Finding zones of stress concentrations and seismic events in deep ore mining affected by high horizontal stresses

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Abstract

Based on the analytical investigation with math modelling and field research using various rock stress–strain state assessment techniques, the authors revealed mechanisms of stress and seismic event concentration zones in rocks during ore extraction.

1   Introduction

In order to successfully and intelligently control stresses in rocks, mining engineers require an unbiased and user-friendly tool for evaluating and forecasting the variable geotechnical situation at any stage of mining. The authors discuss this issue in reference to an iron ore mine located in West Siberia, where mining is carried out at 1050 m below surface, and is affected by tectonic and induced stresses in damaged rocks (Eremenko et al., 2008). Local horizontal stresses exceed vertical stresses by a factor of 1.3–2.6 outside the zone of the extraction influence, and by a factor of 3.5–5.2 inside the influence zone as illustrated in Figure 1 (Safe Mining Guide, 1991; Petukhov and Batugina, 1999).
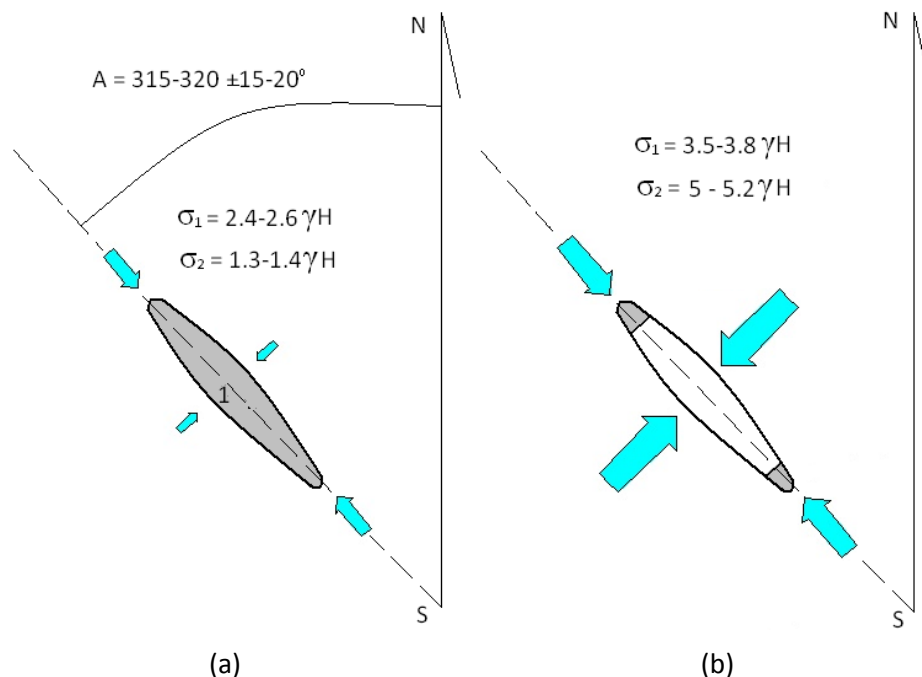

Figure 1   Principal stresses $\sigma1$ and $\sigma2$ outside (a) and inside (b) the impact zone of the extraction.

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1—represents the orebody; and A—the azimuth of the maximum in situ compressive stress,
γ—the bulk weight of the overlying strata; H—the actual mining depth
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One of the widely used extraction methods is sublevel caving where the void is filled with caved host rock (Figure 2). Blasting severely affects the rock mass. In West Siberia, small-scale blasting (0.7–20 t of explosive) and large-scale blasting (120 to 370 t of explosives) results in caving of 30,000 to 250,000 m³ of rocks.

