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JUSTIFICATION OF NEW OPPORTUNITIES FOR THE USE OF THE GRAVITATIONAL ENERGY OF THE EARTH IN UNDERGROUND ORE MINING WITH CONVERGENT GEOTECHNOLOGIES*

The paper describes R&D project results on justification of a new approach to the induced caving of ore using convergent geotechnologies. In this case, the optimized conditions are created for self-caving of ore in block-structure rock mass based on the evaluated limiting exposed span using, among other things, the Mathews—Potvin stability graph. The ore self-caving design solutions include formation of a density discontinuity in the form of a vertical slit in rock mass, as well as different inclinations of sides of the manmade separation and outlining backfill frames. The authors calculate the potential gravitational energy of the Earth, which is accumulated within the dome of natural equilibrium generated in the course of mining.

Keywords: *Gravitational energy of the Earth, convergent geotechnologies, self-caving, exposed span, dome of natural equilibrium, Mathews—Potvin stability graph method, potential energy*

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Introduction

According to the R&D project supported by the Russian Science Foundation, the theoretical research is implemented to validate new ways of using the gravitational energy of the Earth for the enhancement of ecological and economic efficiency of mineral mining with the help of convergent geotechnologies.

The accomplished analysis positively shows that the use of the renewable gravitational energy of the Earth, which is new in the mining industry, is possible within the framework of the common technologies based on ore caving [1–5].

There is a certain conceptual and technological contradiction between the scale of the geophysical change field in the lithosphere and the scale of a structural element of a mining technology (extraction unit) within which this change occurs. The attempts undertaken to overcome this contradiction led to the technological division of the mineral body to be mined out into the cavable layers by means of successive stoping in horizontal layers arranged one above the other within the limits of an extraction panel. That allowed stabilization in the horizontal plane owing to weakening of the roof arch but unavoidably created unequal boundary conditions along the height of the extraction panel and drastically sidelines controllability of caving in time. In such operational flowsheet, disintegration process in each layer of rocks propagates from the anthropogenically softened zone (roof arch) to the zone which is stronger thanks to the effect of self-wedging (arch key), which leads to the increased outlet of oversizes with all ensuing consequences and technical problems [6–10].

Development of the basic concepts of the convergent geotechnologies with preventing and eliminating direct effect of in-situ stresses [11–13] opens new vistas for the cardinal modification of the customary method of block caving [6].

The advanced creation of manmade framing and separation systems in rock mass under mining changes in a big way the geomechanical and structural conditions for the gravity-induced caving to propagate in extraction panels. In the conventional approach, gravitational caving proceeds in an extraction block which occurs in the in-situ stress field and has the continuum boundary with enclosing rock mass. In case of the *frame* geotechnology under discussion in this paper, each extraction block has the discrete external boundaries and is located in the secondary stress field generated during formation and evolution of the anthropogenically altered subsoil as a new object in the lithosphere. The virgin rock and ore mass is described using a physical model of a naturally jointed solid medium [14, 15].

Research results

For optimizing the self-caving technology, it is necessary to calculate the size of a limiting flat and exposed span composed of natural blocks (**Fig. 1**). Let a unit block be isolated in the bottom blocky layer and be subjected to a parabolic load *Q* defined in terms of the exposed span and the height of the dome of natural equilibrium.

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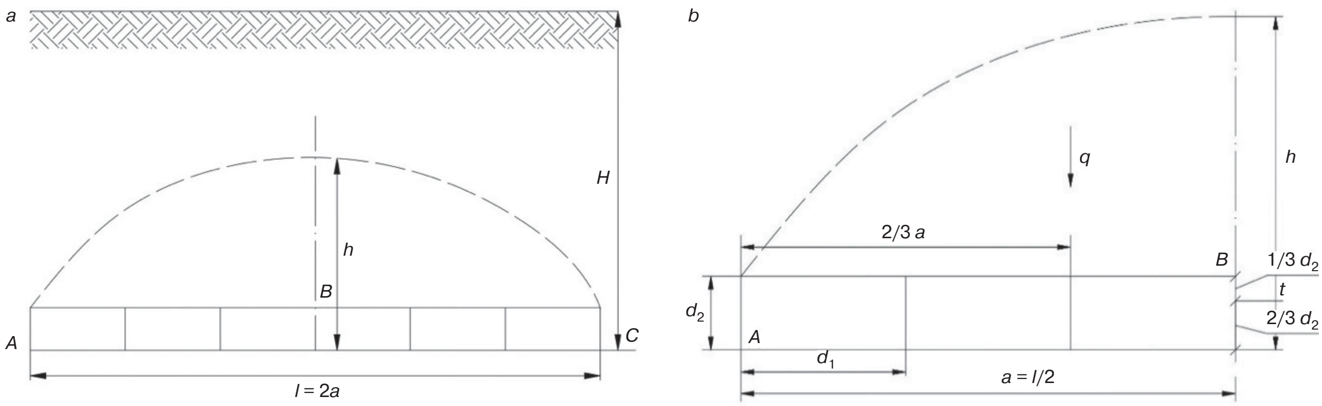

