Implementation of microseismic monitoring for iron ore mines

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Abstract. The seismic station of the Subbot Institute of Geophysics of the NAS of Ukraine (IGP), in Kriviy Rih (Ukraine) ten earthquakes were registered from 2007 to 2013. Such activity is not typical for this region. One of the reasons is mining of mineral resources in this area, leading to irreversible changes in the stress-strain state of the massif, which activate dangerous natural and man-made processes (landslides, flooding, earthquakes, mountain strikes, etc.) The collapse of the mountain massif and the exit of the funnels occurs when the limit value of the loading in the massif is reached. Limit value warning of the stress-strain state of the massif is a condition for the danger of the zone. The task of control is to prevent the stress-strain state of the massif. Any unloading of the massif is accompanied by the formation of a crack, which is characterized by a burst of amplitude and a certain frequency of oscillations. For the geographic information system of mines, it is important to highlight significant phenomena by types of energy, affiliation to the mining allotment of the mine (distance to the hypocenter) and the nature of the primary source - technical or natural. The goal of research is to define a significant phenomena for identifying the stress-strain state of the massif using the microseismic monitoring. To increase noise immunity, it is advisable to use both physical filtration methods and software selection of significant phenomena against the background of man-made noise. To form conclusions, it is necessary to form a sample, so for reliable identification of the stress-strain state of the massif it is necessary to perform statistical processing of the measurement results. The usage of microseismic control at mining enterprises will reduce the possibility of mining shocks, landslides, which will reduce material damage. This will increase the safety of mining operations and ability to prevent man-made earthquakes of magnitude more than five.

1. Introduction
The certain part of Ukrainian territory is situated on a seismic active zone. To the most dangerous zones can be considered such regions as: Transcarpathian, Ivano-Frankivska, Chernihivska, Odeska and Crimea. The earthquakes in these areas have natural origin. Seismic activity is also increasing in the aseismic territory of Ukraine, but earthquakes are mostly man-made.

The table 1 presents the list of earthquakes in the Kryvyi Rih iron ore basin (Kryvbas), characterized by mining for 60 kilometers and a depth of more than 1,500 meters of underground works. The redistribution of stresses and deformations of the surface is due to a large size of dumps and tailings.

As we know from open sources of information there were a series of earthquakes after 2013. On 29th of August 2017 the earthquake in amplitude of 4.1 [2] and another on 20th of February
Table 1. Man-made earthquakes were registered in Kryvyi Rih by the seismic station of the Institute of Geophysics (IGP) of the National Academy of Sciences, in Kriviy Rih (Ukraine) from 2007 to 2013 [1].

| №  | Date       | Latitude | Longitude | Magnitude | Depth       |
|----|------------|----------|-----------|-----------|-------------|
| 1  | 25-12-2007 | 47.79    | 33.38     | 3.3       | 0m          |
| 2  | 13-06-2010 | 48.02    | 32.35     | 4.3       | 447m – 527m |
| 3  | 18-09-2010 | 47.84    | 33.30     | 3.3       | 447m – 527m |
| 4  | 14-01-2011 | 48.10    | 33.40     | 3.5       | 1200m – 1300m |
| 5  | 26-06-2011 | 48.02    | 32.99     | 2.5       | 447m – 527m |
| 6  | 22-10-2011 | 48.89    | 33.24     | 3.1       | 1200m – 1270m |
| 7  | 31-03-2012 | 48.20    | 32.50     | 3.0       | 1200m – 1270m |
| 8  | 17-06-2012 | 47.70    | 33.57     | 3.0       | 1270m – 1300m |
| 9  | 28-11-2012 | 48.10    | 33.50     | 3.1       | 0 m         |
| 10 | 23-06-2013 | 48.04    | 33.42     | 4.6       | 2 000 m     |

2018 in amplitude of 3.2 [3], and on 22nd of January 2022 the earthquake in amplitude of 3.3 [4]. The reason of earthquakes can be both the movement of lithospheric plates and mining. The authors [5] believe that the earthquakes №1,3,4,9,10, of the table 1 can be considered as a man-made. Also, authors classify [6] the earthquake №1 in Table 1 as naturally-anthropogenic and believe that landslides in underground cavities are not the main cause, but may be an additional factor.

Mining in this area causes irreversible changes in the stress-strain state of the massif, which intensifies dangerous natural and man-made processes (landslides, floods, earthquakes, mountain strikes, etc.) The large-scale development of minerals of Kryvbas region is extracted by using of mass explosions in quarries and mines. Herewith, the depth of quarries reaches 450 meters and the mass of explosive substances up to 600 tons. The mass explosions in the mines are made at depths of 1300 meters and with the mass of explosive solutions up to 100 tons.

