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MODELING OF STRESS-STRAIN STATE OF FRACTURED ROCK MASS NEARBY OF CONJUGATED WORKINGS

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МОДЕЛЮВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ТРІЩИНУВАТОГО ПОРОДНОГО МАСИВУ ПОБЛИЗУ СПОЛУЧЕННЯ ВИРОБОК

Purpose. To develop numerical algorithms for estimating 3-D stress-strain state of fractured rock massif in the vicinity of conjugation of mine workings.

Methodology. The boundary element method for numerical modeling of stress-strain state of rock massif around cavities of complex shape in anisotropic medium is applied. The peculiarity is a combination of two models (2-D SSS of linear transversally isotropic medium and 3-D SSS of elastic nonhomogeneous medium).

Findings. Effective algorithms to determine 2-D SSS of linear transversally isotropic medium in the vicinity of a mine working (a number of mine workings) of a free form as well as 3-D SSS of elastic nonhomogeneous medium with cavities of complex shape have been developed. These algorithms have been applied to estimate stresses and displacements in the neighborhood of conjugated mine workings, traversed within fractured rocks. Boundaries of residual strength zones formed in the process of a face advance have been defined according to the analysis of stresses distribution up a roof of coal seam being mined; dependence of these zones height on the degree of rock massif weakening and on the longwall geometry has been obtained.

Originality. A new approach to modeling fractured enclosing rocks by means of combining two models (i.e. 2-D anisotropic medium and 3-D isotropic medium with shaped cavities) has been proposed. Algorithms, that implement this approach, have been developed with the help of numerical methods.

Practical value. A technique to forecast rock pressure manifestations in the vicinity of a breakage face has been developed. The technique makes it possible to relate stresses within the considered area of rock mass with such parameters as the main roof fault and load on powered supports in longwall.

Keywords: *numerical modeling, stress-strain state, fractured rock mass*

Introduction. Progress of coal industry depends on fundamental research and search for new solutions of applied tasks to create effective technologies for the development of deposits. Importance of such research increases because of the tendency towards decrease in mining whose basic factors are the growth of the stress state of the rock massif and the involvement in the development of the sections within deposits having complicated mining and geological conditions. As a rule, common geomechanical approaches rely upon solving plane problems of elasticity, plasticity, and creeping as to stress-strain state of rocks around statically invariable contour of mine workings within homogenous isotropic medium. Analytical methods, despite their diversity [1], are applicable only for a very narrow range of problems and do not allow obtaining complete solutions for modeling such a complex object as a rock massif with excavations.

The improvement on numerical methods has advanced significantly the possibilities to model structural nonhomogeneity of rock mass as well as dimensional and temporal development of mining operations. The finite element method (FEM) is the most popular among them. In [2] with the help of this method, the stresses and displacements of the "roof-cellar-soil" system were calculated taking into account the time factor and structural heterogeneity. Basing upon the FEM, papers [3, 4] model successive advance of a coal face: moving from assembling room and approaching disassembling room. In this context, each successive design stage takes into consideration rock deformations implemented during previous stages. The authors apply elasto-plastic model of medium (model of Hoek-Brown) considering only plane section of a longwall. Moreover, the finite element method makes it possible to take into account nonhomogeneous character of rock mass (i.e. presence of disturbed rocks, stratification) [5], and what is not least important, its application lowers dimension of a problem by an order.

It is common knowledge that maximum intensity of rock pressure manifestations in mine workings is observed at the moments of active changes in rock mass stress condition in the neighborhood of breakage face. So, for example, in [6] the problem of protection of the main drifts from the influence of coal face operations is considered. It is noted that, because of the lack of a reliable method for determining the stresses in a rock mass, the dimensions of the support pressure zone are usually established by the indirect characteristics of the rock pressure, which leads to a large scatter in determining the dimensions of these zones. To ensure the stability of drifts, the width of security pillars is unnecessarily increased. The latter leads to large losses of coal.

Determination of stresses near the face by numerical simulation allows one to take into account the governing factors – the change in the geometry of face area of the rock mass and worked-out area as well as interaction between a breakage face and development workings. In their vision, research studies should have an area of nonhomogeneous rock mass whose stress state is 3-D essentially.

