UDC 550.83

Eduard KUZMENKO[1a], Sergiy BAGRIY[1b], Inna ARTYM[2], Volodymyr ARTYM[3]

[1] Dep. Geotechnogenic security and geoinformatics, Ivano-Frankivsk National Technical University of Oil and Gas, 15, Karpatska, Ivano-Frankivsk, 76019, Ukraine, tel. +38(0342) 504761, e-mail: gbg2020@ukr.net, [1a]https://orcid.org/0000-0002-1994-0970, [1b]https://orcid.org/0000-0003-1190-6222

[2] Dep. Geology and Exploration of Oil and Gas Fields, Ivano-Frankivsk National Technical University of Oil and Gas, 15, Karpatska, Ivano-Frankivsk, 76019, Ukraine, 76019, tel. +38 (0342) 72-71-21, e-mail: viarty1993@gmail.com, https://orcid.org/0000-0002-3388-6827

[3] Dep. Construction and Energy Efficient Structures, Ivano-Frankivsk National Technical University of Oil and Gas, 15, Karpatska, Ivano-Frankivsk, 76019, Ukraine, tel. +38 (0342 57-24-04, e-mail: viartym@gmail.com, https://orcid.org/0000-0002-8938-552X

https://doi.org/ 10.23939/jgd2022.02.065

DISPLAY OF MECHANICAL STRESSES' DISTRIBUTION IN MINING AREAS IN THE INTENSITY DYNAMICS OF THE EARTH'S NATURAL PULSED ELECTROMAGNETIC FIELD

The purpose of the research is to substantiate the theoretical prerequisites for the interpretation of the geophysical method of the Earth's natural pulsed electromagnetic field (ENPEMF). The justification will be performed by quantifying the stress state of the rock massif, modeling of the obtained analytical dependencies for disturbed massifs. The basis for the interpretation is the coordination of the obtained distributions of intensity with the intensity of the electromagnetic field. The initial data are classical formulas of theoretical mechanics, modified to the conditions of the geological structure of the object of research and long-term research by the method of ENPEMF at the object – Kalush-Golynsky potassium salt deposit in the Pre-Carpathian. The research methodology included the development and presentation of models of the stress-strain state of the mining area, followed by the calculation of specific distributions of stress and analysis of their relationship with the dynamics of ENPEMF for specific areas of regime observations. The results of the research are given in the following sequence: 1) an example of calculating model stresses; 2) practical results of ENPEMF; 3) comparison of theoretical model calculations and real observations' data. Examples of calculations are given for a rock massif including a rectangular-shaped mining operation located in a salt formation. The distribution of stresses is calculated for the 2D model, taking into account the actual physical parameters. The series of graphs shows the change in tension both along the profile and with depth. The model is complicated for a variant of two chambers located at different depths. Observation of ENPEMF is demonstrated for a complex section of rocks. Actual plots of the field intensity with a high degree of correlation correspond to the calculated plots at a certain depth. The complication of the section and the presence of different stages of the postoperative period, which is reflected in the regime observations, leads to the deviation of the form of the graphs from the "ideal-model", but at the qualitative level this form corresponds to the theoretical one. The novelty lies in the development of the principles of quantitative assessment of the stress-strain state of the disturbed rock mass as the basis for the theoretical assessment of the distribution of the natural pulsed electromagnetic field of the Earth. In particular, the identity of the results of practical geophysical observations and computational models of the stress-strain state is demonstrated. The results obtained should be considered as a contribution to the theoretical basis of the quantitative interpretation principles of the geophysical method of ENPEMF. At the same time, the ways of further research for the full implementation of this research area are indicated.

Key words: stress state; mining; deformations; intensity of electromagnetic field.

Introduction

The method of natural pulsed electromagnetic field of the Earth today is sufficiently reasoned regarding its use in solving various geological, engineering-geological, hydrogeological, tectonic and geoecological problems [Salomatin et al., 1991; Kovalchuk, 2003; Kuzmenko et al., 2017; Dovbnich et al., 2012; Dzioba, 2020; Malyshkov et al., 2016; Anikeyev et al., 2019].

The main of these tasks are as follows:

– qualitative assessment of the total natural field of mechanical stresses and tracing its dynamics during regime observations;

– prompt detection and forecasting of dangerous geological processes and phenomena (landslides, collapses in karst, rockbursts, suffusion, outbursts in mines);

– determination of geodynamic structures activation, mapping and characterization of fault zones;

– survey of residential buildings, economic premises, structures and communications to establish possible deformations of foundations, walls and constructions;

– assessment of the stress-strain state of dams and other hydrodynamic structures, determination of the disturbances places and water filtration in them.

Recent researches indicate that these tasks should be supplemented by an assessment of the stress-strain state of mining area formed as a result of exploitation, and forecasting the development of subsidence and sinkholes on the earth's surface as a result of mine development of deposits [Kuzmenko et al., 2018; Bagriy et al., 2020; Kryzhanivskyi et al., 2017; Deshchytsia et al., 2016; Kuzmenko et al., 2019; Chepurnyi et al., 2020].

Theoretical foundations indicate the relationship of the natural field's intensity with numerous parameters. At the same time, this relationship is depicted at a descriptive qualitative level, consistent with the general physical and mathematical provisions. The paper [Bagriy et al., 2020] provides general formulas that make it possible to assess and characterize the phenomenon as a whole. These formulas give a general idea of the multifactoriality of the process of forming electromagnetic radiation. However, they cannot claim to be an analytical basis for solving the direct and invers problem of geophysics. There are no such formulas for ENPEMF at all. Therefore, it should be considered that theENPEMF method is qualitative, based on a comparison of geological phenomena and the corresponding changes in the electromagnetic field on the principle of "more or less".

Recently, the researchers of ENPEMF have confined themselves to solving certain applied topics regarding the peculiarities of data processing and the specifics of solving various geological problems.

Among these works, the PhD's thesis should be noted [Bezsmertnyi, 2004; Cheban, 2002; Bagriy, 2016]. According to the directions of the research we should mentionit the works devoted to the study of landslides [Kuzmenko et al., 2013; Kuzmenko et al., 2009] and the study of subsidence of the earth's surface due to karst processes [Kuzmenko et al., 2018; Bagriy et al., 2020], as well as articles devoted to certain issues of interpretation of ENPEMF [Kuzmenko et al., 2017; Dovbnich et al., 2012; Dzioba, 2020].

