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Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).

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STUDY OF THE INFLUENCE OF DISCONTINUITY OF LAYER COHESION ON THE STABILITY OF MINING WORKINGS

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Abstract. *Relevance.* Ensuring the stability of mine workings remains one of the most pressing issues in the coal industry today. When studying such issues, it is essential to consider the actual properties of the rock mass that contribute to the onset of its failure under static and quasi-static fields of superimposed stresses and strains. An important task is to determine the stress-strain state of the rock mass, taking into account the factors affecting the stability of the mine workings' boundaries. From this perspective, it becomes essential to develop a decision-making framework aimed at ensuring the stability of mine workings. *Objective.* Based on theoretical and numerical experiments, to investigate the stability of mine workings oriented in various directions within an inclined-layered rock mass, depending on the degree of discontinuity in their bonding. *Methods*. A mathematical model of an inclined-layered rock mass with discontinuous interlayer bonding is considered. The contacts between plane-parallel layers of an elastic-creeping isotropic rock mass in the vicinity of an underground mine working are represented by identical bridges between collinear slits of equal length. *Results.* Unlike the anisotropic model, the proposed model with discontinuous layer bonding does not have such drawbacks, providing a more complete description of the mechanical processes in an inclined-layered rock mass. Along with a rigorous description of isotropic creep, it takes into account the dip angle φ of the strata just as fully as the anisotropic model does. *Conclusions.* Analysis of the results of numerical simulations of the patterns of change in the stress-strain state of rock masses makes it possible to determine support parameters to improve the stability of preparatory mine workings, as well as to develop new and improve existing technologies for the efficient and safe execution of mine workings in inclined-layered rock masses.

Keywords: inclined-layered massif, stress, displacement, rock pressure, mine workings, stability, discontinuity of cohesion, gap

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ТАУ ҚҰРЫЛЫМДАРЫНЫҢ ТҰРАҚТЫЛЫҒЫНА ТҰТАС ЕМЕС ІЛІГІСУ ҚАБАТТАРДЫНЫҢ ӘСЕРІН ЗЕРТТЕУ

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Аннотация. *Өзектілігі.* Тау-кен жұмыстарының тұрақтылығын қамтамасыз ету қазіргі уақытта көмір өнеркәсібіндегі ең өзекті мәселелердің бірі болып қала береді. Мұндай мәселелерді зерттеу кезінде тау жыныстарының қосымша кернеулер мен деформациялардың статикалық және квазистатикалық өрісінде бұзылуының басталуына ықпал ететін нақты қасиеттерін ескеру табиғи нәрсе. Маңызды міндет тау-кен өндірісінің контурларының тұрақтылығына әсер ететін факторларды ескере отырып, массивтің кернеулі деформацияланған күйін анықтау. Бұл позициядан тау-кен жұмыстарының тұрақтылығын қамтамасыз етуге бағытталған шешімдерді басқару тұжырымдамасын әзірлеу өзекті болып отыр. *Мақсаты.* Теориялық және сандық эксперименттер негізінде әр түрлі бағыттағы тау-кен жұмыстарының көлбеу қабатты массивтегі тұрақтылығын олардың бір бірімен ілігісу дәрежесіне байланысты зерттеу. *Әдістері.* Қабаттардың біртұтас емес ілігісуі бар көлбеу қабатты тау жынысының математикалық моделі қарастырылады. Жер асты тау-кен қазбасының маңындағы серпімді-аққыш изотропты массивтің жазық-параллель қабаттарының жанасуы бірдей ұзындықтағы коллинеарлық саңылаулар арқылы ұсынылған. *Нәтижелері.* Қабаттардың тұтас емес ілігісуін ескеретін, ұсынылып отырған модельде, анизотропты модельден айырмашылығы, ұқсас кемшіліктер жоқ, көлбеу қабатты тау жыныстарындағы неғұрлым толық механикалық процестерді сипаттайды. Изотропты ағудың қатаң сипаттамасымен қатар, ол қабаттардың көлбеу бұрышын φ-ді ескереді (анизотропты сияқты). *Қорытынды.* Тау жыныстарының кернеулі-деформацияланған күйінің өзгеру заңдылықтарын сандық модельдеу нәтижелерін талдау дайындық тау-кен жұмыстарының тұрақтылығын арттыру үшін бекіту параметрлерін орнатуға, сондай-ақ көлбеу-қабатты массивтерде тау-кен қазбаларын тиімді және қауіпсіз жүргізудің жаңа технологияларын әзірлеуге және жетілдіруге мүмкіндік береді.

Түйін сөздер: көлбеу қабатты массив, кернеу, жылжу, тау қысымы, тау құрылымы, тұрақтылық, тұтас емес ілінісу, саңылау

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ИССЛЕДОВАНИЕ ВЛИЯНИЯ НЕСПЛОШНОСТИ СЦЕПЛЕНИЯ СЛОЕВ НА УСТОЙЧИВОСТЬ ГОРНЫХ ВЫРАБОТОК

