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INTEGRATION OF ELECTRIC PROSPECTING METHODS FOR FORECASTING THE SUBSIDENCE AND SINKHOLES WITHIN THE SALT DEPOSITS IN THE PRECARPATHIAN AREA

Objective. The aim of this work is to study the efficiency of combining such methods as: investigation of the natural pulse electromagnetic field of Earth (NIEMFE) and transient electromagnetics (TEM) for the preliminary assessment of the degree of stability of mining fields within the deposits of potassium salts in the Precarpathian area, as well as forecasting the development of deformation processes in the near-surface layer of the geological environment. **Methodology**. Conducting areal and profile observations using NIEMFE and TEM techniques in the territory of the mining fields of potassium salts deposits and constructing the models of geoelectric sections; determination of zones with abnormal values of electrical conductivity and intensity of natural electromagnetic radiation. **Results.** According to the results of profile TEM and areal observations of NIEMFE on the mining field No. 2 of the Stebnytsky deposit of potassium salts, zones of abnormal electrical conductivity and anomalies in electromagnetic radiation intensity were detected and outlined. On the basis of the complex interpretation, the areas of increased karst sinkhole danger on a certain part of the Truskavets – Pisochnaya highway were singled out. The conclusion is that a set of methods NIEMFE and TEM for assessing the degree of karst sinkhole processes in the areas of mining activities is highly informative and efficient. **Scientific novelty.** The scientific novelty lies in the experimentally confirmed efficiency and high informativeness of the complex application of TEM and NIEMFE methods for studying the state of the geological environment endangered by karst deformation processes within the deposits of potassium salts. **Practical significance.** The proposed set of geophysical methods of TEM and NIEMFE allows predicting with high reliability the areas of probable karst sinkhole formation, which will allow taking preventive measures to minimize the consequences of karst deformation processes of a geological nature upon human settlement.

Key words: Stebnytsky deposit; potassium salt; perfusion-filtration process; electrical exploration; gypsum-clay cap; karst, depression.

Introduction

Designing the mining activities in the potassium salt deposits in the Carpathian region (Kalush-Golynske and Stebnytske) was carried out in the 1950–60s. It was believed that the mining method of extraction with due respect for design solutions would ensure the stability of rock masses. Accordingly, at that time, the possibility of subsidence and formation of karst caverns in it were ignored. Reality denied these assumptions.

Within the Kalush-Golynske deposit, the following mining fields were developed: Northern Cainite, Central Cainite, Khotynske Sylvinite, East Golyn, and Sivka Kaluska. In all mentioned mining fields without exception, earth subsidence and karst caverns were observed. The largest subsidence was recorded in the Northern Cainite Field – 4.8 m, where the lake was formed. The area of the largest karst sinkhole was about 0.6 hectares. In the Stebnytsky field, salt deposits were not divided into separate mining fields and were exploited by two mines No. 1 and No. 2. The maximum subsidence at the mine No. 1 reached more than 1.5 m in the area of Lake Bolonya, and in mine No. 2 – 1.76 m. In Kalush-Golynske field, 25 karst caverns were recorded while in the Stebnytske deposit there were 29.

The territory of Stebnytsky mining field is of a particular concern nowadays. There, in September 2017, the most noticeable karst doline in the history of the exploitation of salt deposits in the Precarpathians occurred. The sinkhole was the size of 220–230 m in diameter and 45–47 m deep. As a result, the electricity transmission line 220 collapsed because its towers as well as the water pipe system, which supplied water to the town of Drohobych, fell into the sinkhole. In 2016–2017, the deformation of the area of the Pisochne-Skhidnytsia highway, the main highway towards the resort of national importance Truskavets, was intensified. The distance between the motor road and the karst doline is about 300 m. In the meantime, the salt layer and mining chambers extend under the highway.

The problem lies in the necessity of development of the methodology for spatial and temporal forecast of karst doline phenomena as well as elaboration of a set of methods that can provide the mentioned forecast.

The Precarpathian salt deposits are not an exception in the formation of natural and man-made karst caverns. In a big number of mining fields around the world, there was a discrepancy between geological and hydrogeological models and the real situation. An overview of accidents at salt mines in Russia, Germany, Ukraine is described in the monograph [Gaidin & Rudko, 2016]. Concerning the salt deposits in Ukraine, the individual calculation schemes of stability of rock masses with the forecast of accidents are given in the reports from the scientific research works by the specialists of the Institute “Girkhimprom” (Lviv). The data of these reports is demostrated in the published works [Gaidin, et al., 2014; Gaidin & Rudko, 2016; Gaidin, 2018, Diakiv, et al., 2018]. These works should also include the necessary studies concerning the hydrogeological conditions and the deformation of the Earth surface [Gaidin, et al., 2014; Pavliuk, 2016; Mordvinov, et al, 2018; Burak et al., 2014].