The purpose of the work

The results of research by the method of ENPEMF are usually presented in the form of graphs of field oscillations amplitudes, field intensity – normalized intensity values. A planar form of representation is possible. At the same time, the study noted the connection of the hypothetical stress-strain state of the rock mass with the deformations observed on the surface.

The purpose of these research is:

– quantitative assessment of the stress state of complex rock masses;

– modeling of the obtained analytical dependencies for the rock masses disturbed by mining;

– comparison of the obtained distributions of stresses with the intensity of the natural electromagnetic field and establishing their connection as a prerequisite for creating the basis for quantitative interpretation of the ENPEMF method data.

Initial data (characteristics of the object of research)

The initial data for demonstrating the obtained results are:

– research object – Kalush-Golynske potassium salt deposit, which is located in Pre-Carpathian;

– classical formulas of theoretical mechanics, modified to the conditions of the object's geological structure;

– multiannual research by the method of ENPEMF at the specified object.

The Carpathian region is the only basin of Ukraine in which significant deposits of potassium and rock salts were explored and exploited: Kalush-Holynske (Ivano-Frankivsk region), Stebnytske (Lviv region) and Solotvynske (Zakarpattia region) deposits.

In terms of diversity and ratio of salt minerals present here, these deposits are unique and have no analogues in the world. Extraction and processing of potassium and magnesium ores allowed up to 2000 not only to provide Ukraine with complex sulfate potassium and magnesium fertilizers, but also to export them to the foreign market.

One of the reasons that led to the destruction of the potash industry is, according to our opinion, the ineffective solution of environmental problems of subsoil use. These problems arose in the process of using imperfect technologies of conservation and liquidation of the mining and processing complex (increase in the area of mining operations, extraction of salts and rocks, loss of filtration isolation of the mining area). For example, during the extraction of potassium and magnesium ores at the mines of the Kalush-Golynsky deposit, 17.5 million m^3 of voids has been formed. There are breakthroughs to the salt-rock mass of fresh (aggressive) waters from the surface. This leads to a violation of the balance of the subsoil with the settlement of the earth's surface, the formation of dumping craters, karst cavities and the degradation of drinking water supply sources.

To study these processes, the task was set to develop and implement a system for monitoring deformations of the earth's surface on the mining fields. This system primarily included regime topographic and geodetic observations and observations by the method of ENPEMF.

Research Methodology

The research methodology included the development and presentation of models of the stress-strain state of the mining area, followed by the calculation of specific distributions of stress and analysis of their relationship with the dynamics of ENPEMF for specific areas of regime observations.

Stressed state of rock mass

Consider a sufficiently small volume of a rock mass in the form of a cube with a side equal to one, which is at a depth H from the ground surface (Fig. 1). The specific gravity of the rocks located above is γ.

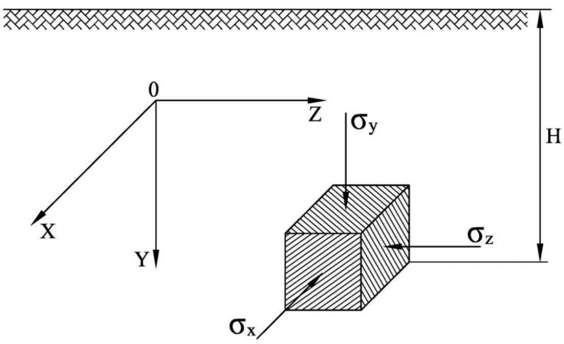


Fig. 1. Calculation scheme for determining the stress state of the mining area

For the volumetric stress state, in which there is an arbitrary point of the mining area, the fair generalized Hooke's law, according to which the horizontal relative deformation is determined by the formula [Pysarenko, 1988]:

$$\varepsilon_X = \frac{1}{E}\left[\sigma_X - \mu\left(\sigma_Y + \sigma_Z\right)\right], \tag{1}$$

where E, μ are respectively the Young's modulus and the Poisson's ratio of the rock.

In connection with the hypothesis of A.N. Dinnik, it is believed that in conditions of compression ε_X, horizontal deformations ε_Z are zero.

From here we get

$$\sigma_X - \mu\left(\sigma_Y + \sigma_Z\right) = 0, \tag{2}$$

where σ_X, σ_Y, σ_Z – normal stresses along the corresponding axes.

Since the coordinate system is chosen arbitrarily, then, for a homogeneous isotropic array, it can obviously be considered that $\varepsilon_X = \varepsilon_Z$ $\sigma_X = \sigma_Z$, a $\sigma_Y = \gamma H$. Then, on the basis of (2), we obtain the following dependence:

$$\sigma_X = \sigma_Z = \frac{\mu}{1-\mu}\gamma H = \lambda\gamma H, \tag{3}$$

where H – depth from the surface of the earth $\lambda = \frac{\mu}{1-\mu}$ is the lateral partition coefficient or Dinnick coefficient.

Determination of stresses around the rectangular shape of the chamber

The task of distributing stresses around rectangular mining was considered by [Shashenko et al., 2005]. The calculation scheme for solving the problem is shown in Fig. 2.

