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# INFLUENCE OF CYCLIC IMPACTS OF POWERED ROOF SUPPORT ON WEAKENING OF IMMEDIATE ROOF ROCKS

## Introduction

Accessibility of cheap energy sources greatly inspires global economic growth. Despite recent dynamics, the basis of economic growth yet remains low-priced and readily available energy [1, 2]. The portion of renewable energy grows, but energy produced from conventional sources still has the largest share in the global energy balance [3, 4]. Coal remains the main raw material for energy production. Although an increased production of lignite, crude oil and gas, coal extraction keeps on a very high level. The cost of energy generated from coal is the lowest, which conditions wide usage of coal [5–9]. A key restriction for coal use in coal mining regions is the environmental impact both during mining and combustion [10–15]. To limit the range of this impact, various measures related with technology and equipment are undertaken. Nonetheless, owing to its prevalence and cost, coal will undoubtedly remain one of the pervasive energy sources in the world [16–18].

Nowadays, the most popular method of underground coal mining is longwalling. Efficiency of longwall machine systems, in particular, powered roof support (PRS), depends on geological conditions and on operating conditions of PRS [19–21]. A powered roof support consists of separate units interconnected using hydraulic and controlling systems, and is an integrated protection system for an area of operation in a longwall. This is critical under conditions of geological hazards induced in the course of operation [22–24].

Technological capabilities and efficiency of PRS are reflected in their characteristics in the course of cyclic repeatable operations [25–28], namely: prop setting load, incremental resistance, operation in the uniform resistance mode.

A powered roof support is a functionally complex mining machine. On the one hand, it performs ground control, and ensures stability and safety of longwall operations; on the other hand, it implements longwall processes. PRS (or its basic structural components, to be more precise) and contact rocks experience continuous loading for days, without regard to periods of PRS advance. For this reason, when selecting parameters and operating modes of PRS, it is necessary to know the critical values of forces applied to roof rocks in terms of their weakening [29, 30]. This article describes the first attempt to estimate numerically the rate of decrease in the strength and stability of roof rocks as a result of cyclic force impact exerted by PRS.

## Materials and methods

This research aims at development of a procedure to estimate weakening of immediate roof rocks in varying geological conditions with regard to the main influences, with their subsequent analysis.

*The research aims at the analysis of influence of cyclic impacts exerted by powered roof support on strength and stability of immediate roof rocks in coal mine longwalls. On the basis of the data obtained in coal faces of the Polosukhinskaya Mine, the method is proposed to estimate the rate of weakening in rocks using the coefficient of roof beating. The results underline the necessity of designing adaptive units of powered roof supports to increase safety and efficiency of coal mining in difficult geological conditions.*

**Keywords:** longwall, powered roof support, immediate roof, operating characteristic, roof beating coefficient

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To set the governing factor of the problem relevance, the integrated in-situ research of roof rocks was carried out in operating longwalls in the Polosukhinskaya Mine.

The analysis of physical processes in rock mass in the face area used various techniques, for instance, theoretical investigation, laboratory testing and in-situ observations. The latter are the basis as they provide the quantitative indicators of force impacts exerted on roof rocks in certain geological conditions.

The scope of the analyses embraced:

- operating conditions of longwall machine systems in mines (geological and geotechnical conditions);
- actual condition of roof rocks in operating longwalls;
- structural zoning of adjacent rock mass in longwall face areas;
- operational data of powered roof support.

## Operating conditions of longwall machine systems in mines

Pursuant to the data courtesy of the engineering office of Sibuglemt Holding, **Table 1** offers a brief characteristic of operating conditions in the Polosukhinskaya Mine.

The analysis of the data in Table 1 shows that coal beds in the test longwalls have an average thickness (1.21–3.5 m) and increased dip angles in a range of 0–20 deg. The coal beds have false siltstone–clayey false roof and argillite false floor prone to buckling.

The previous research of longwall faces pointed at their high risk because of face slip, fracturing and roof rock falls in the face area, which resulted in the dome formation later on. Such processes affected roof rocks, which brought sustained interruptions of work of the longwall machine systems (LMS) and, as a consequence, a drop in production output.