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Аннотация. *Актуальность.* Обеспечение устойчивости горных выработок остаётся одной из наиболее актуальных проблем угольной промышленности. При исследовании устойчивости выработок необходимо учитывать реальные свойства породного массива, способствующие возникновению и развитию разрушений под действием статических и квазистатических полей дополнительных напряжений и деформаций. Особое значение имеет определение напряжённо-деформированного состояния массива с учётом факторов, влияющих на устойчивость контура горной выработки. В связи с этим актуальной является разработка научно обоснованных решений по управлению устойчивостью горных выработок в наклонно-слоистых массивах. *Цель.* На основе теоретических исследований и численного моделирования оценить устойчивость горных выработок различной ориентации в наклонно-слоистом массиве в зависимости от степени несплошности сцепления между слоями. *Методы.* Рассмотрена математическая модель наклонно-слоистого горного массива с несплошным сцеплением слоёв. Контакты плоскопараллельных слоёв упругоползучего изотропного массива в окрестности подземной горной выработки представлены системой одинаковых перемычек между коллинеарными щелями равной длины. Проведено численное моделирование напряжённо-деформированного состояния массива при различных углах наклона слоёв и степени нарушения межслоевых контактов. *Результаты.* Предложенная модель несплошного сцепления слоёв позволяет более полно описывать механические процессы, происходящие в наклонно-слоистом породном массиве, по сравнению с традиционной анизотропной моделью. Наряду с описанием изотропной ползучести модель учитывает угол наклона слоёв толщи φ и особенности перераспределения напряжений и перемещений в окрестности горной выработки. Установлено, что степень несплошности межслоевого сцепления и ориентация выработки относительно слоистости существенно влияют на характер деформирования пород и устойчивость её контура. *Выводы.* Анализ результатов численного моделирования закономерностей изменения напряжённо-деформированного состояния породного массива позволяет обосновывать параметры крепления подготовительных горных выработок, повышать устойчивость их контуров, а также разрабатывать новые и совершенствовать существующие технологии безопасного и эффективного проведения выработок в наклонно-слоистых массивах.

Ключевые слова: наклонно-слоистый массив, напряжение, перемещение, горное давление, горная выработка, устойчивость, несплошность сцепления, щель

Introduction. The most common form of rock pressure is the deformation of rock masses, which leads to a loss of stability and the formation of significant loads on the support. When developing mineral deposits, the roof of the workings is often a limiting factor, since this is where areas of tensile stress are most likely to form, to which rock masses are particularly sensitive due to their structural features and deformation and strength properties.

Studying the effect of discontinuous bonding between layers on the stability of mine workings is a complex engineering task in mining and geomechanics, as rock stratification is often the main cause of roof collapses. The key aspects are:

First, reduced rigidity: in the absence of cohesion, the layered strata ceases to function as a single monolith. Each layer deforms independently, which sharply reduces the overall load-bearing capacity of the structure. Second, stress concentration: additional tensile stresses arise in areas of contact disruption, contributing to the deflection of the lower layers. Third, man-made discontinuity: this often arises not only due to natural factors, but also as a result of blasting or pressure redistribution during tunneling.

Taking into account the discontinuity of layer adhesion allows us to move from empirical estimates to accurate geomechanical predictions. This is necessary to optimize the density of support and prevent sudden collapses in complex rock mass conditions. The creation of underground workings for various purposes, including deep underground workings of all possible configurations, is directly related to the need to develop sound methods for their calculation.

The issue of the stability of the equilibrium state of rock masses near mine workings has remained a pressing concern for the past 50 years. The founder of this field is L.V. Ershov, whose first article on this topic was published in 1962. It examines the axisymmetric problem of the stability of a vertical mine workings with a circular cross-section when modeling rock as an elastic isotropic compressible body.

In his works, M.A. Bio was the first to apply the linearized theory of stability of deformable bodies to the study of flat problems of fold formation. Subsequently, Zh.S. Yerzhanov developed the theory of fold formation in the Earth's crust in the case of discontinuous, dome-shaped, and linear folding based on the Leibenson-Ishlinsky approach.

Literary review. Ensuring the stability of mine workings remains one of the most pressing problems in the coal industry today, relevant both for leading enterprises and for unprofitable mines with low production levels. In repaired sectional workings and workings restored by backfilling, there is no attenuation of the deformation rate; on the contrary, there is an intensification of contour displacements (Zubov et al., 1985; Negrei, 2007; Pankov et al., 2018; Morozov et al., 2021). From this perspective, it becomes relevant to develop a concept for managing solutions aimed at ensuring the stability of mine workings. According to G.N. Kuznetsov, the adhesion on various weakening surfaces can range from zero to 0.6-0.9 of the adhesion of the rock in the layer (Kuznetsov, 1981). Similar information is provided by N.N. Kuvayev and other authors (Kuvaev, 2005).

It is known that mining leads to a redistribution of stresses in the rock mass. From the moment of excavation, several major stages of change in the stress field of the surrounding rock can be identified, which are associated with the formation of a stress-strain state of the rock mass. At the same time, the greater the volume of rock that falls into the stress redistribution zone, the greater the effort required to ensure the stability of the excavation.

The issue of the stability of mine workings with increasing rock pressure and the stress-strain state of the rock mass is of practical importance in modern conditions with the increase in the depth of workings and the complication of the geological conditions of mining. The contours of preparatory workings as man-made structures are the load-bearing elements of the technological structure. An important task is to determine the stress-strain state of the rock mass, taking into account the factors affecting the stability of the contours of the mine workings.

In the work G.N. Savina first noted elastic anisotropy in the form of a lateral pressure coefficient, and S.G. Lekhnitsky solved the problem of the stress state of a heavy elastic transversely isotropic array with a horizontal plane of isotropy, weakened by a mine shaft (Savin, 2014; Lekhnitsky, 2013). The influence of elastic anisotropy of rocks on the stress state is considered in the works of G. Sonntag, H. Werner and P. Felix (Sonntag, 2013; Werner, 2015; Felix, 2013).

