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Assessing the seismic effect of quarry blasting at surface mineral workings on the state of underground mines using PRESS 3D URAL software

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Abstract
Relevance. *The development of numerical and analytical methods of assessing ore in place dynamic overload from quarry blasting impact is due to the need to improve the reliability of underground mines stability analysis.*
Research aim *is to assess the effect of blasting at surface mineral workings on underground mines stability and safety.*
Research methodology *includes the numerical and analytical analysis of dynamic stress within ore in place containing underground mines based on the boundary integral equations method in spatial formulation.*
Research results. *Under conditions of dynamic impact made by quarry blasting, the stability of underground mines may be preserved by means of strengthening the support through bolting with reinforced concrete roof bolts.*
Summary. *The proposed method makes it possible to adjust the value of underground mines factor of safety with the account of the dynamic impact made by quarry blasts.*

Key words: *mechanical earth model; seismic effect; stress state; stability; blasting; opencasting; underground mining; software.*

Introduction. In the course of combined surface and underground mining, quarry blasts impact the stability of multiple-use underground mines and pillars. Under certain conditions, seismic effect of quarry blasting results in breakdown and lower efficiency of mining. In this regard, numerous Russian and foreign specialists call attention to the need for in-depth study of dynamic processes impact on mining safety [1–11].

The assessment of the produced by quarry blasting seismic effect on underground mines should be assessed along with obligatory analysis of the following factors: spatial location of ore in place affected part, mine workings, non-uniform geology of rock mass and pillars, and voluntary arrangement of natural and/or man-induced seismic events foci. In order to solve these problems, Russian special-purpose software package called PRESS 3D URAL has been used which includes Energy software seismic pack.

Research methodology. The works by Russian and foreign specialists in the in-depth study of dynamic processes impact on mining safety have become the methodological framework of the present research. The research framework is made up of the procedure for setting boundary conditions for underground mining impact registration, boundary element method (BEM) of PRESS 3D URAL software numerical and analytical unit [12], and the procedure for assessing the stability of excavations located within stoping zone of influence (stability criterion *K* [13] for orebody and pillars stressed-strained state assessment). The research provides the assessment of the effect produced by blasting at surface mineral workings on underground mines stability and safety using software.

Analysis and discussion. In order to build a 3D mechanical earth model (MEM) of an orebody, in PRESS 3D URAL program, grid reference of geological plan image is fulfilled with further automatic construction of the orebody's generalized block model (fig. 1 and 2). As a result, the database of the 3D orebody is built up consisting of particular independent cells, for further application in the course of MEM construction.

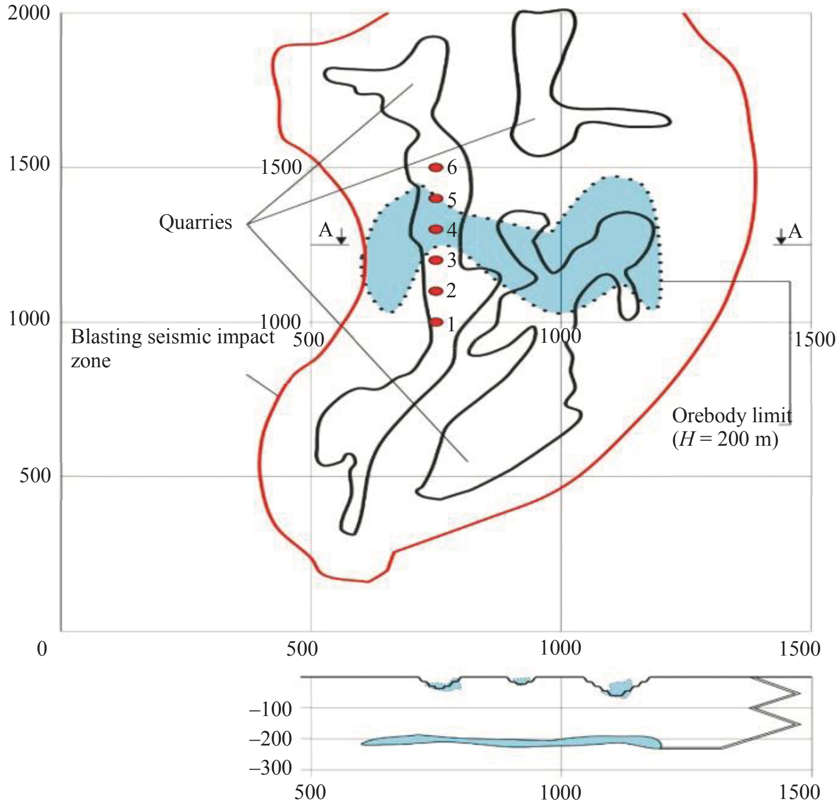


Fig. 1. Scheme for assessing the impact of quarry blasting on underground mining
Рис. 1. Схема к оценке влияния производственных взрывов в карьерах на подземные горные работы

