increased rigidity in relation to the rock layers creating upper and lower areas of rated model. It leads to stress concentration within geometrical area of the specific layer.



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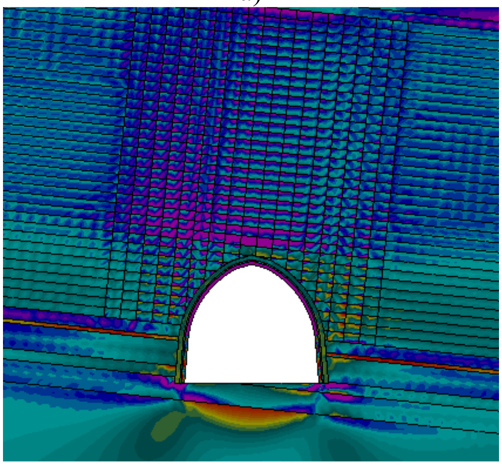


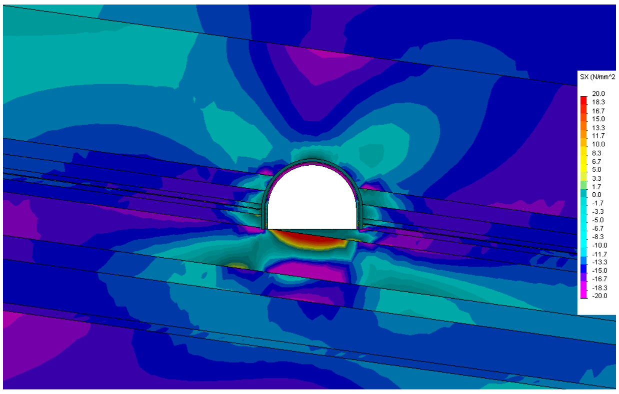
b)

Fig. 1. Intensity of stress in the fractured rock massif around working with the circular KMP (a) and tent KSPR (b) arch.

At the same time, it is necessary to consider that similar contrast in stress distribution is connected with modeling not only the foliation, but also difficult conditions of contacts between rock layers.

Foliation in rated model differently influences separate components of stress, even at the solution of rather simple tasks. For the example we will analyze influence of foliation on distribution of horizontal (Fig. 2,a) and vertical (Fig. 2,b) stresses, the stability of single bedded working that received at the assessment (Jinhai et. al., 2014). Isolines on Fig. 2 have pronounced discontinuous character. On borders of rock layers alternation of zones of the gradient of stress, in some areas with change of the sign is observed. It indicates that in certain conditions during foliation accounting, the contribution to destruction of rocks of horizontal stress can exceed influence of vertical ones considerably.

Therefore, rock pressure cannot be considered as the symmetric function in direct ratio depending on the weight of the column of rocks of the massif over the development arch (Hongpu Kang, 2014).



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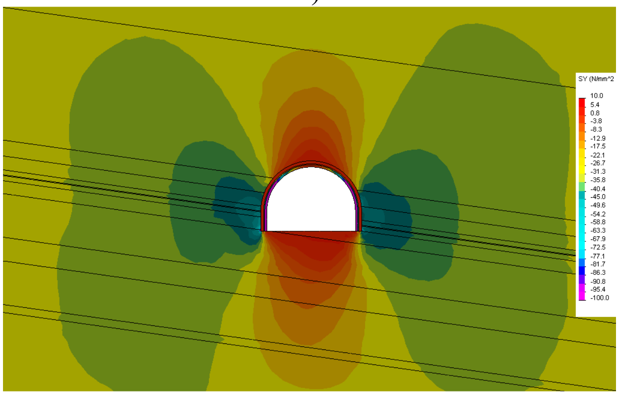


b)

Fig. 2. Distribution of horizontal a) and vertical b) stresses in the thin-layer massif nearby bedded working

Absolutely in a different way foliation influences distribution in rated model of vertical stress (Fig. 2,b). In the provided diagram, forming of zones of the squeezing and pulling stresses practically does not depend on structure of the thin-layer massif. Minor change of outlines of such zones, does not lead to growth of absolute values of stress in their limits. That is, total energy of deformations or destructions does not change.

During foliation accounting, there is the question how important, for adequacy of the received results, accounting of the incidence angle of coal layer is? In the majority analytical and numerical mathematical decisions neglect this factor as it allows to reduce substantially complexity of final mathematical equations and/or to simplify rated model by application of the equations of symmetry. At the same time, often give the arguments or based on separate natural supervision or on the analysis of results of similar computing experiments. That is, artificially narrow area of possible decisions, being guided by private experience. As a rule, such results of researches, according to authors, have qualitative character and cannot be used for the quantitative analysis of stability of underground developments. Similar approach at design and maintenance of bedded extraction workings cannot be repaid. As development as the technology element belongs to group of temporary objects for which cost value of maintenance has to be commensurable with technology and financial expediency. Therefore, margin of safety of such element has to be minimum and sufficient equally.

