International Journal of GEOMATE, July 2023, Vol. 25, Issue 107, pp.95-106
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.107.3789
Geotechnique, Construction Materials and Environment

METHOD OF PREDICTIVE CALCULATION OF THE EARTH'S SURFACE SUBSIDENCE FOR PROTECTING RAILWAYS AGAINST UNDERWORKING

Aigul Kozhas[1], Assel Mukhamejanova[1], Shamshygaiyn Toleubayeva[1], *Gulshat Tleulenova[1] and Akmaral Tleubayeva[1]

[1]Architecture and Construction Faculty, L.N. Gumilyov Eurasian National University, Kazakhstan

*Corresponding Author, Received: 10 Jan. 2023, Revised: 04 Feb. 2023, Accepted: 02 March 2023

ABSTRACT: Underground development of mineral deposits causes deformations of the earth's surface in the form of a displacement trough, which negatively affects buildings and structures undermined. Knowing the parameters of the displacement trough subsidence curve at the design or operation stage of a construction site will prevent the dangerous impact of underground work and reduce the cost of repair and restoration work. A method of predictive calculation of earth's surface subsidence based on the construction of the boundaries of the stress-strain state of rocks zones using curved slip lines is proposed. Curved slip lines are built on the basis of the equation of damped oscillations and take into account the geological and mining conditions in the field under consideration. The predictive method of subsidence of the earth's surface makes it possible to predict and calculate the values of subsidence of the earth's surface at the design stage of underground mining and build a shear trough profile based on them. Based on the predictive method for calculating the parameters of the displacement trough, a method of protecting railways by arranging an embankment at the design stage is proposed. This technique will make it possible to take the needed mining and constructive measures in advance to protect against the harmful effects of underground mining in relation to protected objects without disrupting their operation.

Keywords: Subsidence, Development, Embankment, Curved slip lines, Rock strength passport

1. INTRODUCTION

Human activities are increasingly changing underground conditions, which leads to undesirable deformations of the soil. Excessive ground deformations threaten buildings, line systems, underground structures and ultimately human safety [1-4]. For example, due to groundwater pumping in the Chao Phraya River Basin in Thailand, many problems of soil displacement have arisen [2]. Mining in the course of developing mineral deposits leads to deformation of the soil surface and forms a displacement trough with different zones: dips, collapse, smooth subsidence. Various factors influence the parameters of the earth's surface displacement: the depth and thickness of deposits of field development, mining technology, physical and mechanical properties of rocks, the use of various protective measures. Deformations of the earth's surface lead to deformations of buildings and structures located in the zone of influence of the displacement trough. In Poland, to describe surface deformation, the Budryk-Knote theory is usually used, where the fundamental equations give the relationship between the subsidence of a point located on the surface, and the location of the longwall and time [5]. The slope, the radius of curvature and linear horizontal deformation as the corresponding derivatives of subsidence functions are recognized as fundamental indicators characterizing the underground mining impact on the surface [3].

The deformations of the structure are determined by the average surface subsidence curves. To describe the parameters of the earth's surface subsidence curve under the impact of underground mining of stratified deposits, a three-parameter function is used. It is expressed using the integral of the Gaussian probability and the value of the vertical displacement of reference points measured in situ using reference stations [3]. Work [6] describes a method of estimating subsidence for predicting subsidence troughs in the development of flat and inclined coal seams. The basis of the procedure is the correct definition of the rock massif behavior model, its adequate characterization and its implementation in the FLAC code (FLAC is a two-dimensional explicit finite-difference continuum code that simulates the behavior of structures built of soil, rock or other materials) based on the Finite Difference Method or the FDM numerical modeling method. In work [7], the analysis was carried out to process and to analyze the measured data of subsidence and to develop a numerical model for predicting the mine surface subsidence considered as an example. The model was developed on the basis of the finite element method (FEM). Studies of mining subsidence prediction have achieved many results, and each method has its own advantages and disadvantages [8]. Artificial intelligence, machine learning and other methods are mostly good for extracting and analyzing the absence of relationship between the data labels and features from a large amount of data. Linear dependence often has higher requirements and dependence on the data quality [9]. At present, the main method of mining subsidence prediction and engineering practice in China is the probability integration method that is widely used due to rich theory and convenience of calculation [10].

The recommended measures provide reducing the deformation of the earth's surface at undermined objects and therefore, protecting natural objects and structures against the harmful effects of underground mining and preventing water breakthroughs into mine workings. These protection measures are conditionally divided into four groups: 1) preventive; 2) mining; 3) constructive; 4) complex [11]. Protection of undermined buildings, structures and natural objects on the earth's surface consists in eliminating or minimizing the dangerous impact of underground mining on their safe condition and functioning [12]. One of the mining protection measures is to leave safety pillars: leaving an insufficient size of safety pillars to protect objects can lead to a loss in the bearing capacity of the massif and the development of emergency situations. On the other hand, oversized pillars left forever remains in the depths of mineral reserves [13]. The actual subsidence angles that limit the zones of dangerous impact of mining operations on the earth's surface are determined by the values of critical deformations and under modern conditions of underground mining of coal seams, do not coincide with their standard values [13]. In work [12], it was concluded that the method of determining the boundaries of zones of dangerous impact using the displacement angles in modern conditions of underground mining of stratified deposits is imperfect. In Kazakhstan, at the Zhezkazgan deposit, when developing ore deposits, the boundaries of the hazardous impact of underground mining, the procedure and methods of applying mining and constructive protection measures are established in accordance with the Interim Rules for the Protection of Structures against the Harmful Effect of Underground Mining at the mines of Zhezkazgantsvetmet Corporation [14]. The problem of protecting undermined structures has become the most important in the last decade due to the involvement in the re-development of the left mineral reserves in supporting pillars, as well as due to the ongoing development of deposits mined by the room-and-pillar system, in which the loss of minerals reaches 20…30%, and sometimes 40% (ore deposits of deposits named "Zhezkazgan, Sayak, Zhomart" in the Republic of Kazakhstan) [15].