In order to build a MEM, particular physical and mechanical properties are assigned to each cell of orebody's 3D model: modulus of elasticity, Poisson's ratio, compressive strength, and the data on relief well parameters (man-induced gap thickness). The procedure is automatic with grid reference and further values interpolation in 3D model cell. As a result, the initial MEM of orebody is created.

After a 3D MEM is built, a mine and technological model is constructed, for instance, with the use of a mine map. For that purpose, cells of orebody's 3D MEM are projected onto the mine map. As a result, the mine map is covered with a particular electronic grid of flat rectangular cells. Meanwhile, each flat element displayed on the screen remains three-dimensional in MEM; this condition is taken into account in calculations. Within the electronic grid, particular color, e. g. green, is assigned to the cells belonging to ore in place; the remaining elements identified by PRESS 3D URAL program as belonging to the goaf are transparent elements of the grid. The mine map is eventually covered with the grid of elements belonging to the ore in place and goaf; each element has database connection and unique properties. In accordance with a particular rule, boundary conditions are automatically established in elements belonging to the goaf in the form of superimposed stress relieved from the lying wall.

Innovative approach implemented in PRESS 3D URAL program makes it possible to promptly build 3D mechanical earth models for a particular mining process flow chart. Finally, over a short period of time it is possible to create a substantial number of alternate designs, for instance, corresponding to different mine map layouts.

After the mechanical earth model of the site is built, the required stress, strain, and displacement component is calculated both in the elements of ore in place within the mine map and at any random distance from the orebody within the rock mass. Calculation result may be exported to AutoCAD systems.

Orebody marginal part stability in the course of underground stoping expansion is assessed regardless of seismic activity effect based on the procedure for assessing the stability of excavations located within stoping zone of influence (stability criterion K). When calculating and selecting excavation support method and type, rock classification based on the design value of stability criterion K (construction rules and regulations SNiP II-94-80) is used, developed by MMC Norilsk Nickel specialists and applied in 8 Russian mines.

According to the obtained research results, rock stability criterion is calculated from the condition:

$$K = \frac{K_k K_b \gamma H \left((\cos\alpha)^2 + \dfrac{\mu}{1-\mu} (\sin\alpha)^2 \right)}{R K_\varphi K_t K_{\text{s.w}} K_\psi},$$

where K_k is the coefficient of stress concentration in the excavation contour defined with the use of PRESS 3D URAL; K_b is the coefficient of excavation width impact on rock contour stability; γ is superincumbent rock density, MPa/m; H is the depth of mining, m; α is a bedding angle of the orebody, degrees; μ is Poisson's ratio; R is the mean value of rock linear compression strength in a sample, MPa; K_φ is the influence coefficient of incidence angle φ between the axis of excavation and the most advanced fracture system; K_t is the coefficient of stress rupture; $K_{\text{s.w}}$ is the coefficient of rock mass structural weakening; K_ψ is blasting impact factor.

Actual stress field at the contour of excavation is characterized by the stress concentration factor defined by the formula:

$$K_k = -1.0 + \sigma_{\text{SUPER}}, \quad (1)$$

where σ_{SUPER} is the vertical superimposed stress concentration factor from stoping impact, determined with the use of PRESS 3D URAL.

Let us consider an example of K calculation for the following input data (hor. –200 m): vertical superimposed stress concentration factor σ_{SUPER} in point A of variant no. 1 (fig. 3) determined with the use of PRESS 3D URAL software taken to be equal to –0.7; depending on rock quality, $K_{\text{s.w}}$ coefficient of rock mass structural weakening is taken to be equal to 0.8; the value of the coefficient of excavation width impact on rock contour stability is estimated according to the procedure. Under b = 4.0 m