Application of the abovementioned finite-element method complicates the problem considerably since to obtain solutions with acceptable accuracy it is required to approximate the analyzed rock mass area by means of a considerable body of elements. Thus, papers considering determination of stress-strain state of three-dimensional rock mass area (in particular, area around longwall and entry conjunction) are restricted only to elastic model of medium ignoring structural nonhomogeneous character of the rock mass.

It should be noted that in the Donbass region behavior of rock mass is complicated due to the fracturing of enclosing rocks. As a result, similar mine workings driven in different directions are of different stability. One and the same equipment turns out to be more or less efficient depending upon a direction of a face advancing as to dominating fracture system. That suggests the necessity to consider rock mass structure while analyzing the evolution of rock pressure.

To demonstrate interaction between a breakage face and development workings as well as specific character of mining and geological conditions of Donbas mines (presence of fracture system is meant), the development of more flexible algorithms is required to decrease dimension of the problem saving at the same time the advantages of 3-D model. Such possibilities are offered by a modification of the boundary element method in combination with a concept of "elastic seam element" used in papers by L. V. Novikova. Such an approach is rather efficient to model three-dimensional area of rock mass enclosing thin coal seam.

Thus, **objective of the paper** is to develop efficient algorithm for the determination of three-dimensional SSS of structurally nonhomogeneous medium with cavities of complex shape.

The idea of the paper is to consider changes in SSS of rocks lying within seam roof in the process of a face advance as well as their anisotropy due to their fracturing. In this context, the analysis is based upon the following:

1. Regularities concerning deformation of rock mass, weakened with one fracture system, can be described adequately with the model of transversally isotropic medium. Weakening degree is characterized by a coefficient of rock looseness being a relation between maximum displacements within a mine working contour in anisotropic and isotropic mediums.

2. Stresses and displacements of rocks in the vicinity of a breakage face close to actual ones are obtained as a result of solving three-dimensional problem for nonhomogeneous rock mass area in the neighborhood of shaped cavity formed in the process of coal seam development and extraction on the basis of elastic medium model when rocks are weakened due to their fractured character taken into consideration.

3. Load acting on powered support results from the weight of that share of roof rocks located beyond the limit of residual strength. Boundaries of adequate zone are determined on the strength criterion involving each stress component as well as different resistances of rocks to tensile and compression.

Statement of the problem. Spatial area of elastic rock mass enclosing coal seam, development workings and a face as well as neighboring pillar sections and sections of broken rocks is considered. Partially mined-out coal seam is modeled with the help of a junction involving both sections with freely deformable surfaces and those filled with elastic material which may exhibit characteristics of coal or broken rocks. Development mine workings are represented in the form of arch cross-section cavities. The area is under the conditions of triaxial non-uniform compression. Stress-strain state of the rock mass is identified with the help of boundary element method (BEM) with the use of concept of seam element. A plane being used to approximate thin coal seam acts as a boundary surface. Arched cavities corresponding to development mine workings are represented in the form of a set of rectangular components, inclined to the seam plane at angles from 0 to 180°.

The problem is solved in terms of additional stresses. Full stresses are represented in the form of a sum of initial $(\sigma_{ij})_0$ existing prior to mine workings emerging as well as additional σ'_{ij}, caused by the formation of mine workings: $\sigma_{ij}=(\sigma_{ij})_0+\sigma'_{ij}$. Initial stress state is set by $(\sigma_{xx})_0=(\sigma_{yy})_0=-\lambda\gamma H$, $(\sigma_{zz})_0=-\lambda H$, $(\sigma_{xy})_0=(\sigma_{xz})_0=$ $=(\sigma_{yz})_0=0$, components. In this context γ is volume weight of enclosing rocks, H is the seam depth, $\lambda=\nu/(1\text{-}\nu)$ is the coefficient of lateral pressure, ν is Poison's ratio. Ox and Oy axes are located within the seam plane; Ox is directed towards a face advance, Oy is directed along the longwall. Oz axis is perpendicular to the seam.

The boundary surface consists of components of two types. Type one consists of components corresponding to the seam share which has already been mined out. Full stresses in them are assumed to be equal to zero; hence $\sigma'_{ij}=-(\sigma_{ij})_0$. Components of type two corresponding either to the seam share remaining unmined or to areas filled with broken rocks are characterized by elastic resistance of proper material.