These studies were based on numerous geological materials, drilling data, results of regular hydrogeological research, facts of underground water outbreak into the mines, and observations of the state of the underground mines.

Geophysical studies, which enable scientists to establish the differentiation of rocks at mining fields according to such parameters as the speed of pressure waves, density and electrical resistance of rocks, should be outlined separately. The general overview of these studies is published in the monography [Ogilvi, 1990]. The geophysical methods allow singling out and solving the tasks related to finding and stating the condition of a certain mining field at its certain stages of degradation and provide forecast solutions. However, there are still issues connected to such a complex approach and the determination of an effective set of geophysical methods of non-destructive control of the state and development of geological processes.

The experience of geophysical research in salt deposits in Ukraine shows that, in order to study the salt karst, three methods should be applied: gravimetry, transient electromagnetics (TEM), and investigation of the natural pulse electromagnetic field of Earth (NIEMFE) [Bagriy, 2016; Kuzmenko, et al, 2017; Kuzmenko, et al., 2018; Shurovskyi, et al., 2012, 2013; Deshchytsya et al., 2016; Maksymchuk et al., 2019].

The plane gravimetry solves the problem of extended differentiation of rocks in the mining area according to its solidity. Zones with decreased solidity stand for the zones where salt leaching and increased earth leakage take place. Thus, the discovery of these zones and charting them allows to establish the decrease in stability of the mining area and the probability of subsidence and sinkhole collapse. The experience shows that all karst sinkholes stand for the near-surface dissolution of rocks which always develop to the depth. These sinkholes are the areas of intensive absorption by the underground water and their further active filtration. The main drawback of the gravimetric method is a necessity to provide a quantitative interpretation of geologic models with initial approximation as the basis for which is a series of geologic cross-sections. Meanwhile, the grid of a model site must be commeasurable with a margin of error of geometrization of the final geo density sections and levels. It is possible only on the territories of exploitation, since beyond them the interpretation gets more problematic because of fragmentarity of geologic material. That is why, at Stebnytsky and Kalusky deposits the gravimetry was carried out at certain parts associated with karst dolines [Shurovskyi et al., 2012, Shurovskyi et al., 2013].

The method TEM allows constructing geoelectrical cross-sections and levels, or in other words, establishing differentiation of the rocks according to electrical resistance both laterally and in depth. During this process, dissolution zones, replete with hydrous solution, must stand out based on the change of electrical resistance in the areas of different mineralization. Thus, the problem for monitoring zones with active filtration of the underground water and zones with increased formation of caverns in the mining fields is solved. This allows making forecast conclusions for possible subsidence and sinkholes. Compared to gravimetry, this method has an advantage in the fact that it doesn’t need detailed initial models for interpretation. Any priori information can be applied. The disadvantage of this method lies in the fact that it provides general information, i.e. obtained extension of electrical resistance with depth is “assigned” not to one point but to the whole plane determined by the size of the installation. Construction of a solid grid of observation (as it is usually carried out in gravimetry) gets more complicated due to the high cost of work as well as technical restrictions for performing TEM in urban areas. At salt deposits in the Precarpathian area, the TEM method was applied only in certain areas [Deshchytsya et al., 2016].

The method NIEMFE is based on reflecting in the field natural electromagnetic radiation of stress-deformed state of rocks. A brief description of theoretical information about the method is presented in the work [Kuzmenko et al., 2018]. Thanks to the fact that a signal is recorded in one point by a portable device, there is a possibility to apply a solid grid of observation network. This is why obtained abnormalities in field intensity quite comprehensively reflect projection of zones with deformation development in the mining fields on the earth surface. However, there is no single-valuedness in establishing the depth of the electromagnetic source. This is the main drawback of the method. Recently, the NIEMFE method, which at the end of the previous century was applied for solving engineering-geological tasks only in Russia and Ukraine, has been successfully introduced in other countries [Abaturova et al., 2017; Frid, 1997; Gondwe et al., 2010; Greiling & Obermeyer, 2010; Obermeyer, et al., 2001; Pueyo-Anchuela, et al., 2010; Rabinovitch, et al., 1996].

It is important to mention that in recent times in engineering geology such methods as electrical resistivity tomography (electrical scanning) and radio-frequency survey are applied successfully. It is evident in the materials of the conference [Abaturova et al., 2017]. However, restrictions to use these methods in depth do not allow considering them as prospective in Precarpathian salt deposits.

Objective

The aim of the research is assessing the efficiency and sufficiency of a set of methods NIEMFE and TEM for preliminary assessment of the degree of stability of mining fields within Stebnytsky potassium salt deposits as well as forecasting the development of deformation processes and their physical interpretation.