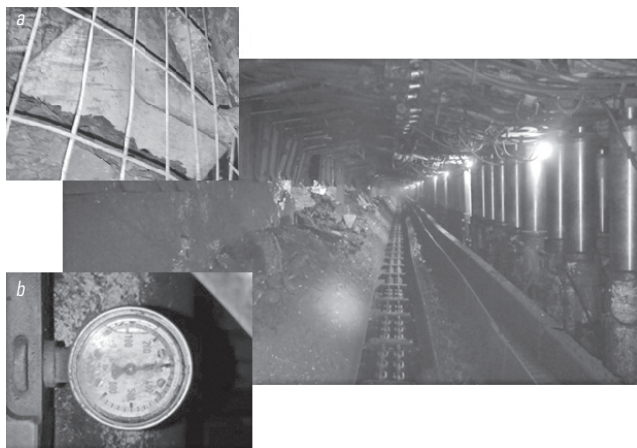
It follows from the aforesaid that the test mining conditions are difficult and, for this reason, performance of LMS–PRS greatly depends on the mechanism of convergence of sidewalls.

## Condition of roof rocks in operating faces

The efficiency criteria of PRS are assumed to be the frequency and size of roof rock falls. The most significant factor of the success of

**Table 1. Mining conditions in Polosukhinskaya Mine**

Coal bed	Thickness, m	Dip angle, deg	Structure	Immediate roof	Immediate floor
30	2.06	0–20	Moderately complex	Fine grain siltstone. Unstable. Pervasive false roof to 0.5 m thick. Siltstone and argillaceous sediments of stagnant water	Insensitive to buckling. False floor—argillite to 0.3 m thick.
29a	2.85	0–20	Moderately complex	Fine grain siltstone. Medium stability. False roof is untypical	Fine grain siltstone. Insensitive to buckling. False floor 0.1–0.3 m thick
26a	1.9	0–20	Moderately complex	Fine grain siltstone. Unstable–medium stability. Pervasive false roof to 0.5 m thick	Insensitive to buckling. False floor 0.1–0.3 m thick



**Fig. 1. Integrated investigation of longwall faces in the Polosukhinskaya Mine:**

loss of stability in unsupported roof spans (a); pressure recorder MP-3U set on hydraulic prop (b)

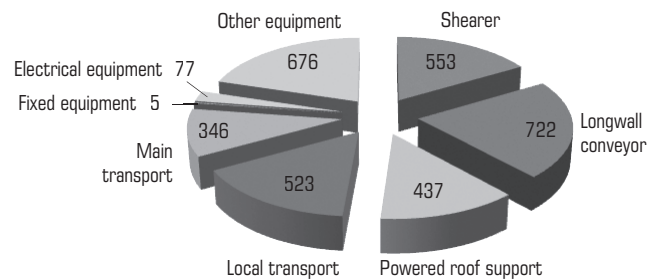
in-situ investigations is the unification of their implementation and interpretation since only this can allow comparison and generalization of a big number of observations.

The investigation of roof rocks in longwall faces in the Polosukhinskaya Mine included recording of the observed phenomena and measurement of the duration of implemented operations (Fig. 1).

A coal longwall 180 m long was conditionally divided into blocks per every even-numbered unit of PRS. Hydraulic props of PRS were equipped with pressure recorders MP-3U (Fig. 1b). The pressure recorders were repositioned on other units of PRS every 2–3 days. Readings were taken from the pressure recorders at intervals of 20–30 min, starting from the moment of the fulfilled pass of a shearer and advance of PRS. Condition of the immediate roof rocks (fractures, falls, discontinuities, splitting) was recorded in each operation cycle of PRS by means of photosurveying and video filming (Fig. 1a).

The investigations of the test longwall faces were carried out in difficult geological and geotechnical conditions. Recording was executed during implementation of various processes: shearing, finishing, process breaks and emergency maintenance (with obligatory identification of the recording time), and during prolonged outages (weekends and public holidays).

Longwall mining of coal bed 26a in the Polosukhinskaya Mine used LMS KM138 composed of PRS 3M-138, longwall shearer KSW-460NE



