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# ESTIMATION OF CRITICAL DEPTH OF DEPOSITS BY ROCK BUMP HAZARD CONDITION

**Vladimir N. TYUPIN**
*Belgorod State National Research University, Belgorod, Russia*

During the development of minerals by the underground method, dynamic manifestations of rock pressure occur at a certain depth, which significantly reduces the safety of mining operations. Regulatory documents prescribe at the exploration and design stages to establish the critical depth for classifying a deposit as liable to rock bumps. Currently, there are a number, mainly instrumental, methods for determining the liability of rock mass to rock bumps and methods based on the determination of physical and technical properties and the stress-strain state of rock massifs.

The paper proposes a theoretical method for determining the critical depth for classifying a deposit as liable to rock bumps. A formula for determining the critical depth of the rock bump hazard condition is obtained. A mathematical analysis of the influence of the physical and technical parameters of the formula on the critical depth is carried out. Its physical and mathematical validity is substantiated. The numerical calculations of the critical depth for 17 developed fields were carried out using a simplified formula. It also provides a comparison of calculated and actual critical depth values.

It is established that the variation of the actual and calculated critical depth is due to the lack of actual data on the value of the friction coefficient and parameters of fracturing of the rock mass in the simplified formula. A simplified calculation formula can be used to estimate the critical depth of a field at the survey and design stages.

More accurate results can be obtained if there are actual data on fracture parameters, friction coefficients and stress concentration near the working areas.

***Key words:*** rock bump hazard; survey and design; critical depth; physical and technical properties of rocks; depth determination formula; numerical calculations

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**Relevance and coverage of problem studies.** Issues of rock-bump hazard arise at deep horizons during underground mining. Regulatory documents* state that the liability to rock bumps at certain mining depth must be determined established at the survey and design stages [1].

The analysis of Russian and foreign literature [1-8, 12-17] shows that liability of rock mass to rock bumps is determined by elastic and strength parameters of rocks, peculiarities of micro and natural fracturing (size of structure, crack width, number of crack systems, the angle of inclination to the outcrop), the parameters of tectonic faults and their location. The liability of rock mass to rock bumps is also determined by the magnitude of the gravitational pressure of rocks and the stress caused by the movement of the lithospheric plates of the Earth [8]. In addition, during the formation of workings, a redistribution of the natural stress state occurs with a significant increase in its proximity to the open surfaces of the rock mass. In addition, in the formation of cavities in the rock mass, some blasting operations lead to the formation of an impact and explosion residual stresses zones [10].

An important parameter of a deposit liable to rock bumps is the critical depth, i.e. the depth from the Earth's surface, at which rock bumps occur during mining, or it is labeled as «dangerous», which corresponds to the hazardous state of the rock mass in the marginal reservoir area, at which rock bump may occur.

The aim of the work is the theoretical determination of the critical depth of the deposit at which the rock bumps can occur during heading in a single goaf.

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* Provision for safe mining operations in deposits liable and dangerous for rock bumps. Federal rules and regulations in the field of industrial safety. Order of Rostekhnadzor N 576. 02.12.2013 // URL: http: // www.consultant.ru/document/cons_doc_LAW_1616871

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The initial mining of single (or parallel) workings, as a rule, is carried out during mining and exploration operations. It should be noted that in case of great angularity of rock mass the critical depth must be reduced.

**Theoretical definition and numerical calculation of the critical depth of the rock mass depending on rock bump hazardousness.** In [10], based on the energy conservation law, a theoretical formula for calculating the radius of the loose zone was obtained during drivage with blasting technique in the stressed fissured rock mass. The formula is obtained based on an experimentally proven mechanism of impact from the explosion of a group of charges of explosives in the stressed fissured rock mass, which consists of two stages.

Stage I. The explosion generates stress waves in the jointings around the charges, which ensures the destruction of cleavages with radial cracks. Further, under the action of the quasistatic pressure of the detonation products (DP), the broken particles begin to shift in the radial direction from the explosive charges, which is accompanied by deformations and friction between the faces of the remote cleavages, as well as their elastic deformations. In this case, the magnitude of deformations and stresses in separate cases decreases with distance from explosive charges, i.e. the strained array at this stage can be represented as an unevenly compressed spring with maximum compression near the charges and decreased compression at a distance.

