Solving the problems of exploitation safety of potassium salt deposit based on joint application of geophysical and geomechanical studies

Yu A Kashnikov¹, D V Shustov¹, A O Ermashov², O O Lebedeva¹, A A Zhukov³ and A M Prigara³

¹ Mine Surveying, Geodesy and Geoinformational Systems Department, Perm National Research Polytechnic University, Perm, Russia
² EuroChem Project, Ltd, Perm, Russia
³ Geophysical Laboratory, JSC «VNII Galurgii», Perm, Russia

gotech@pstu.ru

Abstract. The reliable determination of the physical and mechanical properties of the rock is one of the major issues of geomechanical modelling. It is needed to ensure exploitation safety in underground mine. This is especially relevant for the huge potassium salt deposits which uniqueness is the presence of the watered rocks that lies above the exploiting potassium seams. Particularly, a part of the rock mass that lies between potassium seams and watered rocks is called waterproof strata (WPS). The highest risk is the presence and propagation of the cracks in WPS through which the above-water can probably enter the openings that could lead to the total flooding of the mine. In order to prevent it and to provide exploitation safety the joint application of geophysical and geomechanical studies is suggested. In this paper 2D mine seismic investigations and geomechanical studies are described. And, as the conclusion, the analysis of the stress-stain state of the rock mass and its potential weak zones are presented.

1. Introduction

Geological uniqueness of many potassium salt deposits is the presence of the watered rocks that lies above the extracting potassium seams. Particularly, a part of the rock mass that lies between potassium salt seams and watered rocks is called waterproof strata (WPS). At Verkhnekamskoe potassium and magnesium salt deposit (VKSD), located in the Western Urals, WPS is the part of water-impermeable rock mass of 50-140 m thick. WPS lies between the exploiting potassium seams and the level where weakly mineralized water is contained. There is also active water exchange with overlying freshwater levels of 150-350 m thick [1].

WPS helps to protect the mine from water entrance. However, there can be different anomalous zones in WPS structure that have negative impact on exploitation works at the deposit.

In order to identify anomalous zones in WPS rocks through which the above-water can probably enter the openings the joint application of geophysical and geomechanical studies is suggested [2, 3].

2. Methodological basis

The idea of the proposed approach is as follows. Firstly, to obtain correlations between static and dynamic geomechanical properties with the help of the corresponding equipment. Also, to calibrate the obtained correlations according to the well logging results. After, to obtain the distribution of S-wave rate and acoustic impedance based on 2D and 3D seismic processing results. Then, to identify...
zones with different compaction degree in WPS and potassium salt seams using the obtained correlations. In fact, there is an opportunity to determine values of such geomechanical properties as compression strength, elastic modulus, Poisson ratio and others in any point of WPS. And, finally, to implement geomechanical modelling using particular values of the physical and mechanical properties of the rocks, and to analyse WPS stress-strain state.

The input data is geological information of the deposit, geophysical information received from 3D (or 2D) seismic processing and well logging results, geomechanical correlations obtained on the basis of core sample testing [4, 5].

The main goal of the approach is to obtain the reliable and current information about deformational processes for the different mining parameters, not only for the given.

In this paper the joint application of geophysical and geomechanical studies is used to estimate the possibility of water entrance into the openings at VKSD under given mining parameters.

3. Mining parameters and geological features of the investigated regions

Two regions at the mine field are under investigation. Figure 1 shows plan of development openings at AB seam in grey. Also there are margins of the panels and blocks, location of the regions, location of the geophysical line at the development transport opening at AB seam at 18 west panel (18WP) block 7, and well 1020, where logging was done.

There are two commercial sylvinitic seams: the upper is AB, the lower is RedII. Exploiting system is «chamber – safety block» system. Chambers has longitudinal direction. Loading level C of the safety blocks differs. Loading level is the relation of acting load and bearing capacity.

The first region is developed in one stage. Loading level of the safety blocks C is more than 0.5 that is higher than allowed value [C] = 0.4. Therefore, filling of 0.9 is provided as the safety measure of WPS. Time period between filling and exploiting works is recommended not more than 1 year from the start of the exploitation works at this region.

The second region is developed in two stages (figure 2). In the first stage the chambers are exploiting with wide safety blocks, in the second the chambers are mined through these wide safety blocks. It leads to the safety block loading level increase at this region. The filling works in the first stage are recommended to be done 2-3 years after the start of the exploiting works. The filling works in the second stage are recommended to be done 0.5 year after the start of the exploiting works at RedII. Time period between the start of the exploiting works in the first and the second stage is 4 years.

![Figure 1](image-url)

Figure 1. Location of the investigated regions, geophysical line and well 1020.
The first stage:

Figure 2. Mining works at the second region.

Recommended mining parameters for the regions are presented in table 1.