2. RESEARCH SIGNIFICANCE

Timely prediction of subsidence of the earth surface during the development of mineral deposits is of great relevance for the protection of buildings and engineering structures. In order to solve the problem of protection of undermined structures a method of forecast calculation of subsidence of the earth's surface on the basis of rock strength passport is proposed. A method of protection of railroads by embankment at the stage of its design, preventing the violation of normal operation of railroads and significantly reducing the cost of repair and restoration work, is proposed.

style exactly of this Template.

3. CURVED LINES OF SLIDING SURFACES OF THE THREE FAMILIES

Sabdenbekuly investigated the boundaries of rock mass deformation during underground mining are determined by the SRPSS method (Stability of rock pillars at single sites) [16]. The essence of the method consists in determining the coordinates of normal and tangential stress slip curves to identify the boundaries of the stress-strain state of rocks. In this case, the load formed by the weight of the above-ground building or structure is equated to the weight of the rock column at a single site (SRPSS) at the corresponding depth from the ground surface. By building over the development of a set of natural equilibrium, the degree of underground mining impact on the surface of the earth is determined. The boundaries of the arch of collapse or the arch of natural equilibrium and zones of the discplacement trough (zones of smooth deformation, zones of dangerous shear and collapse, zones of failure formation) are determined by curved slip lines of three families. Determining the boundary of the displacement of the earth massif by curved lines of sliding surfaces, depending on the mining and geological conditions and the parameters of the cleanup space, is first given in works [15, 16]. In order to determine the nature of the slip line curves, two options are considered: 1) the massif located above the roof of the working consists of homogeneous rocks of low strength; 2) the massif located above the roof of the working, consists of alternating layers of rocks of different strength. Having made the appropriate calculations, curved lines of sliding surfaces have been built. The main information carrier for constructing slip lines is the rock strength certificate.

For quantitative and qualitative assessment of rock behavior under different types of stress state, a generalized characteristic called strength passport is used. At present, it is generally accepted that for constructing the strength passport the most acceptable is the Mohr's theory of strength. In Mohr's theory it is postulated that tangential stresses are responsible for the failure and that the failure itself has the character of shear over the areas where the limit state is reached, with the value of the limit tangential stress being a function of the normal stress acting on the sliding $\tau = f(\sigma)$. To characterize the stress state, the relationship between σ and τ can be represented graphically using so-called stress circles or Mohr circles. The enveloping curve of the ultimate stresses is usually taken in the form of curves known from geometry like a parabola, hyperbola or straight line, which does not always reflect the actual shape obtained from experiments. To characterize the stress state, the relationship between σ and τ can be represented graphically using the so-called stress circles, which are plotted as follows. The maximum σ1 and minimum σ3 values of the principal stresses acting on the sample are plotted on the abscissa axis. A circle is drawn on the difference of the segments as on the diameter. In works [17] the equation of envelopes of limiting stress circles is derived on the basis of the theory of damped oscillations, and as a result the following equation is obtained:

$$\tau = \sigma_c \begin{pmatrix} 0.5\cos\sigma_c + \\ \{1 - K_{\exp}[-(\sigma_{ni}/\sigma_c)]\}tg\rho_c \end{pmatrix} \quad (1)$$

where σ_c is normal stress for uniaxial compression, t/m^2; ρ_c is the internal friction angle with uniaxial compression, deg.;

$$K = \exp[0.5(1 - \sin\rho_c)] \quad (2)$$

is a dimensionless parameter.

On the basis of the obtained equation of the envelope of the limiting circles of stresses, the angular, strength, linear values, the coefficients of the lateral thrust and Poisson are determined. Depending on the stress state of the rocks, the coordinates of the curved slip lines are determined. As a result, the existence of three families of sliding surfaces in the rock massif is scientifically substantiated, which are described by the following equations

$$x_{1i} = 0.5(y_i - y_h)\begin{bmatrix} \dfrac{\cos\beta_i}{\sin^2_{\beta_i}} - \\ \ln\left(\dfrac{\beta_i}{2}\right)\sin\beta_i \end{bmatrix} \quad (3)$$

$$x_{2i} = (y_i - y_n)\left[\ln tg\left(\frac{\beta_i}{2}\right)\right]\sin\beta_i \quad (4)$$

$$x_{3i} = (y_i - y_n)\left[\frac{\cos\theta_i}{\sin^2_{\theta_2}} - \ln tg\left(\frac{\theta_i}{2}\right)\right]\sin\theta_i \quad (5)$$

$$y_i = (\sigma_{ni} + \tau_{ni} tg\theta_i)/\gamma \quad (6)$$

where y_i are ordinates of the three families of the curved slip lines points, m; y_W is the depth of the vertical breakaway,

$$y_w = \sigma_s / \gamma \quad (7)$$

σ_s is the rock hardness for uniaxial tension, t/m^2; γ is the rock volumetric weight, t/m^3;

$$\beta_i = arctg\left(\frac{\tau_{ni}}{\sigma_{ni}}\right) \quad (8)$$

τ_{ni} is tangential stress under the i load, t/m^2; σ_{ni} is normal stress under the i load, t/m^2;

$$\theta i = 45^\circ + 0.5\rho_i \quad (9)$$

ρ_i is the angle of the tangent inclination to the envelope at the i-th poit, deg.

The first of them is the line of action of tangential, and the second of normal stresses. The third family is formed in the massif after the formation of boundary conditions, where the contours are limited by the curves of the sliding surfaces of the second family at $\sigma_{ni} \geq \sigma_c$. Curves of sliding surfaces are built for each type of rocks separately, which makes it possible to take into account their specific stress states and physical and mechanical properties. Which, in turn, makes it possible to determine the boundaries of the displacement of rocks in the massif, taking into account in the most detail the mining-geological and mining-technical conditions in the field.