**Fig. 2. Downtime due to equipment malfunctions at coal faces in the Polosukhinskaya Mine**

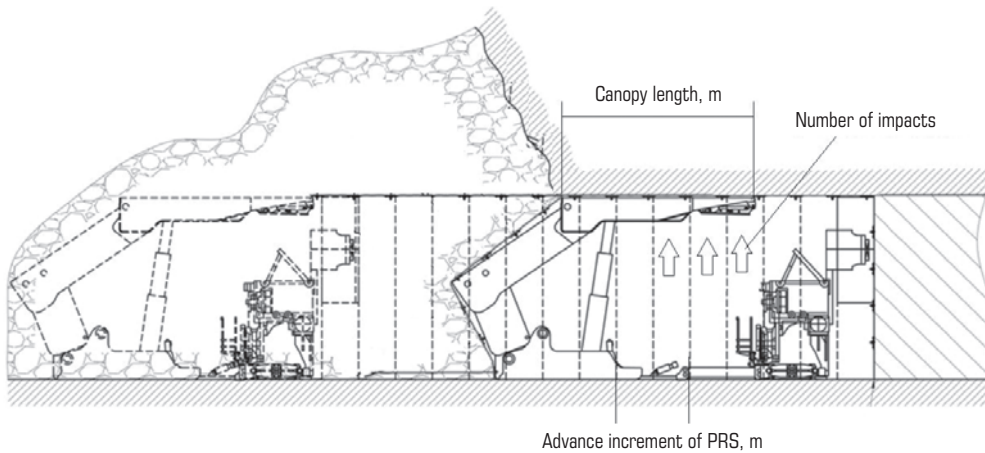
and longwall conveyor RYBNIK 750. The investigation lasted for 30 days, including 100 operating shifts and 63 cycles of cutting, and the advance of the longwall face totaled 80 m.

The observations found out that the production steps (coal shearing, installation of roof support and advance of the conveyor) took from 10 to 18% of the total cycle time. The finishing operations—from 5 to 15% of the total time spent. The largest time of a cycle—from 16 to 23%—is taken by the correction of troubles connected with PRS operation. The downtime because of the conveyor and shear problems total 7 to 12% and 2 to 5%, respectively (Fig. 2).

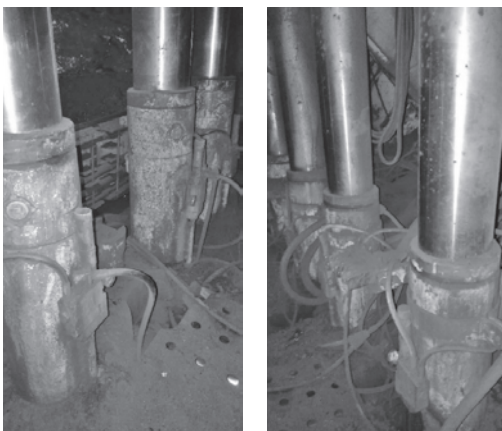
The time consumption analysis shows that the least reliable component of the longwall machine system in ground control and support installation is the powered roof support as the correction of PRS problems takes the largest time. This, in its turn, increases the probability of rock falls in the face area.

The roof rock observations show that during one operation of a cycle, namely, advance of PRS, the canopy of PRS cyclically impacts one and the same area of the immediate roof, which is adverse and leads to fracturing and rock falls in the space between the units of PRS (Fig. 3). The number of cyclic impacts of PRS, i.e. the repetition factor  $K_{pr}$ , can be determined as a ratio of the canopy length ( $L_c = 5$  m) to the advance increment of PRS ( $\lambda_{prs} = 0.6–0.8$  m).

Visual observations revealed critical stresses which formed in the immediate roof in the face area after the pass of the shearer, induced by different yielding in the roof–coal bed–floor and roof–canopy–floor systems. Being much stiffer as compared with the roof and PRS canopy, coal bed ‘punches’ the immediate roof, and fractures are formed in rocks along the upper brim of the face. A fracture formed in the immediate roof, as a rule, separates it into blocks with a width equal to the width of a cut of the shearer drum. The fracture is observed at the upper face brim, at a distance from 10 to 40 m from the shearer drum.