Thus, boundary conditions recorded in the center of the i^{th} component are

$$\begin{cases}\sum\limits_{j=1}^{N}\left(A_{zxx}^{i,j}D_x^j+A_{zxy}^{i,j}D_y^j\right)=\tilde{\sigma}_{zx}^i\\ \sum\limits_{j=1}^{N}\left(A_{zyx}^{i,j}D_x^j+A_{zyy}^{i,j}D_y^j\right)=\tilde{\sigma}_{zy}^i\\ \sum\limits_{j=1}^{N}A_{zzz}^{i,j}D_z^j=\tilde{\sigma}_{zz}^i\end{cases}. \qquad (1)$$

Left parts of equalities (1) are additional stresses in the i^{th} component obtained according to the formulas of basic analytical solution with the use of superposition principle. In equations (1) D_x^j, D_y^j, D_z^j, $j=1,\dots,N$ are components of displacement discontinuities and $A_{zxx}^{i,j}\dots$, $A_{zzz}^{i,j}$ are coefficients of stress effect.

Right parts of ratios (1) $\tilde{\sigma}_{zx}^i$, $\tilde{\sigma}_{zy}^i$, $\tilde{\sigma}_{zz}^i$ are equal to $-(\sigma_{xx})_0$, $-(\sigma_{yy})_0$, $-(\sigma_{zz})_0$, respectively if the i^{th} component belongs to type one. In the second case $\tilde{\sigma}_{zx}^i=-G^iD_x^i/h$, $\tilde{\sigma}_{zy}^i=-G^iD_y^i/h$, $\tilde{\sigma}_{zz}^i=-E^iD_z^i/h$, where E^i, G^i are modules of elasticity and shearing of the i^{th} component, h is the seam thickness.

To avoid the rock mass displacement as the rigid whole, several boundary components are fixed, i.e. displacement components in them are assumed to be equal to zero.

Basic solution is used to determine values of stresses and displacements in any point of the analyzed area according to the displacement discontinuity components obtained from the system of equations.

Boundaries of broken rock zone within the roof of the seam being mined are defined according to Parchevskiy-Shashenko strength criterion

$$\sigma_{eq}=\frac{1}{2\psi}\Big[(\psi-1)(\sigma_1+\sigma_3)-$$
$$-\sqrt{(\psi-1)^2(\sigma_1+\sigma_3)^2+4\psi(\sigma_1-\sigma_3)^2}\Big]\le k\sigma^n, \qquad (2)$$