4. EXISTING MEASURES TO PROTECT UNDERMINED RAILROADS

One of the protected objects at the industrial sites of mining enterprises is the railway tracks used as the main means of transport. The sidings of railways of the IV category, which do not carry out regular technological transportation and are intended only for servicing individual mines, factories, plants, quarries, and electrical substations, are most often exposed to the harmful effects of underground mining. Therefore, protection of the railway track from the harmful effects of mining operations in the underground mining of mineral reserves located near or directly under the railway is of current importance. Construction preventive and operational measures to protect the track and structures include widening the subgrade, laying additional tracks; establishing additional supervision, maintaining the repair of undermined facilities; changing the operating mode, i.e. reducing the speed of trains, reducing the weight norms of trains, stopping shunting operations for the duration of the active stage of the shifting process, applying pushing; transferring the railway lines with heavy train traffic to unworked sections [18,19].

The problems in developing measures to protect railways against the harmful effects of mining near or under the road can arise when:

1) Designing the construction of a railway over a deposit to be mined.

2) Designing the mining operations in the deposit under the existing road.

The existing methods of protecting structures are based on the results of instrumental observations in natural conditions that reflect the deformations of those rocks that make up the massif where the profile lines are laid. This does not correspond to the mining and geological conditions of the deposit as a whole, moreover, it cannot be used in other deposits. To select the optimal measures of protecting a surface object, the deposit development system and the parameters of its structural elements with complete information about the mining and geological conditions of the site must be known. Mining and geological documentation includes several geological sections to the earth's surface, including both along the axis of the railway and in the transverse direction.

5. METHODOLOGY

Predicting the earth's surface subsidence at the design stage of underground mining is of great practical importance, since the impact of undermining on the state of protected objects is foreseen. Based on the mining-geological and mining-technical information, strength certificates are built for all the types of rocks, in which the impact of mining operations can spread. Then, based on the rock strength passports, curved displacement surfaces are constructed depending on the depth of occurrence separately for each type of rocks [15, 16]. The resulting curves of shear surfaces are used to determine the boundaries of deformation in the rock massif by building them on geological sections. The contours of dangerous displacements obtained by constructing a curve of the 2nd family on a geological section along the railway, determine the length L of the zone of possible earth's surface subsidence (the boundaries of the displacement trough). In the contour of a certain displacement trough, the values of subsidence of the earth's surface η are calculated depending on the deformability of the structural elements of the deposit development system and the overlying rock mass. The values of η found by calculation make it possible to determine the values of the slopes of the earth's surface after the subsidence has occurred.

In order to determine preliminarily the values of the earth's surface subsidence in the course of developing deposits by the underground method, the analysis of the rock deformations in the massif under the conditions of the Zhezkazgan deposit was carried out. The mining and geological structure of the Zhezkazgan deposit is a layer-like body of mineralized gray-colored sandstones, alternating in section with barren rocks - red-colored siltstones, mudstones, gray and red sandstones. To build a predictive profile of the displacement trough, it is necessary to calculate the deformations of the side faces of the stope, the deformations of the inter-chamber and barrier pillars, the deformations of the hard rocks of the overlying rock massif. The calculation method is given below.

On the section, at the H depth, there are two stopes separated entirely by a barrier, the overlying rock massif consists of alternating layers of siltstone and sandstone (Fig. 1). To calculate compression deformations of the side faces of the panels, the width of the deforming rocks adjacent to the mined-out space is allocated. From point B to the left and from point D to the right, it is necessary to set aside the angle ρ is the angle of internal friction of gray sandstone (Fig. 2). From their intersection point B′ there is drawn a vertical line to the intersection with the overlying siltstone layer and obtained point E. As a result, there is obtained the trapezoid B′EBD with the cross-sectional area EB $b = 0.5m\, tg(90° - \rho)b$, (where b for calculations is taken equal to 1m), which will be deformed from the Q_1 load. The values of vertical compression deformations of the

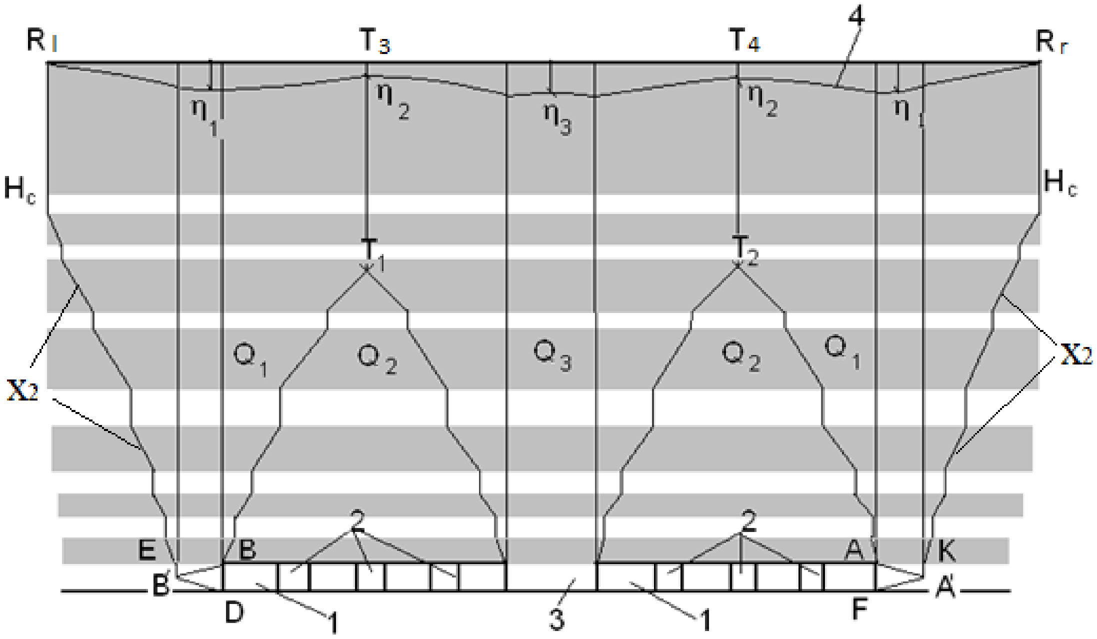

Fig.1 Predictive profile of the displacement trough above two stopes

1–stope; 2–inter-chamber pillars; 3–barrier pillar; 4 –shear trough profile; H_c–depth of formation of uniaxial compression, x_2 – sliding line curves of the second family; Q_1,Q_2,Q_3 – weight of the overlying rock mass, respectively, above the side face of the stope, above the entire barrier and the arch of natural equilibrium, $\eta_{1,2,3}$ – calculated subsidence of the earth's surface

side faces are determined from the consideration of the triangle B´BD.

