Critically Stressed Areas of Earth's Crust as Medium for Man-caused Hazards

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Abstract. Despite advances in rockburst studies, suddenness of major geodynamic events is reported in a number of cases. Phenomenological tectonophysical model is suggested to explain some geodynamics phenomena. Prof. Petukhov I.M. suggested a concept: the Earth crust's critical stress condition is developed due to horizontal compressive forces and entrains rock strata from the sub-surface to a certain depth. The conditions that induced earthquake in 2013 at Bachat coal field in south west Kuzbass are considered in terms of critical stress developed in the top layer of the Earth crust. Estimates show that the size of the critical stress zone, produced presumably by interaction of huge (over 100 km) crustal blocks is at least 10km. Whereas critical stress zone is located in the top part of Earth's crust, mining operations in the pit including blast operations was making a direct impact on this area. Shallow occurrence of critical stress area and its size can provide insight into why mining works brought about induced earthquake with hypocenter at the depth of several kilometers. The conclusion has been made that regional areas of critical stress within rock massif developed as a result of crustal blocks interaction create hazard medium for mining. Key words: rockburst, induced earthquake, earthquake source, critical stress condition, crustal blocks, Bachat earthquake, reactivation of faults.

1 Introduction

Geodynamic safety issue remains to be high on the agenda in various mining areas of the world [1-9]. Significant success has been achieved in Russia in solving rock burst problem, methods of forecasting and prevention have been developed, geodynamic mechanisms have been learned. However, many of the recent severe geodynamic events can not be explained based on established conceptions on geomechanical processes inside the rock massif and onset of its stress strain behavior [9]. As an example, consider Bachat earthquake happened in June 2013. According to [10] its hypocenter was located below pit excavation at the depth of approximately four kilometers. In the meantime such disciplines as rock geodynamics, seismology and geomechanics put forward ideas that critical stress condition is related not only to local rock volumes but to large segments of Earth's crust [11-15].

The idea that significant amount of Earth's crust is in critical stress state was suggested by I. M. Petuchov in his works and was further supported in the book [11]. This work

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substantiates the hypothesis that mechanism and occurrence of Bachat earthquake were related to release of critical stress zone in the Earth's crust resulting from nature tectonic process and man-caused impact.

2 Theory and method

2.1 Insight into critical stress state of lithosphere.

Critical stress state theory in geomechanics is used to explain mechanisms of rock burst, rock behavior in abutment zones, pit slope stability, etc. [11, 15-16]. In situ studies show that impact on the edge of coal seam, such as insertion of shearer's cutting bar, explosion, some other impact, brings about immediate changes in critical stress area, reallocation of loads, their transfer depthward [11, p. 27]. Coal seam in this area maintains the ability to accumulate potential energy of elastic compression. Critically stressed zone is considered as similar to that which is ultimately saturated with potential energy. If, in case of impact on this area, the seam releases the load slowly, this results in brittle failure of coal manifested by rock bumps and bursts. To eliminate these consequences or make them less intensive the cutting rate/shearer advance rate (for example) needs to be slowed down.

Academician Ye. I. Shemyakin defined the area in front of the maximum bearing pressure zone as prefracture zone. Within prefracture zone which as such is in critically stressed state, rock deformation occurs along newly developed surfaces of weakening - through relocation of rock slabs, some of which may be in the state of elastic strain.

Making comparison between processes in coal seam, relying upon geodynamics postulates, was put forward the idea that lithosphere as such is in critically stressed state [11]. Critical stress is developed in the Earth's crust due to horizontal compressive forces and entrains shallow rock strata in the first place. If horizontal stress is great enough, progressively deeper strata of lithosphere acquire critical stress condition. Specific feature of this critically stressed stratum (by analogy to face adjacent part of coal seam) is the presence of elastic areas (volumes) inside. In such conditions a wide range of deformations resulting from man-caused impact may be manifested inside the rock massif - creep, rock bumps, naturally occuring earthquakes.

In seismology basic concepts describing mechanism of earthquakes in the Earth's crust [17], use in one way or other the concept of critical stress state of the stratum in focal area. Some works [12,14] bear direct indications that there are areas in the Earth's crust which state is close to critical.