Stage II. After the pressure drops in the charging planes, the reaction of elastically deformed (maximally stressed by the explosion) cleavages in combination with rock pressure leads to the movement of the massif towards the developed space with the formation of artificial or natural cracks approximately parallel to the goaf outline, i.e. the loose zone is formed.

The distance from the baring outlining to the far edge of the loose zone is determined from the following condition: the energy of the elastic response of the array, accumulated under the action of successive blasting from the center of the working to the periphery and the rock pressure, is equal to the energy required to overcome the friction forces between the cleavages in the marginal working zone:

$$R_{03}=\frac{\sqrt{\pi}}{8}\frac{D\rho_b d_3 c\left(1-\frac{\mu v}{1-v}\right)K_{n\perp}K_{\perp}(N)K_{\text{op}}}{\left[2E\frac{\mu v}{1-v}\frac{\Delta}{d_e}\left(\sum_{i=1}^{k}\sin^2\beta_i\right)^{-1}-P(1-\mu)\right]\Phi}, \qquad (1)$$

where $D$, $\rho_b$, $d_3$ – detonation rate, powder-loading density and explosive charge diameter; $c$, $v$, $\mu$ – longitudinal wave velocity, Poisson's ratio, separate massifs, friction coefficient between cleavages, respectively; $K_{n\perp}$, $K\perp(N)$, $K_{\text{op}}$ – indicators that take into account the interaction of explosive charges and open surface; $E$ – cleavage elasticity modulus; $\Delta$, $d_e$, $k$, $\beta$ – accordingly, the amount of displacement of cleavages, the size of cleavages, the number of fracture systems, the angle of inclination of the fracture system to the outcropping; $\Phi$ – rock fracture index; $P$ – rock pressure,

$$P=K\rho gH, \qquad (2)$$

$K$ – stress concentration factor created due to the formation of workings and tectonic plate movement; $\rho$ – a specific weight of rock mass; $g$ – acceleration of gravity; $H$ – depth of the Earth surface.

The reliability of formula (1) was proved by industrial experiments at the mines of PJSC «Priargunskoye Proizvodstvennoe Ob'edinenie» (PPGHO) at a depth of 300-600 m from the Earth's surface. The results of calculations and practical data are shown in Fig.1.

The critical depth is determined by the rock-bump hazard condition. It is known that with an increase in the distance from the Earth's surface, the stressed state of the rock mass increases and rock bumps occur during blasting (about 60 %) and drilling (about 25 %) operations, i.e. with dynamic impact on rock mass. During a rock bump, as a rule, there is a pulsating displacement of the mass at depth [6, 7] and pressure bump directed towards the developed space. At the same time, «the energy of rock impact is formed from the energy of elastic deformations of a collapsing part of the rock mass and energy released from adjacent rocks» [6, 7]. During rock bump the impact zone is at a radial distance from the working outline, it significantly exceeds the determined size of the loose zone (Fig.1). Then it can be mathematically assumed that in this case, the denominator in (1) tends to zero and $R_{03}$ to infinity.

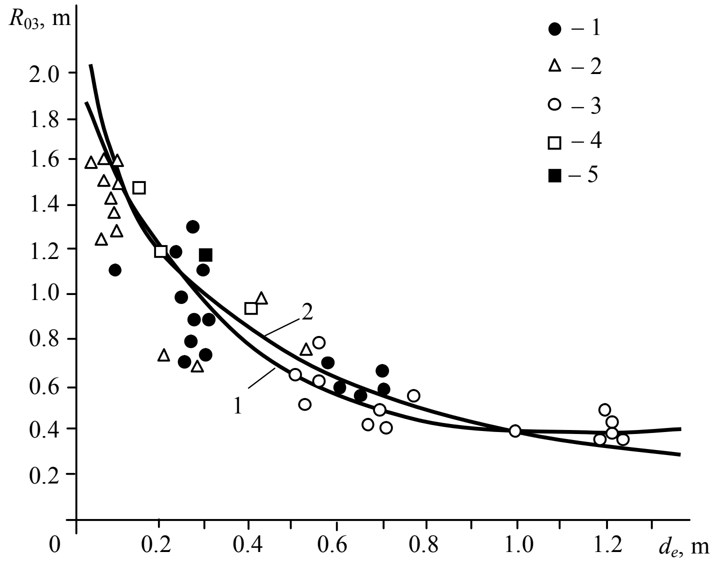


Fig.1. Dependence of the distance between the working outline and the boundary of the loose zone (maximum of stresses) on the size of the cleavage, determined by the goaf walls in various rock massifs instrumentally (core disking, ultrasonic measurements, unloading method, parallel well method) (1) and theoretically (2) ( Formula 1)