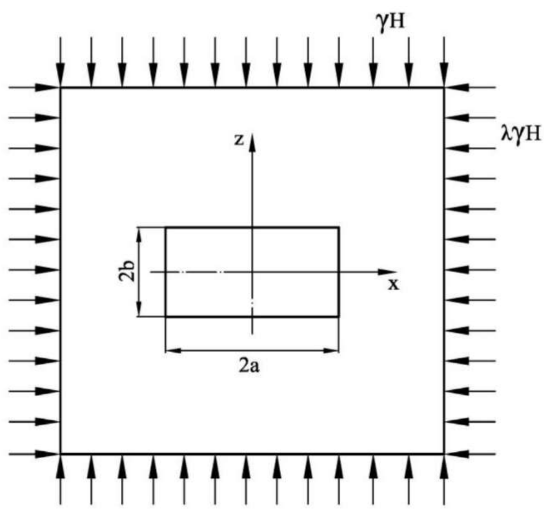


Fig. 2. Calculation scheme to the solution of the stresses' distribution problem around the chamber of a rectangular shape

The results of the calculation showed that the extreme values of normal stresses occur on the contour of mining and are determined by the formulas:

– within the sides of the chamber:

$$\sigma_X = 0, \quad \sigma_Z = \sigma_{Z\max} = \gamma H(1+\alpha) - \lambda\gamma H = \gamma H\left[(1+\alpha) - \lambda\right], \tag{4}$$

– within the body and ceiling of the chamber:

$$\sigma_Z = 0, \quad \sigma_X = \sigma_{X\max} = \lambda\gamma H(1+\beta) - \gamma H = \gamma H\left[\lambda(1+\beta) - 1\right]. \tag{5}$$

In equation (4) and (5), the coefficients α and β are determined depending on the ratios of the width of the chamber 2a to the height of the chamber 2b.

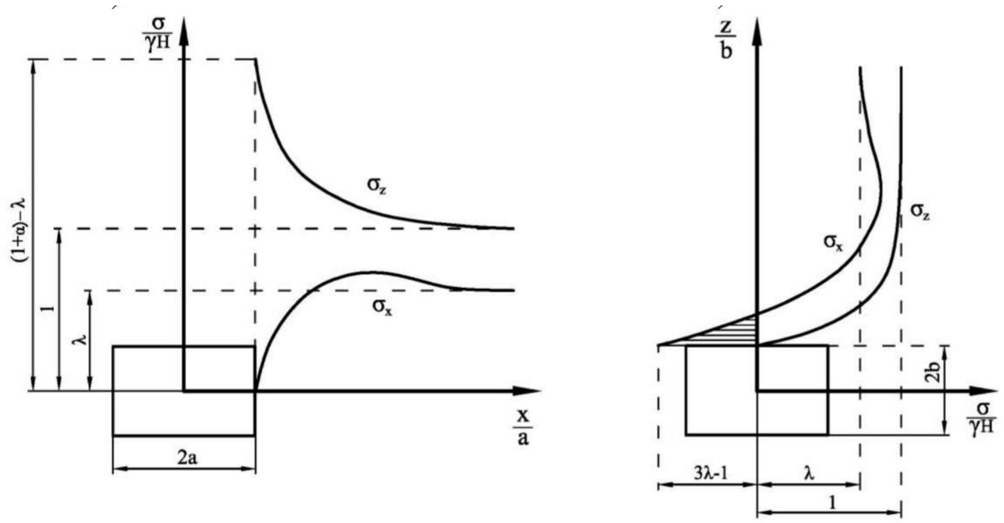
The values of the coefficients are given in Table 1. Diagrams of the stresses' distribution around the production are shown in Fig. 3

With regard to the ENPEMF method, the research consisted in selecting fragments of regime observations, i. e. reproducing the dynamics of intensity and comparing with the calculated models of stresses around the production, and evaluating such a comparison.

Table 1

Values of coefficients α and β

a/b	50	20	5	1	0.2	0.005	0.02
α	17	4	2	0.84	0.2	0.02	0.01
β	0.01	0.02	0.2	0.84	2	4	17



a b

Fig. 3. Diagrams of the stresses' distribution around the chamber of a rectangular shape: a – within the sides; b – within the top and the body

Test results

The results of the research are given in the following sequence: 1) an example of calculating model stresses; 2) practical results of ENPEMF; 3) comparison of theoretical model calculations and real observations' data.

Consider an example of calculating stresses around a rectangular mining operation using the example of the Kalush-Golynske potassium salt deposit.

A rectangular operation is considered, which is sized $a \times b$ and located at a depth H from the ground surface and located in a mining area of kainite and kainite-langbeinite ores.

The following initial values are accepted: $a = 180$ m; $b = 40$ m; $\alpha = 1.95$ $\beta = 0.25$; $H = 125$ m; $\gamma = 19.3 \cdot 10^3\ H/m^3$; $\lambda = 0.49$.

With these data, the extreme values of normal stresses occur on the production contour and are equal to:

- within the sides of the chamber:

$$\sigma_X = 0,\quad \sigma_Z = \sigma_{Z\max} = \gamma \cdot H \cdot [(1+\alpha) - \lambda] = = 19.3 \cdot 10^3 \cdot 125 \cdot [(1+1.95) - 0.49] = 5.94 \quad МПа$$ –

compressive stress;

within the body and top of the chamber:

$$\sigma_Z = 0,\quad \sigma_X = \sigma_{X\max} = \gamma \cdot H \cdot [\lambda \cdot (1+\beta) - 1] = = 19.3 \cdot 10^3 \cdot 125 \cdot [0.49 \cdot (1+0.25) - 1] = 0.934 \quad МПа$$ –

tensile stress;

To analyze the obtained results, we give the values of the strength of salt and saline rocks to uniaxial compression and tensile, Table 2.

As is known from the theory of material resistance, for strength calculations, the permissible tensile and compressive stresses are determined by the formulas:

$$[\sigma_+] = \frac{\sigma_{Мцр}}{n},\ [\sigma_-] = \frac{\sigma_{Мцс}}{n},$$

where $\sigma_{Мцр}$, $\sigma_{Мцс}$ – rock tensile and compressive strength limits, respectively ; n – safety factor.

A promising way to solve the problem of assessing the stress-strain state of rocks in the mining area is to use the finite element method. Existing software makes it possible to create models with arbitrary forms of mining and determine the stress-strain state of rocks with sufficient accuracy in the entire zone of their influence. Fig. 4, 5 show models and results of calculations of the stress state of the rock mass of the Golyn mine field of the Novo-Golyn mine of the Kalush-Golynske potassium salt deposit. The authors of the article developed models for assessing the stress state of the rock mass in a two-dimensional formulation using the condition of flat deformation.

