value of moving of the Earth's surface will correspond to results of experimental measurements. Offered method of investigations is used in system of ensuring of stability of constructive elements of chamber mining of silvinite seams of VKDPS.

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SEISMIC MONITORING IN POTASH MINES: OBSERVATION RESULTS AND DEVELOPMENT ASPECTS*

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Seismological observations in potash mines of Verkhnekamskoe deposit are carried out since 1995. Their start trigger was earthquake situated in mine field of SKRU-2 mine. Exploration of the mine after event was under the treat. As result of the situation, a modern seismic control network covering area of 120 км^2 has appeared. At present the network consists of 35 seismic stations providing representative instrumental data about all seismic events of magnitude $M > 0.3$ for all operating mines. Local seismic subsystems providing information about very small events ($-3 < M < 0$) are working as well. The latter are used to monitor sinkholes appearance above flooded mine. Observation results for years show the natural seismicity may be sensed good and happens very rarely. Induced seismicity is weaker but being under influence of rock conditions (physical-mechanical properties) and technology of extraction (mining, backfilling, blasting) it needs constant attention. Seismic monitoring had made clear many factors affecting seismicity in all operating mines and allowed to determine its relation to deformation processes in undermined massif. Investigation of seismicity due to sinkholes had showed the way to control effectively sinkhole development and help to minimize risk of accidents related to them.

Key words: *seismological monitoring, potassium mine, induced seismicity, triggered seismicity, aftershock, magnitude, sinkhole, prediction of events.*

Verknekamsky potassium salt deposit (VKDPS) is mined for few tens years. But examination of the problem of seismic activity of the area over the mined rock massif has been begun comparatively recently. First seismic investigations at the mines of the deposit

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have been begun in 1995 after Solikamsk earthquake with epicenter on territory of the mine SKRU-2 in the mined zone. It has arisen threat to lose salt resources as a result of consequences of insufficiently known technogeneous earthquakes at the Verkhnaya Kama. Threat has conditioned active development of seismic control at the all areas of the deposit. First local seismic observations in epicenter were used later on as basis for seismic monitoring of the mines. Putting in exploiting in 1999 of regional seismic stations has permitted to enlarge controlled territory far over the bounds of the mine fields [1]. Today development of seismic observations continues. It is connected with necessity to work out in detail monitoring of some problematic areas of the mined territories [2, 3].

Seismic observations at the deposit, as a whole, are carried out at the station belonging to the regional net. Stations Solikamsk (SOKR) and Romanovo (PR1R) are the nearest to the deposit and are located at its territory. Equipment of SOKR is placed directly in the mining workings. Digital record of seismic signals is realized in frequency band to 30 Hz. Final configuration of the net ensures recording of the all seismic events at the deposit beginning from magnitude 1 and in its south zone — from 0.8 (Fig.1).

Seismic monitoring of the mine fields is carried out by the local systems including 35 stations. Taking into account scale of observations (area of control at the end of 2012 was more than 120 km^2) equipment used for monitoring is identical to equipment used at regional stations. Used useful frequency band is from 0.5 to 100 Hz. Evenness of covering of the mine fields varies at the different mines. Comparatively rare nets at the mines BKRU-4 and SKRU-3 ensure record of the all seismic events beginning from magnitude M = 0.3. Most representative observations are carried out at the mines SKRU-1, SKRU-2 and BKPRU-2. It is ensured here record of the all seismic events with M≥0. Above mentioned parameter commonly is lower by 0.5 magnitude in the centre of every arrangement.

Most detailed observations are ensured by the local group of the sensing elements enveloping the rock volume in few thousand meters. For local seismic control it is used commonly the holes sensing elements with the through band from 10 to 2000 Hz and with highly productive digital systems for data collection. Systems are the most demanded equipment for monitoring of the karst gaps formed after flooding of the mine BKPRU-1. Besides, they are used at another objects too including working mines in conditions demanded for obtain of objective information about the weakest processes of destruction that are measured by magnitude from –3 to 0.