Methodology

Presentation of the following research is drawn up in such order: methodology of the field geophysical exploration, analysis of the result materials of TEM, correlating the data of NIEMFE and TEM, geometrization of the abnormal zones laterally and in depth, principles of combining the methods of NIEMFE and TEM, involving the results of geodetic observations of deformation of the earth surface in analysis.

The specific object of research is the motor road section Skhidnytsya-Pisochne and its near-by territory, which is located within the southern-western part of the mining allotment of the mine No. 2 in Stebnytsky deposit. Selection of this section is explained by the following reasons: deformation of the road bed, existance of the mining chambers under the motor road, karst dolines near the road, and substantial subsidence. The motor road is the main highway to the resort town of Truskavets –which impacts international tourism.

From geological-structural aspect, the area of research is situated in the internal zone of Precarpathian downfold. The deposits, which form the geological structure of the territory, belong to Miocene – a lower division of the Neogene. According to its structural characteristics, the cross-section of this part is not complicated. The near-surface layer is formed by quaternary diluvial-alluvial sediment, argillo-arenaceous ground, sand clay with some amount of alluvium. Gypsum-clay cap formation (GCC) underlies at 80–120 m in depth. GCC belongs to quaternary-neogene age (solids, which were laid in Neogene age and underwent substantial metamorphization as a result of eolation and saline wash-out). The next layer is Neogene solids of Vorotyshenska formation. They are divided into upper-vorotyschensky salt-bearing deposits and lower-vorotyschensky salinized breccia. The joints between layers are subvertical.

As a result of defomation of the earth material during salt extraction, the circulation of underground water was intensified within a gypsum-clay layer and washing-out of salt table occurred. Due to the intensive filtrational processes in the mantled and salt-bearing layers, karst and underwashing processes were developing, which led to the dissolution of the rock masses, decrease in the stability of the mantle rocks over the mining diggings and, respectively, the unexpected subsidence and the development of the karst doline. Besides, the cases of the mining chambers collapse are registered. It is recorded that the mine No. 1 is currently in dry condition while the mine No. 2 is being flooded. The total size of the mine No. 2 is 13651400 m^3. At this time, approximately 11.5 m^3 are flooded. The size of the chambers that are in the process of flooding is 120 000 m^2. The square of the mining allotment of the mine No. 1 is 976.8 ha and the mine No. 2 is 1289 ha.

As it was mentioned before, the research was carried out with the help of NIEMFE and TEM methods by the specialists of Ivano-Frankivsk National Technical University of Oil and Gas and the Carpathian Division the Serafym Subbotin Institute of Geophysics (IGP) of the National Academy of Sciences of Ukraine respectively. The observation with the help of NIEMFE method had the plane nature and was performed on a solid area with the grid 20×10 m and general size 1360×140 m. For this, the testing device radio-wave indicator of a tense-deformed state (RWITDS-M) with the frequency range 2–50 kHz was used. The TEM method was applied in the modification "loop in the loop" with the station for shallow (10–60 m, the size of a transmitter loop 30×30 m^2, the size of a receiver loop 20×20 m^2) and deep (50–400 m, loops 125×125 m^2, and 20×20 m^2 ×27 spirals respectively) sounding. Sounding was executed along two main profiles 1330 m long each located subparallelly to the motor road from both sides (Fig. 1).

It must be also noted that along the road to the east, at the distance from the first meters to 40 m, there is a lubber line along which the geodetic leveling studies were carried out annually from 1997 to 2017. It gave a possibility to monitor the dynamics of subsidence and correlate the results with geodetic research.

Results

The final result after processing the data obtained by measuring using TEM method is the geoelectrical cross-section at which the change of electrical resistance with depth is illustrated. For example, in Fig. 2, there is a fragment of the depth section for profile 1, obtained by observation with the device TEM for deep sounding (50–400 m, loops 125×125 m^2 and 20×20 m^2 ×27 spirals). The cross-section involves the interval of subsea depth 280 ÷ -100 m, i.e. the layer 380 m deep.