Materials and methods. A mathematical model of an inclined-layered rock mass with discontinuous layer adhesion was first proposed by Zh.S. Yerzhanov, K.K. Kaidarov, and M.T. Tusupov (Yerzhanov et al., 1989). The contacts of plane-parallel layers of an elastic-creeping isotropic massif in the vicinity of an underground mine are represented by identical bridges between collinear gaps of equal length (see Figure 1). This refers to a finely layered massif in which the thickness of the layer is at least an order of magnitude smaller than the characteristic transverse dimension of the mine workings. The stress state of the intact rock mass is modeled across the strike of the layers, inclined at an angle φ, by an isotropic body weakened by a doubly periodic system of cracks.

When studying the elastic state of a body (plane) with a doubly periodic system of slots, the latter are placed horizontally, and the plane is loaded at infinity by forces q and p such that $\omega_1,\ i\omega_2$ are the main periods; $2a, \gamma_{nm}$ are the length and contours of the slots; n, m are their indexing (see Figure 2).

The origin $x'Oz'$ is placed in the middle of the slit γ_{00}, called the main slit. It is assumed that the edges of the slits do not interact; E, ν is the modulus of elasticity and Poisson's ratio.

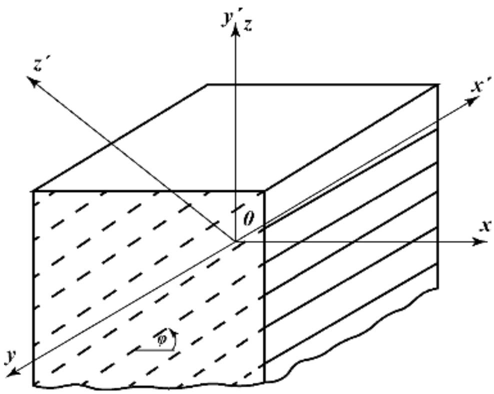


Figure 1. Diagram of a rock mass with discontinuous layer bonding.

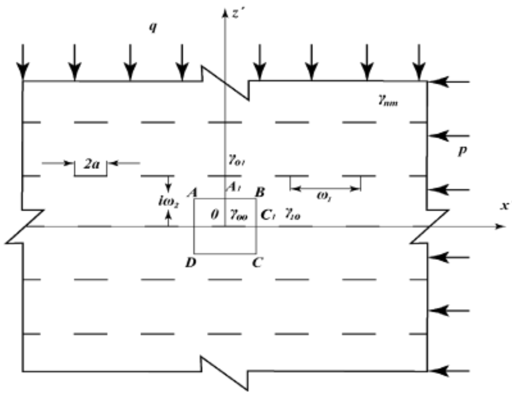


Figure 2. Plane with a doubly periodic system of slits.

To determine the stresses and displacements, a plane with three infinite horizontal rows of slots symmetrical to the abscissa axis is considered. This made it possible to estimate the degree of stress invariance within a characteristic element ABCD (see Figure 2) as the number of slot rows increases and to extend it to a doubly periodic problem. Such a focus of analysis within a single element (ABCD) completely resolves the issue, since, due to the double periodicity of the problem itself, the stresses and displacements near any slit (within any element) will be the same.

The stress state of a plane with a finite number of rows of slots is determined by periodic functions $\varphi(z), \chi(z)$ that satisfy the following conditions on the contours of the slots

$$\varphi(t) + (t - \bar{t})\overline{\varphi'(t)} + \chi(t) = -\frac{p+q}{2}t + \frac{p-q}{2}\bar{t}, \tag{1}$$

where t is the affix of a point on one of the slit contours.

Due to force and geometric symmetry, these holomorphic stress functions outside the slit contours are obtained following A.S. Kosmodamiansky (Kosmodamiansky, 2013). Assuming $\omega_2 \geq \omega_1, \omega_1 > 2a$ and expanding these functions into Taylor series with respect to the small parameter $\frac{R}{\omega_1}$ $(R = \frac{1}{2}a)$ inside the circle encompassing γOl, without touching the neighboring contours, we can write for a plane with five rows of slots:

$$\varphi(z) = \sum_{k=1}^{\infty} \frac{a_{kl}}{[\zeta(z_l)]^k} + \sum_{j=1}^{5} A_j z_l^j, \tag{2}$$

$$\chi(z) = \sum_{k=1}^{\infty} \frac{b_{kl}}{[\zeta(z_l)]^k} + \sum_{j=1}^{5} B_j z_l^j, \tag{3}$$

limiting ourselves to terms containing a small parameter no higher than the sixth degree (third approximation). Here, the first sum is a holomorphic function outside the contour γOl $(l=0,1,2)$; $z_l = z - il\omega_2$; the second reflects the influence of other slits on the stresses near one of the slits γOl. The coefficients A_j, B_j depend on the coefficients a_{jl}, b_{jl}, determined by conformal transformation of the exterior of the slits γ_{nm} to the exterior of the unit circle Γ_{km}. From the boundary conditions on the contours Γ_{00}, Γ_{0l} and Γ_{02}, a system of algebraic equations is obtained for determining the coefficients a_{il}, b_{il} with accuracy up to a constant factor qa. It turns out that $b_{jl} = a_{jl}$, $a_{2l} = a_{4l} = b_{2l} = b_{4l} = 0$. As complex potentials $\varphi(z), \chi(z)$, we can take functions (2) and (3) at $l = 0$. For three rows of slits, it is sufficient to limit ourselves to boundary conditions on two contours γ_{00}, γ_{01}.

Results and discussions. Calculations of the coefficients a_{jl} with an accuracy of qa for various $\frac{\omega_2}{\omega_1}, \omega_1 \geq 2{,}5a$ for three and five rows of slots are given in Tables 1 and 2. These data show that the difference between the coefficients found in the second and third approximations decreases with an increase in the ratio $\frac{\omega_2}{\omega_1}$. At $\omega_2 = \omega_1 = \omega \geq 2{,}5a$, this difference, as well as the values of the new coefficients in the third approximation, do not exceed the error of determining the second decimal place.