Such indicators for real bedded working can be reached only during accounting in rated model of the incidence angle of layer if in natural conditions the size of this corner makes more than 3º.

In confirmation of all previously mentioned we would analyze the stress distribution picture in Fig. 1 and Fig. 2. The main feature of these diagrams consists in lack of symmetry to the vertical axis of bedded working that is stress distribution in sides of development has different qualitative and quantitative character. In addition, the size of the similar imbalance depends both on the size of the incidence angle and on physical characteristics of rock layers. For different rated models, such imbalance can make up to 40% in quantitative indices and to 180% in qualitative one\.

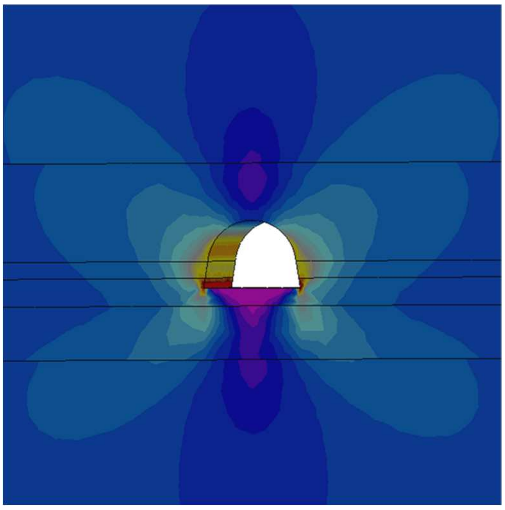
Now we will study features of the diagram of the intensity of stress given on Fig. 1 a more detail. It is accurately visible, in the rock layer forming the direct roof of working in the zone adjoining to working contour at the left the center of the increased compression stresses was created. On the right, such center is absent. As this calculation was executed in elastic statement, it allows the researcher to draw the conclusion on the increased rock pressure that influences on support of workings in the left upper of its contour.

The second feature of this diagram is stress distribution in the zone adjoining the soil of working. As the rock layers forming the soil of working have similar physical characteristics, they are involved in rebound process equally. At the expense of the incidence angle modelled in calculations in the right part of the soil of working the zone of pulling stresses is more, than in left one. Therefore, rebound size in the right part of the soil of working will be more and the size of the zone of the increased pulling stresses will be about 15% more, than in left one.

On Fig. 2 a, it is shown in what considerable degree accounting of the incidence angle influences stress distribution in the rock layers that are directly adjoining the contour of bedded development. In the given stress, case within the separate rock layer change not only the size, but also the sign. It is about the rock layer adjoining the soil of working. If the right part of the layer is loaded slightly, then in left the local gradient practically in all range of the received values of horizontal stress is observed. It speaks about high probability of destruction of this rock layer in the zone of bearing pressure of the left rack workings support.

As well as foliation, the incidence angle slightly influences on distribution of vertical stress (Fig. 2,b). In this case, there is only the insignificant shift of stress along long and lateral axes of rock layers. Degree of such shift relatively is not big at the small range of physical characteristics of rocks and insignificant from 3º to 7º incidence angles of coal layer.

Except that, rock layers can have different geometry and physical characteristics, during modeling, for increase of adequacy of the received results, have to change conditions of contacts on borders of these layers. Generally, it is possible to allocate three types of such contacts. It is rigid contact, contact with slipping and contact taking into account friction force. Application of this or that type of contact can lead to high quality and quantitative changes of the picture of stress distribution that presented on Fig. 1 and Fig. 3.



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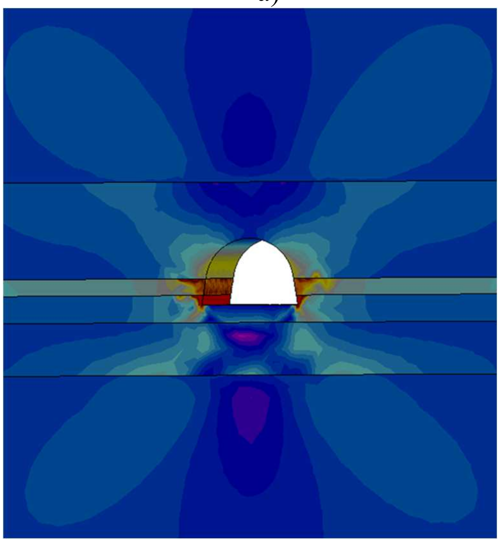


b)

Fig. 3. Distribution of intensity of stress in the massif without (and) and with (b) accounting of slipping on borders of rock layers.