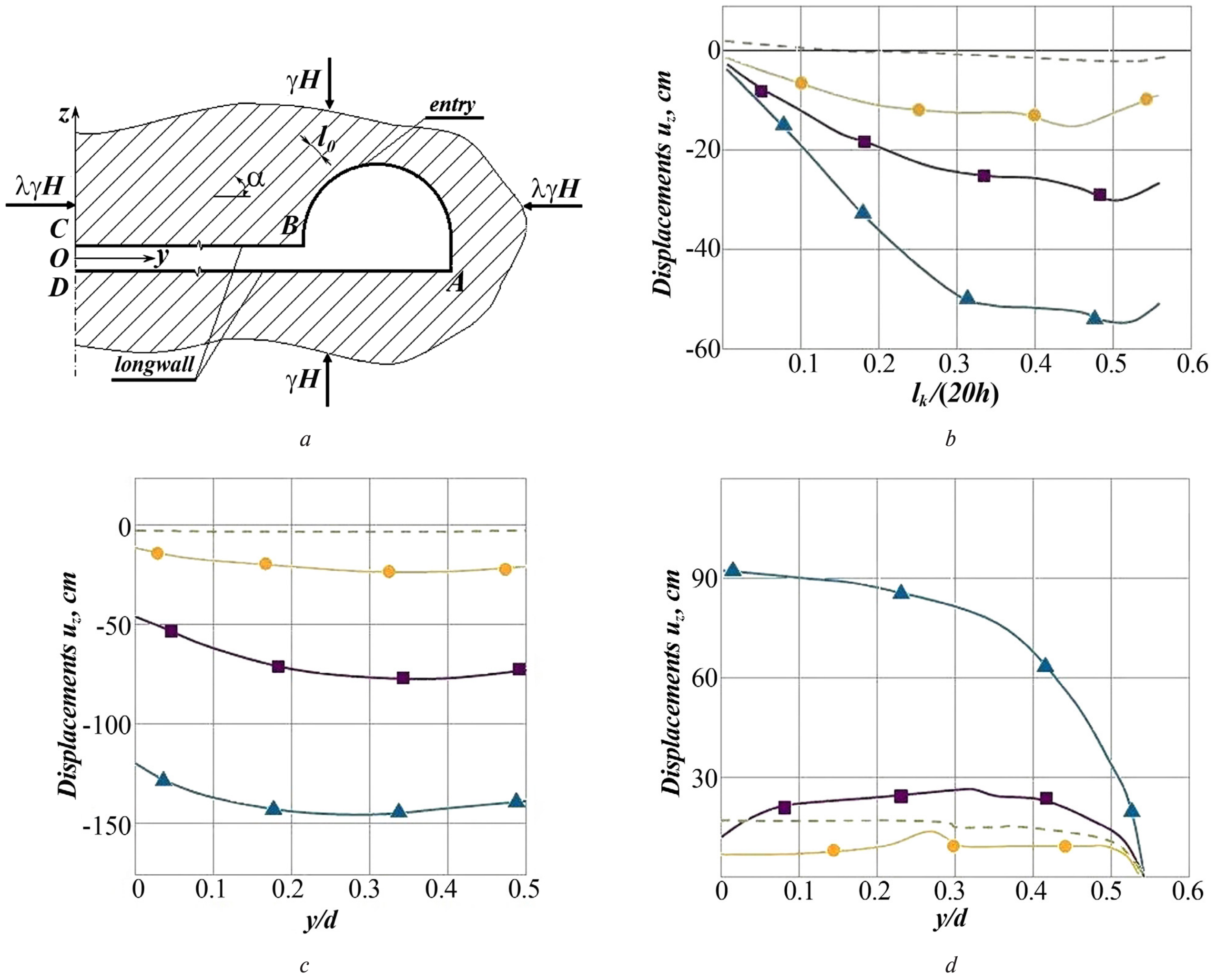
where σ_{eq} is equivalent stress; σ_1, σ_2 , are primary stresses; $\psi=\sigma^t/\sigma^c$, where σ^t, σ^c are ultimate tensile and compression strength. The criterion is applicable for the rocks, for which parameter $\psi<0.5$. Stress σ^n determined according to the elasticity law and corresponding to the ultimate residual strength within the three-link compression diagram typical for brittle rocks is used as ultimate stress in the right part of (2). Multiplier k is the coefficient of structural loosening.

As a rule, the structural loosening coefficient is understood as a difference of rock mass strength from laboratory sample strength. The coefficient is determined either empirically or on the basis of probabilistic and statistic approach. The paper applies the analogue of the coefficient – parameter of rock loosening $\tilde{k}$. It is calculated as the ratio between maximum displacements of a mine working contour within fractured and solid media. Rock mass containing a great number of neighboring displacement surfaces is considered to be continuous anisotropic rock mass having loosened stiffening properties towards the normal line to fissures. The abovementioned hardly preserves all characteristics of disturbed rock mass; however, it may be a working assumption to analyze the effects of anisotropy caused by fracturing. Thus, fissured rock mass is simulated by means of transversally anisotropic medium. Values of $\tilde{k}$ parameter obtained by the proposed method are in compliance with the results [7].

Solution method and results. Stage 1 considered plane problem of elasticity theory for transversally-anisotropic medium in the neighborhood of the development mine working and the breakage face conjunction. Stresses and displacements in the vicinity of contour $DABC$ (Fig. 1) were determined by means of the boundary element method (BEM) in the form of fictitious loads. $DABC$ contour is a cross-section of longwall conjunction with an entry in a cross-section of the longwall. Fissures are perpendicular to the face plane with inclination angle α to stratification plane. Calculation were performed for longwall length being $d=36$ m when radius of development working was $r=3$ m. Value l_k in Fig. 1, b is the arc length of a contour of development mine working; it is measured from point A towards point B.

Physical and mechanical properties of coal-bearing rocks belonging to a class of weakly resistant ones were used as initial data for the calculations. Coal seams whose roofs contain sandy and clay shale were analyzed. Mining depth was $H=450$ m and seam thickness was $h=1$ m. Characteristics of medium were as follows: volume weight was $\gamma=2.5$ t/m^3; coefficient of horizontal stress was $\lambda=0.2$; parameters of rock stiffness towards fissures were $E_s=3.5\cdot10^4$ MPa, $\nu_{sn}=0.17$; in the direction of the normal to fissures was $E_n=3.5\cdot10^3$ MPa, $\nu_{sn}=0.02$; and shear modulus was $G_{sn}=1.4\cdot10^3$ MPa. Distance between fissures is $l_0=10$ cm, normal line and tangent of fissure stiffness were $K_n=3.9\cdot10^3$ MPa/cm, $K_s=3.5\cdot10^2$ MPa/cm.