Natural seismic activity has not been noted at the deposit before beginning of systematic control at the Verkhnaya Kama (before 1995). All known facts of the natural tectonic activity in the region were found far away of the salt deposit. It has been revealed single events within the bounds of the deposit (see the table). But it is difficult to tie some

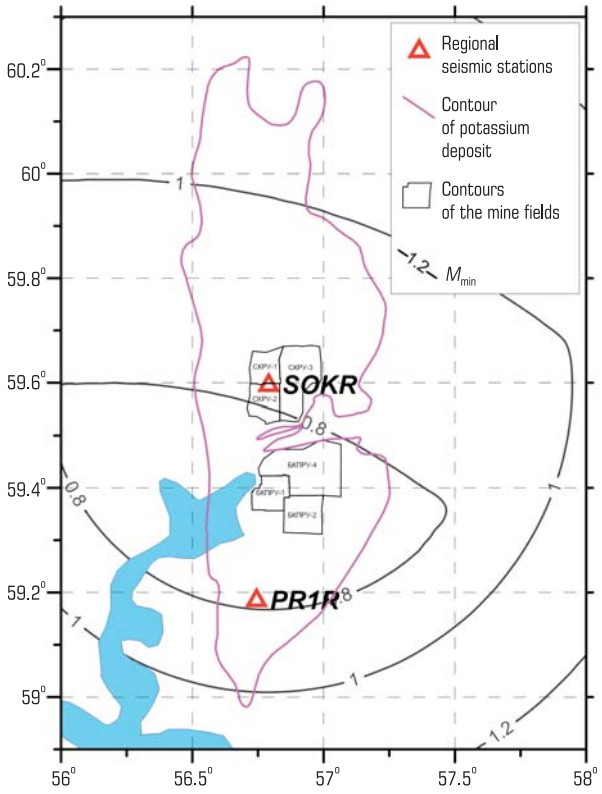

Fig. 1. Recording possibilities of regional seismic net in the region Verkhnaya Kama

events together with tectonic activity. Most powerful earthquake in January 5, 1995 has been considered primarily as tectonic one. But later, on the base of results of simulation [4] it has been found technogeneous nature of the earthquake. It was consequence of the mass caving of mining workings at the mine SKRU-2. Oil extraction at the deposit casts doubt on natural character of the events that took place in July 3, 1995. Most probably that earthquake centre has been tied with oil extraction at Un'vinsky oil deposit. Two consecutive shocks with the interval 6 sec. have taken place in October 25, 1993. Their nature has been considered as tectonic one, since their epicenters are located outside the bounds of mined in this period oil deposits. Besides, character of macro-seismic events with M = 3-4 is confirmed by deep location (about 4 km) of the earthquake centers. Earthquake in October 8, 1997 was analogous to above mentioned one by its macro-seismic parameters (intensity in Beresniky-town — to 5). Its centre has been located

Table Earthquakes recorded by apparatus within the bounds of VKDPS

Date and time	Latitude, grad	Longitude	Magnitude (MLH)	Probable type of Earthquake
1993.10.25 13:31:04	59,23	56,768	2,6	Tectonic
1993.10.25 13:31:10	59,213	56,705	2,9	Same
1995.01.05 12:46:02	59,59	56,80	3,5	Technogeneous
1995.07.03 09:04:10	59,22	56,92	2,1	Same
1997.10.08 20:57:33	59,36	56,93	2,8	Tectonic

in middle of the field of the mine BKPRU-2, but technogeneous character of the event has not been confirmed. Most likely it was conditioned by tectonic moving.

Great number of comparatively powerful events has been recorded at the deposit after 1997. But development of the new local nets has increased significantly quality of recognition of the earthquake centers. Results of monitoring indicate lack of the natural earthquakes. All seismic events were conditioned by mining of potassium deposit or by consequences of flooding of the mine BKPRU-1.

Long-term study of seismic activity at potassium mines gives valuable information about processes of disturbance in mined rock-salt massif. Systems of seismic monitoring permit to fix single facts of disturbance and to compare seismic parameters and features of

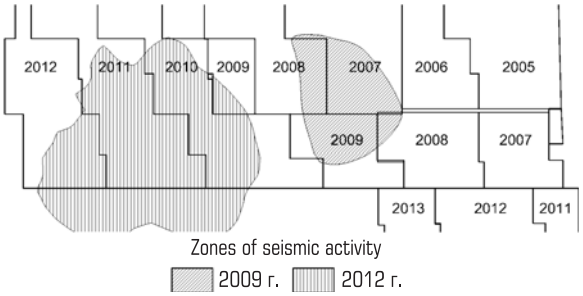

Fig. 2. Zones of seismic activity relatively to areas of mining at the mine BKPRU-2

mining. Nets for seismic monitoring in mining workings have permitted to obtain in this period rich factual material about nature of recorded seismic events. Examination of the zones of the most powerful events has always revealed obvious facts of disturbance connected, as a rule, with the most weaken elements of mining systems (pillars between the passageways, closing of mining workings with acute angle, arch zones of the folds and so on). Simulation of seismic response of the different types of disturbance has permitted to show that caving of the roof is the most probable process in the earthquake centre in potassium mines [5]. But great number of weakening factors has not been studied yet. It restrains discovery of nature of the events.