**Fig. 3. Cycle operations in longwall face of coal bed 26a in the Polosukhinskaya Mine**



**Fig. 4. Immediate roof rocks broken into small pieces**

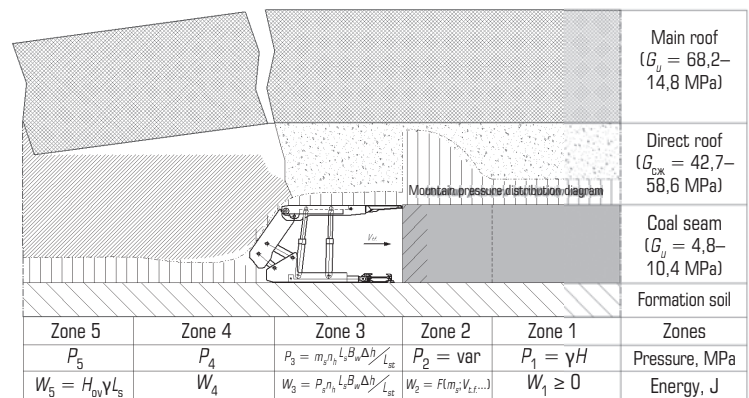
Sometimes, such fracture is invisible; but, as the longwall advances, because of the roof deformation, the structural blocks displace, and a small fracture widens and turns into a visible fracture 3–10 mm wide, running in parallel to the face line. Fracturing promotes detachment of blocks of the immediate roof from the main rock mass. The fracturing growth direction depends on the cleavage, but mostly fractures propagate vertically. The blocks displace along these fractures. The height-wise displacement varies from 20 to 50 mm. As a rule, the second–third block off the face fails into smaller parts, and rocks above PRS, nearby the rear row of the props are incoherent. As a result, broken small pieces of rocks of the immediate roof flow through the gaps between the units and props of PRS to the face area in the form of inrushes (Fig. 4).

**Structural zoning of adjacent rock mass in longwalls**

According to present-day concept, structure of adjacent rock mass in longwalls is conditionally divided into 5 zones. Behavior of rocks under the impact of rock pressure is different in each zone. The initial data are assumed as the potential displacement energy of roof rocks (Fig. 5).

Structural zoning:

- Zone 1 is ahead of the face, where coal and sidewall rocks experience stress state conditioned by constant rock pressure;
- Zone 2 is in face-adjacent rock mass exposed to varying rock pressure;



**Fig. 5. Schematic interaction between PRS and immediate roof rocks**

- Zone 3 is dynamic force interaction between PRS and intermediate roof; parameters of this interaction are determinable;
- Zone 4 is caved rocks behind PRS (goaf side), which is unstable, and its parameters are indeterminable unambiguously;
- Zone 5 is mined-out void with stabilized rock pressure.

It is most interesting to investigate Zone 3 as the parameters effective in this zone are uncontrollable.

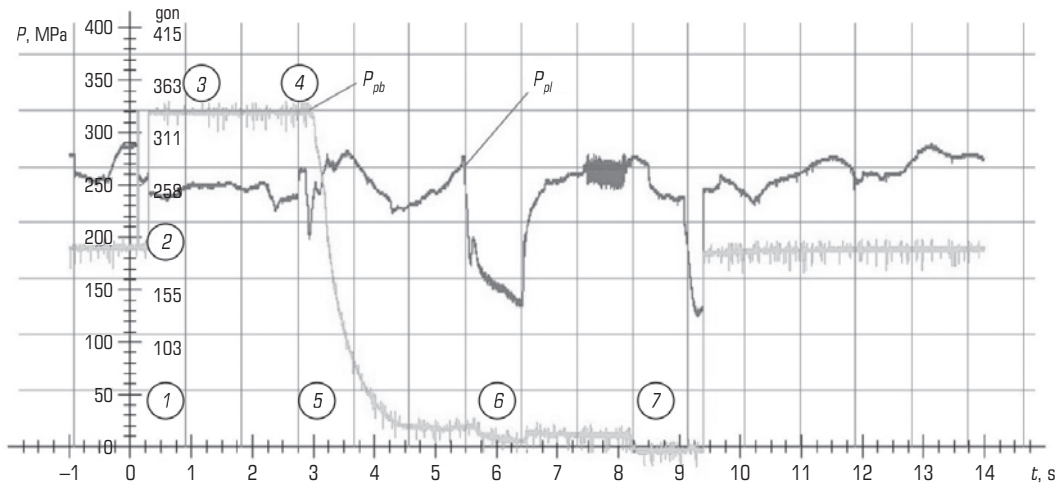
Efficiency of the face area support in many ways depends on the characteristics of a roof support system. Thus, for different geological conditions, it is necessary to determine rational forces and design data of PRS, namely:

- resistance and yielding;
- initial and residual expansion of props;
- unit pressure on enclosing rocks and its distribution along PRS;
- kinematics of PRS and its typical working characteristic.

**Operational characteristics of powered roof support**

A typical working characteristic of powered roof support is understood as an integrated operational factor including: dependence of pressure in piston barrel of a hydraulic prop on its yielding in the mode of ground control and the mechanism of change of this pressure depending on the sequence of PRS advance steps.