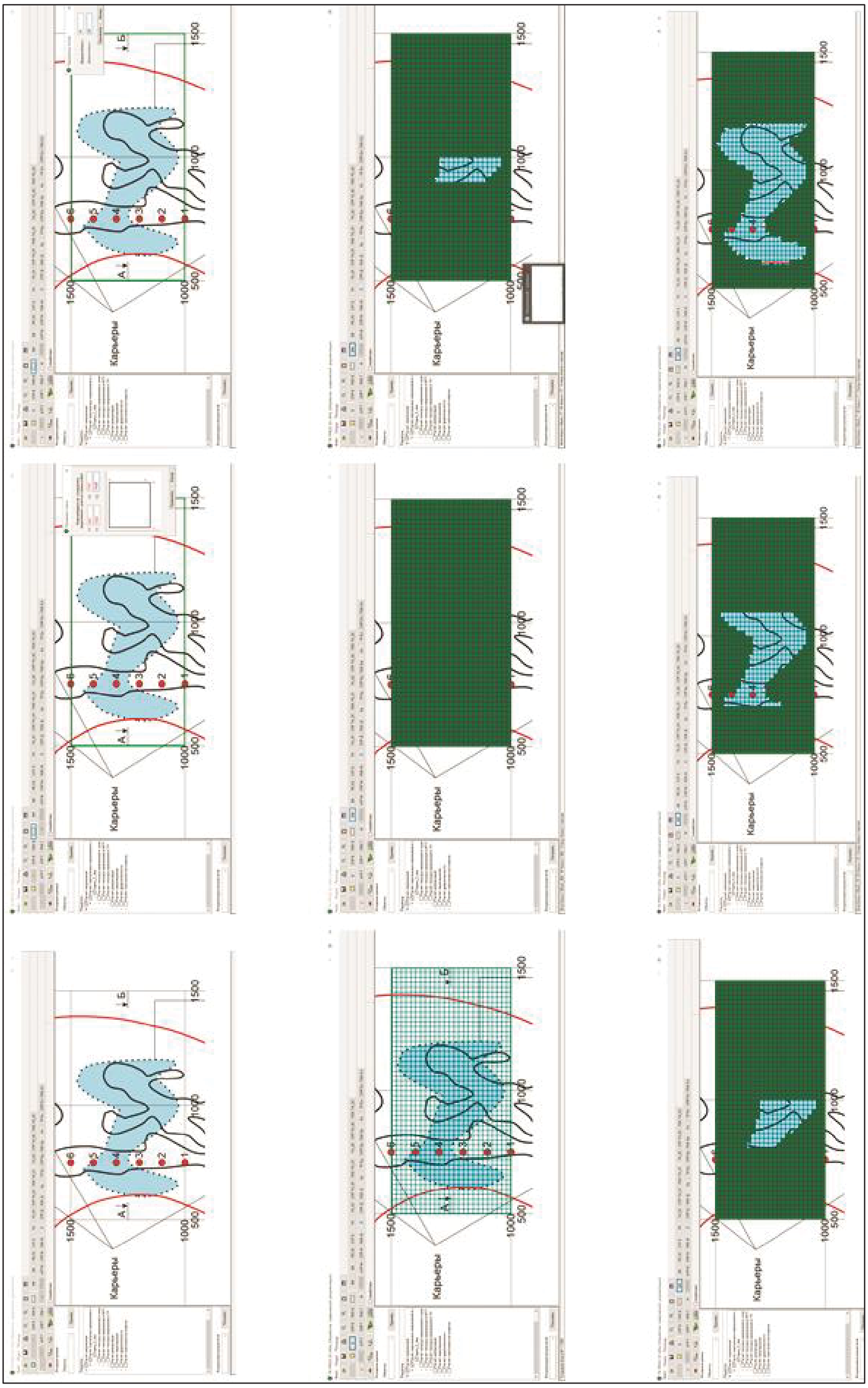


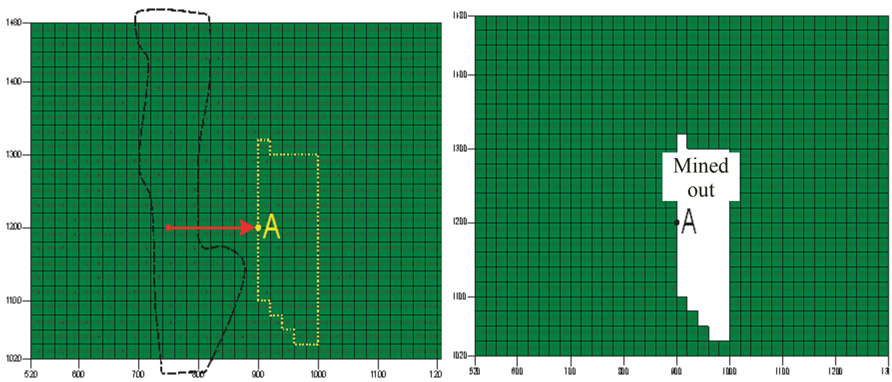
Fig. 2. Stage-by-stage formation of ore deposit design mining-technological model
Рис. 2. Поэтапное формирование расчетной горно-технологической модели рудной залежи