Fig. 1. Free exposed roof span determination in jointed rocks:
(*a*) total; (*b*) half-span. H—depth of stope below ground surface; *l*—limiting exposed span equal to the span of the dome of natural equilibrium; *a*—half-span; *h*—height of dome of natural equilibrium; d_1 and d_2—respectively vertical and horizontal sizes of unit extraction block; *q*—specific loading of block rock mass within arch

The total load Q_1 due to formation of the natural equilibrium dome is found from the expression:

$$Q_1 = \frac{4}{3}\frac{l}{2}h\gamma, \text{ kN}.$$

It is found for the block rock mass that:

$$h = \frac{1}{2\nu}, \ \nu = 2\frac{d_2}{d_1}\frac{R''}{R'},$$

where l is the limiting exposed span equal to the span of the dome of natural equilibrium, m; h is the height of the dome of natural equilibrium, m; γ is the bulk density of rocks, t/m^3; ν is the stability factor of jointed rocks; d_1 and d_2 are, respectively, the vertical and horizontal sizes of a unit extraction block; R' and R'' are, respectively, the compression strengths in the directions of gravity and lateral earth pressure.

Inserting all values in the initial expression offers:

$$Q_1 = \frac{l}{12}\frac{d_1}{d_2}\frac{R'}{R''}\gamma, \text{ kN}.$$

The later earth pressure force T is governed by the value of the compression strength of the central block:

$$T = \frac{1}{3}d_2\frac{R''}{K}, \text{ kN}.$$

The coefficient $K \geq 1$ defines the difference between the actual exposed span (l_a) and its limiting value ($l_{\min}$).

The bottom layer of wedged blocks loaded by the weight of rock blocks within the dome of natural equilibrium and by the lateral earth pressure represented by the response of the other half-span which is in equilibrium. For this reason, the equation of the moment of force due to the load Q_1 relative to the point A (see **Fig. 1**) is:

$$M_q = \frac{2}{3}\frac{l_{\lim}}{2}\frac{l_{\lim}^2 d_1 R'}{12 d_2 R''}\gamma = \frac{l_{\lim}^3 d_1 R'}{36 d_2 R''}\gamma.$$

The moment of force due to the lateral earth pressure is found from the expression:

$$M_T = \frac{2}{9}d_2^2\frac{R''}{K}.$$

Since the sum of the moments in the equilibrium system equals zero, we have the equality:

$$\frac{l_{\lim}^3 d_1 R'}{36 d_2 R''}\gamma = \frac{2}{9}d_2^2\frac{R''}{K}.$$

From the equality, we obtain:

$$l_{\lim}^3 = \frac{2d_2^2 R'' 36 d_2 R''}{9K d_1 R' \gamma} = 8d_2^3\frac{R''^2}{K d_1 \gamma}, \text{ m}$$

and, finally:

$$l_{\lim} = 2d_2\sqrt[3]{\frac{R''^2}{K d_1 \gamma R'}}, \text{ m}.$$

When the compression strengths of unit rock blocks are equal in the directions of gravity and lateral earth pressure (when $R' = R'' = R$ and $K = 1$), the expression above transforms to:

$$l_{\lim} = 2d_2\sqrt[3]{\frac{R}{K_1 d_1 \gamma}}, \text{ m}.$$

In all other cases when $K > 1$, the work size for an extraction block (l_a) is chosen with regard to the stability factor:

$$l_a = \frac{1}{\sqrt[3]{K}}2d_2\sqrt[3]{\frac{R}{d_1\gamma}}, \text{ m}.$$

Unlike the conventional geotechnical systems with gravity-induced caving of ore, the *frame* geotechnologies are based on the idea of the advanced (preventive) construction of a system of artificial separation blocks, with subsequent preparation extraction of blocks from inside the frames. The geometry of such objects is designed with due regard to the geomechanical stability condition of the undermined exposed surfaces. The values of the latter (l_a) is found from the above-given formula and based on the preset safety factor K as per the industrial safety standards. This means that self-caving to be implemented in an extraction unit with the fixated perimeter needs that the equivalent length of the exposed span is increased to a critical value. The stable span size and its increase versus the safety factor K is demonstrated in **Fig. 2.**

The credibility of the approximation in the graph is $R^2 = 0.9871$.