Seismic events are mostly recorded in the active stoping areas and at the bottom blocks adjacent to goafs, where many development headings are located. These dynamic events have seismic energies ranging from 10 to 10^9 J and cause rockbursts of greater than 10 m³ in capacity, which results in breakage or damage of lining, displacement of mining machines and equipment, and disrupts the extraction process.
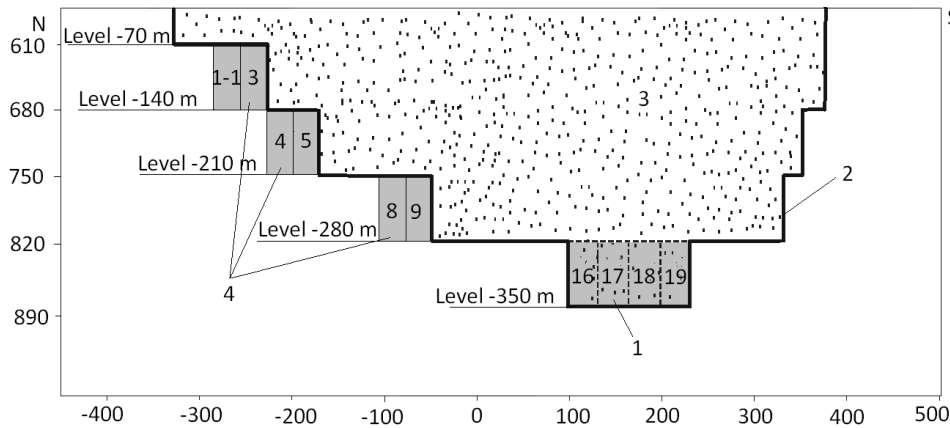


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Figure 2   Schematic illustration of actual extraction at one of the mining districts of the
           Tashtagol iron ore mine (profile along the orebody strike). 1—uncovering blocks; 2—
           boundary of mined—out space;
           3—mined—out space; 4—extraction blocks (1—1 to 19 are numbers of the extraction blocks)
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2   Analytical and experimental findings on the location of stress concentrations and seismic events

Analysis of the numerical modelling results allowed the localisation of concentrated horizontal stress zones versus the length-to-height ratio of mined-out space, as well as against the horizontal components of stresses, λ (Figure 3).
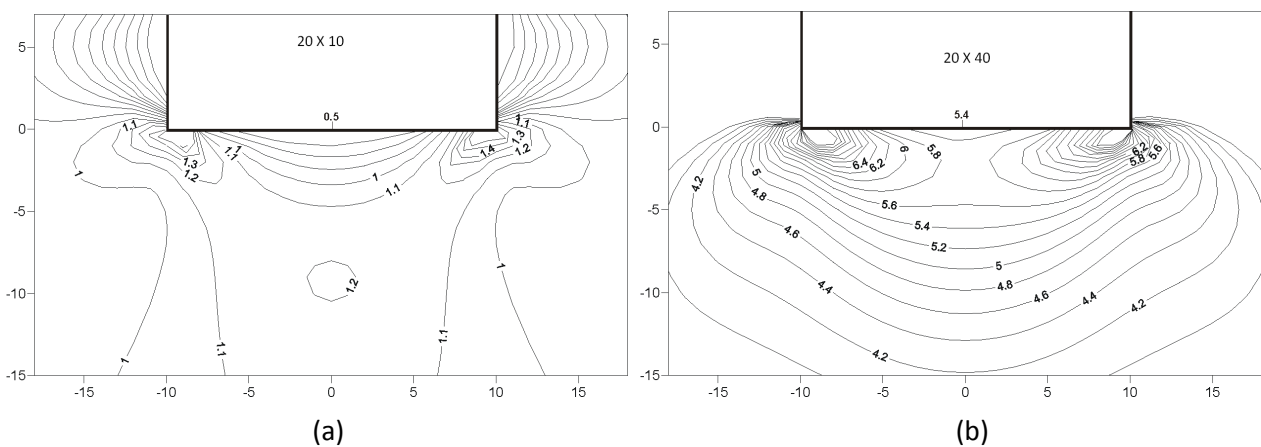

(a)

(b)

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Figure 3   Distribution of induced stresses around the mined—out void for different ratios of stress:
           a) 20 m long x 10 m high goaf and λ = 1; b) 20×40 m—length/height of the goaf and λ = 3
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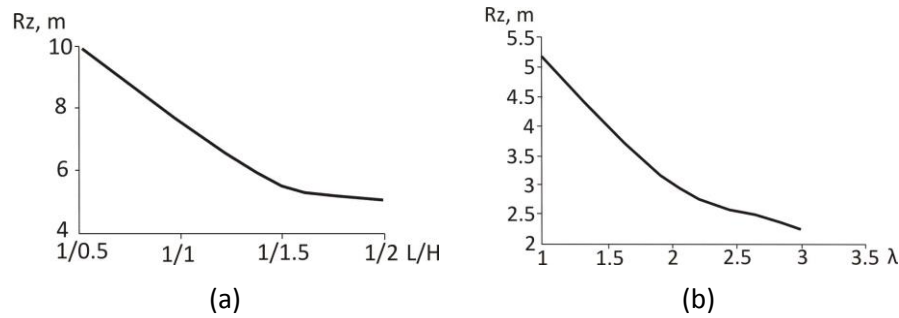
Figure 4 Location of the maximal horizontal stress zone, Rz, versus (a) the length/height ratio of the mined out void, L/H, and (b) coefficient of horizontal component of stresses, λ