Table 2

Strength of salt and saline rocks for uniaxial compression and tensile

No.	Rocks	Boundary of compressive strength, MPa			Tensile strength limit, MPa
		$\sigma_{\min}$	σ_{av}	$\sigma_{\max}$	
1	Silvinite – Cainite	25.4.	31.2	39.9	1.2–1.5
2	Cainite – Lagnbeinite	36.5	41.5	45.7	1.8–2.5
3	Cainite – Halite	18.9	21.5	24.5.	1.0–1.4
4	Brecciate saline clay	8.5	11.3	23.5.	0.8–1.4
5	Carnallite – Halite	19.6	24.5.	27.6.	1.0–1.5
6	Cainite	18.2	25.2	31.7.	1.4–2.2
7	Saline clay	26.3	30.3	34.6	1.2–2.2
8	Argillite-like clay	0	7.25.	14.5	not defined

To avoid the influence of edge effects, sufficiently large dimensions of the cross-section of rocks is used, namely, the length of the study area – 2000 m, depth – 500 m. Models of such large sizes are very difficult to solve by the method of finite elements in a static formulation due to the problems of potentially large movements in sufficiently limited areas around the mining. Algorithms for solving this problem were used by stepwise increasing the load with recalculation of equivalent state stresses at each stage. In this case, the load is the force of gravity. This allows you to reduce the boundary conditions of the model to the simplest limitation of movements. To assess the stress-strain state, the Transient Structural module of the ANSYS software complex was used. The model was tested for mining chambers with dimensions of 180 m length and 40 m width at a depth of 75 m (Fig. 4). Above the model are graphs of the equivalent stresses distribution on slices that correspond to depths of 5, 40 and 75 m.

At a depth of 5 meters, we have a significant near-surface anomaly in the center – this is an anomaly of the actual mining, which depends on the width of the mining and is associated with subsidence. Edge anomalies are less intense.

With increasing depth (40 m), the central anomaly practically disappears, but the edge anomalies increase, that is, we have a typical double-humped picture. With the approach to the level of the mining's top (75 meters), the edge anomalies increase in magnitude, but are localized along the edges of the mining. At the same time, the central anomaly appears again, but of lower intensity. In the model, the maximum intensity of stresses is observed in the upper corners of the chamber, but the size of these zones is quite insignificant.

Fig. 5 shows a two-chamber model. From the analysis of the results, it can be argued that the influence of the lower mining is significant in the area of its placement and practically does not affect the near-surface effect. However, the intensity of equivalent stresses has significantly increased (about one and a half times).

For a comprehensive assessment of the mining's impact, it is advisable to use the distribution of equivalent stresses. This distribution takes into account the impact of all stresses, counting the significantly different strength of the rocks under tension and compression. This task can be used both for a single chamber and for a mining system.

Analyzing the obtained results, it can be concluded that on the contour of the mining, the conditional strength within the sides $\sigma_{Z\max} \le [\sigma_{-}]$ is performed, and within the top and soil $\sigma_{X\max} \le [\sigma_{+}]$ – not performed. This means that significant equivalent stresses occur in the top and soil, which lead to the loss of stability of the mining and possible destruction. This conclusion fully coincides with the results obtained in [Shashenko et al., 2005].

Theoretical studies were confirmed by the measurement results of the natural pulsed electromagnetic field. Numerous studies were performed at the Kalush-Golynsky and Stebnytsky deposits of potassium salts. Thanks to these studies, the correlation of the anomalies of ENPEMF to the stages of subsidence in the Kalush-Golynsky field was revealed (Table 3). The presence of these observations indicates the possibility of a greater or lesser intensity of electromagnetic radiation in general, but does not deny the theoretical results.