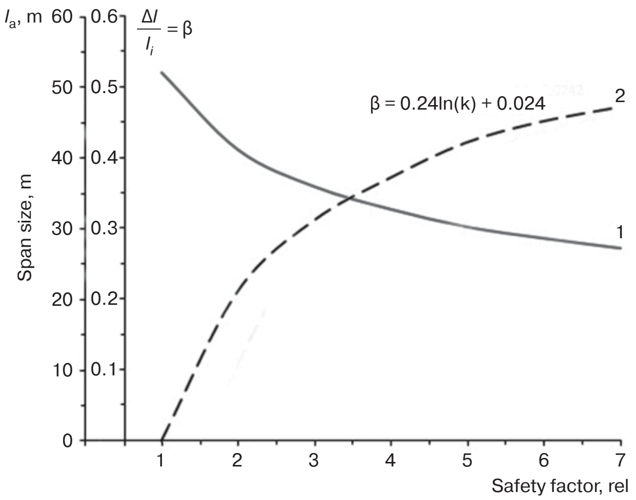

Fig. 2. Stable span size (1) and its relative increment (2) versus safety factor

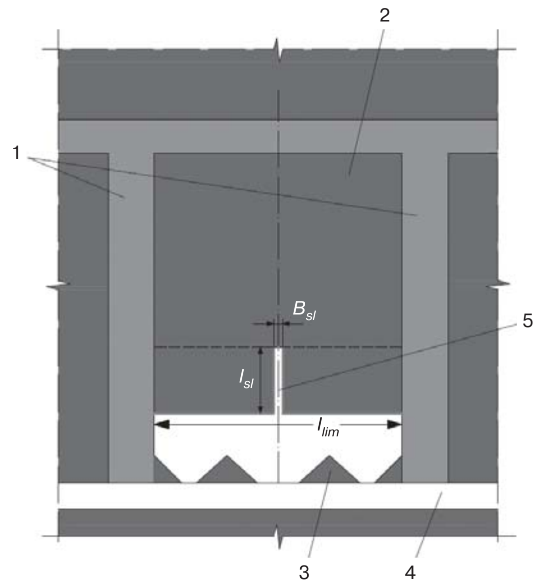

Fig. 3. Manmade density discontinuity chart in extraction unit of frame mine structure:
1—manmade separation blocks; 2—extraction unit; 3—bottom stopes; 4—level stope; 5—vertical slit; l_{sl}—length of vertical slit; B_{sl}—width of vertical slit; l_{lim}—limiting exposed span

In this case, based on the known definition of the criterion as the quantitative model of objectives, the long-term efficiency of self-caving may be assessed in terms of the relative increase of the exposed rock mass span (β):

$$\beta = \frac{l_a - l_{\text{lim}}}{l_a} = \frac{\Delta l_i}{l_a}.$$

In every specific cases, this criterion is evaluated from the empirical expression:

β = 0.24ln(*K*) + 0.24.

According to the geomechanical model proposed by Prof. V. N. Rodionov for the lithosphere as a solid medium containing density discontinuities, relaxation from the external stresses takes place at the external boundaries of these discontinuities, which is equivalent to the decrease in the stability of the system [14, 15]. Regarding the problem being solved, this means that origination of a density discontinuity in the form of a vertical slit in the operation layer of ore is equivalent to the increase in the length of the undermined span (l_a) to the values required by the conditions of self-caving (l_{lim}) (**Fig. 3**).

This means that in each specific case at the assumed values of l_{lim} and *K*, we have:

$$l_a = \frac{l_{\text{lim}}}{1-\beta}, \text{ m}.$$

Then the vertical slit length (l_{st}) required to initiate self-caving is:

$$l_{st} = \frac{0.5 l_{\text{lim}} \beta}{1-\beta} = 0.5 l_{\text{lim}} \frac{\beta}{1-\beta}, \text{ m}.$$

Stability of exposed surfaces in stopes and in the structural components of the convergent geotechnology in the variants of the frame and honeycomb mine structures in the secondary stress fields was estimated as the case-studies of 16 operating ore mines using the stability graph method by Mathews–Potvin [16, 17].

The Mathews–stability index N includes four components: *Q'*, *A*, *B* and *C*.