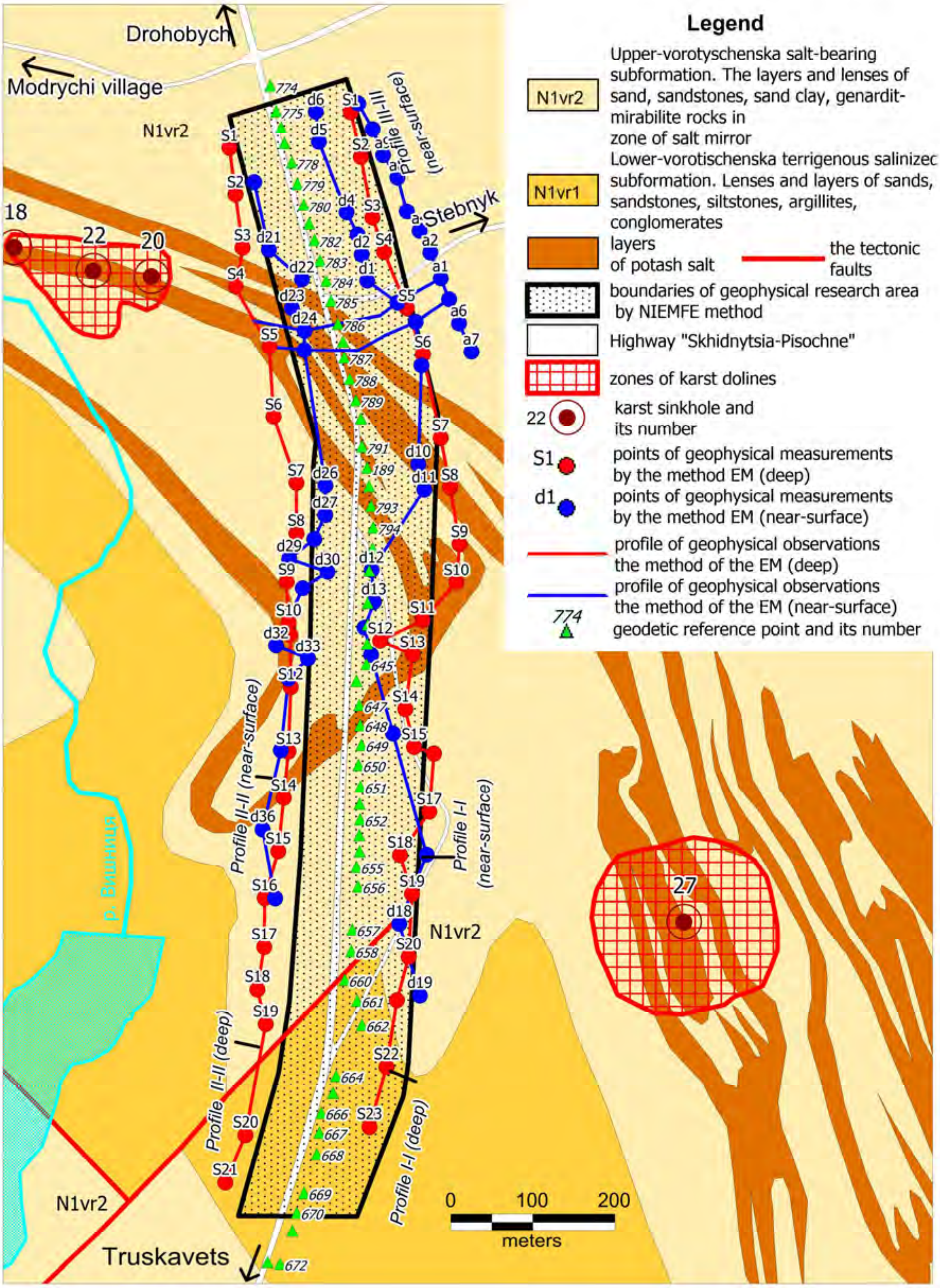

Fig. 1. The scheme of location of the area of geophysical research at Stebnytsky potassium salts deposit

This is quite enough for analysis and objective conclusions. At the cross-section from the point +150 to the deep, there is a layer of highly resistant rocks (40–400 Om·m), which are divided into blocks by deep splits. Zones with deep splits tend to have decreased resistance (2–20 Om·m).