It has been found that in higher stopes (increased from 20×10 m to 20×40 m as shown in Figure 4a), as well as with the higher coefficient of the horizontal component of stresses, λ, from 1 to 3 (Figure 4b), the zone of the maximal horizontal stresses moves closer to the goaf bottom and the stress concentration factor increases. The stress concentration factor also changes with depth inside the rock mass, not only with varying length-to-height ratios of the mined-out voids, but also under different stress environments (Figures 5a and 5b).

The modelling results on stresses and their concentration zones are confirmed with the field research of the stress–strain state in rocks. The maximum stress zone and their association with clusters of seismic events were determined based on electrometry and microseismic detections. Stresses were assessed from core disking and relieve slot making (Petukhov and Zaprygaev, 1975).
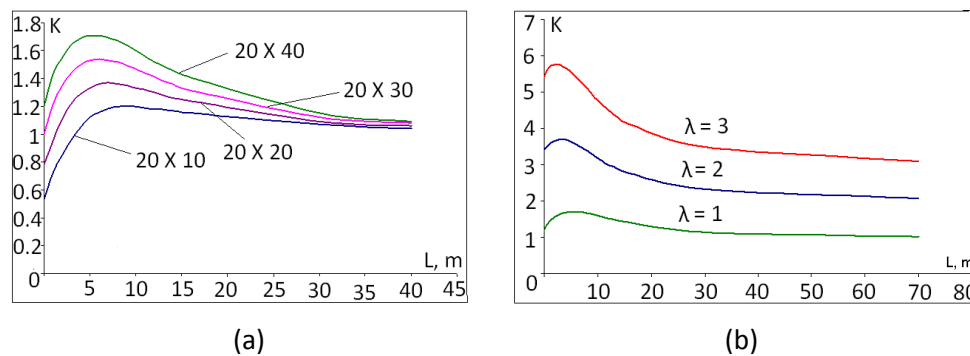

Figure 5 Variation in the stress concentration coefficient K (determined as the ratio of the measured stresses to in situ stresses) with depth into the intact rock mass, D, for (a) different L/H of mined out voids and (b) different coefficients of horizontal component of stresses, λ, and the 20×40 m goaf

The authors have found regularities in the concentration zones of horizontal stresses and seismic events in rocks during sublevel ore caving (Figure 6). In the top-down mining of steep orebodies, considering the orebody thickness, as well as the internal friction and cohesion of rocks, the maximal stress zones occur 20 to 70 m below the bottom of the operational level. Empirically, the occurrence of the maximum horizontal stress can be expressed as:

$$Rz = T\left(1.174 - \frac{0.00033C\cos\varphi}{1 - \sin\varphi}\right)$$

(1)

where Rz—is the maximal stress zone location (in m); T—is the thickness of the orebody (in m); C—is the rock cohesion (in MPa); φ—is the internal friction angle (in degrees).
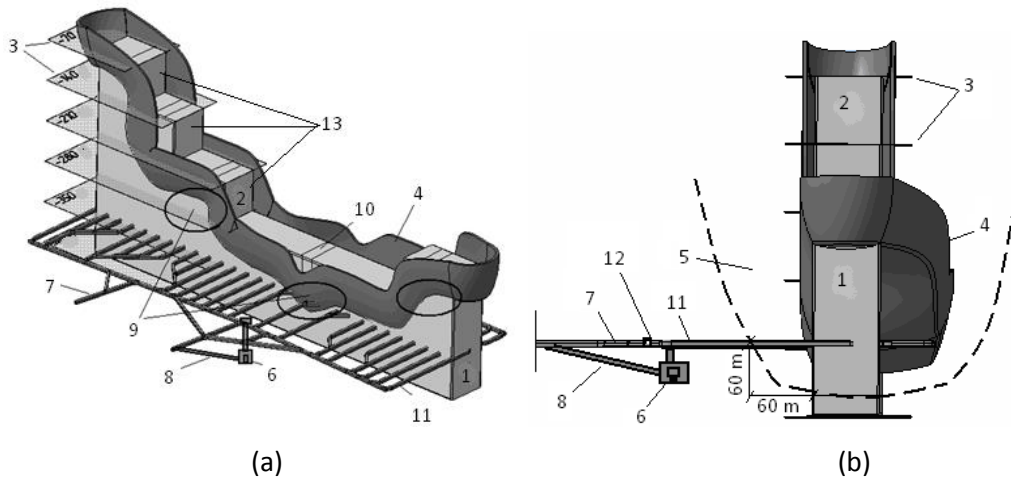
(a) (b)