2.2 Identifying mining risk bearing areas by geodynamic zoning

Mining practice gives evidence that adverse geodynamic events are manifested in particular zones. By mid- 1970s it became obvious that probability of adverse geodynamic events in mines is dependant, among other factors, on natural forces that are responsible for stressed condition and structure of the rock massif. The idea of upfront identification of areas hazardous for mining activity based on the knowledge of tectonic stress areas and current rock massif block structure has found its reflection in geodynamic zoning method [18].

According to the concept of geodynamic zoning, zones of danger in the area of the deposit are formed due to the interaction of geodynamically active crust blocks (modern tectonic blocks) of various hierarchical ranks, the formation of which is associated with global geodynamic processes and the divisibility of lithospheric plates.

2.3 Evaluation of rock massif stressed state by tectonophysical methods

Evaluation of the stress condition of the massif is the key to understand the conditions for occurrence of geodynamic phenomena [1-8, 19-27]. Tectonophysics methods here have an important advantage over instrumental methods because they give a possibility to investigate the stress condition of large volumes of rock massif based on analysis of rock slabs shifting along current faults [18, 28]. Many tectonophysical methods offer graphic solutions in which the displacement vector on the indiscriminately oriented fault plane should be positioned in a specific manner on the stereogram thereby showing the relationship between the displacement direction and orientation of the primary stress axes. Moreover, it follows on the ideas of the hierarchy of the stress fields [29] that the movement along the fault of the specified size can be induced only by the stress field of a certain rank. The stress field causing the movement along the fault remains active in some areas which includes this dislocation and which is also regional towards it.

Since present tectonic crustal movements are reflected in the relief of the Earth's surface, and the block boundaries are detected by indicators of relief, then it is assumed that the method of geodynamic zoning reveals currently active structural elements and stress field of the Earth's crust. Using the data on blocks displacement along their boundaries with tectonophysics methods makes it possible to study present stress fields [18].

3 Geodynamic position of Bachatsky coal pit

Block composition of Kuzbass is represented in Figure1. Bachat coal deposit is located at the south west edge of Kuzbass next to intersection of two present-day regional tectonic zones II-II and I-II-IV.

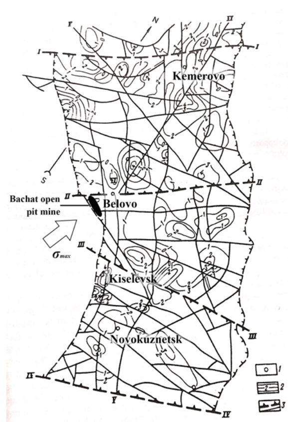

Fig. 1. Scheme of Kuzbass block composition [18]. 1- towns, 2- isoline of moving of earth surface; 3- boundary of block (2nd and 3rd ranks)

Fault zone I-II-IV stretches to the north-west and aligns with major boundary thrust fault separating Kuzbass from Salair mountain range located to the south–west. Fault zone II-II strikes transversally to key Kuzbass structures, stretching to the north-east. Geologists point out high structural complexity of Bachatsk coal deposit stretching along 1-1 boundary line. The deposit is divided into Northern and Southern parts and is located within one of tectonic plates limited by thrust faults striking in the north-west direction (Figure.2-a). It is assumed that due to Salair's pressure on Kuzbass coal bearing deposits a series of several major thrust faults acquired their shape during one of folding phases. These are Tyrgan, Bachat and Salair thrust faults, dipping to the south-west at 50-70 degree. There are no detailed studies on the deep structure of this part of Kuzbass, yet regional geologic materials suggest that these thrust faults stretch down to greater depth and undercut Bachat coal pit at a depth mark of several kilometers (Figure 2).