and $K_{s.w}$ = 0.8 then K_b = 1.02; superincumbent rock density γ = 0.026 MPa/m; excavation depth H = –200 m; orebody angle of dip α = 0 degrees; Poisson's ratio μ = 0.3; mean value of rock linear compression strength in a sample R = 40 MPa = 400 kg/cm^2; under $K_{s.w}$ = 0.8 then K_φ = 1.1 according to the procedure; under t < 5 years, the coefficient of stress rupture K_t = 1.0 (construction rules and regulations SNiP II-94-80); K_ψ factor which accounts for linear compression strength variation under dynamic impact, is recommended to be taken equal to 0.85.

Given these considerations, let us determine rock stability criterion:

$$K = \frac{(-1+(-0.7))\cdot 1.02\cdot 0.026\cdot(-200)\left((\cos 0)^2 + \dfrac{0.3}{1-0.3}\cdot(\sin 0)^2\right)}{40\cdot 1.1\cdot 1.0\cdot 0.8\cdot 0.85} = 0.3.$$

The stability of ore marginal part under K = 0.3 is ensured by using sprayed concrete support [13].



With regard to the impact made by the seismic effect, K = 0.6

Without regard to the impact made by the seismic effect, K = 0.3

Fig. 3. Distribution of σ_{SUPER} over the block mechanical earth model
Рис. 3. Распределение $\sigma_{доп}$ по блочной геомеханической модели

Computer simulation of ore stress-strained state with the account of quarry blasting impact (seismic effect) on underground mining. The value of the released elastic (seismic) energy, J, may be determined from the expression:

$$\Delta Э_{total} = \left(\frac{2(1+\nu_P)\tau_{max}^2}{E_P}\Delta_0\sum_{i=1}^{N} S_i\right)\cdot 10^6, \qquad (2)$$

where ν_P is the Poisson's ration for a cell; E_P Young modulus of elasticity for a cell, MPa; τ_{max} is maximum shear stress in contact strength certificate, MPa, the values of τ_{max} are determined with the use of Kelvin's solution; Δ_0 is crack width in rock under dynamic impact, Δ_0 = 0.005 m; S_i are the areas of cells with shifts caused by the action of a blast, m^2; N is the number of cells with recorded shifts.

By transforming expression (2), it is possible to determine the areas of shift and dynamic overload values in the rock mass under various values of blasting seismic energy (table 1, fig. 4).

Shift area S_{shift}, m^2, under the value of blasting seismic energy E, J, is determined in accordance with the GITS procedure [14].

The regularities of dynamic stresses concentration coefficients distribution in the orebody's elements (in parts γH, γ = 2.6 t/m^3; H = 200 m), caused by the action of quarry blasting in shot point no. 3, under explosion energy E = 10^5 J; E = 10^6 J; E = 10^7 J; E = 10^8 J, are shown in fig. 4.

Table 1. Determining the area of shift in the rock mass caused by the action of a quarry blast
Таблица 1. Определение площади подвижки в массиве горных пород от действия взрыва на карьере

Shot point number	X, m	Y, m	Z, m	Shift area S_{shift}, m^2, under the value of blasting seismic energy E, J			
				10^5	10^6	10^7	10^8
3	750	1,200	0	22,486	85,486	359,077	1,588,400

Assessing orebody marginal part stability in the course of underground stoping expansion with the account of quarry blasting impact (seismic effect) on underground mining. In order to assess the stability of underground mines with