Figure 6 Top-down extraction with the induced block caving technique and the location ore crushers. The perspective view is (a) and side view is (b). 1—orebody with dip angle 70 to 90°; 2—extraction blocks; 3—extraction levels; 4—zone of maximal stresses; 5—zone of increased stress concentration; 6—crusher cell; 7—offset; 8—conveyor roadway; 9—zones of concentrated seismic events; 10—uncovering of the lower-lying level; 11—crossdrift; 12—cross-strata heading;
13—boundary of the mined-out space

If several levels are being mined concurrently, the Rz relative to the first extracted level can be expressed as:

$$Rz = H(n-1) + T\left(1.174 - \frac{0.00033 C \cos\varphi}{1-\sin\varphi}\right)$$

(2)

where H is the height of a level (in m); and n is the levels extracted.

Formation of the stress concentration zones follows complex patterns both in space and in time, since orebody extraction proceeds on a number of levels concurrently, and can be advanced from the sides to the centre of the orebody, and, from the centre toward the sides. In the beginning of ore extraction on a new level, or in the uncovering blocks, the stress concentration zone is at a depth of 30 m under the bottom of the extraction level. As the extraction advances, the stress concentration zone shifts to 60–70 m, below the extraction level. The relationship between the occurrence of the maximal stress zone and the width of the stoping front in a level where 1 to 30 blocks are being extracted is shown in Figure 7.
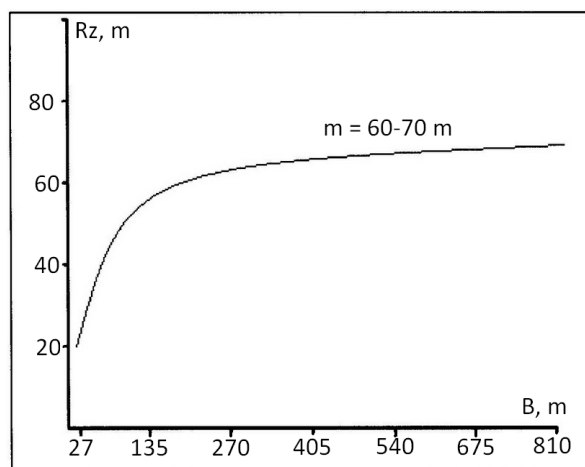

Figure 7 Depth of the maximal stress concentration zone, Rz, beneath the extraction level against the width of the stoping front, B. In this case, the orebody is 60 to 70 m thick, B = 27

m—one block is under extraction in the level; B = 135 m—five blocks are under extraction; B = 810 m—thirty blocks are under extraction
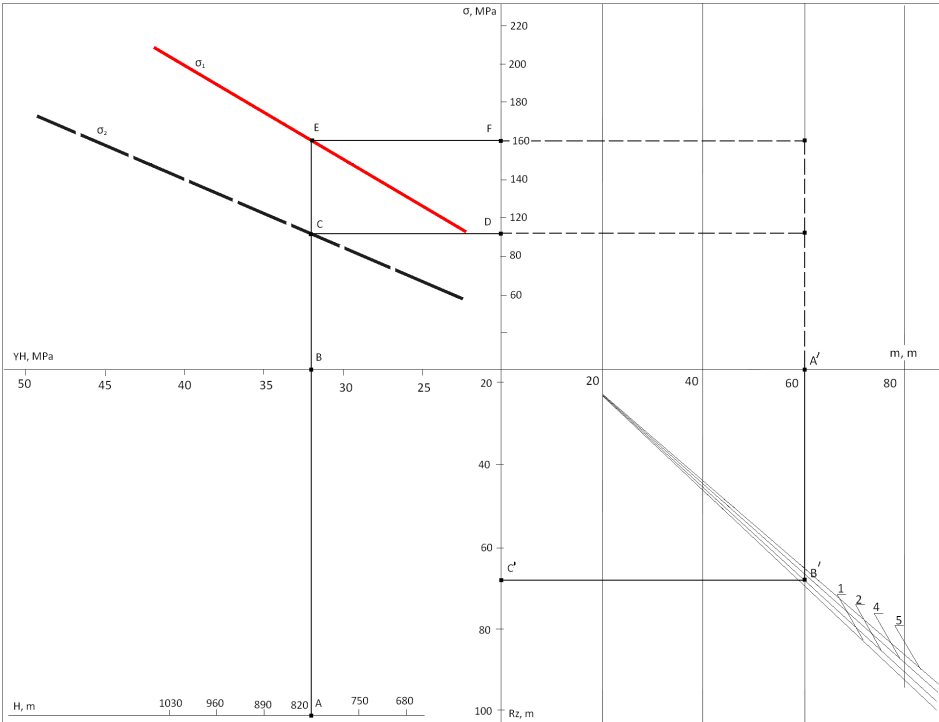