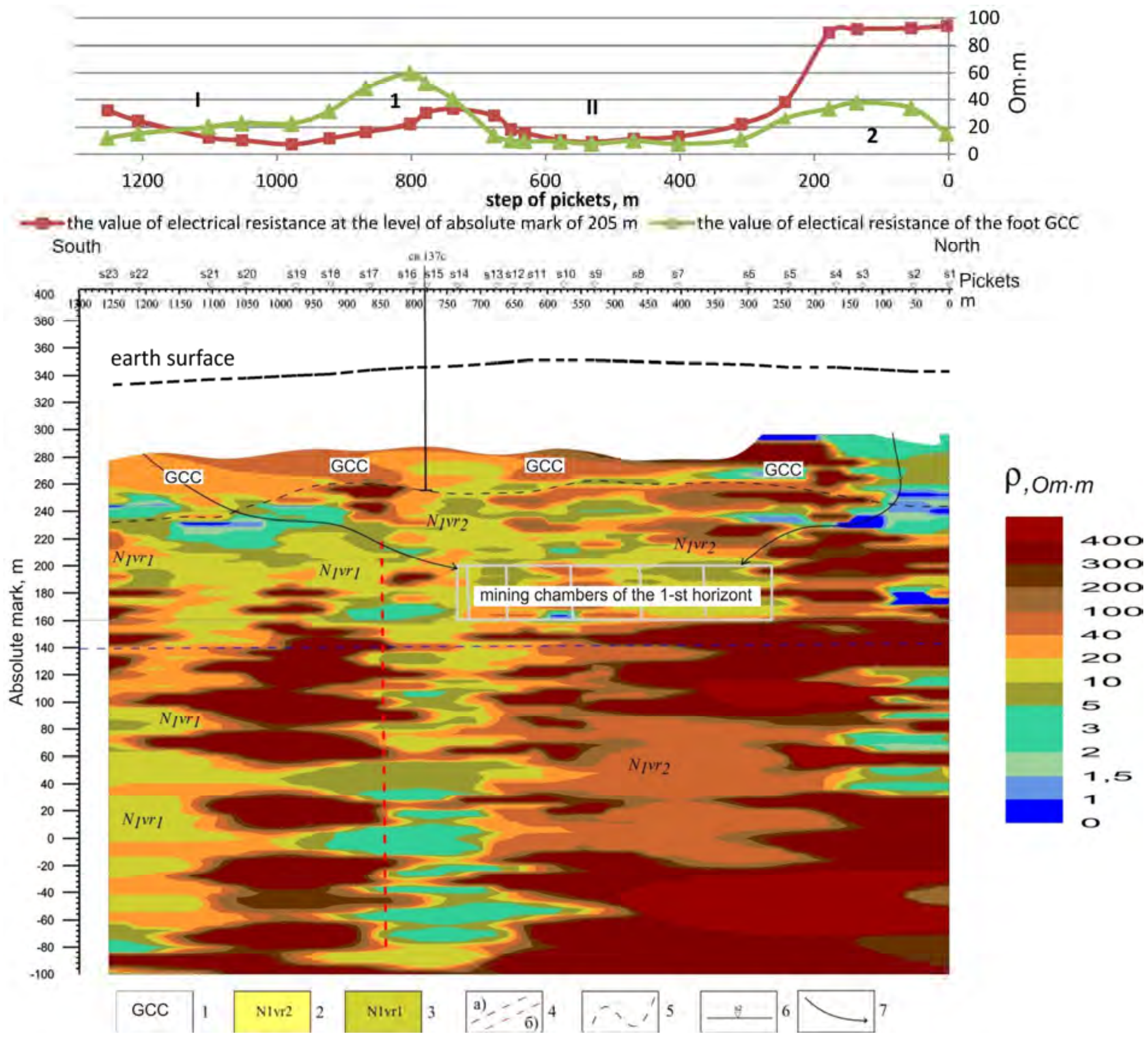

Fig. 2. Geoelectrical cross-section with the diagrams of the apparent resistivity according to the data of TEM along the profile I-I (near-surface)

1 – deposits of gypsum-clay cap; 2 – deposits of upper-vorotyschenska formation; 3 – deposits of lower-vorotyschenska formation; 4a – the level of the ceiling of the 2nd adit level chamber; 4b – tectonic deformation; 5 – lithologic borders; 6 – surveyor' stations for TEM; 7 – ways of water penetration into the chambers

Splits in the southern part of the profile correspond to lithologic junction between upper- and lower-vorotyshensky rocks. The second split, which is opened up by the drill hole in the upper part (shown in the cross-section), has the vertical fall and was unknown before. At the cross-section, there are mining chambers, the foot of which is located at 155 m, and the chisel-like ceiling – at 201–210 m. The chambers are flooded by 2/3, which is shown as zones of decreased resistance – 5–20 Om·m at the cross-section, although some chambers are not outlined by the isolines of resistance, taking into account the integral features of TEM method. It is probable that at the area of stations s9, s10 (500–600 m from the beginning of profile) the ceilings collapsed, which is shown as high resistance (over 300 Om·m) in the zone of chambers. Apart from the specified structural and man-made properties, zones of active filtration of the underground water are observed at the cross-section; meanwhile the arrows, which show the direction of the filtration processes in Fig. 2, cross the depression (lowering the relief) along the border “the foot of GCC – the cover of neogene vorotyshen rocks”, which is a confirmation of allocation validity at the cross-section of electrical resistance. The centres of the mentioned depression are projected to the earth surface at the marks 700 m (between the stations s13 and s14) and 1100 m (s21).