Mathews' index from his authorial rock mass classification system is calculated from the formula:

$$N = Q' A\, B\, C = \frac{RQD}{J_n} \frac{J_r}{J_a} A\, B\, C,$$

where *Q'* is the index of rock mass quality by Barton; *RQD* is the rock quality designation; J_n is the joint set number; J_r is the joint roughness number; J_a is the joint alteration number; *A* is the ratio of rock mass compression/shear strength; *B* is the coefficient of joint set orientation relative to exposed surface; *C* is the coefficient of inclination of exposed surface.

The estimate of the exposed surface stability needs to parameters: stability index *N* and hydraulic radius *HR*. The hydraulic radius of an exposed surface is found as a ratio of the area to the perimeter of the surface:

$$HR = \frac{E(H)W}{2E(H)+2W} \Rightarrow W(\text{allowable span}) = \frac{2E(H)HR}{E(H)-2HR}, \text{ m},$$

where *E*(*H*) is the height of exposed surface, m; W (allowable span) is the width of exposed surface, m.

The hydraulic radius of the stable and unstabe exposed surfaces was determined using the Mathews–Potwin stability graph (**Fig. 4**) and the stabiity index *N* which was determined experimentally in the test mines.

It should be mentioned that the procedure and the lab-scale results of the experimental data processing differed qualitatively from the in-situ observations in the test mines.

The implementation of the *frame* geotechnology concept offers novel but reasoned opportunities to using the available knowledge on gravity energy on the qualitatively next level, for ore production by self-caving (gravity-induced caving), which is almost forgotten so far.

The proposed concept allows transition from the classic method of uncontrolled self-caving to the controllable

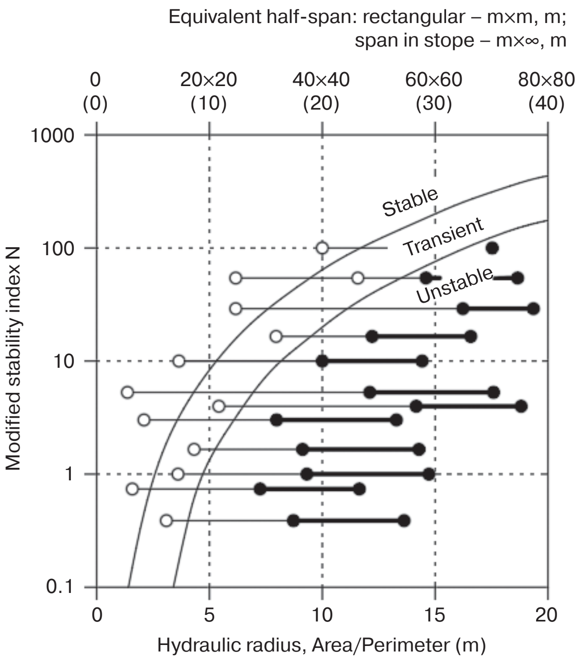

Fig. 4. Stability chart for reinforced and free unsupported exposed surfaces:
● —instability ranges recommended for self-caving;
○ —stability and transient stability (actual in-situ data from mines)

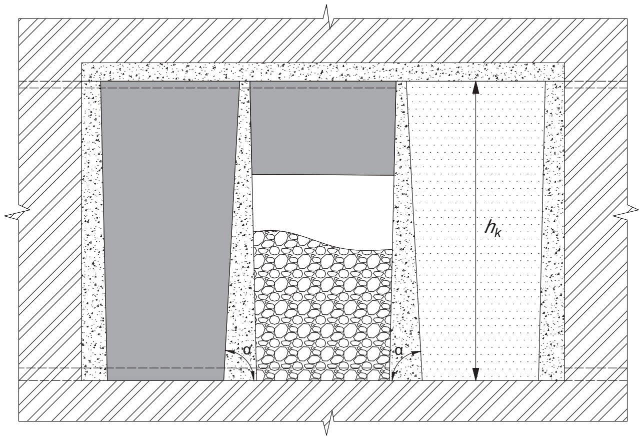

Fig. 5. General view of the frame mine structure with the trapezoid-shaped backfill frames:
hs—operating stope height; α—inclination of lateral sides of backfill trapezoids

blasting-and-gravity induced layered self-caving with blasting to only initiate self-caving of a unit layer of limited thickness. In the prepared extraction block (level) with a height H_{lev}, within the manmade separation frame, one horizontal cross-section size is assumed to equal the estimated length of the limiting equilibrium arch, and the other horizontal cross-section is taken to be smaller. Along the short axis of the block and to its whole height, a row of vertical boreholes is drilled. Explosion at the low ends of the boreholes damages arch key for the first stoping layer and creates a slit to the whole height of this layer (l_{sl}) (see Fig. 3). As a result, the equivalent length of exposed surface is increased by $2l_s$ and self-caving is initiated in the layer. As self-caving stops, the process is triggered in the next following layers. The self-caving process runs under control, the favorable conditions are created for opening of higher order cracks in rock mass being caved, and the effect of self-wedging, which degrades fragmentation quality in the classic variant of self-caving, is eliminated.