Fig. 2 represents the curves of tangential stresses σ_{yz} within $DABC$ contour referred to initial stress γH for various values of angle α as well as for the case of isotropic medium. The curves demonstrate that fracturing parallel to bedding ($\alpha=0°$) is the most unfavorable one since significant tensile stresses arise within upper part



a *b*

c *d*

Fig. 1. Calculation scheme to solve two-dimension problem using boundary-element method (a) and curves of vertical displacements of DABC contour sections:

b – AB; c – CB; d – DA; –●– *– $\alpha = \pi/2$;* –■– *– $\alpha = \pi/4$;* –▲– *– $\alpha = 0$;* - - - - *– without fissure*

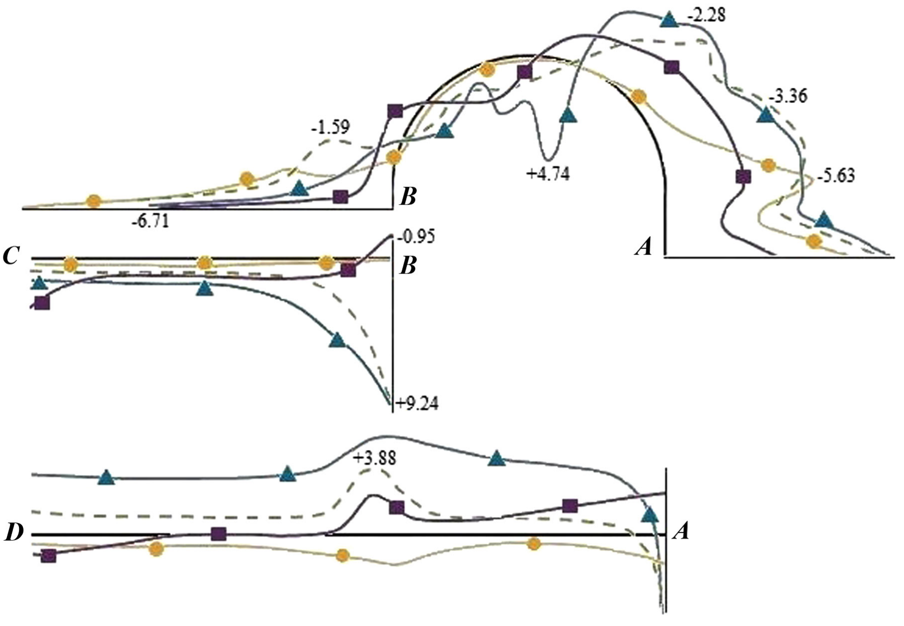


Fig. 2. Curves of $\sigma_{yz}/(\gamma H)$ values within DABC contour sections:

–●– *– $\alpha = \pi/2$;* –■– *– $\alpha = \pi/4$;* –▲– *– $\alpha = 0$;* - - - - *– without fissure* of an entry, within the section of conjunction with longwall, and along the whole longwall. If ($\alpha = 90°$), then the situation with the stresses is almost similar to that in isotropic medium except sharp increase in compressive stresses within the entry walls and within the conjunction.

The calculation results made it possible to obtain the dependence of equivalent stresses, in terms of criterion (2), within the entry arch on the angle of fissures inclination (α is indicated in radians), MPa

$$\sigma_{eq} = 14.47 e^{4.68\sin^2\alpha - 4.33\sin\alpha}. \qquad (3)$$

While analyzing displacement curves in Fig. 1 one can see that the presence of fissures results in considerable increase in vertical displacements within the whole contour especially within longwall-entry conjunction. Moreover, the closer fissure inclination to stratification plane is, the brighter displacement growth is. The results obtained at point *B* have been used to determine a coefficient of rock mass loosening $\tilde{k} = u_z / u_z^{fis}$ where u_z^{fis} and u_z are displacements in fissured medium and in solid one.

The Table demonstrates the results of the parameter calculation in terms of various fissure directions relative to the horizon.