If to draw an angle φ from points B and D (the angle of deviation of the sliding surfaces from the vertical load), there will be obtained the trapezoid D_1B_1BD with the cross-sectional area $B_1C_1 \times b = 0.5m\ tg\varphi b$.

The volume compression deformation $B_1C_1DD_1$ (Fig. 2) is determined from consideration of the equilibrium equation expressed in terms of displacement functions. The face B_1C_1 with the width of 1 m is under the action of stress:

$$\sigma_w = \frac{Q_1}{0.5mtg\varphi} \tag{10}$$

where Q_1 is the overlying rock strata weight acting on the face of the stoping working with the width of 0.5m·tgφ, t/m^2; m is the deposit thickness, m;

φ is the angle of internal friction; as a result of which the B_1D_1 face will be under relative compression [16]:

$$\varepsilon_1 = \frac{\sigma_w}{E} \tag{11}$$

where E is the elasticity modulus of gray sandstone. At the same time, with respect to the horizontal stress $\sigma_б = m_б \sigma_в$, (where $m_б$ is the coefficient of lateral expansion), the B_1C_1 face relative to the B_1D_1 face will experience relative elongation:

$$\varepsilon_2 = -\mu \frac{m_b \sigma_w}{E} \tag{12}$$

where μ is the Poisson coefficient;

m_b is the horizontal stress coefficient.

The the full relative deformation of the D_1B_1BD trapezoid in the B_1D_1 direction will be the sum:

$$\varepsilon_y = \varepsilon_1 + \varepsilon_2 \tag{13}$$

or, if to substitute (11) and (12) into (13):

$$\varepsilon_y = \frac{\sigma_w}{E} - \mu \frac{m_b \sigma_w}{E} \tag{14}$$

where ε_y is relative compression deformations of the stoping working side faces rock.

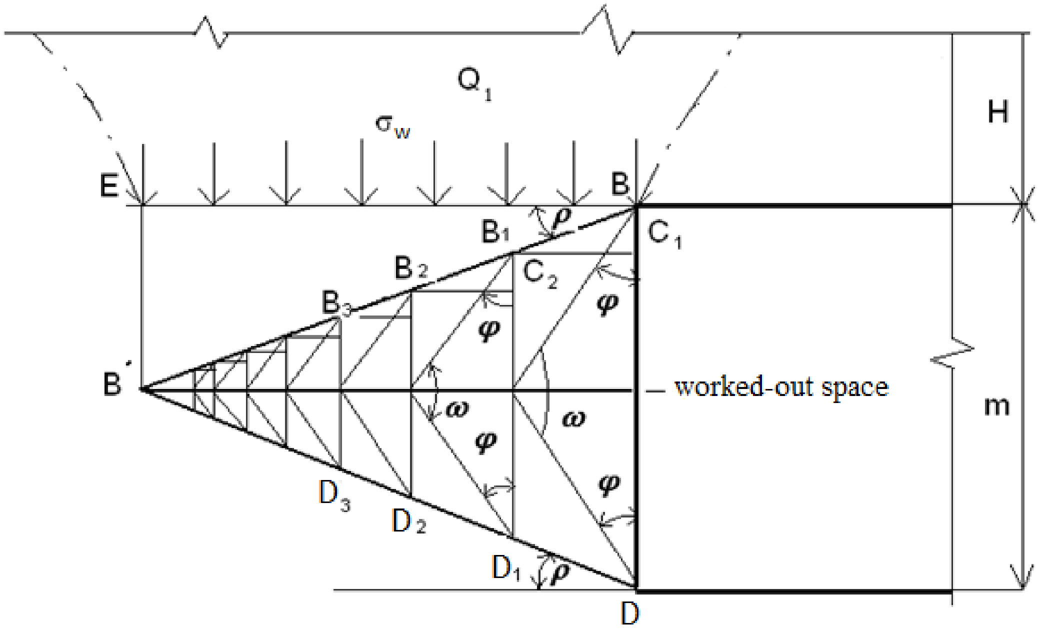

Fig.2 Zone of deformation of the side faces

It is known that relative compression (elongation) ε with compression (tension) in the case of a linear problem $\varepsilon = \frac{\Delta l}{l}$ then, by substituting $\frac{\Delta l}{l}$ by $\frac{\Delta h_{b.g}}{h_{b.g}}$ and using (14) there can be obtained the formula for determining the compression deformations of the stoping panel side faces compression:

$$\Delta h_{b.g} = \frac{\Delta h_{b.g}}{E}\left(\sigma_w - \mu m_b \sigma_w\right) \quad (15)$$

where $h_{b.g.}$ is the length of the trapezoid considered base (B_iD_i), m.

With elastic deformations $m_б = \mu/(1-\mu)$ then Eq. (8) will take the form:

$$\Delta h_{b.g} = \frac{\sigma_w h_{b.g}}{E}\left(1 - \frac{\mu^2}{1-\mu_b}\right) \quad (16)$$

Then, from points B_1 and D_1 draw the angles φ and get a trapezoid $D_2B_2B_1D_1$ with the cross-sectional area of $0.5B_1D_1 \cdot tg\varphi \cdot b$ and calculate its compression deformations in a similar way according to the obtained formula. So, the subsequent trapezoidal parts of the triangle B´BD are calculated until the width along the top of the last trapezoid is the smallest and tends to the point B´.