The inevitable consequence of such 3D frame structure constructed in rock mass in case of using the gravity-induced caving technology is the uncompensated softening of the springing block in each extraction unit down to the value of strength at the manmade separation boundary and ore body interface. For increasing the strength of the springing block and creating favorable conditions for self-caving in each ore layer, all vertical manmade frames, which are parallel to one of mutually orthogonal axes of the horizontal cross-section of the site under mining, are shaped as trapezoids with longer bottoms. For the outlining manmade frames, these trapezoids are rectangular with the vertical side arranged along the ore interface, and for the separation frames—these trapezoids are equilateral.

The inclinations of the lateral sides of the manmade trapezoids (**Fig. 5**) are found from the ratio of an operating stope height to the difference between the top and bottom sizes of a trapezoid:

$$\mathrm{tg}\alpha = \frac{hs}{m' - m}, \text{ deg.}$$

The top size is found as the summed up weight P_w of the arch and the horizontal pressure P_r of the outlining rock mass to the compression strength (σ) multiplied by the number of manmade vertical frames (N_i) in the site under mining:

$$m = \frac{P_w + P_r}{N_i \sigma}, \text{ m.}$$

The bottom size of the trapezoid is determined based on its shearing condition, in terms of the ore weight (P_0) in the extraction block and the shear strength of the manmade backfill (τ):

$$m' = \frac{P_0 \lambda}{\tau}, \text{ m.}$$

The inclination of the sides of the manmade trapezoids is found from the expression:

$$\mathrm{tg}\alpha = \frac{hs\sigma\tau N_i}{N_i P_o \lambda\sigma - (P_w - P_r)\tau}, \text{ deg.}$$

where *hs* is the height of the operating stope, m; σ and τ are, respectively, the compression and shear strength of the manmade backfill frames, MPa; λ is the lateral earth pressure coefficient; P_w, P_r and P_o are the weights of rocks within the natural equilibrium dome, upper part of the manmade backfill framing and ore, respectively, t/m.

In the framework of the research, the potential gravitational energy of the Earth, which is accumulated within the dome of natural equilibrium in rock mass is calculated gas been calculated as:

$$E_p = \frac{l}{12} \frac{d_1 R'}{d_2 R''} \gamma g h, \text{ J,}$$

Potential gravitational energy of the Earth (E_p), which is accumulated within the dome of natural equilibrium, and blasting energy (E_{blast}) for the same ore volume (per 1 m)

No.	Limiting exposed span, m	Rock mass quality index Q	E_p, MJ	E_{blast}, GJ	E_{blast}/E_p
1	40	40	22	528	$24{\cdot}10^3$
2	40	20	53	435	$8.2{\cdot}10^3$
3	40	1	105	326	$3.1{\cdot}10^3$
4	60	40	49	1181	$24.1{\cdot}10^3$
5	60	20	117	984	$8.4{\cdot}10^3$
6	60	1	235	787	$3.3{\cdot}10^3$

where g is the acceleration of gravity, m/s^2; h is the height of dome of natural equilibrium (layer to be caved), m.

The **Table** compiles the calculated values for the potential gravitational energy of the Earth, which is accumulated within the dome of natural equilibrium, and the energy required to blast the same volume of ore, for the comparison. The blast energy was calculated using the common procedure for borehole charges with ammonite 6ZHV. The calculation shows that the potential gravitational energy accumulated within the dome of natural equilibrium is a few orders of magnitude lower than the blasting energy for the same volume ore body. Furthermore, only a little energy of blasting is spent for rock disintegration (efficiency of large-diameter and small-diameter borehole charges is 10% and 2–3%, respectively), while much energy is spent to induce cracking, alter the stress–strain behavior in enclosing rock mass, etc., which essentially decreases rock mass stability.

Conclusions

On the whole, the theoretical elaboration of the new concept of the approach to using the gravitational energy of the Earth for optimizing ore self-caving conditions offers the real prospects for the enhanced efficiency, as well as for the improved environmental and industrial safety of underground ore mining owing to well-founded design of structural elements of convergent geotechnologies. The safety and efficiency of the proposed engineering solutions are achieved, among other things, owing to the reduced impact exerted on the enclosing rock mass and backfill, which, as a consequence, improves the rock mass and backfill stability in the course of mining and enhances safety of the anthropogenically altered subsoil.

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