Figure 8   Nomogram for determining the occurrence depth of the maximal stress concentration, Rz. Curves 1, 2, 3, and 4 are plotted, respectively, for σ_{com} = 217.8; 181.8; 147.6, and 114.3 MPa. The domain ABCD: H = 820 m, γH = 32 MPa, σ_2 = 112 MPa. The domain ABEF: H = 820 m, γH = 32 MPa, σ_1 = 160 MPa. A' B' C' : m = 60 m, σ_{com} = 147.6 MPa, Rz = 69.6 m

Figure 8 presents the developed nomogram intended to assess the stress concentration zone occurrence Rz versus the direction of the maximal horizontal stresses (across the strike is σ_1 and along the strike is σ_2, MPa) in the extraction area, vertical stresses (γH, MPa), orebody thickness (T, m), mining depth (H, m), and the ultimate compression of rocks (σ_{com}, MPa).
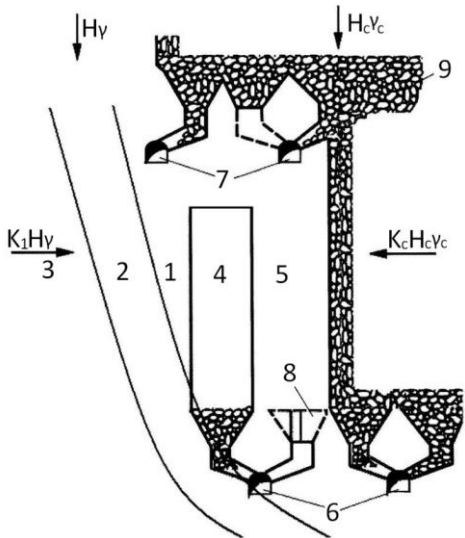

Figure 9   Stress-strain state of rocks in the course of mining with block caving. 1—post-limit stress state area; 2—limit stress state area; 3—elastic stress state area; 4— "balance chamber" (a chamber specially driven on a level or a sublevel to be caved, is intended to accommodate the expanded volume of caved rocks); 5—pillar between blocks; 6—crossdrifts on

the lower level; 7—crossdrifts on the higher level; 8—ore drawing outlets; 9—caved rocks;
H—mining depth, m; γ—specific weight of ore, t/m³; H_c—height of caved rocks, m; γ_c—
specific weight of caved rocks, t/m³;
K_1—stress concentration coefficient in orebody (across the strike); K_c—stress concentration
coefficient in caved rocks