The total value of the earth's surface subsidence η_1 above the side faces of the stope is determined taking into account the compression deformation of the sandstone layers of the overlying stratum $EHR_lT_1T_3B$ (Fig. 1). The volume of the overlying stratum $EHR_lT_1T_3B$ is limited by curves of the second family [14-16]. The deformations of each subsequent 1, 2, ..., n layers of sandstone overlying from the side faces of the stope are calculated as compressive deformations of the barrier pillar, since the sandstone layers are similar in size and shape to the barrier pillar (BP). Therefore, the formula for determining the BP compression strain [16-18] will be used to determine the compression strain of sandstone layers:

$$\Delta h_{is} = \frac{(1-\mu)\left[\sigma_w - \gamma H(1-2\mu)/(1-\mu)\right]h_{is}}{E} \quad (17)$$

where Δh_{is} – the thickness of the i-th layer of sandstone; σ_w – vertical stress from the weight of the overlying rocks Q acting on the cross sectional area of the ith layer of sandstone S_{si}, where its length is limited by the curves of the second family, and the width is accepted 1 м.

$$\sigma_w / S_{is} \quad (18)$$

where γ – the volumetric weight of the rocks;

H – depth of the sandstone layer in consideration.

Then the full value of the earth's surface subsidence η_1, due to the side faces of the stope deformations is calculated by the formula:

$$\eta_1 = \Delta h_{b.d} + \sum \Delta h_{i,s} \quad (19)$$

where Δh_{is} – the sum of compression deformations of each overlying layer above the stoping side face. The earth's surface subsidence η_2 above the stope, due to the compression deformations of inter-chamber pillars Δh_{ist} [20, 21] taking the under-dome load Q_2, is calculated by the formula:

$$\eta_1 = \Delta h_{ist} \quad (20)$$

$$\eta_2 = \frac{\Delta h_{ist}\left[\sigma - (1-2\mu)\gamma H\right]}{E} \quad (21)$$

where Δh_{ist} – the ICP thickness; H – the development depth; σ – vertical stress on the cross-sectional areas of inter-chamber pillars from the under-dome rock strata; $\sigma = \dfrac{\gamma S_s l}{q_{ist} S_{ist}}$

where γ – the volumetric weight of the rocks t/m^3; S_s – the dome area; l – the distance between the ICP axes, m; q_{ist} – the number of ICPs in a row that are located between barrier pillars (side faces);

S_{ist} is cross sectional area of ICP, m^2.

The dome of natural equilibrium is built by the curved slip lines of the second family, Eq. (2), (Fig. 1) [16].

The earth's surface subsidence η_3 above the entire barrier is defined as the sum of the compression deformation of the barrier pillar itself and the overlying layers of sandstone above it. The barrier pillar perceives the load from the post-arch rock stratum Q_3 enclosed between the curves of the second family built from the edge points of the barrier pillar to the earth's surface (Fig. 1). The compression deformation of the barrier pillar Δh_{BP} is calculated by the formula

$$\Delta h_{bt} = (1-\mu)\left[\sigma - \frac{\gamma H(1-2\mu)}{1-\mu}\right] h_{bt} \quad (22)$$

where σ – vertical stress from the weight of the after-dome load Q_3 acting on the area of the transverse layer of the barrier pillar, t/m^2; H – the depth of development, m; H_{bt} – the barrier pillar height, m, then the earth's surface points subsidence η_3 above the barrier pillar

$$\eta_3 = \Delta h_{bt} + \sum \Delta h_{i.s} \quad (23)$$

where $\sum \Delta h_{ist}$ – the sum of compression deformations of each overlying sandstone layer above the barrier pillar, m.

According to the calculated values of the earth's surface subsidence, there is built the displacement trough profile (Fig. 1). To compare the theoretical methods of the predictive method for calculating subsidence of the earth's surface with experimental data, an experimental model was made using the method of equivalent materials [22]. In the model with observance of the condition of similarity reproduce the process of excavation of minerals, as a result of which there is a process of shifting of rocks, similar to the nature. Geometric dimensions of the model are taken on the basis of:

1) The possibility of observing the formation of sliding surfaces from the boundaries of the excavated space and the barrier pillar to the ground surface.

2) Determination of possible vertical displacements of the Earth's surface and construction of the trough of displacement.

The reconstructed mining and geological conditions in the model are taken as applicable to the conditions of the South Zhezkazgan mine (Kazakhstan). Considered areas deposits PYZ-8-I, PYZ-9-I, II, III, which ranges in thickness from 3 to 19 m, the thickness of the deposit thickness of 120-310 m. The host rocks are mainly red-colored siltstones. In order to model the whole sequence of rocks, the scale of the model must not exceed 1:100 - 1:300, so the scale 1:200 is adopted in the model. The thickness consists of the following layers of rocks:

1) The thickness hz = 14-15 cm.

2) The first siltstone layer with thickness h1r = 5 cm.

3) The second sandstone layer with thickness h1s = 13.5 cm.

4) The second layer of siltstone with thickness h2r = 10 cm.

5) The second layer of sandstone with thickness h2s = 2.5-3 cm.

6) The remaining part to the ground surface consists of siltstones.

7) Deposit development depth = 120 cm.