There are two diagrams of electrical resistance for characteristic elements of this cross-section illustrated over the geoelectrical cross-section. The foot of the GCC was selected as the first element. The surface of the salt table, which lies lower, is mostly likely in the process of washing out. That is why, the change in the resistance along this surface contains the information about the degree of this wash-out and probable development of the natural and man-made karst. The subsidence of the rocks in the developed karst caverns leads to dissolution of the overlying level and further deformation (subsidence, sinkhole) of the earth surface. For the second element, the level of absolute mark (205 m), which on average corresponds to the level of the chamber ceilings, was selected. The change of resistance at this level can witness dissolution, resulting from filtration of the salt brine into the mining chambers, as well as the ceiling collapse. In the corresponding Fig. 2, abnormalities of the increased resistance (marked as 1 and 2) and abnormalities of the decreased resistance (I, II) correlating between each other are illustrated.

Abnormality I corresponds to the zone of intensive inleakage of the surface water with further movement of the salt brines to the north and north-east, that is to the direction of chambers. Abnormality II is related to the general dissolution of rock masses from the GCC level to the chambers, which leads to the decrease in stability of the upper layers and results in deformation of the earth surface over the salt deposit.

In contrast to observarions with TEM, which due to some external reasons are carried out at individual profiles and are displayed graphically in certain cross-sections, the survey with NIEMFE has a plane format. Respectively, the results are presented as maps of electromagnetic radiance intensity according to the directions X (latitudinal), Y (longitudinal), Z (vertical) based on the direction of the device antennae. The map of c $I=\sqrt{X^2+Y^2+Z^2}$ show the influence of signals according to each antenna, which usually correlate between each other.

In order to compare the results of the methods TEM and NIEMFE, the diagrams of electical resistance of the foot GCC, absolute depth mark 205 m (Fig. 2) and the complete vector of the NIEMFE intensivity were contrasted in Fig. 3. Simultaneous analysis of the charts indicates that in the right part of the figure, the abnormalities in the graphs coincide. Particularly outstanding is this coincidence for the intensity and decrease in resistance at an absolute depth mark of 205 m. It is worth paying attention to the abnormality II and 2 on the I-I profiles, where zones of lower resistance correlate with the areas of reduced intensity and vice versa. In the meantime, the zones of reduced values of intensity and resistance correspond to the areas of exhausted salt deposits by the first level of chambers.

In Fig. 4, a graph illustrates the intensity of the NIEMFE and the displacements of the earth surface on the geodetic datum according to the geodetic observations along the lubber line which is located in the area of survey with NIEMFE (Fig. 1). The visual analysis of the correspondence between the subsidence graphs and the abnormalities of NIEMFE shows that: 1) everywhere where there is subsidence and abnormalities; 2) NIEMFE is a leading indicator for the areas with the abnormalities.

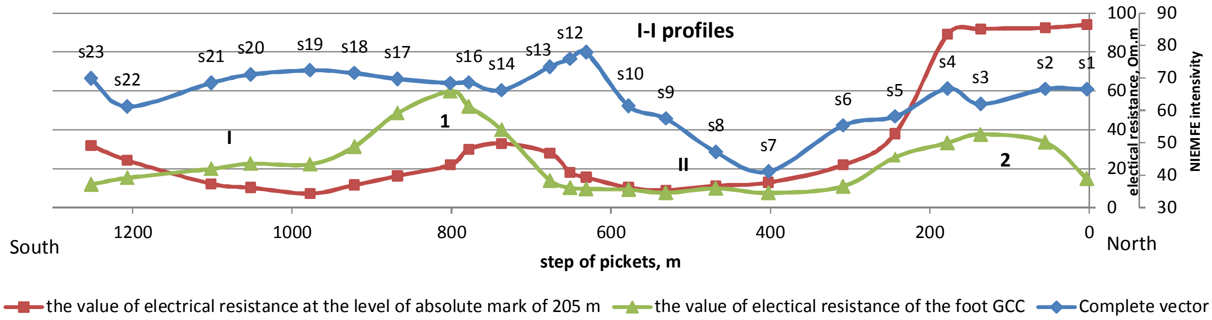

Fig. 3. The graphs of the change in electrical resistance and the complete vector of intensity NIEMFE

