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# EFFICIENT AND ACTIVE MONITORING OF STRESSES AND STRAINS IN ROCK MASSES*

*The full-scale research has been undertaken in mines in Gornaya Shoria, Khakassia, Buryatia, Northern Kazakhstan and Western Australia to study geometrics of deformation of holes using special equipment—video endoscope, laser range finder, dip compass, hole treatment device, downhole operation device and guide rods. Keywords: clearing face, management, combine, aerological state, methane content in mine workings.*

*The new developed technology of live stress and strain monitoring in rocks allows basic characteristics of local areas in rocks to be determined within a short time: orientation and range of major principal stresses, relative deformation, location of damage rock zones (fractured rocks), zones of shearing and compression, sizes and dynamics of cracks, zone of influence of drivage and working excavation, mechanisms of failure and time of relaxation in rocks (maximum abutment pressure zones).*

*The active monitoring technology is recommended for stress estimation in mining with caving with natural and manmade support.*

*In the framework of the technology, the method is developed for downhole detection of damaged rock zones and the device is engineered for applying fast-drying coating on inner surface of holes for better examination of crack growth. Initiation and growth of cracks, as well as deformation and shearing in hole are clearly observed on negative images.*

*To measure the length and width of cracks and for assessing dynamics of their growth, the measuring probes are designed and the downhole crack measurement technique is elaborated.*

*After the full-scale mapping of holes, the data are processed, interpreted and presented in graphical form for analyzing geometry of deformation and jointing in holes.*

***Key words:*** *monitoring, stress–strain state, rock mass, damaged rock zones, fracturing, excavation, stoping zone, drill hole.*

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## Introduction

Damaged and rockburst-hazardous ore bodies mined with underground method in difficult ground conditions and complicate geomechanics make 60% in Russia. Deep level mines, for instance, in Australia, Canada, South Africa, Sweden and other countries face similar challenges. The package of geomechanical issues revealed calls for the obligatory operational geomechanical monitoring in mines.

From the comparison, different countries practise similar methods to evaluate geomechanical state of rocks: Russia—categories of underground excavation stability; Norway—Barton's Q-system, Canada and Australia—Rock Mass rating (RMR) system by Bieniawski, South Africa—Mining Rock Mass Rating (MRMR) system developed by Laubscher, etc. [1–7].

Geomechanical monitoring reveals shortcomings of methods and techniques currently used in mines for assessment of stresses and strains in rocks, for instance, high labor input, difficulty and long run of measurements in large areas in mines, bulky equipment, complicated mathematical apparatus and intricate interpretation of the results. It often happens that mine planning or research uses data on effective stresses determined for the entire rock mass. In fact, stress outside and inside the zone of actual mining are distinct, and this difference is considerable even in the limits of a single ore locus. Furthermore, stresses can vary within shot periods of time. Principal stresses orient as a rule subhorizontally and subvertically rather than horizontally and vertically. These conditions are to be accounted for in mining planning, since incomplete understanding of rock mass behavior under mining and the influence of lithostatic pressure on mine structures result in inefficiency and unsafety of mining [8–12].

Efficient and active monitoring of stresses and strains in rock mass allows prompt, within a period up to 7 days, estimation of basic characteristics of stress state in localized areas up to 50000 m$^2$: orientation of maximum principal normal stresses and their ranges; relative strains; location of damage zones (jointed rocks); location of shearing and compression zones; dimension and dynamics of fractures; zone of influence of stoping; energy concentration zones (maximum abutment pressure).

## Analysis of distortion of wells and holes

In full-scale conditions in Gornaya Shoria, Khakassia and Buryatia in Russia, at mineral deposits in Eastern Kazakhstan and Western Australia, as well in a laboratory of the IPKON institute, Russia, geometry of distortion of various purpose wells and holes was analyzed using specialized equipment—video endoscope, ranging laser, circumferentor, hole treating devices, downhole device and guide rods. As a result, the method and facility have been developed for downhole detection of damage zones [13] and improved analysis of fracture opening process with fast-dry white-color coating of well (hole) walls (**Fig. 1**). Processes of growth and closure of cracks, or distortion and shearing of a hole are clearly visualized by negative imaging (**Fig. 2**). A hole treating devices for holes of any diameter starting from 32 mm is applicable at zero power, water and compressed air available, and suitable to complicated conditions in mines.