Table 1. Coefficients a_{jl} for three rows of slits.

Three rows of slits							
$\frac{\omega_1}{a}$	$-a_{jl}$	First approximation	Second approximation		Third approximation		
		j=1	j=1	j=3	j=1	j=3	j=5
$\omega_2/\omega_1 = 0{,}75$							
2.5	l=0	0.627	0.761	0.017	0.692	0.002	-0.001
	l=1	0.654	0.741	0.011	0.713	0.005	$-0.4\cdot 10^{-3}$
3	l=0	0.582	0.632	0.007	0.615	0.003	$-0.3\cdot 10^{-3}$
	l=1	0.597	0.630	0.005	0.623	0.003	$-0.1\cdot 10^{-3}$
4	l=0	0.543	0.556	0.002	0.554	0.001	$-0.4\cdot 10^{-4}$
	l=1	0.550	0.559	0.001	0.558	0.001	$-0.2\cdot 10^{-4}$
6	l=0	0.518	0.521	$0.4\cdot 10^{-3}$	0.520	$0.3\cdot 10^{-3}$	$-0.4\cdot 10^{-5}$
	l=1	0.521	0.523	$0.2\cdot 10^{-3}$	0.523	$0.2\cdot 10^{-3}$	$-0.1\cdot 10^{-5}$
$\omega_2/\omega_1 = 1{,}00$							
2.5	l=0	0.668	0.727	0.007	0.727	0.007	$-0.5\cdot 10^{-6}$
	l=1	0.675	0.723	0.006	0.730	0.008	$-0.1\cdot 10^{-3}$
3	l=0	0.606	0.628	0.003	0.628	0.003	$-0.2\cdot 10^{-7}$
	l=1	0.609	0.628	0.003	0.629	0.003	$-0.3\cdot 10^{-4}$
4	l=0	0.554	0.560	0.001	0.560	0.001	$0.3\cdot 10^{-8}$
	l=1	0.556	0.561	0.001	0.561	0.001	$0.4\cdot 10^{-5}$
6	l=0	0.523	0.524	$0.2\cdot 10^{-3}$	0.524	$0.2\cdot 10^{-3}$	$0.7\cdot 10^{-9}$
	l=1	0.523	0.524	$0.1\cdot 10^{-3}$	0.524	$0.1\cdot 10^{-3}$	$0.4\cdot 10^{-6}$

Table 2. Coefficients a_{jl} for five rows of slots.

Five rows of slots							
$\frac{\omega_1}{a}$	$-a_{jl}$	First approximation	Second approximation		Third approximation		
		j=1	j=1	j=3	j=1	j=3	j=5
$\omega_2/\omega_1 = 0{,}75$							
2.5	l=0	0.629	0.763	0.018	0.693	0.003	-0.001
	l=1	0.628	0.762	0.017	0.693	0.003	-0.001
	l=2	0.654	0.741	0.011	0.713	0.005	$-0.3\cdot 10^{-3}$
3	l=0	0.683	0.630	0.007	0.615	0.003	$-0.3\cdot 10^{-3}$
	l=1	0.583	0.630	0.007	0.615	0.003	$-0.3\cdot 10^{-3}$
	l=2	0.597	0.630	0.005	0.623	0.003	$-0.1\cdot 10^{-3}$
4	l=0	0.543	0.556	0.002	0.554	0.001	$-0.4\cdot 10^{-4}$
	l=1	0.543	0.556	0.002	0.554	0.001	$-0.4\cdot 10^{-4}$
	l=2	0.550	0.559	0.001	0.558	0.001	$-0.2\cdot 10^{-4}$
6	l=0	0.518	0.521	$0.4\cdot 10^{-3}$	0.520	$0.3\cdot 10^{-5}$	$-0.4\cdot 10^{-5}$
	l=1	0.518	0.521	$0.4\cdot 10^{-3}$	0.520	$0.3\cdot 10^{-3}$	$-0.4\cdot 10^{-5}$
	l=2	0.521	0.523	$0.2\cdot 10^{-3}$	0.522	$0.2\cdot 10^{-3}$	$-0.1\cdot 10^{-5}$
$\omega_2/\omega_1 = 1{,}00$							
2.5	l=0	0.668	0.727	0.007	0.727	0.007	$0.2\cdot 10^{-8}$
	l=1	0.668	0.727	0.007	0.727	0.007	$-0.2\cdot 10^{-6}$
	l=2	0.673	0.723	0.006	0.736	0.008	$0.9\cdot 10^{-4}$
3	l=0	0.606	0.628	0.003	0.628	0.003	$0.2\cdot 10^{-10}$
	l=1	0.606	0.623	0.003	0.628	0.003	$-0.1\cdot 10^{-7}$
	l=2	0.609	0.627	0.003	0.629	0.003	$0.3\cdot 10^{-4}$
4	l=0	0.554	0.560	0.001	0.560	0.001	$0.2\cdot 10^{-11}$
	l=1	0.554	0.560	0.001	0.560	0.001	$0.2\cdot 10^{-8}$
	l=2	0.556	0.561	0.001	0.561	0.001	$0.4\cdot 10^{-5}$
6	l=0	0.523	0.523	$0.2\cdot 10^{-3}$	0.524	$0.2\cdot 10^{-3}$	$0.7\cdot 10^{-12}$
	l=1	0.523	0.524	$0.2\cdot 10^{-3}$	0.524	$0.2\cdot 10^{-3}$	$0.3\cdot 10^{-9}$
	l=2	0.523	0.524	$0.1\cdot 10^{-3}$	0.524	$0.1\cdot 10^{-3}$	$0.4\cdot 10^{-6}$

Therefore, for simplicity, we can limit ourselves to $\omega_2 = \omega_1 = \omega$, i.e., a square arrangement of the centers of the slots ("square lattice"). Then, for $2{,}5a \leq \omega < 6a$, a second approximation is sufficient, and for $\omega \geq 6a$, a first approximation is sufficient.