The concentrated stresses have an effect on the entire area between the host rocks and the extracted ore block. The highest stresses are observed in the rock mass that is in the limit stress state due to mining operations, and stresses in these areas approach the value of the ultimate strength of rocks or even exceed it (Figure 9).
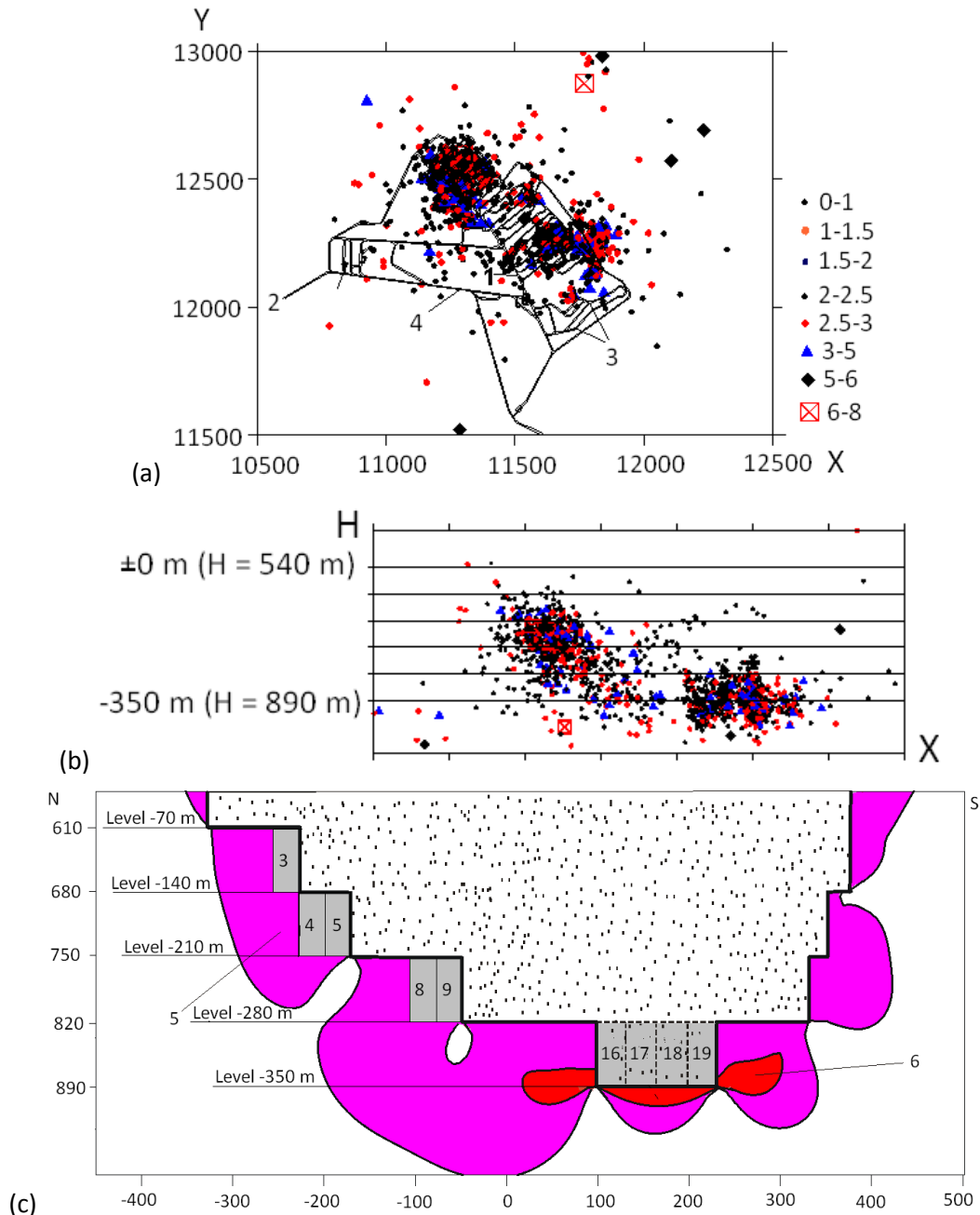
Figure 10 Induced seismic events and inelastic strain zones in one of mine districts in the Tashtagol Mine (Kuzbass) during large-scale blasting (data of 2010). Figures (a) and (b) show the seismic event concentrations on Level −280 m in horizontal and vertical planes. Figure (c) shows the inelastic strain zones. Blasting was carried out in Block No. 19 on Level − 350 m. H—depth from the daylight surface

The post-limit stress state is induced in rocks by the mining operations and due to the natural stress state. High intensity displacements, deformations and seismic events take place in the post-limit stress areas. Numerical modelling with the Mohr–Coulomb failure criterion showed that the induced seismic events concentrate in the zones of inelastic strains as illustrated in Figure 10 (Bulychev, 1994; Baryshnikov and Gakhova, 2009).

The numerical modelling assumed that, due to structural weakening, the rock cohesion, C, varies from 0.5–10 MPa. The inelastic strain zones in Figure 10 have been determined for shearing stress σ_s comparable with the cohesion, i.e. $\sigma_s \geq 0.5$ MPa in soft rocks and $\sigma_s \geq 10$ MPa in hard rocks.