1 – granites; 2 – felsites; 3 – conglomerates; 4 – trachydacites; 5 – tufogravellites

Substituting (2) into (1) and equating the denominator to zero and solving the equation, we obtain the formula for determining the critical depth of the rock bump impact hazard for drivage of a single goaf:

$$H_{cr} = \frac{2E\mu v\Delta}{K\rho g(1-v)(1-\mu)d_e\sum_{i=1}^{k}\sin^2\beta_i}. \tag{3}$$

Analysis of dependence (3) shows that with an increase in the transverse strain coefficient, the compressive load is compensated by lateral expansion of the rock, i.e. with an increase in $v$, $H_{cr}$ increases, which is mathematically reflected in (3). The friction between the faces of the cleavages holds the mass from bumping and, with increasing μ the depth should be greater. The greater the volume of the overlying mass of rocks, the less is $H_{rf}$. Field observations on horizon 10 of mine No. 8 of PJSC PPGHO [11] found that the most frequent rock-bump hazard situations (dynamic roof rock slip) are observed when there are systems of cracks perpendicular to the outcrops of mine workings, which is mathematically obtained in formula (3). According to the data of [6, 7], in a rock mass with large cleavages, $d_e$ the magnitude of rock pressure is greater, which means that the probability of rock bump is higher. This mathematical analysis indicates the validity of the obtained formula for determining the depth of the dynamic manifestations of rock pressure when driving single workings. For further proof of the validity of the obtained formula (3), its numerical calculations and comparison with the data* were carried out for several fields in the Russian Federation, developed by underground mining. The physical-mechanical properties of rocks for calculations were selected in [9] and presented in the table as average values.

Numerical average values of parameters for calculations in the formula (3) are equal to the following: $\rho = 2.6 \cdot 10^3$ kg/m$^3$; $g = 9.8$ m/s$^2$; $d_e = 0.4$-$1.0$ m (0.7 m in average); $\mu = 0.3$-$0.6$ (0.45 in average); $\Delta = 10^{-3}$ m; $\sum_{i=1}^{k}\sin^2\beta_i = 1.75$ at $\beta_i = 0$; 60; 90°; $K = 2$.

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**Assumed and calculated critical depth for rock bump hazard condition**

| Deposit | Rocks and ores prone to brittle fracture | $H_a$, m | $E$, $10^{10}$ Pa | $\nu$ | $H_{cr}$, m |
|---|---|---|---|---|---|
| Goroblagodatskoe | Microsyenites, skarns, garnet-magnetite rocks | 300 | 2.2 | 0.21 | 152 |
| Korobkovskoe | Iron Quartzites | 600 | 7.0 | 0.24 | 576 |
| Tashtagolskoe | Syenites, skarns, tuffs, iron ore | 400 | 8.0 | 0.2 | 588 |
| Shereshegskoe | Syenites, granites, hornfels | 600 | 5.8 | 0.24 | 644 |
| Krivorozhskoe | Granites | 500 | 6.0 | 0.23 | 468 |
| Dzhezkazganskoe | Sandstones | 400 | 6.9 | 0.20 | 450 |
| Zyryanovskoe | Microquartzite | 600 | 7.5 | 0.23 | 585 |
| Mirgalimsayskoe | Limestone, Dolomites | 400 | 4.0 | 0.3 | 448 |
| Tekeliyskoe | Quartzits | 600 | 6.0 | 0.24 | 495 |
| Oktyabrskoe and Talnakhskoe | Hornbacks, gabbro-dolerites | 700 | 9.4 | 0.22 | 692 |
| Khaydorkasnkoe Yuzhnoe | Limestone | 215 | 3.97 | 0.25 | 345 |
| Tyrnauzskoe | Skarns | 800 | 6.0 | 0.25 | 523 |
| Apatitoviy tsirk | Iyolite-urtites, poor and rich ores | 200 | 5.4 | 0.25 | 470 |
| Partomchorrskoe | Iyolite-urtites, poor and rich ores | 400 | 5.0 | 0.25 | 435 |
| Rasvumchorrskoe | Iyolite-urtites, poor and rich ores | 400 | 7.5 | 0.26 | 688 |
| Kukisvumchorrskoe | Iyolite-urtites, poor and rich ores | 300 | 7.0 | 0.22 | 516 |
| Streltsovskoe ore deposit (PJSC PPGHO) | Granites | 500 | 5.3 | 0.23 | 413 |