Additional stresses σ_x^{00}, σ_z^{00} and displacements u^{00}, w^{00} at points A_1, O, C_1 of the element $ABCD$ (see Figure 2), calculated in the third approximation, are given in Table 3. As can be seen, the stress and deformation states of the element $ABCD$ at $\omega_2 = \omega_1 = \omega \geq 2{,}5a$ for three and five rows of slots in the third approximation coincide with an error (discrepancy) of no more than 1%. Consequently, this state of the element with the specified error is preserved even when the plane is weakened by a doubly periodic system of slots with main periods $\omega_1, i\omega_2$, where $\omega_2 = \omega_1 = \omega \geq 2{,}5a$.

Table 3. Additional stresses and displacements of the element $ABCD$.

$\frac{\omega_2}{\omega_1} = \frac{\omega}{a}$	Element point	Three rows of slots				Five rows of slots			
		σ_x^{00}/q	σ_z^{00}/q	$u^{00}\frac{10^5}{qa}$	$w^{00}\frac{10^5}{qa}$	σ_x^{00}/q	σ_z^{00}/q	$u^{00}\frac{10^5}{qa}$	$w^{00}\frac{10^5}{qa}$
2.5	A	-0.294	-0.072	0.000	3.250	-0.293	-0.073	0.000	3,249
	O	-1.000	-1.000	0	4,456	-1,000	-1,000	0	4,456
	C_1	1,660	1,660	-0.119	0	1,631	1,661	-0.119	0.000
3	A	-0.147	-0.129	0.000	2.426	-0.147	-0.129	0.000	2,425
	O	-1.000	-1.000	0	3,870	-1,000	-1,000	0	3,870
	C_1	0.832	0.832	-0.048	0.000	0.832	0.832	0.048	0.000
4	A	-0.051	-0.121	0.000	1.693	-0.051	-0.121	0.000	1,693
	O	-1.000	-1.000	0	3,464	-1,000	-1,000	0	3,464
	C_1	0.371	0.371	-0.017	0.000	0.371	0.371	0.017	0.000
6	A	-0.011	-0.072	0.000	1.094	-0.011	-0.072	0.000	1.094
	O	-1.000	-1.000	0	3,243	-1,000	-1,000	0	3,243
	C_1	0.145	0.145	-0.006	0.000	0.145	0.145	-0.006	0.000

Therefore, when calculating the stress and strain states of a plane with a doubly periodic system of slots with this given error, complex potentials (2) and (3) can be used for five rows of slots. Stresses and displacements are found using them according to the known formulas of Kolosov-Muskhelishvili (Mushelishvili, 1966).

The criterion for selecting a continuous anisotropic plane equivalent in stiffness to a plane with slots is the equality of the corresponding average displacements $< u >_{BC}$ and $< w >_{AB}$ of the sides of the element $ABCD$ (see Figure 2). In this case, the displacements of the points are expressed in terms of the potential (2) by the formulas

$$u = \frac{1}{2G}\left[(\varkappa - 1)u_1 - u_2 + u_3\right], \quad w = \frac{1}{2G}\left[(\varkappa + 1)w_1 - w_2 + w_3\right], \tag{4}$$

where

$$u_1 = Re\varphi(z), \quad u_2 = Re\left[(z - \bar{z})\overline{\varphi'(z)}\right], \quad u_3 = \left[(\varkappa - 1)\frac{p+q}{4} - \frac{p-q}{2}\right]x', \; w_1 = \quad Im\varphi(z), \; w_2 = Im\left[(z - \bar{z})\overline{\varphi'(z)}\right], \quad w_3 = \left[(\varkappa - 1)\frac{p+q}{4} - \frac{p-q}{2}\right]z', \tag{5}$$

The displacements of the points of the contour $ABCD$ (see Figure 2), but only in a continuous homogeneous transversely isotropic body, whose plane of isotropy coincides with the plane of extension of the slots, under the action of the same forces *q* and *p*, are found by integrating the corresponding equation of Hooke's generalized law:

$$u_0 = (b_{11}p + b_{13}q)x', \; w_0 = (b_{31}p + b_{33}q)z', \tag{6}$$

where

$$b_{11} = \frac{1-\nu_1^2}{E_1}, \quad b_{13} = b_{31} = -\frac{\nu_2(1+\nu_1)}{E_1}, \quad b_{33} = \frac{1}{E_2} - \frac{\nu_2^2}{E_1}. \tag{7}$$

E_1, E_2 are the moduli of elasticity for directions in the plane of isotropy and perpendicular to it; ν_1, ν_2 are the corresponding Poisson's ratios.