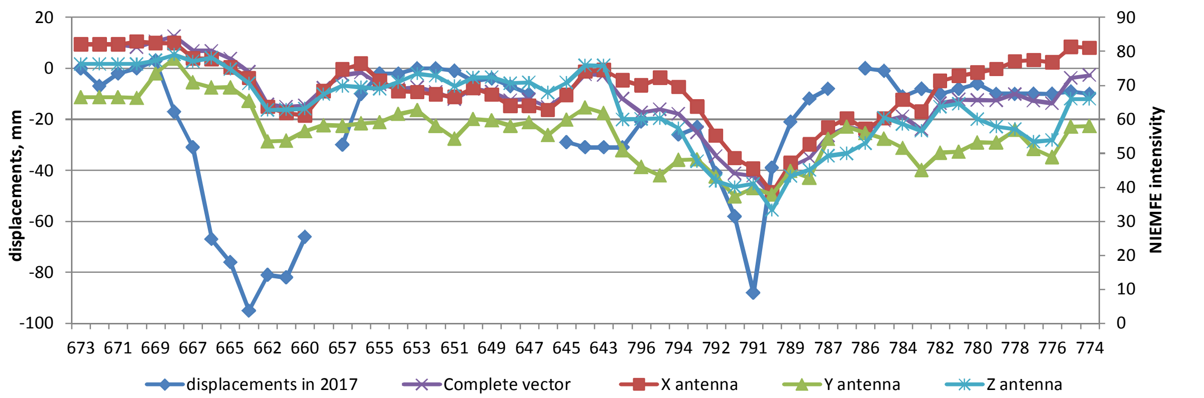

Fig. 4. The graphs of NIEMFE intensity and displacements of the earth surface at geodetic datum

Evaluating the results of NIEMFE, it must be mentioned that the degree of intensity of electromagnetic radiation corresponds to a certain stage of deformation of the rock masses and the degree of subsidence. In accordance with years of geophysical research and gradation of the activity of subsidence adopted in the practice of geodetic monitoring [Kryzhanivskyi, et al., 2008], it is proposed to single out 5 stages of deformation, the characteristics of which are given in Table 1.

For the zone of development of the salt layers within the research area, the deep continuous minimum of NIEMFE (pickets 200–800) is observed. This minimum corresponds to the destructive stage of deformation, which will further develop in the northern direction. In the southern part of the profile (pickets 1100–1200), deformation goes into the attenuation stage.

Let's perform a correlation analysis between all the geophysical data involved. The results are presented in the form of a cross-correlation diagram (Figure 5). The correlation, as it should be, is positive, and the correlation coefficient is about 0.4; this value is close to a significant one (the dashed line in the figure corresponds to the level of significance). Thus, the methods of TEM and NIEMFE correlate with each other even in a completely different physical approach to obtaining resultant signals. It should be noted that the deviation of the maximum value of the correlation coefficient in the graph (Fig. 5) is explained by the layer extension from the northwest to the southeast, which will be illustrated further.

Table 1

Classification of stages of deformation of the earth surface

Stage of deformation	Characteristics of the electromagnetic field	State of a rock mass	State of the earth surface by geodetic observations
Zero	The background average intensity (hundreds or thousands cps) with a possible slight deviation due to lithologic heterogeneity	No preconditions for deformations and changes in the stress-strain state of a rock mass. Usually, there are no mines working	No changes over a significant period of observation
Pre-initial	Insignificant increase in the intensity of the field (by hundreds, rarely the first thousand cps)	Minor deformation processes in the rock masses are associated with a certain change in the stress state due to salt leaching, possible human-made effect, solidification or dissolution	Surface deformations are absent, no subsidence
Initial	Increasing the intensity of the field (by hundreds or the first thousand cps), usually with a mosaic distribution in area	Development of dissolution of the rock masses, activation of infiltration and filtration of groundwater with a display of deformation in the near-surface layer	The initial subsidence in millimeters or the first dozens of millimeters
Active	Significant increase in the intensity of the field (by thousands cps). Possible alternations in the areas of moderate and significant abnormalities	Significant increase in underground karst-sulphosity processes with a visual display of the deformations of the earth surface and structures	Significant subsidence for hundreds and thousands millimeters, formation of karst dolines, usually in the shape of individual sinkholes. The rate of subsidence is hundreds millimeters a year
Destructive	Significant decrease in the intensity of the field (by thousands cps). On the edges of abnormalities of low values, a ring of high intensity is usually formed due to lateral tension	Continuation of development of significant underground changes with the subsidence of rocks on the surface	Significant subsidence for hundreds and thousands millimeters. Along with insignificant karst dolines, there is a possibility of formation of catastrophic collapses
Attenuation	The intensity of the field increases to an insignificant level (by hundreds and first thousands cps). Possible both decrease and increase of the signal in comparison to a background one	Leveling in general stress-strain state, that is, stress release, while the final local deformation are still in progress	The rate of subsidence decreases to several millimeters per year and eventually falls to zero