On diagrams of stress that presented on Fig. 1, it is well visible as the choice of contact with taking into account friction for all borders of lithologic differences can influence the overall picture. These diagrams contain sites on which "ripples" in the field of stress are accurately looked through. This effect is caused by features of the numerical methods applied to definition of the equilibrium condition of rated system on contacts of its separate elements. This effect has strictly localized emergence zones. These zones completely match finite elements which separate nodes belong to the contacting surface.

Emergence of this effect is connected with impossibility of "smooth" distribution of internal stresses of finite elements at the certain combination of size of friction force, rigidity of the contacting rock layers and sizes of the enclosed external loading. Manifestation of this effect in most cases says that at this conjuncture the rated area is on the verge of transition from the condition of the standing balance to conditions of the dynamic state.

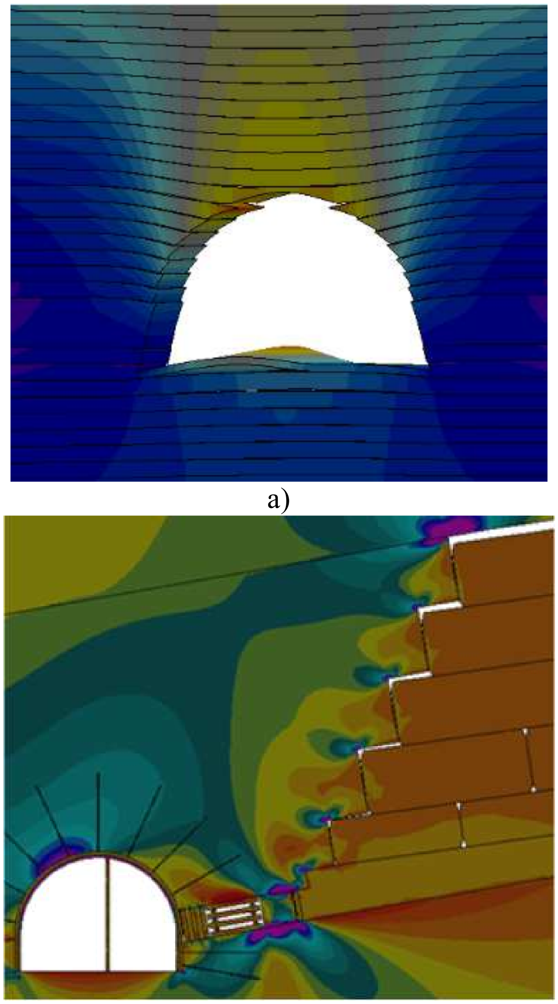
If layer thickness in rated model concerning width of the model size smaller much and more, then is involved in this phenomenon all its material. This feature is often used in calculations for modeling of conditions of contacts with friction force when between "real" layers place the layer model with special deformation characteristics. It allows emulating in the conditions of rigid contact interaction of separate elements of rated model in the conditions that are brought closer to real and at the same time not to be beyond the standing balance of all system.

Now let's consider the diagrams that presented on Fig. 3. For the case of rigid contact (Fig. 3,a), at the horizontal bedding and insignificant range of physical characteristics of rock layers, the stress distribution picture substantially matches stress distribution in the model which is not considering foliation (Zhang et.al., 2015). In addition, here in case of Fig. 3, the picture of stress substantially would differ from stress distribution in model without foliation. Such change in quality and quantitative indices of the picture of stress is caused by introduction to rated model of mutual slipping of rock layers. One this characteristic in specific conditions of computing experiment conducting completely changed structure of stress distribution in coal layer. Now the level of stress in coal layer is higher, than and its contribution to increase of stability of working considerably increases in surrounding rocks.

On the other hand, stress distribution in the soil of working had changed. The received picture of stress indicates change of nature of rebound and its quantitative indices. If on Fig. 3, a stress indicates development of rebound of the soil in the form of the segment of the circle or the oval, then on Fig. 3, it would be visible that rebound will form in two stages and at the first stage will take the trapezium shape. Such discrepancy in results requires different technology solutions on ensuring stability of mine working.

For the model that given on Fig. 4,a, fracturing was considered as the macrocharacteristic. As the rock layers adjoining to mine working possessed pronounced system of the cracks oriented on the horizontal plane and during experiment it was necessary to study influence of this system of cracks on deformation of working contour the decision to model these violations of the uniformity of the massif as the pack of layers which height is equal to the cracking step was performed. The received results showed high adequacy of rated model in relation to the effects that are really observed in bedded working.