*Note.* $H_a$ – assumes depth*; $H_{cr}$ – calculated critical depth.

The simplified calculation formula is

$$H_{cr} = 2{,}62 \cdot 10^{-8} \frac{E\nu}{(1-\nu)}. \quad (4)$$

Numerical calculations for (4) are presented in the table and in Fig.2.

The analysis of Fig. 2 shows that with an increase in the value of $E\nu(1-\nu)^{-1}$, the critical depth increases, while the calculated values are practically on the straight line. The spread of actual values relative to the calculated curve is on average ± 150 m, which is quite significant. This is explained by the fact that assumed unknown mean values of the parameters are taken: the coefficient of friction between the edges of cleavages, the magnitude of the displacement and the size of the cleavages, the number of fracture systems and their angle of inclination to the outcrop plane, the coefficient of stress concentration. Therefore, formula (4) can approximately estimate the critical depth of rock bump hazard. In this case, the elastic modulus and the Poisson's ratio is determined in laboratory conditions by the core of exploration wells. The coefficient of friction correlates with the coefficient of the strength according to M.M.Protodyakonov [10].

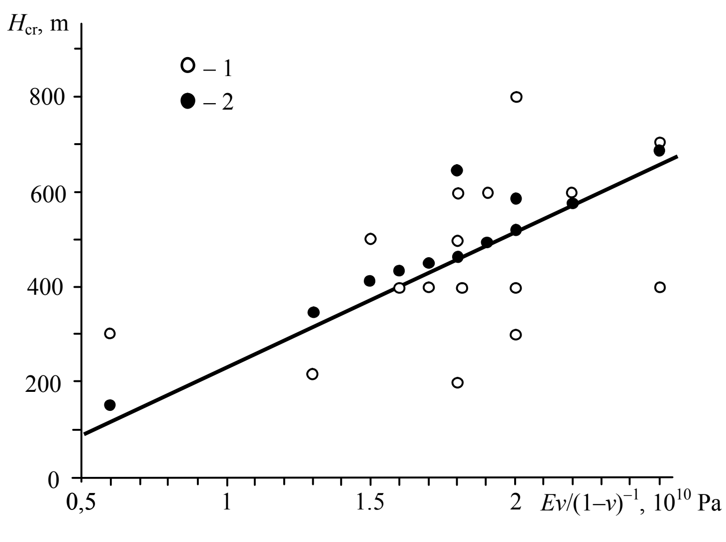


Fig.2. Dependence of critical depth and rock bump hazard from the elastic properties of rocks

1 – actual values*; 2 – calculated values

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## Conclusions

Based on the analysis of technical literature, theoretical studies, numerical calculations and comparing them with the development of hazardous deposits, we can draw the following conclusions:

1. A theoretical formula has been developed for calculating the critical depth of a deposit according to the rock bump hazard condition when driving a single working. The formula considers the physical-technical properties of the rock mass, the parameters of its fracturing, and stress concentration near the working.

2. Mathematical analysis and numerical calculations using the formula prove its validity. The scatter of the actual and calculated critical depth in the simplified calculation formula (4) is explained by the lack of actual data on the values of the friction coefficient and parameters of the rock mass fracture, and stress concentration the working.

3. A simplified calculation formula can approximate the critical depth of a deposit at the survey and design stages.

4. More accurate results can be obtained if there are actual data on fracture parameters, friction coefficients and stress concentration near the working.

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***Author:*** **Vladimir N. Tyupin**, *Doctor of Engineering*, *Professor*, *tyupinvn@mail.ru* (*Belgorod State National Research University, Belgorod, Russia*).
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