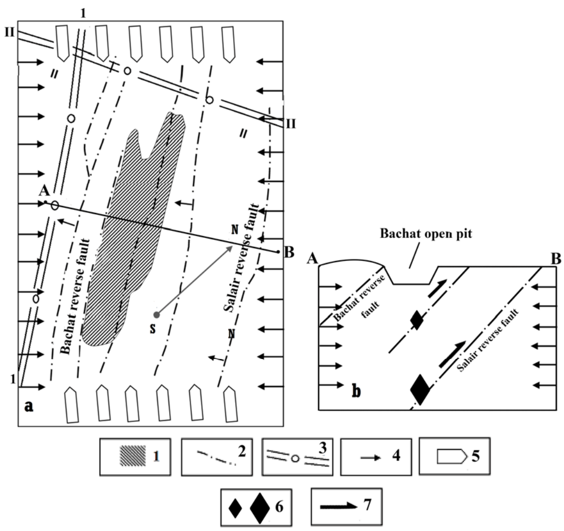

Fig. 2. A simplified tectonophysics scheme of the Bachat open mine area: 1 - Bachat open pit; 2 - tectonic faults; 3- boundaries of blocks of rank II; 4, 5 - direction of maximum stress axis of present stress fields of ranks II and III respectively, defined by tectonophysical method; 6 - aftershock and main shock hypocenters; 7 - direction of the displacement along the reverse faults during the earthquake

Taking into account the direction of relative displacement of the walls of regional fault II-II and reverse fault displacement of the southwest wall of Bachat thrust, it is possible to determine the direction of regional stress in this part of the Kuzbass area: SW – NE (Fig 2).

Bachat coal pit is approximately 300 m deep, about 10km long and its width is 2km. Mining operations involve routine blasts with up to 350 t mass of charge.

The earthquake (M=6) that happened at the turn of the 20st century near Novokuznetsk city is known as the heaviest earthquake in Kuzbass. Throughout the time of instrumental monitoring up to 2013, no earthquakes of over 4.5 magnitude was observed [30]. However, Kuzbass today is one of the mining regions in Russia with technogenic seismicity. Since 2006, an increase in seismic activity is observed in the area of operating deep mines and pits in the western part of Kuzbass (Leninsk-Kuznetsk and Bachat districts). In 2013, there was Bachatsky earthquake of $M_L = 6.1$ which is rated as the strongest mining-induced earthquake in coal mining areas by the nature of the main shock location and the subsequent aftershocks (at Bachatsky open mine). Focal mechanism solutions show that the main shock event was reverse fault. The depth of seismic focus was assessed as 4km [10].

4 Tectonophysical model of Bachatsky earthquake.

Present day tectonic stress field in west Kuzbass is partially derived from one of paleotectonic stress fields. The existing thrust faults are represented in surface relief and in present day stress field and go through reactivation process which is manifested by nodal surface orientation of the main shock and aftershocks of Bachat earthquake. At the same time NE striking shears are developed transversal to thrust faults, which is also reflected in the structure of current surface relief. Development of present day tectonic deformations next to and around Bachat coal pit and seismic activation processes allow to draw a conclusion: tectonic stress in the Earth's upper crust has reached its critical state in this region. As Bachat coal pit is located at the intersection of two current major faults in the Earth's upper crust, critical stress state could be reached primarily here.

Tectonophysical studies at rock-burst mines show that the hazard of tectonic rockbursts and mining-induced earthquakes is connected with the possibility of reactivation of large tectonic faults, oriented in a certain way in the massif [31]. On the basis of the approach developed by us, it can be supposed that the mechanism of Bachat earthquake is related to the influence of present regional stress field to the fault planes of major faults, Figure 2.

Under the influence of present regional contraction on tectonic faults existing in the massif, depending on their orientation in space, high shearing stresses may be achieved. The calculated ratio $\tau^* = \tau_n / \tau_{max}$ of shearing stress (τ_n) in thrust fault planes and the maximum shearing stress of this stress field (τ_{max}) are presented in Table 1.