During computing experiment conducting that directed on detection of features of behavior of the working roof at the block collapse of the massif (Fig 4,b), fracturing was considered as the microcharacteristic and was modelled in the form of the coefficient lowering durability of rocks.



a)

b)

Fig. 4. Deformation of the thin-layer massif on the contour of bedded working (a) and distribution of vertical stress in the massif at the block collapse of the roof (b) after stoping operations conducting

Features of fracturing and complexity of rated model defined the choice of such approach. Firstly, in this case, in rock of the roof two mutually perpendicular systems of cracks with the small step were observed. Modeling of the similar type of cracking leads in the geometrical way to significant increase in level of complexity of rated model that reduces computing stability of system. Secondly, availability in rated model of the large number of elements (rock blocks) which interact in difficult contact conditions repeatedly increases calculation time. Thus, modeling of fracturing leads to growth of volume of calculations on square function (from 30 to 380% in absolute measures). However, its influence on stress distribution rather evenly (from 9 to 27% in absolute measures) has also no basic character.

Based on the executed experiments, the given criterion of efficiency of the description of the element of the rated scheme ECM (effectiveness of computational model) was elaborated. In the general view value of this criterion is defined from *ECM* equation = *by T(EP1, ..., EPn)* where *T* discrete function of the description of rated object of the certain type; parameter of efficiency of the description of the specific characteristic of rated object; n – number of parameters of the description in each function.

The graphic decision in the given coordinate system of accuracy "the description calculation" is applied to implementation of the choice of optimum parameters of the description of objects of rated model of computing experiment (Fig. 5).

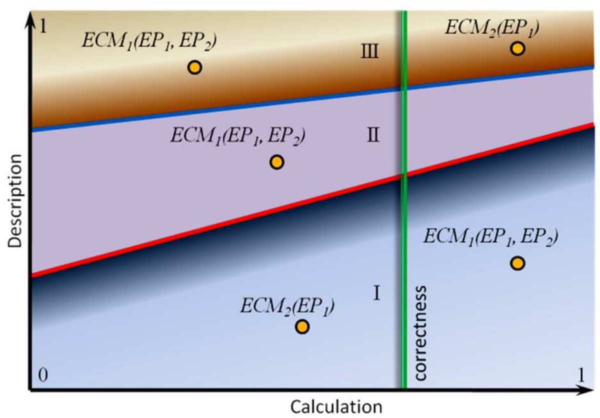


Fig. 5. The example of implementation of the given criterion of efficiency for two rated objects of different types of description

On the provided figure, admissible decisions for two chosen objects of rated model to the right of the declared limiting accuracy of calculations of computing experiment (correctness vertical). In both cases of the decision are unambiguous and at the same time belong to different groups of the description – for the first object the microcharacteristic, and for the second, the macrocharacteristic.

Results. Influence of non-uniformity of the rock mass on distribution of internal efforts grows in geomechanical model with increase in number of qualitative characteristics of non-uniformity. Decrease in extent of this influence to insignificant, from the point of view of rated model, happens under different laws and comes to the end at different distances from the contour of the considered development (Bondarenko et al. 2016; Fomychov et al., 2017). For conditions of extraction workings on the mines of Ukraine drived at depths from 400 to 900 m, change of extent of influence of characteristics of non-uniformity of the rock mass on results of calculations happens under the law close either to linear, or to exponential. That respectively allows developing two approaches of accounting of characteristics of non-uniformity of the rock massif or in the form of the correction factor, or in the form of three-stage system of descriptions of the specific characteristic.

Besides, extent of influence on the intense deformed condition of the rock mass massif of foliation and fracturing depends on the relation of geometrical parameters of cracks and rock layers to height and width of the contained working. Then, during calculating, mine workings drived in soft rocks these characteristics become defining for the optimum choice of the design of bolting system. As show the natural supervision, results that based on the executed computing experiments using the considered procedure allowed to keep operational characteristics of extraction workings with economy of materials and labor costs at the level of 9 – 17%.

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Conclusions. Application of procedure of optimization of rated model of the rock mass by the choice of the most adequate mechanisms of modeling of nonlinear characteristics of the rock mass provides increasing of accuracy of forecasting of mine working's contour behavior that drived in conditions of Western Donbas mines. Increasing in rated costs of 70 – 180% during computing experiment conducting allows to achieve approach of design values to natural measurements at the size within 5% that in absolute measures for the considered tasks, makes less than 40 mm of size of linear deformation in the point on the mine working contour.

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