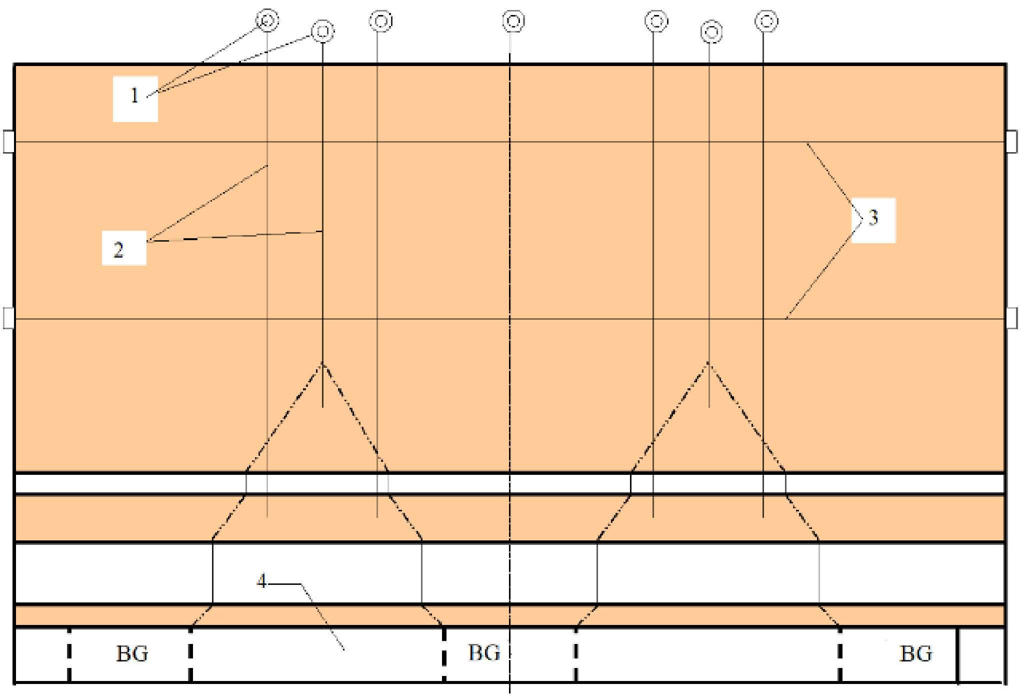

Fig.3 Depth gauge placement in the model
1–indicators of ICh type, 2–glass tubes, 3–firmly fixed horizontal bars, 4–panel, 4– clearing space, BG–barrier pillar

When determining the length of the model in the considered geological section from the boundaries of the mined space and the barrier pillar, the assumed boundaries of the shear trough are plotted by slip lines of the second family, limiting the zone of dangerous shifts and deformations, based on which the section of the geological section of 450 m long (225 cm in the model) is assumed. The width of the model is 28 cm (in reality 56 m). For underground mining works at depths of 240-250 m the height of the model is taken as 150 cm. As a result, a model was made with internal dimensions of 225x28x150 cm. The longitudinal sides of the model are covered with sheet glass 5 mm thick, which allows to see the process of displacement of rocks in the overlying thickness. The transverse side walls of the model are made of wooden material that reduces the friction of the equivalent material against its walls. After the model form has been made, in its longitudinal direction at different heights from the bottom of the model two wires, 0.2 cm thick, are stretched and firmly fixed horizontally. On the wires there are installed depth rods, which measure the displacements of the rock mass in the model. Places of installation of depth reference points are determined by taking into account the expected boundaries of the rock mass displacement, formed over the mining space.

Depth references were laid in glass tubes of diameter 0.4 cm; a strong thread or wire of diameter 0.05 cm was led through the tubes; round-shaped bodies of diameter 0.2 cm and thickness 0.3 cm were tied to the lower end of the wire pulled through the tube; the upper end was attached to an indicator of type ICh-5 (Fig. 3). The composition of the model material was selected by testing samples with different ratios of inert and binding materials. Samples of sand mixed with the required amount of paraffin were tested for uniaxial compression strength on the press TC-14-250 (Fig. 4). The test results of identical in geometric dimensions samples with different content of paraffin are shown in Table 1. The required number of specimens tested in uniaxial compression, determined by the following formula [24]:

$$n = t^2 \cdot \frac{W^2}{K_d} \tag{24}$$

where W – the deviation coefficient; t – weighted deviation; K_d – the value of the allowed error.

As a result of the tests, the following amount of paraffin per sample was established: 4% – for gray sandstone; 1.8% – for siltstone. Figures 5,6 show the general view of the model. The results of the experimental studies showed that the processes taking place in the model were similar to those in

Table 1 Results of determining the strength of layers of equivalent material poured into the model

Number of indicator readings	Paraffin content in sample, g.				Deviations from the arithmetic mean Indicator readings for a certain amount of paraffin in the sample			
	15	20	25	30	ε_{15}	ε_{20}	ε_{25}	ε_{30}
1	2,6	3,28	6,54	5,3	0,04	0,08	0,115	0,14
2	2,5	3,01	3,65	5,25	0,14	0,09	0,005	0,19
3	2,67	2,94	3,68	5,7	0,03	0,16	0,025	0,25
4	2,8	3,25	3,75	5,5	0,16	0,48	0,24	0,64
$\sum$	10,57	12,38	14,92	21,75	0,37	0,48	0,24	0,64
a_{mid}	2,64	3,1	3,655	5,44	9,5%	12%	6%	16%

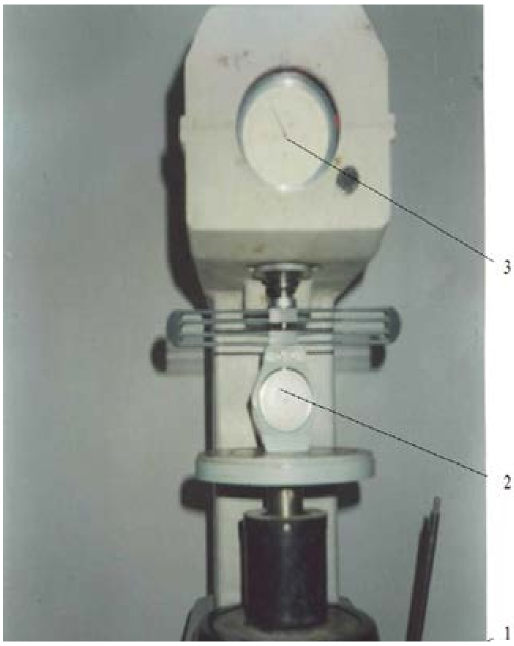

Fig.4 TK-14-250 press
1–TK-14-250 press; 2–DOSM-3-0.2 dynamometer; 3–PM type press indicator

Fig.5 General view of the model

Fig.6 Model: bottom view
1–sandstone layer, 2–artificial struts, 3–layering line, 4–measuring rulers, 5–model strut

nature, with the formation of the crack zone not exceeding the boundaries of the hazardous collapse and shear zone bounded by the slip lines of the second family. Experimental studies were conducted to determine the boundaries of the collapse zones, the zones of smooth shear of the shear mull, and the formation of the fracture character.