It should be mentioned that the Krivyi Rih city itself is situated on the junction of some tectonic plates. Due to these factors in Kriviy Rih iron ore structure the earthquakes in amplitude higher than 5 may be caused [7]. In addition to the general destruction of the basin, the seismicity of the zone is affected by industrial explosions and the presence of technological voids.

Except the impact of industrial explosions on the man-made seismicity of the region also affects the mining works, which increases the seismicity of this zone.

2. Method

Man-made seismic phenomena, namely the collapse of the mountain massif, the exit of the funnels occurs when the limit values of rock tension is reached. The graph in the (figure 1) it is the dependence of deformation on the load for the rocks of different geotechnical qualities [8].

Under the action of forces (loads), any rock goes through the next three stages of deformation. The first stage of elastic deformation (segment OA in figure 1) – is reversible deformations, i.e., when the load is removed, the deformations disappear, and the rock completely restores its original shape and volume. The second stage of plastic deformation (segment AB in figure 1) is realized when the rock irreversibly changes the shape and volume, but without breaking the integrity of the rock. This stage is manifested when the forces exceed the elastic limit, but not above the strength limit of the rock. At this stage, the folds are created. The third
Figure 1. The strain-stress curves. The $\sigma$ axis is the normal load. The $\varepsilon$ axis is a strain.

The strain-stress curves (segment BC in figure 1) is manifested when the forces exceed the strength limit of the rock and the rock is deformed with loss of integrity, with the formation of cracks of separation and chipping. Depending on the certain geological conditions, different stages of deformation can get different degrees of development, up to tectonic cracks [8]. Deformations for glass, quartz and ore are similar and depend on the load. Approaching the limit value of the stress-strain state of the massif (segment AB in figure 1) is a condition of the danger zone. This dependence is the basis of microseismic control of the state of the massif. The task of control is to prevent the stress-strain state of the massif. Small cracks are registered with the help of microseismic monitoring, the number of cracks and their epicenter will indicate the stress of the massif. The increase in the number of cracks in time will indicate the second stage of plastic deformation (segment AB in figure 1) in which mining is a dangerous process. The registration of small cracks to predict powerful phenomena this is the task of microseismic monitoring. Therefore, this method is called microseismic control. Due to a microseismic activity, strong seismic phenomena can be predicted.

In the technical literature there are well-known example of determining the stress-strain state of a rock by the characteristics of the oscillation of the massif [9].

In order to be able to predict local earthquakes, landslides, mining strikes and safe mining operations at mining enterprises, it is necessary to introduce microseismic control. It will avoid material costs and increase the level of people’s safety. It is important to control constantly or periodically the stress-strain state of the array for forecasting and prevention of dangerous natural and man-made processes.

Low-powered destruction in the form of cracks (unloading of the stress-strain state of the massif) in rocks causes seismic oscillations in the massif. This creates requirements for controlled parameters for measuring the speed or acceleration of microseismic oscillations of the massif [10].
3. Investigation of massif oscillations
High sensitivity of measurement channels is required to control low-powered destructions. Along with the signals of destruction of random periodicity in the mountains massives there are a constant fluctuations - microseisms [11]. In most cases, the signals of microcracks are commensurate with the microseisms of the Earth. Due to the short distance to the expected phenomenon or to the monitoring area it is possible to separate the impact of both microseisms and man-made noise. On figure 2 is demonstrated the example of Earth's microseism.

![Figure 2](image.png)

**Figure 2.** The sample of Earth’s microseism in Artem’s mine - 1, 17.05.2018 yr. 
$T_m = 38 ms, f_m = 26.3 Hz; T_m$ – period of microseismic oscillations; $f_m$ – characteristic frequency of microseismic oscillations.

The amplitude and frequency of the Earth’s microseismic changes over time in a fairly significant range – 2.3 times [12]. The example of a microseismic on the surface of the mine Artem-1 in figure 3. It depends on several factors, for example: the seasons, the gravitational action of the Moon on the water, the distributed resonant qualities of the array and others. But due to the random components of fluctuations in the level of the microseismic in time, the influence of factors is insufficiently studied. The sample of a microseismic activity on the surface of the mine Artem-1 in figure 3.
Figure 3. The sample of Earth’s microseism on the surface of Artem’s mine -1, 29.04.2021 yr. $T_m = 94.3 \text{ ms}; f_m = 10.6 \text{ Hz}; T_m$ – period of microseismic oscillations; $f_m$ – characteristic frequency of microseismic oscillations.