From the conditions of equivalence

$$< u >_{BC_1} =< u_0 >_{BC_1}, \quad < w >_{A_1B} =< w_0 >_{A_1B} \tag{8}$$

at

$$q \neq 0, \; p = 0 \quad и \quad q = 0, \; p \neq 0$$

we have

$$b_{13} = \frac{1}{G\omega}[(\varkappa - 1)(0{,}125\omega + < u_1 >) - (0{,}125\omega + < u_2 >)],$$

$$b_{33} = -\frac{1}{G\omega}[(\varkappa + 1)(0{,}125\omega + < w_1 >) - < w_2 >],$$

$$b_{11} = \frac{\varkappa+1}{8G}, \qquad b_{31} = \frac{\varkappa-3}{8G}. \tag{9}$$

From equality (9), taking into account (7) E_1, E_2, ν, ν_2, the physical (E, ν) and geometric $(a, \; \omega_2 = \omega_1 = \omega)$ parameters of the medium are determined. The relationship $b_{13} = b_{31}$ for the body of the structure under consideration is approximately satisfied – the maximum deviation at $\omega_2 = \omega_1 \geq 2{,}5a \; and \; \nu \geq 0.2,$ which are usually used in calculations, is 4.5%.

Thus, at $\omega_1 \geq 2{,}5a$ from (9), taking into account $E_1 = E$, the following representations apply

$$E_1 = E, \; E_2 = E(A_1\nu^2 + A_2\nu + A_3)^{-1}, \nu_1 = \nu, \; \nu_2 = \nu, \tag{10}$$

where A_1, A_2, A_3 are some coefficients. The shear modulus G_2 can be found in a similar way, considering the shear of the element $ABCD$ under the action of tangential forcesτ applied at infinity, in the following form:

$$G_2 = G(A_4\nu + A_5)^{-1}, \tag{11}$$

where the numerical values of the coefficients $A_1 - A_5$ for different ω are summarized in Table 4.

Table 4. Numerical values of the coefficients $A_1 - A_5$ for various ω.

ω/a	A_1	A_2	A_3	A_4	A_5
2.5	-1.514	-0.019	2,495	-1,110	2,271
3	-0.896	0.003	1.899	-0.688	1.792
4	-0.446	0.008	1.454	-0.332	1.386
6	-0.184	0.005	1.190	-0.138	1.158

The values of $E_1, E_2, \nu, \nu_2, G_2,$ determined by formulas (10) and (11), act as some reduced elastic parameters of the model.

The described averaging of the structural features of a plane with slots allows its stress state to be determined by means of an equivalent continuous anisotropic (transversely isotropic) plane. The angle of inclination of the slots can be taken into account using the formulas for transforming the elastic constants of an anisotropic body when rotating the coordinate axes. The parameters (10) and (11) are functions of the physical constants $E \; and \; \nu$, therefore, according to the Volterra-Rabotnov principle, replacing them with time operators directly reveals the isotropic creep of a body weakened by a system of slots. This allows the calculation of the stress and deformation states of underground mine workings in an inclined-layered massif to be based on the methods of rock creep theory. It should be noted that: the anisotropic model reveals the effect of the angle of inclination of the rock mass stratification plane on the initial stress state of mine workings. The limitations of this model approach are related to the fact that its results reflect the influence of the anisotropy of the elastic properties of rocks, which is established on the basis of rock samples. Another methodological shortcoming is the incomplete description of creep deformations.

The proposed model of a massif with discontinuous layer adhesion does not have such disadvantages, unlike the anisotropic model, describing more completely the mechanical processes in an inclined-layered rock massif. Along with a rigorous description of isotropic creep, it takes into account the angle of inclination φ of the layers of the thickness as fully as the anisotropic model. Together with it, the thickness of the layers ω_2 and the degree of continuity of their adhesion (so important for assessing the strength of the rock mass) are reflected; the latter is determined by the ratio $\frac{\omega-2a}{\omega}$ (for a "square lattice"), equal to one in the absence of gaps. In general, this model is very representative and promising in applications.

Let us first determine how the degree of discontinuity of the adhesion between layers affects the stressed and deformed states of an inclined-layered massif with mining. We will consider two cases of determining the lateral pressure coefficient:

1) when the stress state of the intact massif is non-hydrostatic and $\lambda_x = (\varphi, \omega, l)$, $\lambda_y = \lambda_y(\varphi, \omega, l)$ (Solonenko et al., 2017; Makhmetova et al., 2019; Solonenko et al., 2022). Table 5 shows their values for an aleurolite massif at different distances between the centers of the cracks and angles of their inclination. These data indicate a significant influence of the inclination of the stratification plane (slots) on the stress state of the massif at $\omega < 4a$;

Table 5. Values of λ_x, λ_y for siltstone at different distances between the centers of the cracks.

$\frac{\omega}{a}$	Lateral pressure coefficient	φ, deg				
		0	30	45	60	90
2.5	λ_x	0.250	0.390	0.356	0.238	0.100
	λ_y	0.250	0.278	0.271	0.248	0.220
3	λ_x	0.250	0.331	0.314	0.235	0.131
	λ_y	0.250	0.266	0.263	0.247	0.226
4	λ_x	0.250	0.283	0.274	0.233	0.172
	λ_y	0.250	0.257	0.255	0.247	0.234

2) when the stress state of the intact rock mass is hydrostatic and $\lambda_x = \lambda_y = 1$ (Solonenko, et al., 2025).

The stresses σ_θ on the rock contour of the round drift and crosscut, calculated for $\varphi = 0 \; and \; \varphi = 60^0$, are summarized in Tables 6 and 7. As can be seen, they depend on the degree of discontinuity of the layers. At $\lambda_x = \lambda_x(\varphi, \omega, l), \lambda_y = \lambda_y(\varphi, \omega, l)$, an area of tensile stresses appears in the roof of these workings, and it decreases with increasing distance between the gaps. At $\lambda_x = \lambda_y = 1$, the maximum compressive stresses on the contour of the drift are confined to the points $\theta = 90^0 + \varphi$; they decrease with increasing distance between the gaps. On a steep dip, the effect of the discontinuity of the adhesion between the layers on the stress state of the crosscut is insignificant, and at $\varphi = 90^0$, the latter coincides with the state of a continuous isotropic massif around the working.