6. RESULTS AND DISCUSSION

There is proposed a method of protecting railways by arranging an embankment under the railway, the height of which will be equal to the value of the expected subsidence of the earth's surface, and its length is determined by curved slip lines built on the basis of the rock strength passport [15-17]. To compare the results of theoretical methods of calculation with field data on the proposed method, the geological section along the profile line 115 of the East Zhezkazgan Mine (Kazakhstan) was considered. Within the

Table 2 Results of calculations and field observations of deformations of the Earth's surface

Panel No.	Calculated values of land surface subsidence, η, mm	Actual values of the ground surface, η, mm	Mean value of actual data, mm	% deviation of actual and calculated values of land surface subsidence
Panel 1	18.3	18.3 – R14 19.7 – R15 21.2 – R16 17.8 – R17	19.25 difference – 0.95	4.94
Between panel 1 and 2	46.9	46 – R18	0	0
Panel 2	33.4	31.8 – R22 32.3 – R23	32.05 difference – 6.35	4,9
Between panel 2 and 3	33.8	32.3 – R23 32.4 – R24	32.35 difference –1.45	4.29
Panel 6	8.8	8.8 – R49 7.1 – R50 9.2 – R51 8.4 – R52	8.375 difference – 4.25	4.88
Panel 10	43.2	46.8 – R33 42.6 – R34 36.9 – R35 36.8 – R36	40.775 difference – 2.425	5.61
Panel 11	40	38.4 – R38 30.7 – R39 34.1 – R40	34.4 difference –5.6	14
Between panel 11 and 12	34.3	38.2 – R44 29.1 – R45	33.65 difference – 0.65	1.9

limits of benchmarks 1-70, the values of the earth's surface subsidence above fourteen production panels were calculated, where, among other things considered. The percentage of deviation of the actual values from the calculated ones of the earth's surface subsidence averaged 5 % (Table 2) [15]. The values of the slopes (i) determined after the possible earth's surface subsidence are compared with the allowable (i_{adm}). If the values of the expected actual slopes along the projected railway line do not exceed the admissible value, then it is assumed that the railway will be operated without any special complications. In the event that along the projected railway route in the zone of the base subjected to deformation of rocks, sections are formed where the slopes exceed the admissible value, then the following conditions can arise:

$$S_{sm} = S_{emb} \text{ with } \frac{\eta}{L-x} \le [i_{adm}] \tag{25}$$

or

$$S_{sm} > S_{emb} \text{ with } \frac{\eta - h_{emb}}{L-x} \le [i_{adm}] \tag{26}$$

where L is the displacement trough length; x is the distance from the trough end to the point of maximum value of the earth's surface displacement, h_{emb} is the height of the embankment constructed; $[i_{adm}]$ is the admissible slope when the trains are moving.

The scheme of practical implementation of protecting the railway against the harmful effects of mining is shown in Fig. 7, where 1 is the design line in the longitudinal profile of the embankment under construction under the railway lines; 2 –

displacement trough; i is the corresponding slope; h_{emb} is the height of the embankment being constructed; h is the expected subsidence of the shear trough; h1, h2 – deflection arrows of curvature radii R^+_1, R^-_2; n – staking parameter; b is the angle of rotation equal to the central angle of the circular curve with radius R^+_1, a is the angle of rotation equal to the central angle of the circular

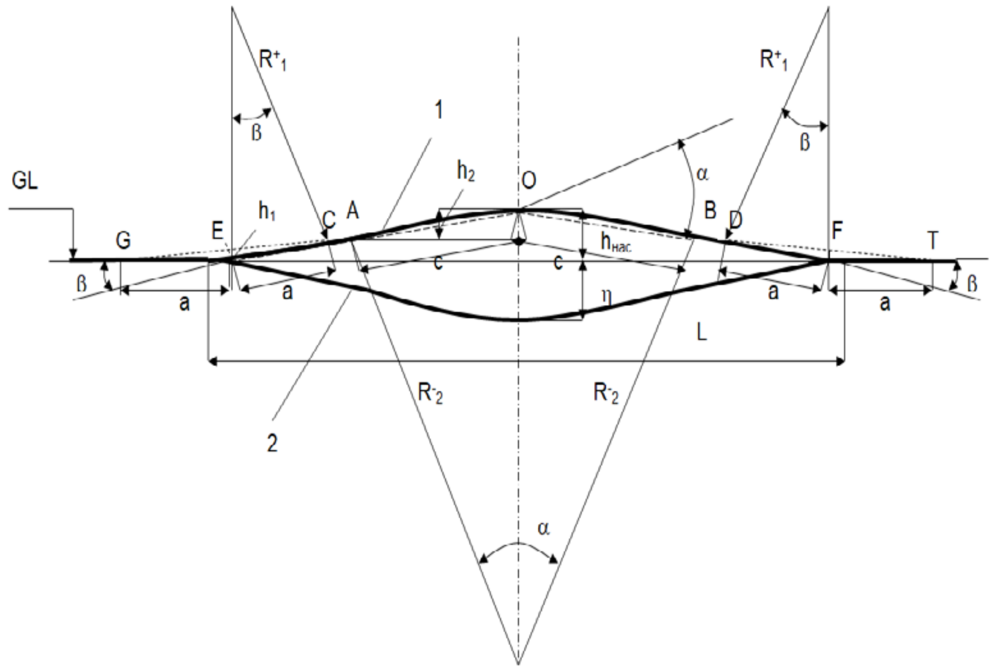

Fig.7 Method of railway protection

curve with radius R^{-}_{2} [20]. Section I is a straight line GE and a circular curve EC with radius of curvature and GE = a is a. Sections II, IV are straight lines CA and BD, where CA = BD = b. Section III is a circular curve AOB with angle of rotation a, where AO = OB = c. Section V is a circular curve DT and a straight line FT, where DT= FT.