Determination of the imaging scope (for calculation of relative strains and identification of orientation of maximum stresses) involved mapping of untreated holes using a video endoscope, mapping of coated holes and mapping of holes where inner surface of wall was covered with full-circle mark-

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**Fig. 1. Horizontal hole no. PS (Ø 105 mm, H = 750 m) with a special white color coating, East site, Tashatgol Mine**

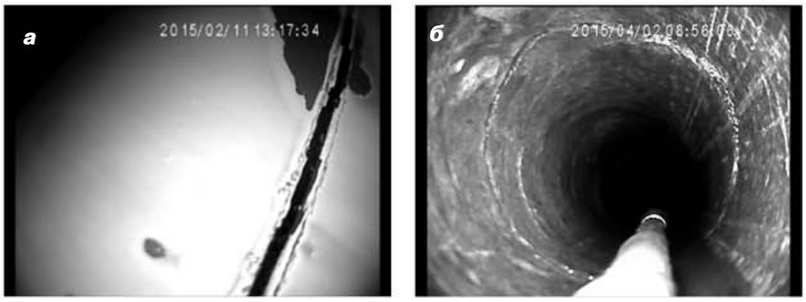

**Fig. 2. (*a*) 7 mm wide crack in (*b*) the horizontal hole no. PN (Ø 59 mm, H = 750 m) 5.2 m downward of the hole mouth; distortion of the hole is observable**

**Fig. 3. Prod meant for measurement of width of a fracture and for estimation of fracture growth dynamics**

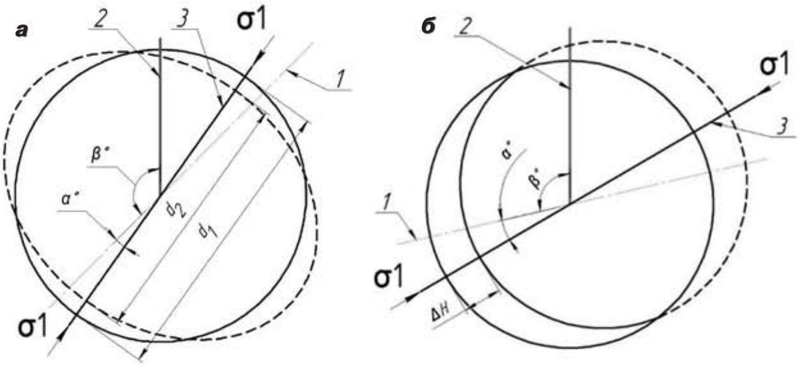

**Fig. 4. Distortion of a horizontal hole under (*a*) compression and (*b*) shearing:**
*1* — vertical line along the plumb; *2* — "imaginary" vertical (cell's vertical); *3* — orientation of maximum stresses; $d_1$ and $d_2$ — respectively, the initial and final diameters of the hole, mm; ΔH — shear, mm; α — angle between the lines of the vertical and maximum stresses, deg; β — angle between the "imaginary" vertical and the maximum stresses, deg

ing by means of a special downhole device (mechanical arm) and guiding rods suitable for work in inaccessible places at a distance of up to 20 m from the hole mouth [14].

The measurement and surveying data are processed using a delimitation algorithm including four filters for finding horizontal, vertical and diagonal boundaries [15].

Positioning of the camera relative horizon and finding of orientation of distortions, shears and fractures in horizontal and inclined holes used plumbing with guiding rods. The survey has shown that water cut in the hole allows defining the horizontal without a plumb. A dip needle is also usable.

Size and growth dynamics of fractures was estimated with a special-design instrumentation prod (**Fig. 3**) using a new-developed method of fracture measurement in holes [16].

### Assessment of stresses and strains in rocks

After in situ data-based mapping of holes has been completed, the maps are processed and presented graphically in order to offer a convenient tool for the analysis of the geometry of hole distortion and dynamics of crack opening.

First, the limits of a survey section in a hole are determined. Then, the survey section and its compression or shear is presented graphically (**Fig. 4a** and **4b**, respectively).

For example, mapping of 40 shot holes drilled for level caving in Northwest site of Tashtagol Mine has displayed zones of compression in all of the holes, at a distance up to 2.5–5 m from the hole mouths (i.e. walls of mine workings). It has been found that maximum stresses are effective in the zone of stoping in the northward direction, in azimuth 355 ± 10°.

Compression is dependent on the maximum stress $\sigma_1$. The higher maximum stress induces increased axial strain $\varepsilon = \frac{d_2 - d_1}{d_2} \cdot K_n$ ($d_1$ — initial diameter of hole; $d_2$ — smallest diameter of distorted hole; $K_n$ — empirical factor to account for physico-mechanical properties and structural damage of rocks) in the line of the maximum stresses. This approach makes it possible to record distortions of hole walls in photo and video material processing within the accuracy of 0.1 mm, which matches the relative strain accuracy of 0.001. For a specific area in an ore body, or for a particular type of rocks, the relative strain of a hole is related with stress level, considering physico-mechanical properties and structure damage of rocks (**Fig. 5**) [17]. As shearing and compression increase, so do actual stresses. It is unnecessary (and unfeasible) to have precise values of maximum stresses in a mine. Rather, it is sufficient to define the range of the maximum values of stresses in order to forecast probable scenarios of rock pressure behavior and work out relevant countermeasures. It should be pointed at the necessity to map not a single hole (holes) but maximum possible number of them—process hole, blast holes and holes specially drilled for mapping — if reliability of data on a particular area of an ore body is of importance. In case of stratification and structural damage of rocks, distortion and shearing in holes is not always in line of the maximum stresses. Then, it is required to analyze characteristics of systems of joints and identify mechanisms of deformation.