Correlation dependence of $\tilde{k}$ parameter on α angle is expressed in radians

$$\tilde{k} = 0.068 \cdot e^{1.22\alpha}. \qquad (4)$$

Three-dimensional problem was solved during stage 2. Spatial area of rock mass including a stope and development mine workings, coal pillar in front of a face, worked-out area partially filled with broken rocks as well as pillar sections or broken rocks neighboring development mine workings, i.e. all basic components forming stress-strain state of roof rocks of the coal seam being mined was considered.

Table

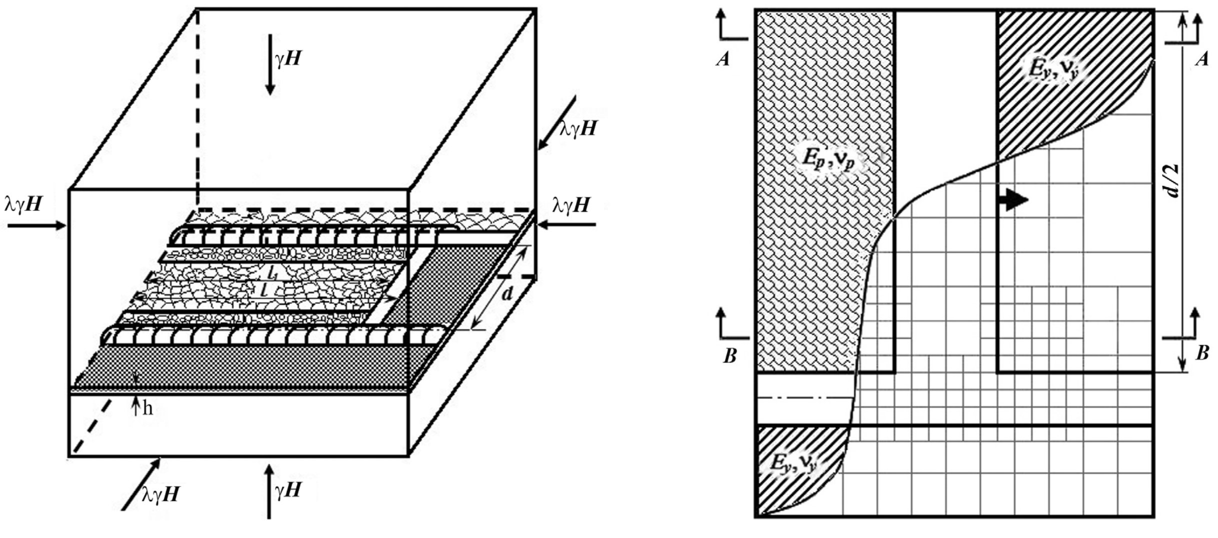
Values of loosening coefficient $\tilde{k}$ depending upon the angle of fissures inclination α

α	0°	30°	45°	60°	72°	90°
$\tilde{k}$	0.068	0.129	0.177	0.243	0.314	0.460

Fig. 3 demonstrates calculation scheme of the problem where *d* is longwall length, *h* is seam thickness, *l* is the distance from face entry to a stope, l_1 is the length of a broken rock section. *Ox* and *Oy* axes are located within the seam plane – according to its extension and rise respectively. *Oz* axis is directed along a normal line to the seam towards the earth's surface. The considered rock mass area is under the effect of distributed load with γH components along *Oz* axis and $\lambda\gamma H$ along *Ox* and *Oy* axes.

Fig. 3, *b* shows the view of the boundary surface. Here you can also see the separation into boundary elements – non-uniform network with the accumulation near hypothetic stress concentrators. Physical and mechanical properties are: enclosing rocks – Young's modulus is $E = 3.5 \cdot 10^4$ MPa, Poison's ratio is $\nu = 0.17$, coefficient of horizontal stress is $\lambda = 0.2$ volume weight is $\gamma = 2.5$ t/m^3 coal is $E_y = 3.2 \cdot 10^3$ MPa, $\nu_y = 0.13$; and broken rocks are $E_p = 3.0 \cdot 10^2$ MPa, $\nu_p = 0.06$. Depth of the seam and its thickness are $H = 450$ m, $h = 1$ m, $l = 56$ m. The following value parameters were used for the calculations: $l = 56$ m, $l_1 = 24$ m, $d = 36$ m.