7. CONCLUSION

The proposed methodology of predictive calculation of the subsidence of the earth surface on the basis of the construction of the boundaries of the trough zones by the first and second family of slip lines will allow:

1) Predict and calculate the values of subsidence of the earth surface at the stage of underground development design and build a profile of the shear trough on them.

2) To take in advance necessary mining and structural protection measures against the harmful effects of underground mines in relation to the protected objects without disturbing their operation.

3) Determine the boundaries of the rock deformation zone formed during underground mining operations for different mining and geological conditions.

The advantages of the proposed method of protection of the line of undermined railroads:

1) Is laid down in the design and implemented during construction of the railroad if it is newly built or at the beginning of deposit development based on the developed design if the existing railroad is undermined.

2) Prevents the disruption of normal railroad operations and significantly reduces the cost of repair and restoration work.

3) Reduces losses of minerals left in the safety pillars.

4) Will reduce the loss of mineral reserves lost in the Earth's interior due to the loss of bearing capacity of inter-chamber, barrier pillars and the side faces of mined-out panels.

8. REFERENCES

[1] Ramirez R. A., Abdullah R. E. and Rubio Ch. J.P., S1-Psinsarmonitoring and Hyperbolic Modeling of Nonlinear Ground Subsidence in Naga City, Cebu Islandin the Philippines. International Journal of GEOMATE, Vol. 23, Issue 100, 2022, pp.102-109.

[2] Intui S., Jindawutthiphan J., Inazumi Sh., Evaluation of Displacement on Unsaturated Soils in Bangkok Plain. International Journal of GEOMATE, Vol. 23, Issue 100, 2022, pp. 126-133.

[3] Trofimov V.A., Makeev T.G., Forecasting Parameters of Earth Surface Subsidence to Assess Safe Operation of Engineering Structures, in Proc. MATEC Web of Conf. on Theoretical Foundation of Civil Engineering, 2017, pp. 1-7.

[4] Utenov E. S., Zhusupbekov A. Zh., Abdrakhmanova K. A., Tanyrbergenova G. K., Mukhamedzhanova A.T., Numerical Analysis

of Settling of Foundations of Heightened Buildings by the Modulus-Free Method. Soil Mechanics and Foundation Engineering, Vol. 56, Issue 4, 2019, pp. 239-245.

[5] Florkowska L., Example Building Damage Caused By Mining Exploitation In Disturbed Rock Mass. Studia Geotechnica et Mechanica, Vol. 25, Issue 2, 2013, pp.1-37.

[6] Alejano L. R., Ramírez-Oyangurenb P., Taboada J., International Journal of Rock Mechanics and Mining Sciences, Vol. 36, Issue 4, 1999, pp. 475-491.

[7] Sidki-Rius N., Sanmiquel L., Bascompta M. and Parcerisa D., Subsidence Management and Prediction System. A Case Study in Potash Mining Minerals, Vol.12, Issue 9, 2022, pp.1-13.

[8] Gu Zh., Yanlin Zh., Gao R. and Wu L., Research on the Prediction Model of Mine Subsidence Based on Object-Oriented and Probability Integration Method. Hindawi Geofluids, Vol. 2022, 2022, pp. 1-14.

[9] Zhang G. J., Yan W. and Jiang K.G., Inversion method of mining subsidence prediction parameters based on variable weight PB combination prediction model. Chinese Journal of Mining and Rock Formation Control Engineering, Vol. 3, Issue 1, 2021, pp.1-9.

[10] Zhang Z., Qin H., Liu Y., Wind speed forecasting based on quantile regression minimal gated memory network andkernel density estimation. Energy Conversion and Management, Vol. 196, 2019, pp.1395-1409.

[11] Suchenko V.N., Alafar H.S., Methods of protection of buildings and structures from the effects of mining. Vestnik (Herald) of the Russian University of Peoples Friendship, Vol. 2, 2014, pp.119-123.

[12] Kulibaba S. and Esina E.A., New Approach to the Problem of Protection of Undermined Objects on the Earth's Surface, in Proc. 3th Int. E3S Web of Conf. Innovative Mining Symposium, Vol. 01043, 2018, pp.1-13.

[13] Makarov A. B., Mosyakin D. V., Ananin A.I., Mining journal, Vol. 3, Issue 32, 2017, pp.1-8.

[14] Temporary Rules of Protection of Structures from the Harmful Effects of Underground Work at the Mines of JSC Zhezkazgantsvetmet., KazNIMI, JSC Zhezkazgantsvetmet, 1997, pp.1-70.

[15] Kozhogulova K. Ch., Takhanov D. K., Kozhas A. K., Imashev A. Zh. and Balpanova M. Zh., Methods of Forward Calculation of Ground Subsidence above Mines. Journal of Mining Science, Vol. 56, Issue. 2, 2020, pp.184-195.

[16] Sabdenbekuly O.C., Geomechanics, First Edition, Sanat-Poligrafia, 2009, pp.1-75.

[17] Sabdenbekuly O. C., Physics of rock shear, Karaganda State Technical University, 2011, pp.1-96.

[18] Belyaev E.V., Protection of undermined structures, Nedra, 1989, pp.1-182.

[19] Belyaev N.M. Strength of Materials, Training Manual for High Schools, Nauka, 1965, pp.1-856.

[20] Kozhas A.K., Forecast of subsidence of the Earth surface at the stage of designing of underground development Scientific and Technical Support of Mining Production, in Proc. of Kunayev D.A. IM, 2005, pp. 37-43.

[21] Muller G., The Basics of Tracing and Breakdown of Roads and Railroads, First Edition, Transport, 1990, pp.1-239.

[22] Nasonov N.D., Modeling of Mining Processes, First Edition, Nedra, 1978, pp. 1-256.

[23] Seidel A.N., Elementary estimates of measurement errors, First Edition, Nauka, 1968, pp.1-75.