To find ranges of stresses using the efficient monitoring approach, it is recommended to compare and use in the calculations the reference data thanks to application of geomechanical techniques — core discing or destressing. For example, mapping of walls in a core drill hole in the sidewall of a development crosscut (width 3.95 m, height 3.72 m) has displayed zones of damage and compression. Furthermore, the mapping has shown the presence of the zone of influence exerted by the development crosscut on the surrounding elastic rock mass, with a radius making 1.2 of the zone dimension.

The data of the mapping were compared with the core drilling data obtained in the same hole. It is found that a distance from 4.5 to 6 m from the horizontal hole mouth, heavy core discing is observed (discs 12.5 and 16.7 mm thick), which matches with the axial stress of approx 40–50 MPa during core drilling in rocks with $E = 8.7 \cdot 10^4$ MPa (**Table 1**).

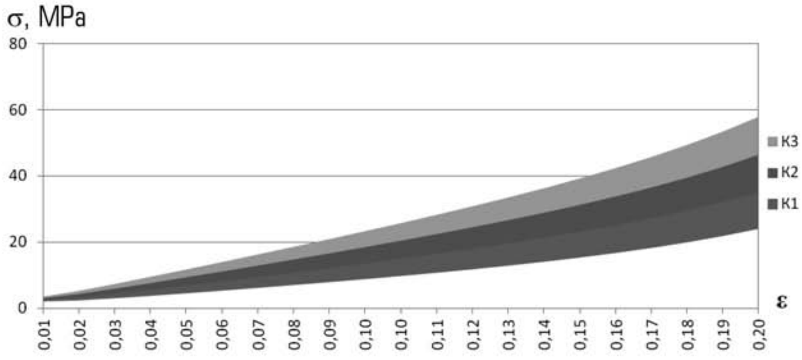

**Fig. 5. Local example of the relationship between strain ε in a hole and stress σ of rocks with different properties:**
$K_1$ — elastic modulus $E = 5 \cdot 10^4$ MPa; Poisson's ratio $\upsilon = 0.21$ and jointing index $K_j = 0.2$; $K_2$ — $E = 6.9 \cdot 10^4$ MPa, $\upsilon = 0.20$, $K_j = 0.1$; $K_3$ — $E = 8.7 \cdot 10^4$ MPa, $\upsilon = 0.20$, $K_j = 0.1$

**Table 1. Characteristics of core discing in horizontal hole drilling**

| Depth intervals, m | Min and max size of fragments, cm | Amount of fragments | Shape of fragments | Size t, mm | Core output, m |
|---|---|---|---|---|---|
| 4.0–4.5 | 50 | 1 | Cylinders | 50 | 0.5 |
| 4.5–5 | 1–22 | 4 | *Discs, cylinders* | 12.5 | 0.5 |
| 5.0–5.5 | 12.5–20 | 3 | *Cylinder* | 16.7 | 0.5 |
| 5.5–6 | 5.5–18 | 4 | *Discs, cylinders* | 12.5 | 0.5 |
| 6.0–6.5 | 50 | 1 | Cylinders | 50 | 0.5 |

### Examples of efficient monitoring of stresses and strains in rocks

It is advised to monitor day-to-day stresses and strains in rock mass under mining with caving and with natural and man-made support. For example, assessment of roof collapse rick in a mine using method of roof-and-pillar in thin and medium-thick ore bodies (gently dipping and inclined) and estimation of roof rock collapsibility under mining and blasting [18, 19]. **Fig. 6** shows a pattern of drill holes for monitoring of "true" and "false" roof in stoping blocks. Vertical drilling is impossible due to structural parameters of the block (minimum thickness, incline, etc.) and limited rock-drill capabilities. Hole drilling at an angle of 60º to horizontal allows roof rock monitoring with holes 2.5 m long in the range of 2 m from exposure.