In order to reveal peculiarities of interaction between PRS and immediate roof rocks, the working characteristic of PRS is analyzed



**Fig. 6. Oscillogram of pressure in hydraulic prop of PRS M-138 per cycle of its advance in longwall 26-325 in the Polosukhinskaya Mine:**  $P_{pl}$ —pressure in pressure line;  $P_{pb}$ —pressure in piston barrel; 1–2—prop setting load; 2–3—mode of increasing resistance; 3–4—reaction of safety valve (mode of equal resistance); 4–5—prop setting load relief; 5–6—advance of PRS; 6–7—hydraulic pull of PRS to conveyor and in-between clearance fit

using the pressure oscillograms in the piston barrel of a hydraulic prop and in the supply line of PRS during its advance in operating longwall 26-325 in the Polosukhinskaya Mine (Fig. 6).

It is found that the main adverse factors that affect the immediate roof rocks are:

1. Periodic reactions of safety valve (Fig. 6, coordinates 3–4). They form the ‘uniform resistance’ curve and are the cause of transient (dynamic) processes in hydraulic props. These processes, in turn, intensify fracturing and splitting in the immediate roof, which is named *dynamic roof beating*.

2. Cyclic force impacts exerted by PRS canopy on the immediate roof during relaxation of propping and PRS advance. Because of a high pressure difference in the pressure line (Fig. 6, coordinates 4, 5)—from the minimal values during PRS advance to the maximal values governed by setting of the safety valve, these impacts lead to increased loading of the immediate roof, to fracturing and rock falls, as well as to instability of ground control.

These factors are embraced by the known and common term of ‘roof beating’. However, there are yet no quantitative techniques of estimation of the process. For this reason, it is suggested to introduce the *roof beating coefficient* in estimation of cyclic force interactions between PRS and the immediate roof rocks.

### Results and discussion

For the case of the steady-state process, it is proposed to estimate the rate of reduction in the strength and stability of the immediate roof in the course of cyclic operations using the roof beating coefficient given by:

$$K_b = C_{cr} \cdot K_{\sigma} \cdot K_{rf} \cdot K_{fr} \cdot K_{spl}, \quad (1)$$

where  $C_{cr}$  is the strength coefficient of the immediate roof (roof class);  $K_{\sigma}$  is the stress coefficient of the immediate roof rocks at the contact with PRS canopy in the mode of ground control;  $K_{rf}$  is the repetition factor of impacts of PRS canopy on the immediate roof rocks;  $K_{fr}$  and  $K_{spl}$  are the weakening coefficients of the immediate roof rocks because of fracturing and splitting, respectively.

The stress coefficient  $K_{\sigma}$  is found from the formula:

$$K_{\sigma} = C_1 \frac{\sigma_{act}}{\sigma_{cr}} = C_1 \frac{P_{sf} \cdot S_{pb} \cdot n_{prop}}{L_c \cdot \lambda_{PRS} \cdot \sigma_{cr}},$$

where  $P_{sf}$  is the pressure of the safety valve reaction in a prop, MPa;  $S_{pb}$  is the cross-section area of the piston barrel in a prop, mm<sup>2</sup>;  $n_{prop}$  is the number of props;  $L_c$  is the length of PRS canopy, mm;  $\lambda_{PRS}$  is the PRS spacing along a longwall, m;  $\sigma_{act}$  is the actual stress of the immediate roof rocks;  $\sigma_{cr}$  is the critical stress when the immediate roof rocks fail.

The values of  $K_{rf}$  are found from the ratio:

$$K_{rf} = C_2 L_c / \lambda_{PRS}, \quad (3)$$

where  $C_1$  and  $C_2$  are the coefficients of weakening of the immediate roof rocks at the change in their actual stress state and loading repetition factor (these values are determined experimentally);  $\lambda_{PRS}$  is the PRS spacing along a longwall, m.

In this manner, after transformations of formula (1), the roof beating factor is given by:

$$K_b = \frac{C_{cr} \cdot C_1 \cdot P_{sf} \cdot S_{pb} \cdot n_{prop}}{\sigma_{cr} \cdot \lambda_{PRS}} \cdot \frac{C_2 \cdot K_{fr} \cdot K_{spl}}{\lambda_{PRS}}.$$

Ground control using modern PRS is executed in conformity with the standard performance cycle as a sequence of the following modes (stages): increasing and equal resistance, relief of the propping-induced load and prop setting load.