Comparative evenness of emission of seismic energy in time is peculiarity of seismic activity in potassium mines. Analysis of flow of seismic energy has permitted to find long periods (months and years) with constant rate of emission of seismic energy. It is evident that above mentioned character of the energy emission is conditioned by physical properties of disturbed rock, first of all, by plasticity of the rock. It is confirmed by analysis of spatial distribution of seismic events recorded at the mines. Thus, majority of the epicenters are located in the areas where mining workings exist long time (few years) and are weakly tied with the zones of bearing pressure formed by current mining works (Fig. 2). It has been noted that most of the marked seismic active zones are the areas between protecting pillars where the empty space has not been filled or has been filled partially. Areas correlate well with the zones with increased rate of lowering of the earth's surface. Besides, it has been found that level of seismic activity within the bounds of the seismic zones, in its turn, depends on the number of technogeneous and natural factors. Technogoneous factors represent different mining-technical conditions of mining of the deposit.

First factor — is productive seam with driven mining workings. Most of the mining workings in the seam KrII at the two Solikamsk mines and in the seam AB at the mine BKPRU-1 (before flooding) are characterized by the lowest level of micro-seismic activity. Since parameters of mining of above mentioned seam and the other ones do not differ significantly, it is supposed that low level of micro-seismic activity is conditioned by physical and mechanical properties of the rock. It is marked increased density of emission of seismic power on territory of the mine SKRU-2 in the areas of three-seams mining. Besides, high level of micro-seismic activity is observed on the plots of two-seams mining where one of extracted seams is Bc-seam.

Second factor — is presence and type of filling (stowing) of the workings. Comparison of micro-seismic activity at the different plots of the mine fields in different periods has shown that timely fulfilled stowing decreases emission of seismic energy 1.3–2 times. Application of the dry filling mixture ensures significant greater decrease of emission of seismic power than in case of usage of hydraulic mixtures.

Third factor — is life ("age") of mining workings. Comparison of the diagrams of change of density of emission of seismic energy depending on age of the mining workings at the different mines shows that for silvinite seams significant (few times) increase of micro-seismic activity takes place after 7–10 years. It is evident that it takes place gradual accumulation of plastic deformations in bearing pillars and in surrounding massif with increase of the rate of disturbance of the rock in time. Process of activation of mined rock massif within carnallite seam may begin soon after completion of mining. It is conditioned by low strength of carnallite.

Among available for analysis natural factors it has been examined influence of the waves of powerful distant earthquake [M ≥ 5] on

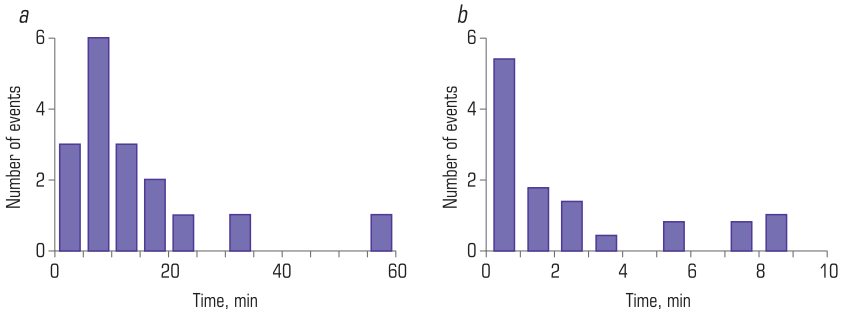

Fig. 3. After-shock activation after technological blasts

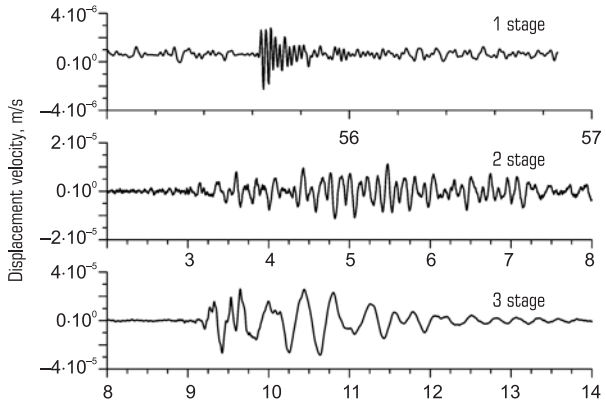

Fig. 4. Typical seismograms of three types of seismic events (explanation in the text)

level of seismic activity within the bounds of the all mine fields. In course of observations it has been noted trigger effect. It means considerable increase (1.5–3 times) of emitted seismic energy of the local events recorded in first hours after passing of the tele-seismic wave through the rock massif of the mine [6].