The boundary element method in the form of displacement discontinuities in combination with seam components concept was used. The latter are required to model a thin layer being in the form of junction sections whose surfaces are connected with the help of a spring operating for compressions and shearing. Stiffness characteristics of the spring correspond to the material filling the junction. Cavities are approximated with the help of components of displacement discontinuities.



a *b*

Fig. 3. Calculation scheme (a) of the studied three-dimensional problem and view of boundary surface (b) in the process of the spatial problem solving

According to the modeling results, the highest stress concentration occurs in horizontal direction. Thus, peak values σ_{xx} are almost five times more than the initial ones $(\sigma_{xx})_0$ while σ_{zz} values are only two times higher than the initial ones $(\sigma_{zz})_0$. The fact observed under real conditions can be often explained by the tectonics. On the other hand, such distribution of stresses is a result of geometry of mine workings formed in the process of coal seam development and extraction as well as nonhomogeneous nature of the studied area. As for the character of changes in σ_{xx} and σ_{zz} stresses, it should be considered that there is a dome-like unloading area right above the mine working. While moving away up from the mine working, compressive stresses increase; at certain height they become equal to the initial ones. Opposite situation is above coal pillar and broken rocks filling worked-out area: right over the seam compressive stresses achieve their maximum; then they decrease down to the initial ones while move upwards.

Further, stress values obtained at each point of the analyzed area are used to determine equivalent stresses σ_{eq} according to criterion (2) as well as height of the zones within roof in which σ_{eq} values reaches ultimate stresses σ^n. Stress corresponding to the residual strength boundary within three-link diagram typical for brittle materials is used as an ultimate one. Diagram section characterizing the stage of breaking corresponds to values of elastic stresses $\sigma_{eq} > \sigma^n$. That is why the area where the criterion is disturbed corresponds to destructed rocks zone.

Fig. 4 shows isolines of equivalent stresses σ_{eq} within the seam roof in terms of cross-sections A and B. Lines within which $\sigma_{eq} = \sigma^n$ (curves 1) restrict breaking zone if enclosing rocks are solid. Vertical dimension of the zone H_p is considered as the height of rock breaking within the seam roof. In the case of rocks loosened by fissures, analogous zones are restricted by curves 2. If so, breaking height is H_p^{fis}.

The algorithm was applied for calculations performed for step-by-step increase in distance from face entry to a stope from 24 to 72 m. In this context values of longwall length varied in the range of 72–216 m as well as values of $\tilde{k}$ coefficient corresponding to inclination angles of fissures being 0° < α < 90°. As a result, dependence of height H_p^{fis} on the longwall geometry and degree of rock loosening was been obtained, m

$$H_p^{fis} = 0.072 \cdot l^{0.75} \cdot d^{0.25} \big/ \tilde{k}. \tag{5}$$

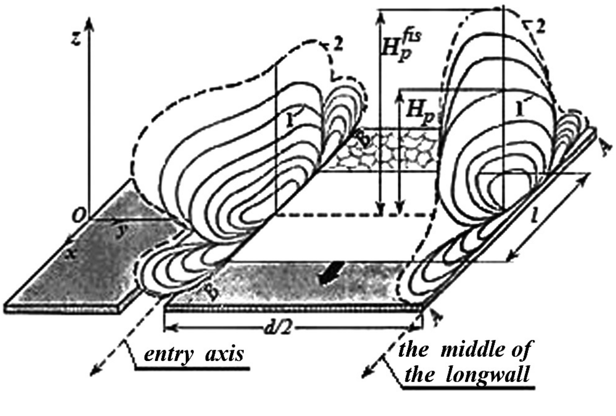


Fig. 4. Isolines σ_{eq} within the seam roof in the vicinity of the conjunction of a stope and development mine working:

1 – solid rock mass; 2 – rock mass loosened by fissures

Conclusions. Basic scientific conclusions are as follows. The boundary element method was used to develop efficient algorithm for the determination of 3D stress-strain state of elastic rock mass in the vicinity of mine workings formed in the process of coal seam development and extraction. Contrary to the available algorithms, it takes into consideration nonhomogeneous nature of the studied area and system fissility of enclosing rocks.

Algorithm to determine SSS of rock mass with one system of fissures around mine workings of arbitrary shape has been developed within the framework of plane stress state hypothesis on the basis of a model of transversally isotropic medium. The model takes into consideration orientation of fissures and distance between them. The algorithm has been applied to determine coefficient of coal-bearing rocks loosening.