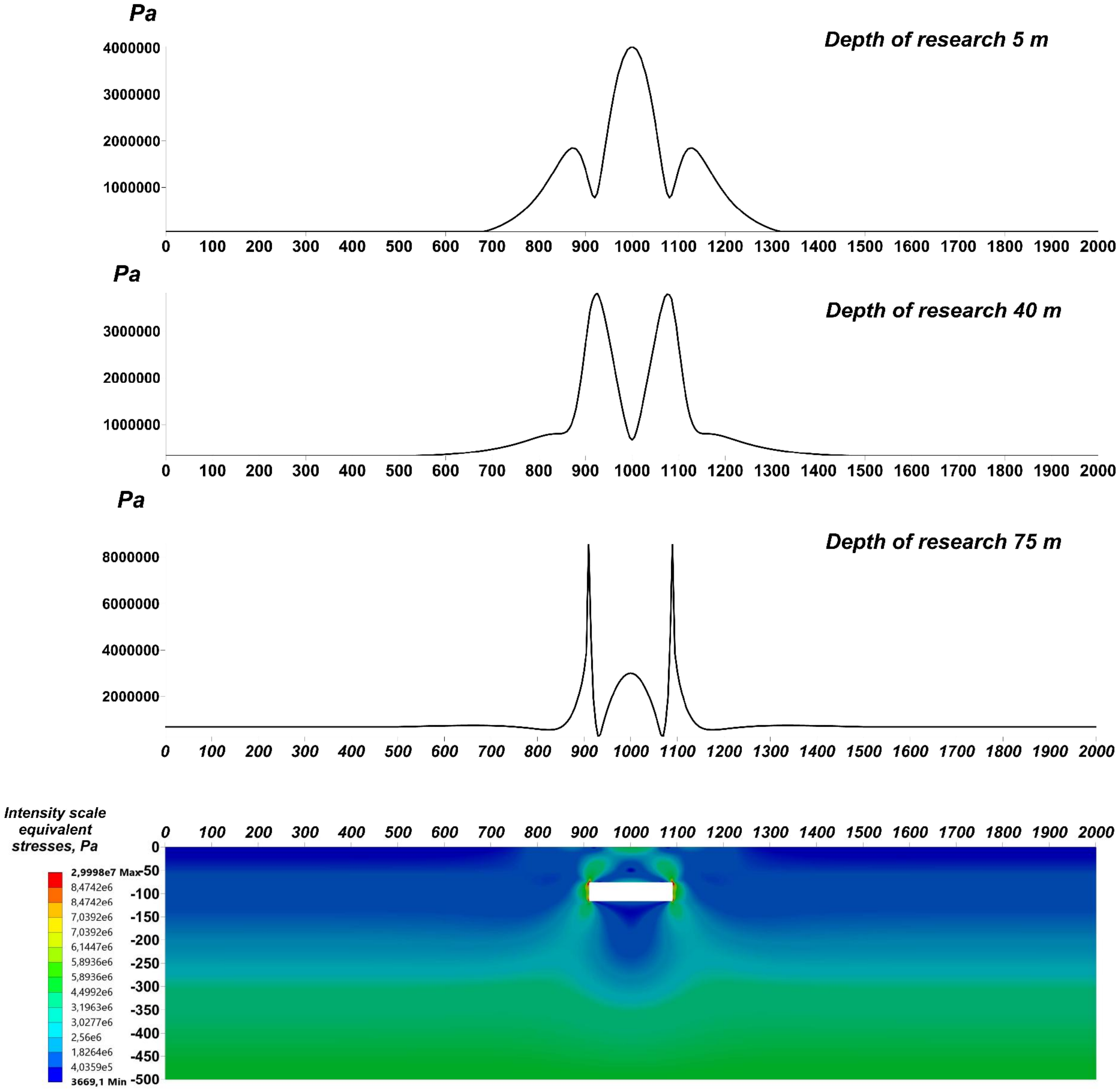


Fig. 4. Distribution of equivalent stresses in the surroundings of empty chamber

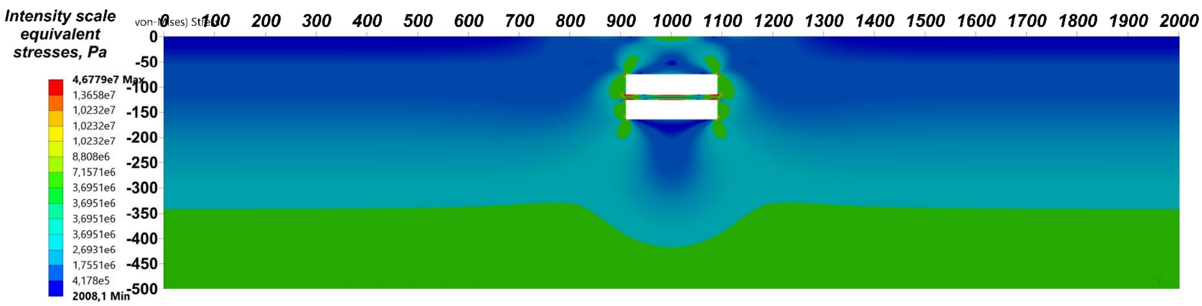


Fig. 5. Distribution of equivalent stresses in the surroundings of two chambers

Table 3

Correspondence of ENPEMF anomalies to the stages of subsidence within the Kalush-Golyn field

<table>
<tr><th rowspan="3">Mine</th><th rowspan="3">Ore field, area</th><th rowspan="3">Maximum value of subsidence of the ground surface, m</th><th rowspan="3">Maximum settling speed</th><th rowspan="3">Settling stage</th><th colspan="5">Characteristics of ENPEMF anomalies</th><th rowspan="3">Other geophysical methods</th></tr>
<tr><th colspan="3">In the plan</th><th colspan="2">By supporting profiles</th></tr>
<tr><th>By Intensity imp/s</th><th>By Size m×m</th><th>By shape</th><th>By Intensity imp/s</th><th>By Size m</th></tr>
<tr><td>“Kalush”</td><td>Khotynske sylvinite field</td><td>2.8</td><td>211 mm/year</td><td>Attenuation</td><td>65–85
significant</td><td>100×100
150×150
and bigger</td><td>annular, isometric</td><td colspan="2">No profiles</td><td>Gravimetry,
VES method,
TDEM method</td></tr>
<tr><td rowspan="2">“Novo-Golyn”</td><td>East Golyn</td><td>2.1</td><td>188 mm/year</td><td>Active</td><td>65–90
significant</td><td>100×100
180×280
and bigger</td><td>annular, isometric</td><td>65–90
significant</td><td>20–70
medium, large</td><td>Gravimetry,
VES method,
TDEM method</td></tr>
<tr><td>Sivka-Kaluska</td><td>0.48</td><td>17 mm/year</td><td>Initial</td><td>20–50
small
40–65
significant</td><td>20×20
40×40
small,
medium</td><td>Any, isometric</td><td>40–65
medium</td><td>20–85
medium,
small</td><td>Gravimetry,
VES method,
TDEM method</td></tr>
<tr><td>“Golyn”</td><td>Golyn</td><td>1.57</td><td>24 mm/year</td><td>Attenuation</td><td colspan="3">There were no observations.</td><td>65–90
significant
40–65
medium</td><td>60–180
medium, large</td><td>Not Applicable</td></tr>
</table>

Fig. 6 shows fragments of geological models of one of the minefields of the Kalush-Golynsky field and observation graphs of the ENPEMF over these geological structures. Graph of Fig. 6 fully corresponds to the model representations – two identical edge anomalies over the salt extraction chamber, which at the time of research was partially filled with brines.