Resembling by character increase of emission of seismic energy is marked in course of carrying out of the blasts. But this effect is barely visible and is localized within small volume of the rock massif. Phenomenon is similar to after-shock processes after powerful earthquakes. It is known at the others mining objects [7, 8]. Time interval for decrease of seismic activity to the phon values depends on the blast power. Statistic data for few tens of the blasts (Fig. 3) show that in course of the first hour during 20 min after the blast (Fig. 3, *a*) it takes place exceed of the average phon values. Analysis of more prolonged stretches of time, comparable with the average interval between the blasts, carried out in the same place, shows presence of residual effects during the three days (Fig. 3, *b*).

Necessity to monitoring the karst in salt has arisen in the end of 2006 owing to emergency situation at the mine BKPRU-1 that has led to flooding of the mine. Collection of information about seismic activity, accompanying active karst processes in the zone of expected caving, has been begun in the first days after begin of flooding. Subsequent caving has been accompanied with putting in advance of additional seismic sub-systems. It has permitted to retrace in detail development of destruction and to generalize seismic dynamics in course of forming of the karst gaps and after filling of the some cavities [2].

In common flow of the events it has been found three types of the seismic centers with different mechanism of demolition: forming of the cracks in consolidated rock massif (1); crumbling of the surface layers, caving of the roof and walls of the karst cavity (2); compression of the sandy-gravel mixture filling the karst cavity (3). They generate the wave fields (Fig. 4) with significantly decreasing parameters [2]. Spatial analysis of the epicenters has permitted to find clear enough criterions for prognostication of development of the karst cavities. Initially their forming is accompanied with scanty and comparatively weak seismic events with predominance of the centers of the first type. Later on seismic flow stops, indicating stabilization of the rock massif, or it changes actively its structure confirming inevitable forming of caving. Thus, it has been noted significant increase (ten times) of flow of the events of second type and average energy up to few hundred and thousand J few days before appearance of the karst gap on the surface. Large caving of the banks of the open caves is proceeded with accumulation of the seismic events that take place in average two weeks before visual appearance of caving. Filled cavity generates periodically seismic events of the third type. Open cavities find, in due course, the stable bounds and become the objects with low seismic activity.

Estimating perspectives of development of seismic observations at VKDPS it has to be noted construction of the new mines in near future. It supposes creation and introducing, step by step, of seismic monitoring from beginning of exploiting of the mines. Corresponding projects are already worked up for some un-developed licensed plots. Current state of observations at the working mines may be considered as the optimum one. But preconditions for modification of some elements of the systems of monitoring are present here. Modernization of the seismic apparatus and increase of its faultless functioning in aggressive surrounding are the principal directions for further development of the seismic observations at the deposit. Concentration of the net and partial replacement of the vertical sensors with three-component ones are one on the simplest and efficient methods of modernization for enlargement of number of the tasks solved by seismic monitoring. It will permit to increase precision of locating and to decrease of threshold of sensitivity for weak events. At the same time the last aspect will not be important in case of expansion of working frequency. In its turn it will demand application of another sensing elements and more efficient systems for collection and working of the data and for decrease of the time interval between revealing of the seismic events and publication of complete information about above mentioned events and corresponding threats.

In conclusion we would like to emphasis that current seismic monitoring at VKDPS is the most efficient and demanded method for control of mining and prediction of emergency situations. Seismic activity, recorded at the deposit, is the diverse one and is presented by the almost all known types and forms. But its natural component, that is very rare but appreciable one in the region, is badly studied phenomenon.

Technogeneous component is presented widely and is close tied with different processes of mining (mining of the rock-salt, stowing of empty space, blasting and so on) and with physical-mechanical properties of mined rock. Fulfilled observations permit to do enough versatile estimation of technogeneous seismic activity in all its forms at the operating potassium mines. It permits to consider the data obtained in course of monitoring of seismic activity as adequate indicator of deformations in mined rock massif and to take their into account in planning of further development of mining. It permits to restrain in proper time negative processes of demolition in the rock

massif and it is generally adopted at the all potassium mines at the deposit. Study of seismic activity of the karst cavities is directed to ensuring of safety in liquidation of supernumerary incidents and emergency situations. This form of seismic monitoring develops most dynamically at the deposit. It ensures obtain of the new data about inside processes in the rock massif with the karst cavities, that will be used undoubtedly in further works. ГИ

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