Reducing of the influence of the microseismic on the measurement is achieved by limiting the minimal amplitude of significant signals at the level of three amplitudes of the microseismic in manual processing and ten amplitudes of the microseismic in automatic processing. And also at allocation of considerable signals it is expedient to use differences in a complex of characteristics of signals.

The low-power phenomenon differs from the Earth’s microseismic in amplitude, frequency, duration, and shape, which can be seen in figure 4 [12]. To identify the phenomenon of the Earth a microseismic is considered an obstacle.

Any unloading of the massif is accompanied with creation of crack which is characterized on the recordings by sharp increasing amplitude and a certain frequency of oscillations. Examples of recording of the crack at the Frunze mine from 03.03.2020 are shown in figure 5.
**Figure 4.** The sample of microseism with the low-powered phenomenon in Artem’s mine -1, 18.04.2018 yr. $T_m = 42\, ms$, $f_m = 23.8\, Hz$, $t_p = 100\, ms$, $T_p = 6.2\, ms$; $f_p = 161\, Hz$; $T_m$ – period of microseismic oscillations; $f_m$ – characteristic frequency of microseismic oscillations; $t_p$ – duration of the phenomenon; $T_p$ – period of oscillations of phenomena; $f_p$ – characteristic frequency of oscillations of phenomena.

**Figure 5.** The sample of crack’s signal recording in Frunze’s mine, 03.03.2020 yr. $t_p = 250\, ms$; $f_p = 113\, Hz$; $T_p = 6.2\, ms$; $t_p$ – duration of the phenomenon; $T_p$ – period of oscillations of phenomena; $f_p$ – characteristic frequency of oscillations of phenomena.
The authors made a spectral analysis of the frequencies of phenomena at the Artem-1 mine [13]. Directly in the epicenter of the crack formation with a conditional diameter of a few dozen meters has a length of about 1 ms and can be considered as a single impulse. At a distance from the epicenter due to the distributed resonant properties of the massif, oscillations occur with a certain frequency and a certain duration in (figure 4,5). The oscillations happen due to the distributed resonant qualities of the massif, and the frequency of oscillations depends on the elasticity and density of the rock.

Due to the filtering properties of the array with the distance from the phenomenon of the signal frequency decreases. With the distance from the phenomenon, the frequency of the signal decreases (figure 6) shows the most remote signal in accordance with the frequencies of 92 Hz.

![Figure 6. The signal of a crack on the distance of 40 m in Frunze's mine, 03.03.2020 yr.](image)

$t_p = 130ms; f_p = 92Hz; T_p = 6.2ms$;

$t_p$ – duration of the phenomenon; $f_p$ – characteristic frequency of oscillations of phenomena.

$T_p$ – period of oscillations of phenomena;

In volume of geo-informational system of the mine, it is important to identify significant phenomena in terms of energy, territorial affiliation to the mine allotment (distance to the hypocenter) and the nature of the primary source - technical or natural [14]. The experience of the use of microseismic monitoring for iron ore mines and sizes of working horizons of most mines has shown the feasibility of a monitoring radius within 400 meters. The horizons of existing mines as a rule are usually have smaller width. The location of the measuring probe is chosen by compromising between the requirement to approach to the phenomenon and the requirement of safety of measurement. To increase noise immunity, it is advisable to use both physical filtration methods and software selection of significant phenomena on the background of man-made noise. This processing is called the primary processing of measurement results.
4. Conclusions
To identify the stress-strain state of the massif by the microseismic method, it is necessary to collect an array of data which includes: the number of phenomena, the epicenter of the location of phenomena and their power.

High quality of primary data processing is achieved by using the identification of phenomena, namely: Earth microseisms, cracks, collapses, rock strikes, explosions, mass explosions, man-made earthquakes. This is done by processing 14-16 indicators or factors of microseismic signals, the main of which are: the frequency of oscillations of the array, the amplitude and duration of phenomena what presented on the figures 4,5,6. Along with the well-known complex methods for determining the coordinates of the hypocenter of phenomena (requires 4 spaced probes) in the GIS of mines, it is advisable to use simplified methods for estimating the location of the epicenter using a single probe. According to the amplitude of oscillations, we distinguish the power of the phenomenon and the distance. By the duration of the phenomenon we can estimate the distance to the epicenter.

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