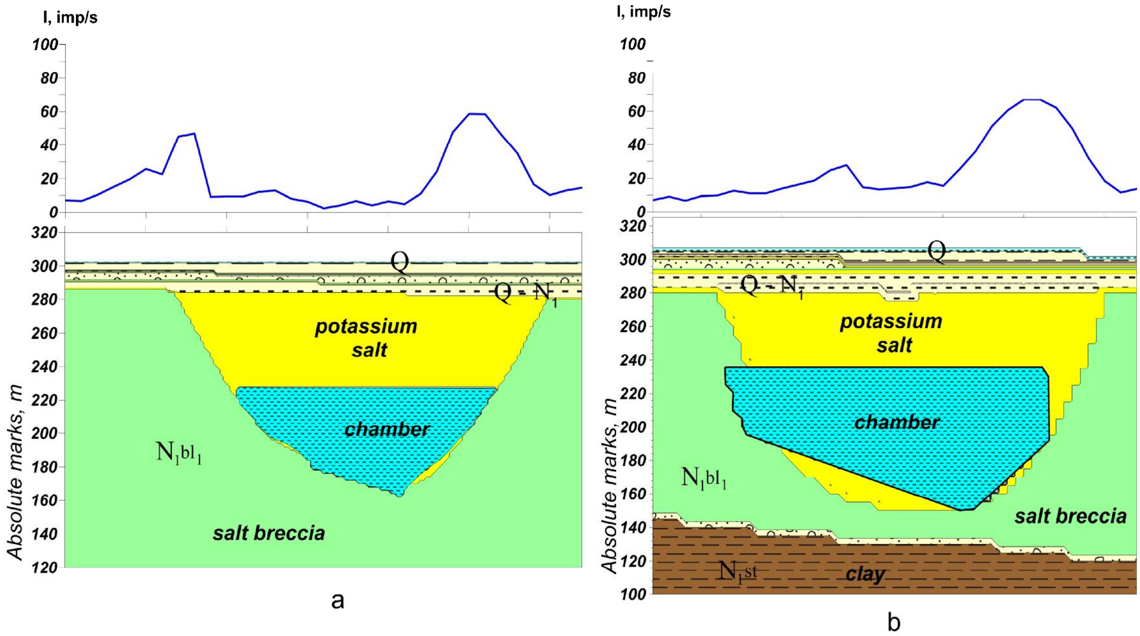


Fig. 6. Fragments of geologic models and corresponding ENPEMF curves:
a – solitary chamber, two parietal anomalies; b – solitary chamber, parietal anomaly

It should be noted that research using the ENPEMF method can be performed in different frequency ranges. Shown in Fig. 6 and further in Fig. 7 graphs are obtained for a frequency range of 2–50 kHz, which corresponds to depths from several meters to tens of meters. The change in the carrier frequency leads to a change in the depth and shape of the anomalies of ENPEMF, as can be seen in Fig. 4. The issue of depth is considered in more detail [Kuzmenko et al., 2018].

This indicates the need for field research in different frequency ranges. This will, firstly, provide the ENPEMF method with the properties of probing, that means research at different depths, and secondly, provide the possibility of selecting computational models for quantitative interpretation.

It is clear that both the physical properties of rocks and the geometry of their location can vary, leading to a change in the electromagnetic field. This is evidenced by the ENPEMF graph in Fig. 6, *b*, where a change in geometry resulted in a redistribution of the intensity values of the anomaly. This points to the fact that interpretation based on the use of theoretical research can be ambiguous.

The ENPEMF method was performed in all mininge fields of the Kalush-Golynsky field. Thus, a significant amount of geophysical material has been accumulated. For most areas, the method of ENPEMF was performed in the monitoring mode, as well as mode geodetic observations of subsidence of the earth's surface. The effectiveness and reliability of the ENPEMF method and the compliance of the results with theoretical studies are confirmed by the results of regime observations, an example of which is shown in Fig. 7.

In 2005, three peak-like anomalies of 25–50 imp/s were observed above the chambers, which corresponded to the presence of dynamic deformations within the side zones of the chambers and above the top (points 1150–1270). No subsidence of the earth's surface was observed, which means that the stage is pre-initial (latent). In 2013, the intensity of the electromagnetic field anomaly significantly increased (to 65 imp/s) for edge anomalies and 30 imp/s for the central one, and the subsidence stage went to the initial, and then to the active stage. The presence of these field anomalies, according to gravimetry, is explained, in addition to the action of the chamber, by the development of the loose zone. The development of this zone is associated with deformation processes and possibly with the washing of salt from rocks during the infiltration of surface water into the chambers. In 2021, there was a further development of the active stage, which was accompanied by a significant increase in the anomalies of the field intensity above the chambers within the area of points

1150–1260. Edge anomalies were probably amplified due to the presence of layers of lower deposits. In the same year, the processes of subsidence of the earth's surface in anomalous zones of ENPEMF according to topographic and geodetic observations intensified.

We should also note the increase in the field intensity in the left part of the profile compared to the background of 2005. This indicates the development of deformation processes due to the presence of the lower etage of chambers.We note that the distribution of anomalies of ENPEMF in Fig. 7 does not contradict model ideas of Fig. 4, 5 but indicates the need to develop the latter in connection with the complication of the initial models.