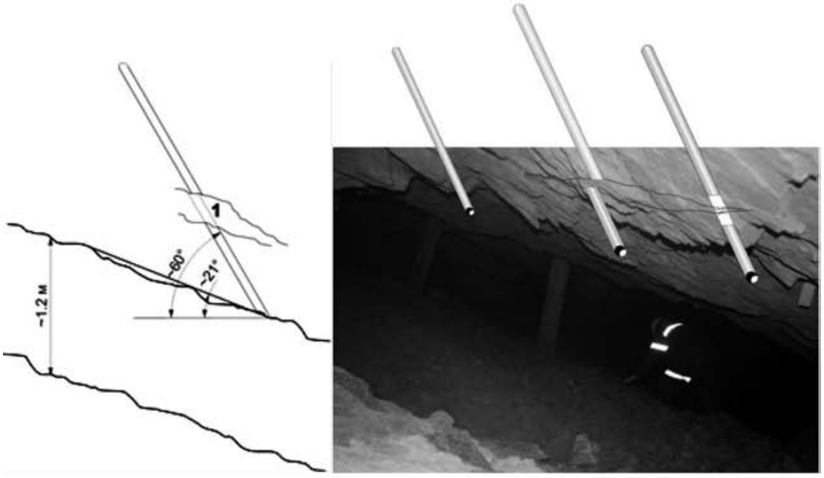

**Fig. 6. Drill hole pattern in roof of stoping bands in Irokinda Mine, Buryatia:**
*1* — damaged rock zones (fracturing, exfoliation)

In Abakan Mine, Khakassia, assessment of stresses and strains in the damaged rock mass employs a gypsum layer–hole measurement station installed in an exploration hole at a depth of 785 m below surface [20]. During second mining in ore body IV, the excavation site where the station is installed falls in the zone of high concentration vertical and horizontal stresses. The excavation (between the face and the middle point) has already come under rock pressure and is failing. The monitoring station allows timing the onset of deformation and destruction, measuring movement of excavation walls, identifying damaged rock zones and analyzing fracturing parameters.

Cohesion $C_0 = 15$ MPa; internal friction angle $\varphi_0 = 50°$; bulk weight $g = 2.7–2.9$ t/m$^3$. The rocks are heavily jointed, natural joints are spaced at 0.2–0.5 m. If excavation driven in tuffsandstone is not properly and timely supported, heavy duty type support deforms, and falls of small pieces of rocks take place. From the viewpoint of geomechanical monitoring aimed at day-to-day estimation of stresses and strains in a damaged rock mass, the installation of the hypsometric station in tuffsandstone is justified and furnishes with the required data.

The surface of walls and roof in the excavation with the cross section 2.3×2.7 m is applied with a gypsum layer 40 cm wide and 4–10 mm thick, or more depending on the surface roughness. The gypsum layer is red-colored for better visibility. Four radial holes Ø 100 mm are drilled toward second mining for a depth of over 540 m, out of which there are two

**Table 2. Hole mapping**

| Hole | Distance between hole mouth and fractures, m | Remark |
|---|---|---|
| Hole 1 horizontal | 0–0.3 | Induced fractures (blasting). Water |
| Hole 2 horizontal | 0–0.4 | Induced fractures (blasting) |
| Hole 3 inclined | 0–0.45 | Induced fractures (blasting) |
| | 1.7 | Single fracture |
| | 3.70 | Damaged rock zone |
| | 3.90 | |
| | 4.20 | |
| | 7.10 | Damaged rock zone |
| | 7.20 | |
| | 7.50 | |
| Hole 4 vertical | 1.40 | Damaged rock zone |
| | 2.00 | |
| | 2.50 | |

horizontal holes, one hole is an inclined raise, and the last hole is vertical. Reference measurement of vertical and horizontal convergence in the excavation is carried out. For detection of damaged rock zones, joints in the walls of the holes are periodically mapped using the efficient monitoring technique (**Table 2**). In has been found that the rock mass undergoes increased horizontal stresses since damaged rock zones are detected in the inclined and vertical holes rather than in the twp horizontal holes.

Based on the measurements of convergence of gypsum layer, analysis of gypsum layer fracturing in exploration drift no. 1 and mapping of holes with the efficient and active monitoring technique, locations of damaged rock zones and orientation of principal stresses have been determined in the mine in 2015.

## Conclusion

The developed and approved technique of efficient monitoring of stresses and strains in rocks allows prompt, in a short period of up to 7 days, estimation of prime stress–strain state parameters in local areas up to 5000 $m^2$ in rock masses: orientation of maximum principal normal stresses and their ranges, relative strains, location of damaged rock zones (fracturing), zones of shear and compression, dimension and dynamics of fracturing, zone of influence of actual mining and mined-out void, mechanisms of destruction and relaxation of rock masses and location of zone of rock mass energy concentration (zones of maximum abutment pressure).

It is recommended to carry out efficient and active-monitoring for assessment of stresses and strains in rocks in ore mining with caving and with natural and man-made support of mined-out voids.

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