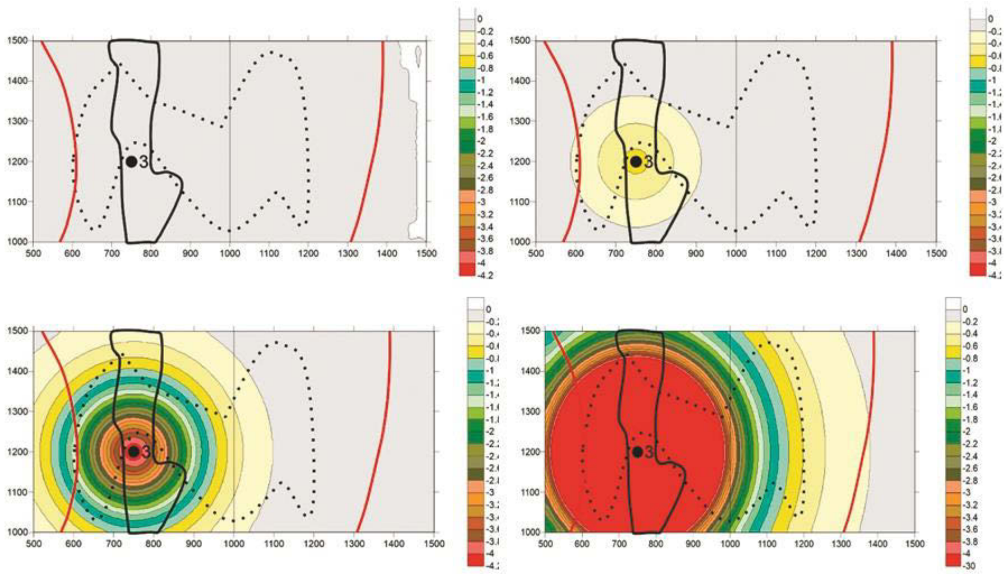


Fig. 4. Distribution of dynamic stresses concentration coefficients in the orebody's elements (in parts γH, γ = 2.6 t/m^3; H = 200 m), caused by the action of quarry blasting in shot point no. 3
Рис. 4. Распределение коэффициентов концентрации динамических напряжений в элементах рудной залежи (в долях γH; γ = 2,6 т/м^3; H = 200 м), возникающих от влияния взрывных работ на карьере в пункте № 3

the account of quarry blasting impact, similar procedure is applied [13]. In this case, vertical superimposed stress concentration factor σ_{SUPER} used in formula (1) should be taken with the account of seismic event's impact caused by the quarry blast.

Let us consider an example of K calculation with the account of seismic event's impact for the accepted input data (hor. –200 m): dynamic stress concentration factor σ_{SUPER} in shot point A (determined with the use of Energy modulus of PRESS 3D URAL software) is taken for the condition of blasting in shot point no. 3 with energy E = 10^7 J equal to –1.65.

The remaining input data are taken similar to the one contained in variant 1:

$$K = \frac{(-1 + (-0.7) + (-1.65)) \cdot 1.02 \cdot 0.026 \cdot (-200)\left((\cos 0)^2 + \dfrac{0.3}{1 - 0.3} \cdot (\sin 0)^2 \right)}{40 \cdot 1.1 \cdot 1.0 \cdot 0.8 \cdot 0.85} = 0.6.$$

According to instruction data from technique [11], under $K = 0.6$ and if taking into account the impact made by the quarry blast, the stability of ore marginal part is ensured by means of bolting with reinforced concrete roof bolts.

Summary and scope of results. In the course of geomechanical assessment with the use of PRESS 3D URAL, the following work has been done: 3D mechanical earth model creation; computer simulation of the stress-strained state of ore without regard to the impact of seismic activity caused by quarry blasting; computer simulation of the stress-strained state of ore taking into account the impact of quarry blasting (seismic effect) on underground mining; assessment of ore marginal part stability under underground stoping expansion with the account of quarry blasting (seismic effect) on underground mining. Activities on supporting the works have been developed with the account of the dynamic impact made by quarry blasting.

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Оценка сейсмического воздействия промышленных взрывов, производимых при ведении открытых горных работ, на состояние подземных выработок с применением программного обеспечения PRESS 3D URAL

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Реферат
Актуальность работы. *Развитие численно-аналитических методов оценки динамической пригрузки рудного массива от воздействия взрывов на карьере связано с необходимостью повышения достоверности прогноза устойчивости подземных горных выработок.*
Целью работы *является оценка влияния взрывных работ при открытой разработке на устойчивость и сохранность подземных горных выработок.*
Метод исследования. *Численно-аналитический расчет динамических напряжений в рудном массиве, включающем подземные горные выработки, на основе использования метода граничных интегральных уравнений в пространственной постановке.*
Результаты исследования. *В условиях динамического воздействия взрывов на карьере устойчивость подземных выработок может быть сохранена путем усиления крепи за счет применения анкерного крепления железобетонными штангами.*
Вывод. *Применение предложенного метода позволяет скорректировать значение коэффициента устойчивости подземных горных выработок с учетом динамического воздействия взрывов в карьере.*

Ключевые слова: *геомеханическая модель; сейсмическое воздействие; напряженное состояние; устойчивость; взрывные работы; открытые горные работы; подземные горные работы; программное обеспечение.*

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