According to the results of the analysis of spatial rock mass SSS for mining and geological conditions typical for the mines of Donbas, the following regularities have been identified:

- the ratio between the coefficient of horizontal and vertical stresses concentration stipulated by the geometry of cavities formed in the process of coal seam development and extraction as well as physical nonhomogeneity of the studied area is 1.3 to 3.5 at various points of the studied area;
- dependences of equivalent stresses within mine working contour (3) and coefficient of structural loosening (4) on fissure inclination angle to stratification plane were obtained; that made it possible to define that fissures along stratification are the most unfavorable ones from the viewpoint of the effect on stresses and displacements within the contour of mine workings;
- dependence of destructed rocks zone height within coal seam roof (5) on the geometric parameters of longwall and rock loosening coefficient was obtained. As it has already been mentioned, load on powered support is formed by the weight of that share of roof rocks, which are beyond residual strength. Therefore dependence (5) allows forecasting such manifestations of rock pressure as the main roof fault in the process of a stope advance. The latter may be used while selecting both equipment and technology to mine minerals; among other things it concerns mining of thin coal seams using plowing machines providing complete mechanization of the whole coal-mining process.

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Мета. Розробка чисельних алгоритмів оцінки тривимірного напружено-деформованого стану (НДС) тріщинуватого породного масиву поблизу сполучення виробок.

Методика. Використання методу граничних елементів для чисельного моделювання напружено-деформованого стану області породного масиву навколо порожнин складної форми в анізотропному середовищі. Особливістю є комбінування двох моделей (2-вимірного НДС лінійного трансверсально ізотропного середовища та 3-вимірного НДС пружного неоднорідного середовища).

Результати. Розроблені ефективні алгоритми для визначення: двовимірного НДС лінійного трансверсально ізотропного середовища в околі виробки (ряду виробок) довільної форми, а також тривимірного НДС пружного неоднорідного середовища з порожнинами складної форми. Дані алгоритми використані для обчислення напружень і зміщень поблизу сполучення очисної й підготовчої виробок, пройдених у тріщинуватих породах.

Наукова новизна. Запропоновано новий підхід до моделювання тріщинуватих порід, що вміщують вугільний пласт, шляхом використання комбінації двох моделей (двовимірної анізотропного середовища й тривимірної ізотропного середовища з порожнинами складної форми). Розроблено алгоритм, що реалізує запропонований підхід за допомогою чисельних методів.

Практична значимість. Розроблена методика прогнозування проявів гірського тиску в околі очисної виробки, що дозволяє встановити зв'язок між напруженнями в досліджуваній області породного масиву й такими параметрами, як крок посадки покрівлі та навантаження на механізоване кріплення в лаві.

Ключові слова: *чисельне моделювання, напружено-деформований стан, тріщинуватий породний масив*

Цель. Разработка численных алгоритмов оценки трехмерного напряженно-деформированного состояния (НДС) трещиноватого породного массива вблизи сопряжения выработок.

Методика. Использование метода граничных элементов для численного моделирования напряженно-деформированного состояния области породного массива вокруг полостей сложной формы в анизотропной среде. Особенностью является комбинирование двух моделей (2-мерного НДС линейной трансверсально изотропной среды и 3-мерного НДС упругой неоднородной среды).

Результаты. Разработаны эффективные алгоритмы для определения: двумерного НДС линейной трансверсально изотропной среды в окрестности выработки (ряда выработок) произвольной формы, а также трехмерного НДС упругой неоднородной среды с полостями сложной формы. Данные алгоритмы использованы для вычисления напряжений и смещений в окрестности сопряжения очистной и подготовительной выработок, пройденных в трещиноватых породах.

Научная новизна. Предложен новый подход к моделированию трещиноватых пород, вмещающих угольный пласт, путем использования комбинации двух моделей (двумерной анизотропной среды и трехмерной изотропной среды с полостями сложной формы). Разработан алгоритм, реализующий предложенный подход с помощью численных методов.

Практическая значимость. Разработана методика прогнозирования проявлений горного давления в окрестности очистной выработки, позволяющая установить связь между напряжениями в исследуемой области породного массива и такими параметрами, как шаг посадки кровли и нагрузка на механизированную крепь в лаве.

Ключевые слова: *численное моделирование, напряженно-деформированное состояние, трещиноватый породный массив*

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