Interaction efficiency between PRS and immediate roof and floor rocks in longwalls is governed by two groups of factors: geological conditions (including their ranges) and design and duty parameters of PRS.

Consequently, operational characteristics of a powered roof support should conform with these conditions. As it is economically inefficient to design PRS for every longwall, enhanced ground control requires development of PRS with adaptive kinematics and contact properties. Such machines should ensure:

—required rate of installation and rational modes of interaction with roof rocks;

—improved uniformness of pressure distribution over the contact area between PRS canopy and roof rocks to improve stability of the process control;

—advance of PRS with minimal loss of contact between canopy, props and roof and floor rocks;

—enhanced stability and safety of coal mining technology in longwalls.

### Conclusions

The estimate of the effect exerted by cyclic forces applied by a powered roof support on weakening of the immediate roof rocks in the Polosukhinskaya Mine has made it possible to find out that:

—the rate of reduction in strength and stability of the immediate roof rocks under cyclic impacts depends on the number of loading cycles and on the stress state of rocks at the contact with the PRS canopy, and can be evaluated in terms of the roof beating coefficient;

—the variation ranges of the contact stresses in the immediate roof rocks under impacts exerted by PRS can be decreased via design and introduction of the adaptive units of powered roof supports;


—the weakening coefficients of the immediate roof rocks ( $C_1$  and  $C_2$ ), reflective of the influence of stresses and repetitive loading, can be determined in the course of the further experimental research.

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## APPLICATION OF ADVANCED TECHNOLOGIES IN SLOPE STABILITY MONITORING IN OPEN PITS IN THE ZHILANDY ORE FIELD

### Introduction

One of the most critical problems in large-scale mining at structurally complex rock masses is induced seismicity. It can involve both catastrophic technical and economic consequences, including triggered earthquakes, rock bursts and landslides, and also deaths of people. This fact was highlighted at the International Symposium on Rockbursts and Seismicity in Mines [1–3]. The problems of control over such processes draw heightened attention, which is proved by the growing number of publications [4–6].

Reduction of risk of induced catastrophes is a topical question in Central Kazakhstan which is a region of actual large-scale mining. High-intensity mineral production is carried out in the Zhilandy field of copper ore deposits such as Eastern and Western Saryoba, Kipshakpay, Karashoshak and Itauz.

All deposits of the Zhilandy group adjoin grey sandstone strata of the Taskuduk Formation and bottomset beds with grey-greenish and grey sandstone interbeds, intra-formation conglomerates, dark grey or black siltstone and argillite with bands of limestone with fauna. The subsoil is complicated by faults and rock interfaces, which makes mining largely difficult [7–9].

At the same time, this tectonically active area of Central Kazakhstan yet remains understudied. It is required to implement an integrated research of seismicity and geodynamics in order to evaluate more accurately the nature and parameters of tectonic stresses (especially in the region of high-output mining), and to undertake reasonable measures of geodynamic risk reduction.

Globally, the leading part in the safe and efficient subsoil use is assigned to mine surveying. At the present time, objectives of surveying are much more complex due to deeper level mining and field expansion,

*The features of geomechanical processes in mines of the Zhilandy ore field in Kazakhstan are discussed. The ways of preventing hazardous events in the course of mineral mining are proposed. The procedure of integrated geodynamic monitoring is developed. A new method of the structural analysis of rock mass and the method of creating a geodynamic testing site is put forward.*

*The research findings are introduced at operating mines within the framework of the projects: High-Effective Monitoring Procedure for Geotechnical Conditions of Rock Masses for the Assessment and Prediction of Deformation Processes in Mineral Mining; Geotechnical Monitoring of Geodynamic Condition of Geological Environment in Rock Masses Toward Industrial Reliability of Subsoil Use, and are included in the education process at the Satbayev University.*

**Keywords:** induced seismicity, geodynamics, tectonic structure, stress-strain behavior, rock mass, geomechanical monitoring, geodynamic testing site

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which requires scrupulous, highly precise and well-timed survey-based monitoring. It is possible to handle problems connected with geodynamic prediction and monitoring in the high-output ore mining regions in Central Kazakhstan with the help of the integrated monitoring procedure using geological and tectonic information, advanced equipment and authorial seeing aids, developed at the Department of Surveying and Geodesy of the Satbayev University.

### Methods

The research used an integrated approach including: engineering-geological studies of structure and tectonics of rock mass with mapping of dislocations, faults and crushed rock zones; surveying using