Table 1. Recommended mining parameters for the regions.

| Region | Panel | Seam  | Chamber width $a$, m | Safety block width $b$, m | Extracting thickness $m_o$, m | Depth, m | Loading level C | Maximum subsidence, m |
|--------|-------|-------|----------------------|--------------------------|-------------------------------|----------|----------------|----------------------|
| 1      | 16WP  | AB    | 3.2                  | 6.3                      | 3.2                           | 342      | 0.279          | 0.19                 |
|        |       | RedII | 5.5                  | 4.0                      | 5.4                           | 350      | 0.509          | 0.74                 |
| 2      | 18WP  | AB    | 3.2                  | 13.8                     | 3.2                           | 328      | 0.106          | 0.02                 |
|        |       | RedII | 5.5                  | 11.5                     | 5.8                           | 335      | 0.142          | 0.09                 |
|        |       | AB    | 3.2                  | 5.3                      | 3.2                           | 328      | 0.332          | 0.28                 |
|        |       | RedII | 5.5                  | 3.0                      | 5.8                           | 335      | 0.724          | 1.16                 |

According to the advanced mine exploration the structure of WPS is full and there is no anomalous zones. WPS thickness above AB is on average 95-100 meters. In the middle of the regions there is a huge substitution zone of exploiting sylvinite seams that is classifies as the anomalous zone of the third risk group.

In the north-west part there is dipping of the seams in the east direction from 239.7 m to 358.3 m, with depth fluctuations of 118.6 m. Also there is thickness increase of both AB and RedII mainly in the west direction, KCl content decrease in AB in the east direction and clay content decrease in RedII in the north-west direction.
4. Geophysical studies

4.1. Geophysical field works

2D mine seismic survey studies were done along geophysical line of 1084 m long in west-east direction at the development transport opening at AB at 18WP block 7 (figure 1).

Field seismic survey observations were done with the prior art seismic reflection method of common middle point (CMP) by method for underground shear-wave seismic of geological structure with separation of reflections [6, 7, 8].

A 1.5 kg hammer was used as the source of elastic vibrations. For shear-wave vibrations the impulses were done to opening wall in horizontal direction. There were five accumulations on each source point that allowed increasing the relation signal/noise of the recorded signal.

For field works digital seismic station TELLS-3 was used. This station has analog-to-digital converter of 24 rank and 4-byte recording format with floating point.

While recording variable survey system was used – from flange to centre. Recording was done by multichannel equipment with channel number – 96, interval between source points – 4 m, interval between receiver points – 2 m, array length – 190 m. Sampling frequency is 0.25 ms in the open channel, record length is 256 ms.

Horizontal receivers of seismic waves were used for upward and downward soundings. The receivers were installed in holes drilled in the opening’s wall. S-waves have maximum amplitude in the direction that is radial to the impulse axis. Therefore, there will be interfering reflections that arrive from above, below and sideways in one and the same section for subhorizontal bedding.

To separate interfering reflected waves during the field studies, injection of vibrations is done along two lines spaced from each other over \( \frac{1}{4} \) wave length. This approach gives a difference of 0.5-1.0 ms (S-wave rate in salts is 2500 m/s) depending on the spacing between shot lines that is sufficient to define the direction of elastic wave arrival.

4.2. Geophysical processing results

In order to identify elastic characteristics of the rocks the well logging results of well 1020 were used in addition to 2D mine seismic studies results. Well 1020 is located to the east of the investigation line.

Present development of seismic survey allows using seismic data not only for the construction of the model structure of the seam, but for the seam petrophysical properties determination. In order to solve this problem seismic inversion is used, that is the inverse dynamic problem solving. The distribution reconstruction of elastic properties of geologic environment with the recorded wave field is considered. Acoustic inversion, that assumes zero wave incidence angles (sum traces of time section), is known to be applied both to P- and S-waves [9].

Due to the fact that time seismic section on monotype S-waves was gained as the seismic investigation result, shear impedance (S-impedance) is to be determined. Inversion technology was used for petrophysical model construction suitable for quantitative digital model [9].

Conversion from time to depth grid was done by calculations for average wave rate obtained from rate analysis. Depth seismic and geological section with marked reflecting levels is presented on figure 3.

5. Geomechanical studies

For the quantitative estimate of strength properties the relations of S-impedance and physical and mechanical parameters of salt rock are used. These values were obtained by results of laboratory sample testing on PIK-UIDK/PL equipment of the Centre of Geomechanics and Geodynamics of Perm National Research Polytechnic University (PNRPU).

As for S-impedance:

\[
S = V_S \cdot \rho, \quad \rho = m/V, \quad (1)
\]

where \( V_S \) – S-wave rate by results of laboratory sample testing (m/s); \( \rho \) – density of the sample (g/cm\(^3\)); \( m \) – sample weight (g); \( V \) – sample volume by geometry (cm\(^3\)).
Plots of uniaxial compressive strength and elastic modulus against S-impedance are presented on figure 4. These relations and derived from them physical and mechanical properties is geomechanical part of the geological and geomechanical model of WPS and exploiting seams.