As extraction advances toward the centre of the orebody, the zones of the high density seismic events gradually move toward the edge of the orebody and the energies of the seismic events increase (Figure 11).
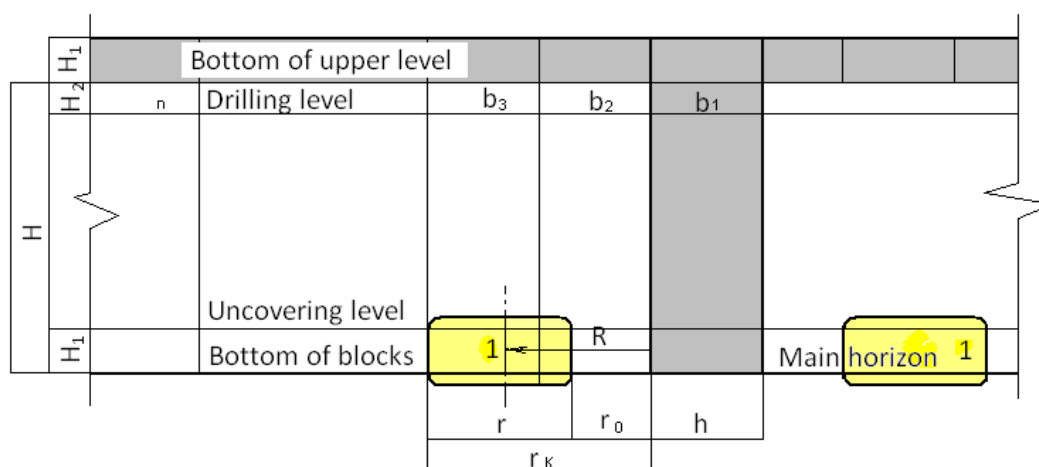

Figure 11 Zones of high density seismic events (indicated with 1). b_1–uncovering block on a level; b_2-b_n–blocks under extraction; h–width of b_1; R–distance between the mined-out void and the centre of the high density seismic events zone; r–width of the high-density seismic zone; r_0 and r_k–boundaries of this zone; H–height of the level; H_1–height of the bottom of block; H_2–height of the drilling level

The boundaries r_0 and r_k of the zone of high density seismicity in the course of extraction advance from the centre toward the periphery of the orebody and are calculated from the expression:

$$\{r_0 ; r_k\} = \{(r+h(n-1.67));(r+h(n-0.33))\}$$

(3)

where r_0 is the distance between the mined-out void and the near (relative to the goaf) boundary of the high density seismic zone, m; r_k is the distance between the mined-out void and the distant (relative to the goaf) boundary of the high density seismic zone, m; r is the width of the high density seismic zone, m; h is width of an extraction block, m; n is the number of the extraction block (n = 1 is the first uncovering block on a level).

The distance between the mined-out void and the centre of the high density seismic zone, R, is calculated from:

$$R = h(n+0.33)$$

(4)

It has been found that large-scale blasting produces seismic events with energies from 10^5 to 10^8 J at the bottom of the extraction blocks, and with energies from 10^2 to 10^4 J in the roof and floor of the mined-out void. The stress concentration zones are traced at a distance of 100 m from the mined-out void, in the walls and bottom of the extraction block, and at a distance of 150 m from the mined-out void, in the roof of the extraction block.

Based on these findings, the authors have developed some recommendations, including a decrease in height for levels and a height increase to avoid the main horizon and cutting workings to occur in the zones of high horizontal stress concentration. In addition, it becomes possible to install different kinds of supports in mine workings in the favourable time determined by the zones of high density seismic events.

3 Conclusions

When the height of a mined-out void is being increased and lateral stress is increased, the zone of the maximum stresses shifts towards the bottom of the void and the concentration factor of the horizontal stress increases. The stress concentration factor changes with distance from the mined-out void.

In the course of the top-to-bottom extraction of an iron orebody in West Siberia, the authors found that stress concentration areas and seismic events at the bottom of the extracted level—with regards to the orebody thickness, internal friction angle and cohesion of rocks—is illustrated by Equation (1).

Seismic events occur in the inelastic strain zones.

As extraction advances towards the orebody centre, the high density seismic zone gradually moves to the sides of the orebody and the energy of the events in these zones rises.

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