Table 1. Tectonophysical conditions of large faults in the present stress field

Fault	$\boldsymbol{\tau^* = \tau_n / \tau_{max}}$	
	stress field of rank II with orientation of axis $\boldsymbol{\sigma_{max}}$ to SW-NE	stress field of rank III with orientation of axis $\boldsymbol{\sigma_{max}}$ to SE-NW
Bachat, Salair thrusts	0.8	0.6
In-plane shear	0.9	0.4

The table shows that the thrusts are located in planes with high shearing stresses, i.e. they are hazardous in manifestation of movements through them in the stress field of rank II. In the field of rank II with SW-NE orientation of axis σ_{max} and vertical σ_{min}, Salair and Bachat thrusts behave as classic-type reverse faults.

Indeed, main shock mechanism is interpreted as a proper thrust fault, i.e. at the time of the earthquake major thrust faults got reactivated in agreement with the tectonophysical model under consideration, Figure 2-b.

5 Discussing the findings

Based on the data available in paper [32, Figure 3], where generalized empiric formula determined by a number of authors provide assessment of earthquake seismic focus size L as function of its magnitude M, we may assume that seismic focus size L of Bachat earthquake of magnitude M_L=6.1, is at least 10km. This assessment correlates with aftershock zone size which according to data [10], covers not just the pit area but the space beyond its boundaries. Let us take into account that the hypocenter of the earthquake main shock was at the depth of 4 km. Considering that the size of seismic focus exceeds 10km, this means that the Earth's upper crust in vicinity of the pit was in critically stressed state from the day surface down to the depth of several kilometers. In this case mining operations in the pit including blasts of up to 350t explosives can be regarded as factor of permanent impact upon this regional critically stressed area. It is discovered that cyclical impact is able to influence for nature of seismic displacement along fault [33]. Due to mining operations and development of large scale voids - mined-out space - equilibrium in shallow part of this area is inevitably disrupted, hence stress redistribution may propagate to much greater depths than mining levels. In this relation the fact that earthquake hypocenter was located at a great depth below the pit could be so explained: actually, mining works were executed within critically stressed area of the region.

Furthermore, considering the relation between tectonic bump focal size *r* and areal size of this event preparation process *R*, *R/r*=10-30 [31, 34] it is possible to estimate sizes of the

Earth's upper crust blocks involved in preparation of induced earthquake. If the size of seismic focus area equals 10km, the relevant event preparation area shall be 100km to 300km, and this is comparable with the size of crust blocks of the 2nd rank, as shown in Figure 1. In this case, conceivably, due to interaction of large blocks of lithosphere, within or at the boundaries of these large plates critically stressed areas are built up. As geologic processes are really slow, energy encapsulated in critically stressed areas have enough time to release in the rock massif and no conditions are developed for dynamic rupture. In case of mining works with high rate of face advance in deep mines and/or mass scale blasts in pits, load increment rate may exceed the rate of load release, thus conditions are created for onset of adverse geodynamic events. Taking into account that critically stressed areas built up due to geodynamic processes embrace first and foremost subsurface layers of the Earth's upper crust, monitoring shall be envisaged as part of mining operations both in deep and surface mines.

4 Conclusions

1. Influence of mining operations on major seismic events with hypocenters at great depth such as Bachats earthquake may be explained using the concept of critically stressed condition of the Earth's upper crust.
2. Analysis of conditions contributing to Bachat earthquake occurrence shows that with seismic focus area size of over 10km and earthquake hypocenter depth of 4 km the Earth's upper crust in vicinity of the pit was in critically stressed state from the day surface down to the depth of several kilometers. In fact, mining operations were carried out within an extensive critically stressed area, and this is the reason why stress equilibrium in this part of subsurface zone was continuously disrupted. Ultimately it triggered dynamic release throughout the critically stressed zone with rock blocks shifting along the major fault.
3. Size of Bachat earthquake preparation area might have exceeded a hundred kilometers, and this is comparable with the size of crust blocks of the 2nd rank, participating in their own tectonic motion. Major upthrust faults and lateral shears in present day stress field coinside with high shearing stress planes, which explains why such direction of displacement when the above upthrust faults and shears got reactivated at the time of earthquake.
4. Under specific conditions triggered both by tectonic processes and man-caused impact it is the upper part of the Earth's crust that first becomes critically stressed, and this creates conditions provoking occurrence of risk bearing geodynamic events in case intensive mining is performed in these areas.

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