**Figure 3.** Depth seismic and geological section with marked reflecting levels.

**Figure 4.** Plots of uniaxial compressive strength and elastic modulus against S-impedance.
Figure 5 shows uniaxial compressive strength distribution for the section along the investigation line that is at the development transport opening at AB at 18WP block 7.

In general, the analysis of physical and mechanical properties distribution allowed identifying rocks with low strength (carnallite and clay) and with normal and increased strength (sylvinite and salt rock) for the whole section. Carnallite seams with strength less than 10 MPa are clearly specified in seams from G to K, where interbedding of carnallite and salt rock with more strength (20-25 MPa) is noted. It can be seen that in the west part of the section for 110-135 m depth interval the seams with decreased strength are thinning, and at the same time strength of salt rock and sylvinite increases (28 MPa). In these areas there is local seam extension with increased strength (salt rock, sylvinite). In the east part of the section according to strength distribution and decrease of G-E seams from west to east direction the thinning is also observed. At the same time there is no strength increase of salt rock in these areas (about 20 MPa).

Totally, it is determined that geological bedding is conformable, WPS thickness is sustainable within the lateral, WPS structure is full. Folded structures of G-E seam with maximum amplitude of the fold about 5-7 m are observed against relatively conformable horizontal and layered bedding of geological seams within the investigation line for 750-1000 m points from altitude –155 m to –165 m. For 840-990 m points the reflection from G seam is blurred and has relatively sharp incidence angles, that is probably connected with substitution of carnallite seam G. Here also while mining works the geologists of the mine have allocated substitution zone in seam B by salt rock.

Figure 5. Uniaxial compressive strength distribution for the investigation line.
6. Stress-strain state analysis of the rock mass under mining

The next step is the construction of geomechanical model for a specified area with the given mining parameters and real physical and mechanical properties. Salt rock deformation and fracture rheological model is the basis of the calculations. The model allows considering transient, steady-state and progressive creep deformations, also taking into account damage and softening of the rock under dilatancy [10, 11]. This model is based on viscoplasticity flow theory. Viscoplasticity deformation increments are defined by analogy with plasticity theory through scalar value derivative $Q$ – plastic potential:

$$\left\{ \frac{d\varepsilon^{vp}}{dt} \right\} = \{\varepsilon^{vp}\} = \begin{cases} 0, & \text{if } F \leq 0; \\ \frac{1}{\eta} F \left( \frac{\partial Q}{\partial \sigma} \right), & \text{if } F > 0. \end{cases}$$

(2)

where $F$ – yield function; $\varepsilon^{vp}$ – viscoplasticity strain rate; $\eta$ – rock viscosity.

For WPS stress-strain state forecasting based on geological and geomechanical model the finite-element model along the investigation line through the development transport opening at AB at 18WP block 7 was created. Mathematical model took into account main geological structure of both WPS and exploiting seams. Levels gained from 2D mine seismic survey studies processing were used for model construction. Also due to this processing the static physical and mechanical properties of the rock were used.

To estimate fracture level of WPS it is necessary to identify in what seams technogenic cracks occur through which the water could enter the openings and flood the mine. The estimation of the crack propagation in WPS is done in compliance with Drucker-Prager criteria distribution that defines creation of progressive creep deformations in salt rock. Physically meeting Drucker-Prager criteria means the beginning of crack formation in the rock. In order to provide some safety margin, it is suggested that the creation of shear cracks occur when $K_t > 0.9$.

Estimation of the WPS fracture conditions was done considering stress-strain state changes under deformational process in time. Figure 6 shows the distribution of Drucker-Prager criteria ($K_t$) in WPS for the first region. In this region the most fractured places are in transitional zone (TZ). In other seams there are local zones of increased criteria ($K_t$). Taking into account that the criteria included the safety margin, it can be concluded that these zones do not constitute a danger for WPS safety state.

In general, taking into account local seams damage along the whole section, there is no uniform damage zone. Also criteria ($K_t$) was taken with safety margin, and cumulative thickness of non-fractured subseam of salt rock in WPS significantly enlarges minimal allowed one. It can be concluded that obtained zones of possible damage for the regions with the given mining parameters do not constitute a danger for WPS safety state.

![Figure 6. Drucker-Prager criteria distribution for the first region within 10 years of mining.](image-url)
7. Conclusion
According to the processing results of acoustic logging of the well, 2D mine seismic survey and laboratory sample testing the geological and geomechanical model of the overlying rock for the investigated regions was created. In the further geomechanical modeling problem solving of WPS stress-strain state the use of particular values of rock physical and mechanical properties of potassium salt seams and WPS allows determining risk level of water entering into the mine.

Conducted investigations illustrate that joint geophysical and geomechanical studies allow defining zones with different strength properties in rock mass and solving problems of safety mining more meaningfully on the basis of geological and geomechanical modelling.

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