Table 6. Stresses σ_θ on the rock contour of a circular drift.

θ, deg	$-\sigma_\theta/\gamma H$ (drive)											
	$\lambda_x = \lambda_x(\varphi, \omega, l)$, $\lambda_\tau = 0$						$\lambda_x = 1$, $\lambda_\tau = 0$					
	$\varphi = 0$			$\varphi = 60^0$			$\varphi = 0$			$\varphi = 60^0$		
	2.5 a	3a	4a	2.5a	3a	4a	2.5 a	3 a	4a	2.5a	3a	4a
0	2.609	2.652	2,687	2,745	2,769	2,785	2,134	2,109	2,065	1,884	1,918	1,958
15	2,446	2,472	2,504	2,220	2,311	2,418	2,075	2,059	2,034	1,855	1,884	1,931
30	2,024	2,017	2,015	1,714	1,782	1,862	1,947	1,954	1,970	1,947	1,954	1,970
45	1,946	1,391	1,340	1,202	1,210	1,213	1,855	1,884	1,931	2,075	2,059	2,034
60	0.726	0.652	0.584	0.673	0.622	0.560	1.884	1.918	1.958	2.134	2,109	2,065
75	-0.131	-0.114	-0.093	0.199	0.121	0.036	2.066	2.056	2.034	2.075	2.059	2,034
90	-0.631	-0.497	-0.385	-0.122	-0.180	-0.234	2.211	2.150	2.079	1.947	1.954	1,970
105	-0.131	-0.114	-0.093	-0.215	-0.202	-0.171	2.066	2.056	2.034	1.855	1.884	2,931
120	0.726	0.652	0.584	0.046	0.158	0.283	1.884	1.918	1.958	1.884	1.918	1,958
135	1,446	1,391	1,340	0.947	1,054	1,141	1,855	1,884	1,931	2,066	2,056	2,034
150	2,024	2,071	2,015	2,391	2,266	2,143	1,947	1,954	1,970	2,211	2,150	2,079
165	2,446	2,472	2,504	3,057	2,912	2,761	2,075	2,059	2,034	2,066	2,056	2,034
180	2,609	2,652	2,687	2,745	2,769	2,785	2,134	2,109	2,065	1,884	1,918	1,958

Table 7. Stresses σ_θ on the rock circuit of a circular drift.

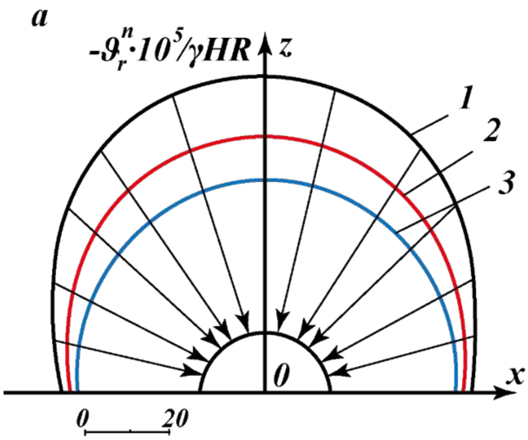
θ, deg	$-\sigma_\theta/\gamma H$ (crosscut)											
	$\lambda_y = \lambda_y(\varphi, \omega, l)$, $\lambda_\tau = 0$						$\lambda_x = 1$, $\lambda_\tau = 0$					
	$\varphi = 0$			$\varphi = 60^0$			$\varphi = 0$			$\varphi = 60^0$		
	2.5 a	3 a	4a	2.5 a	3 a	4 a	2.5 a	3 a	4 a	2.5 a	3 a	4 a
0	2.609	2.652	2,687	2,667	2,688	2,713	2,134	2,109	2,065	2,008	2,007	2,004
15	2,446	2,476	2,503	2,505	2,517	2,530	2,075	2,058	2,034	2,004	2,003	2,002
30	2,024	2,017	2,015	2,039	2,030	2,019	1,947	1,954	1,970	1,996	1,996	1,998
45	1,446	1,391	1,339	1,338	1,315	1,289	1,855	1,884	1,931	1,991	1,993	1,996
60	0.726	0.652	0.584	0.548	0.533	0.517	1.884	1.918	1.957	1.995	1.996	1,998
75	-0.131	-0.114	-0.093	-0.100	-0.091	-0.079	2.066	2.056	2.034	2.004	2.003	2,002
90	-0.631	-0.497	-0.385	-0.355	-0.332	-0.305	2.211	2.150	2.079	2.009	2.007	2,004