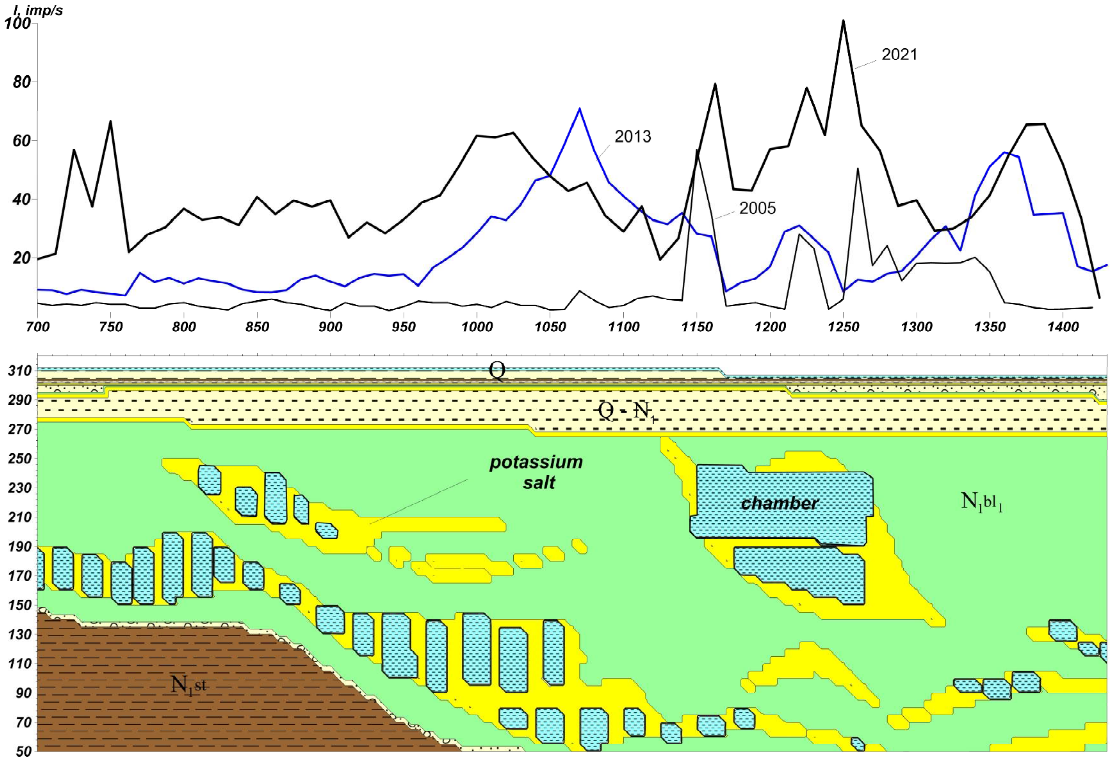


Fig. 7. Monitoring observations using the ENPEMF method

Scientific novelty

The novelty lies in the development of the principles of the disturbed rock mass stress-strain state quantitative assessment as the basis for the theoretical assessment of the natural pulsed electromagnetic field distribution. In particular, the study demonstrated the identity of the results of practical geophysical observations and computational models of the stress-strain state. The obtained results should be considered as the theoretical basis for the quantitative interpretation of the ENPEMF method.

Practical significance

The ENPEMF method has recently gained recognition as one of the geophysical methods capable of solving a number of engineering-geological, geo-ecological, geological and hydrogeological problems. Therefore, the immediate problem for the development of the method is the issue of developing the basis for its quantitative interpretation. A partial solution of the problem is given in the article. At the same time, the theoretical models are accompanied by practical results of research carried out on the territory of the Kalush-Golynsky potassium salt deposit.

Conclusions

1. The relationship between the distribution of mechanical stresses in the mining area and the accompanying natural pulsed electromagnetic field of the Earth should be considered as proven.

2. This relationship is confirmed by the identity of the stresses model calculations' results in the conditions of disturbed rock mass and ENPEMF graphs obtained in the field.

3. The display of the man-made disturbance of the mining area and its changes in the post-exploitation period is demonstrated in the field of ENPEMF on the example of the Kalush-Golynsky potassium salt deposit in the Pre-Carpathian region.

4. It seems necessary to analyze the regime observations of ENPEMF in the considered conditions in the system of ecological and geological monitoring, taking into account theoretical calculation models in order to predict the development of dangerous processes with the aim of preventing emergencies of anthropogenic nature.

References

Anikeyev, S. G., Bagriy, S. M., & Hablovskyi B. B. (2019). Imitation modelling technology for gravity inversion cases. *Visnyk of V. N. Karazin Kharkiv National University, series "Geology. Geography. Ecology"*, 51, 8–25. https://doi.org/10.26565/2410-7360-2019-51-01

Bagriy, S. M. (2016). Geophysical monitoring of the geological environment within potassium salt deposits (on the example of the Kalush-Golinsky deposit): dis. ... Candidate of Geological Sciences: 04.00.22. Ivano-Frankivsk National Technical University of Oil and Gas. Ivano-Frankivsk

Bagriy, S., Kuzmenko, E., & Dzoba, U. (2020). Correlation of natural pulsed electromagnetic field of the Earth with stresses and deformations, which appeared in exhausted salt fields in the Precarpathians for karst creation forecasting. *Visnyk Taras Shevchenko National University of Kyiv. Geology. 2.* 79–88. http://nbuv.gov.ua/UJRN/VKNU_geol_2020_2_13

Bezsmertnyi, A. F. (2004). Comprehensive geophysical studies of landslides and construction of predictive models of their activity (on the example of the South Bank of the Crimea): dis.... cand. of geological sciences: 01.04.12. Simferopol:

Cheban, V. D. (2002). A set of geophysical methods for predicting landslides on the example of Transcarpathia: dis.... cand. of geological sciences: 04.00.22. Ivano-Frankivsk: IFNTUNG.

Chepurnyi, I., Bagriy, S., Kuzmenko, E., & Chepurna, T. (2020). Time series analysis of karst breakdown development on the potassium salt deposit areas within Pre-Carpathian region. *Journal of Geology, Geography and Geoecology*, 29(2), 258–268. https://doi.org/10.15421/112024

Deshchytsia S. A., Podvirnyi O. I., Romaniuk O. I., Sadovyi Yu. V., Kolyadenko V. V., Savkov L. G., & Myshchyshyn Yu. S. (2016). Assessment of the state of ecologically problematic objects of the Kalusky mining and industrial district by electromagnetic methods and their monitoring. *Science and Innovations*, 5, 47–59.

Dovbnich, M. M., Stovas, G. M., & Kanin, V. O. (2012). Observation of ENPEMF and the vertical gradient of the Earth's magnetic field on the field of the mine named after O. F. Zasyadka. *Scientific works of UkrNDMI NAS of Ukraine*, 10, 342–348.

Dzioba, U. O. (2020). Effectiveness of the application of the ENPEMF method for monitoring the state of the geological environment in solving applied engineering problems. *Bulletin of the Odessa National University.* Vol. 25 No. 2(37), 238–253. https://doi.org/10.18524/2303-9914.2020.2(37).216574

Kovalchuk, S. P. (2003). Put your house correctly, (practice of the geophysical method of the ENPEMF). Odessa: Chernomorye, 112 p.

Kryzhanivskyi, E. I., Kuzmenko, E. D., Tarayevskyi, O. S., & Bagriy, S. M. (2017). Assessment of the change in the load of pipelines on the sections of underground-ground crossings. *Oil and gas industry of Ukraine*, 4, 28–33.

Kuzmenko, E. D., Bezsmertnyi, A. F., Vdovyna, O. P., Kryviuk, I. V., Cheban, V. D., & Shtogryn, L. V. (2009). Study of shear processes by geophysical methods Ivano-Frankivsk National University of Oil and Gas. monograph, 294 p.