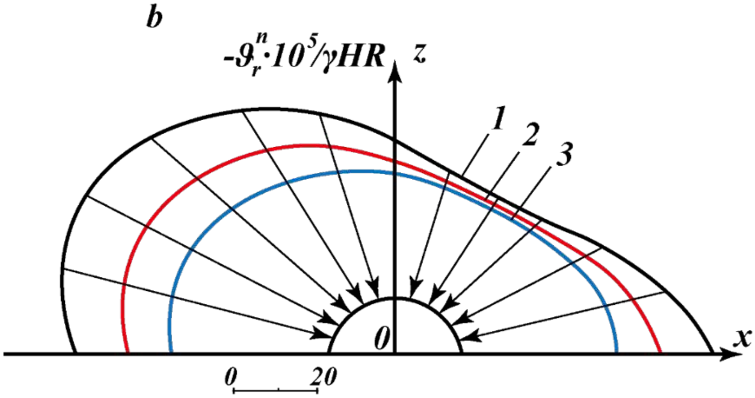
Figures 3 and 4 show the displacement diagrams $(-\vartheta_r^n \cdot 10^5/\gamma HR)$ around the circular drift and crosscut at $\varphi = 0\ and\ \varphi = 60^0$. These data show that at $\lambda_x = \lambda_x(\varphi, \omega, l)$, $\lambda_y = \lambda_y(\varphi, \omega, l)$, the maximum displacement in the drift roof shifts toward the hanging side of the roof, while in the crosscut it is located strictly in the middle of the roof. The minimum displacements of both the drift and the crosscut are observed at the sides and are directed towards the rock mass, which indicates the complexity of the stress state. At $\lambda_x = \lambda_y = 1$, the maximum displacements on the drift contour are confined to points with coordinates $\theta = 90^0 + \varphi$, but their magnitude remains constant; on the crosscut contour, they are in the roof, and for $\varphi = 90^0$, the discontinuity does not affect the displacements of the crosscut contour points.

Analysis of the numerical results shows:

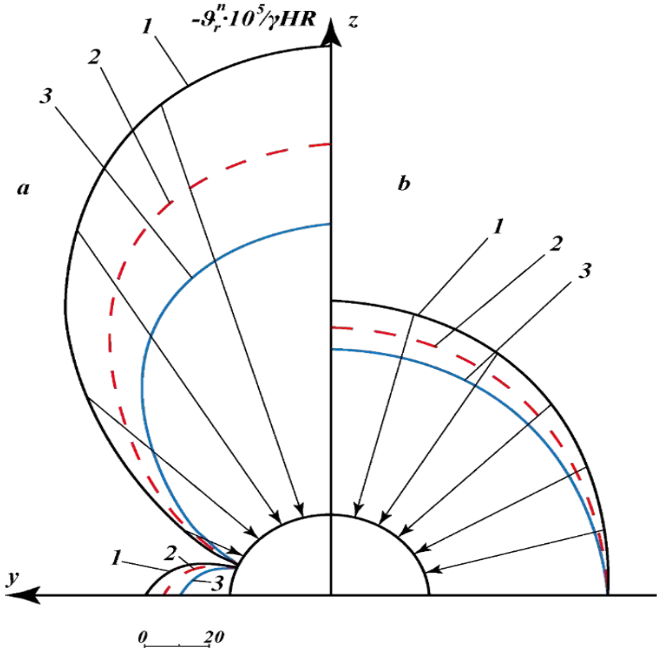
1. In the case of $\lambda_x = \lambda_x(\varphi, \omega, l)$, $\lambda_y = \lambda_y(\varphi, \omega, l)$: the maximum displacements are observed on the hanging side of the drift and in the middle of the roof of the crosscut; the minimum displacements of both the drift and the crosscut are observed on the sides and are directed towards the rock mass.

2. In the case of $\lambda_x = \lambda_y = 1$: the maximum displacements on the contour of the drift are confined to points with coordinates $\theta = 90^0 + \varphi$; on the contour of the crosscut – in the roof, and for $\varphi = 90^0$, the discontinuity does not affect the displacements of the points on the contour of the crosscut.





The curves correspond to: $1 - \omega = 2{,}5a$; $2 - \omega = 3a$; $3 - \omega = 4a$;
at $\lambda_x = 1, \lambda_\tau = 0$: $a - \varphi = 0^0$, $б - \varphi = 60^0$.
Figure 3. Diagrams of displacements of the contour of a round profile drift caused by creep of the rock mass with discontinuous adhesion of layers.



The curves correspond to: $1-\omega=2{,}5a;\ 2-\omega=3a;3-\omega=4a;$
$a-\lambda_y=\lambda_y(\varphi,\omega,l),\lambda_\tau=0,\varphi=0;б-\lambda_y=1,\lambda_\tau=0,\varphi=60^0.$
Figure 4. Diagrams of displacements of the contour of a round profile tunnel caused by creep of a rock mass with discontinuous layer adhesion.

Conclusion. It should be noted that the anisotropic model reveals the effect of the angle of inclination of the rock mass stratification plane on the initial stress state of mine workings. In addition, the anisotropic model does not take into account creep deformations. The proposed model with discontinuous layer adhesion does not have such disadvantages, describing mechanical processes in an inclined-layered rock mass more completely. Along with a rigorous description of isotropic creep, it takes into account the angle of inclination and thickness of the layers, as well as the degree of continuity of their adhesion. Overall, this model is very representative and promising in applications.

At $\lambda_x=(\varphi,\omega,l)$, $\lambda_y=\lambda_y(\varphi,\omega,l)$, the maximum displacement in the roof of the drift shifts towards the hanging side of the roof, while in the crosscut it is strictly in the middle of the roof. The minimum displacements of both the drift and the crosscut are observed at the sides and are directed towards the massif, which indicates the complexity of the stress state. At $\lambda_x=\lambda_y=1$, the maximum displacements on the drift contour are confined to points with coordinates $\theta=90^0+\varphi$, but their magnitude remains constant; on the crosscut contour, they are in the roof, and for $\varphi=90^0$, the discontinuity does not affect the displacements of the crosscut contour points.

At $\lambda_x = (\varphi, \omega, l)$, $\lambda_y = \lambda_y(\varphi, \omega, l)$, an area of tensile stress appears in the roof of the drift and crosscut, decreasing as the distance between the gaps increases. At $\lambda_x = \lambda_y = 1$, the maximum compressive stresses on the drift contour are confined to the points $\theta = 90^0 + \varphi$; they decrease as the distance between the gaps increases.

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