Kuzmenko, E. D., Kryviuk, I. V., & Shtogryn, L. V. (2013). Development of methods for predicting landslides using geophysical methods. *Geodynamics*, 1. 176–187. http://nbuv.gov.ua/UJRN/geod_2013_1_23

Kuzmenko, E. D., Bagriy, S. M., Chepurnyi, I. V., & Shtogryn, M. V. (2017). Assessment of the danger of near-surface deformations of rocks within the Stebnytsky potash deposit by the method of ENPEMF. *Geodynamics*, 1(22), 98–113. https://doi.org/10.23939/jgd2017.01.98

Kuzmenko, E. D., Bahrii, S. M., Dzioba, U. O. (2018). The depth range of the Earth's natural pulse electromagneticfield (or ENDEMF). *Journal of Geology, Geography and Geology*, 27 (3), 466–477 https://doi.org/10.15421/111870.

Kuzmenko, E. D., Maksymchuk, V. Y., Bagriy, S. M., Sapuzhak, O. Y., Chepurnyi, I. V., Deshchytsya, S. A., & Dzoba, U. O. (2019). Integration of electric prospectingmethods for forecasting the subsidence and sinkholes within the salt deposits in the Precarpathian area. *Geodynamics*, (2 (27)), 54–65. https://doi.org/10.23939/jgd2019.02.054

Malyshkov, Y., & Malyshkov, S. (2016). The algorithm for calculating the earth's core runs on the parameters of natural pulsed electromagnetic field of the earth. Paper presented at the *IOP Conference Series: Earth and Environmental Science*, 48(1). DOI:10.1088/1755-1315/48/1/012028

Pysarenko, G. S. (1988). Reference book on the resistance of materials. Kiev: Naukova dumka, 736 p.

Salomatin, V. N., Mastov, S. R., & Zashynsky, L. A. (1991). Methodological recommendations for the study of the stress state of rocks by the method of registration of the natural pulsed electromagnetic field of the Earth (ENPEMF). Simferopol: KIPKS, KOSNIO.

Shashenko, A. N., Mayherchyk, T., & Sdvyzhkova, E. A. (2005). Geomechanical processes in rock mass National Mining University. D., 319 p.

Едуард КУЗЬМЕНКО[1а], Сергій БАГРІЙ[1б], Інна АРТИМ[2], Володимир АРТИМ[3]

[1] Кафедра геотехногенної безпеки та геоінформатики, Івано-Франківський національний технічний університет нафти і газу, вул. Карпатська, 15, Івано-Франківськ, 76019, Україна, тел. +38(0342)504761, ел. пошта: gbg2020@ukr.net ; [1а]https://orcid.org/0000-0002-1994-0970, [1б]https://orcid.org/0000-0003-1190-6222

[2] Кафедра геології та розвідки нафтових і газових родовищ, Івано-Франківський національний технічний університет нафти і газу, вул. Карпатська, 15, Івано-Франківськ, 76019, Україна, тел. +38 (0342) 72-71-21, ел. пошта: viarty1993@gmail.com, https://orcid.org/0000-0002-3388-6827

[3] Кафедра будівництва та енергоефективних споруд, Івано-Франківський національний технічний університет нафти і газу, вул. Карпатська, 15, Івано-Франківськ, 76019, Україна, тел. +38 (0342)57-24-04, ел. пошта: viartym@gmail.com, https://orcid.org/0000-0002-8938-552X

ВІДОБРАЖЕННЯ РОЗПОДІЛУ МЕХАНІЧНИХ НАПРУГ У ГІРНИЧИХ МАСИВАХ У ДИНАМІЦІ ІНТЕНСИВНОСТІ ПРИРОДНОГО ІМПУЛЬСНОГО ЕЛЕКТРОМАГНІТНОГО ПОЛЯ ЗЕМЛІ

Метою досліджень є обґрунтування теоретичних передумов інтерпретації геофізичного методу природного імпульсного електромагнітного поля Землі (ПІЕМПЗ) за допомогою кількісної оцінки напруженого стану масиву гірських порід, модельного зображення отриманих аналітичних залежностей для порушених масивів та координації одержаних розподілів напруженості з інтенсивністю електромагнітного поля як підґрунтя інтерпретації. Вихідними даними є класичні формули теоретичної механіки, модифіковані до умов геологічної будови об’єкта досліджень, та багаторічні дослідження методом ПІЕМПЗ на об’єкті – Калуш-Голинському родовищі калійної солі на Передкарпатті. Методологія досліджень передбачала розроблення та подання моделей напружено-деформованого стану гірничого масиву з подальшим розрахунком конкретних розподілів напруженості та аналізом їх зв’язку з динамікою ПІЕМПЗ для конкретних ділянок режимних спостережень. Результати досліджень наведено у такій послідовності: 1) приклад розрахунку модельних напружень; 2) практичні результати ПІЕМПЗ; 3) зіставлення теоретичних модельних розрахунків та даних реальних спостережень. Приклади розрахунків наведено для масиву гірських порід, що містить гірничу виробку прямокутної форми, розташованого у соляному пласті. Розподіл напруженостей розраховано для 2D-моделі з урахуванням реальних фізичних параметрів. У серії графіків показано зміну напруженості як по профілю, так і з глибиною. Модель ускладнена для варіанта двох камер, розміщених на різній глибині. Спостереження ПІЕМПЗ продемонстровано для складнопобудованого розрізу гірських порід. Фактичні графіки інтенсивності поля з високим ступенем кореляції відповідають розрахованим модельним механічним напруженням на певній глибині. Ускладнення розрізу та наявність різних стадій постексплуатаційного періоду, що відображається у режимних спостереженнях, призводить до відхилення форми графіків від “ідеально-модельного”, проте на якісному рівні ця форма відповідає теоретичній. Наукова новизна полягає у розробленні засад кількісного оцінювання напружено-деформованого стану порушеного масиву гірських порід як основи теоретичного оцінювання розподілу природного імпульсного електромагнітного поля Землі. Зокрема, продемонстровано ідентичність результатів практичних геофізичних спостережень та розрахункових моделей напружено-деформованого стану. Отримані результати можна розглядати як внесок у теоретичне підґрунтя засад кількісної інтерпретації геофізичного методу ПІЕМПЗ. Окреслено сферу подальших досліджень для повної реалізації цього напряму.

Ключові слова: напружений стан; гірничий масив; деформації; інтенсивність випромінювання електромагнітного поля.

Received 28.06.2022