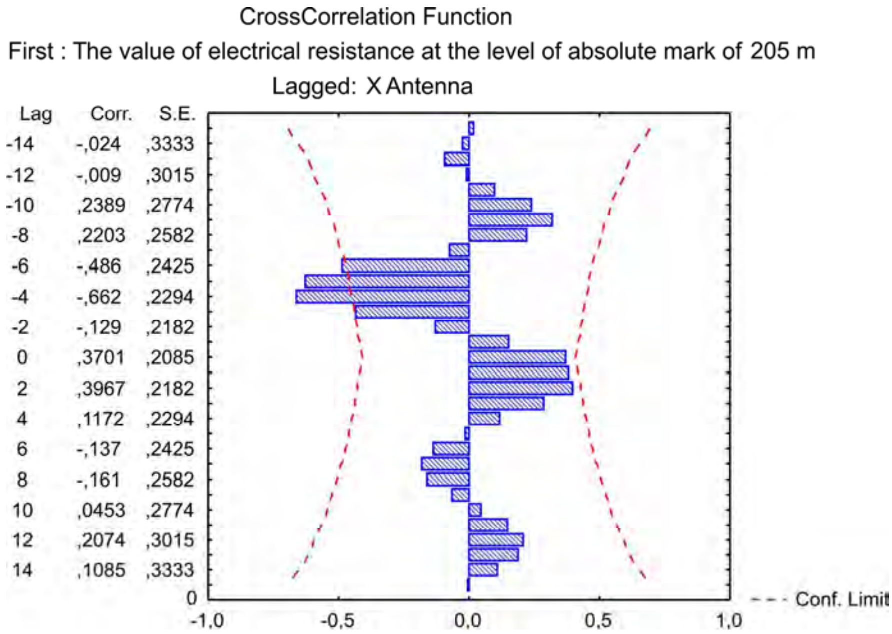

Fig. 5. Cross-correlational graph of the data TEM and NIEMFE

Now it is necessary to understand at what depth the NIEMFE signals are generated and whether a certain dominant range of depths is distinguished at the same time. In order to answer this question, the value of the electric resistance along the profile with a discrete horizontally, equal to the distance between the points of the profile, is selected, and vertically – 10 m for the interval of absolute marks from 100–270 m. For each selected absolute mark, the degree of correlation of NIEMFE intensity values and resistance according to TEM is determined. The obtained correlation graph for the X antenna is graphically generated and presented in Fig. 6.

Before analyzing the graph (Fig. 6), it is important to remind that the position of the foot of the GCC varies within the absolute values from 240–260 m, the ceiling of the chambers – within 201–210 m, and the foot of the chambers at 155 meters. The distinctive zones of the positive correlation coefficients are observed in intervals of 200–210 m and 160-170 meters. It is obvious that the first interval corresponds to the rocks that are slightly below the level of the GCC foot and are deformed (diluted) as a result of subsidence into voids formed as a result of the erosion of the salt table. The second interval of increased values coincides with the position of the chambers, namely, their flooded part, and is probably caused by the change in the intra-chamber pressure of salt brines.

Now, let's go to the plane characteristics. In Fig. 7, it is illustrated the northern part of the survey area, which contains a salt layer with extraction chambers as well as the host rocks of saline breccia. The presented map contains a field of intensity of NIEMFE and a section of changes in electrical resistances (abnormalities of high and low values). The width of the sector corresponds to the size of the TEM loop, that contains the generalized resistance determined for the area of the loop.

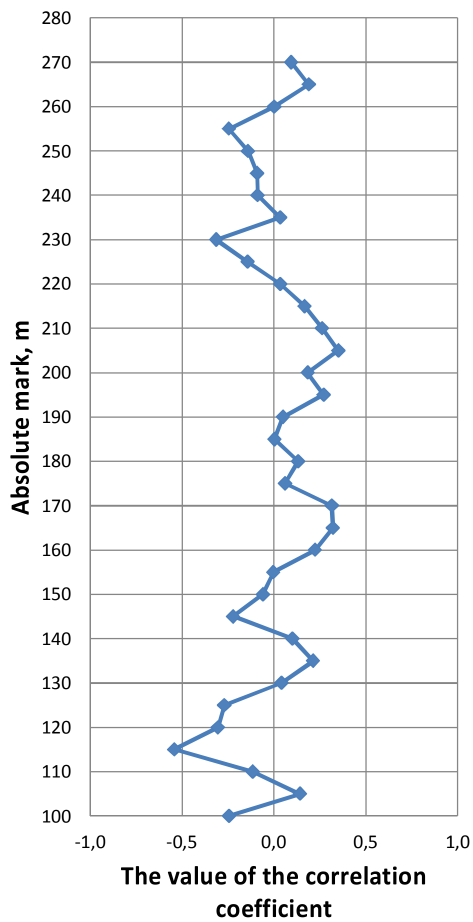

Fig. 6. Correlation of NIEMFE and TEM data at the level of different absolute geoelectric cross-section markers

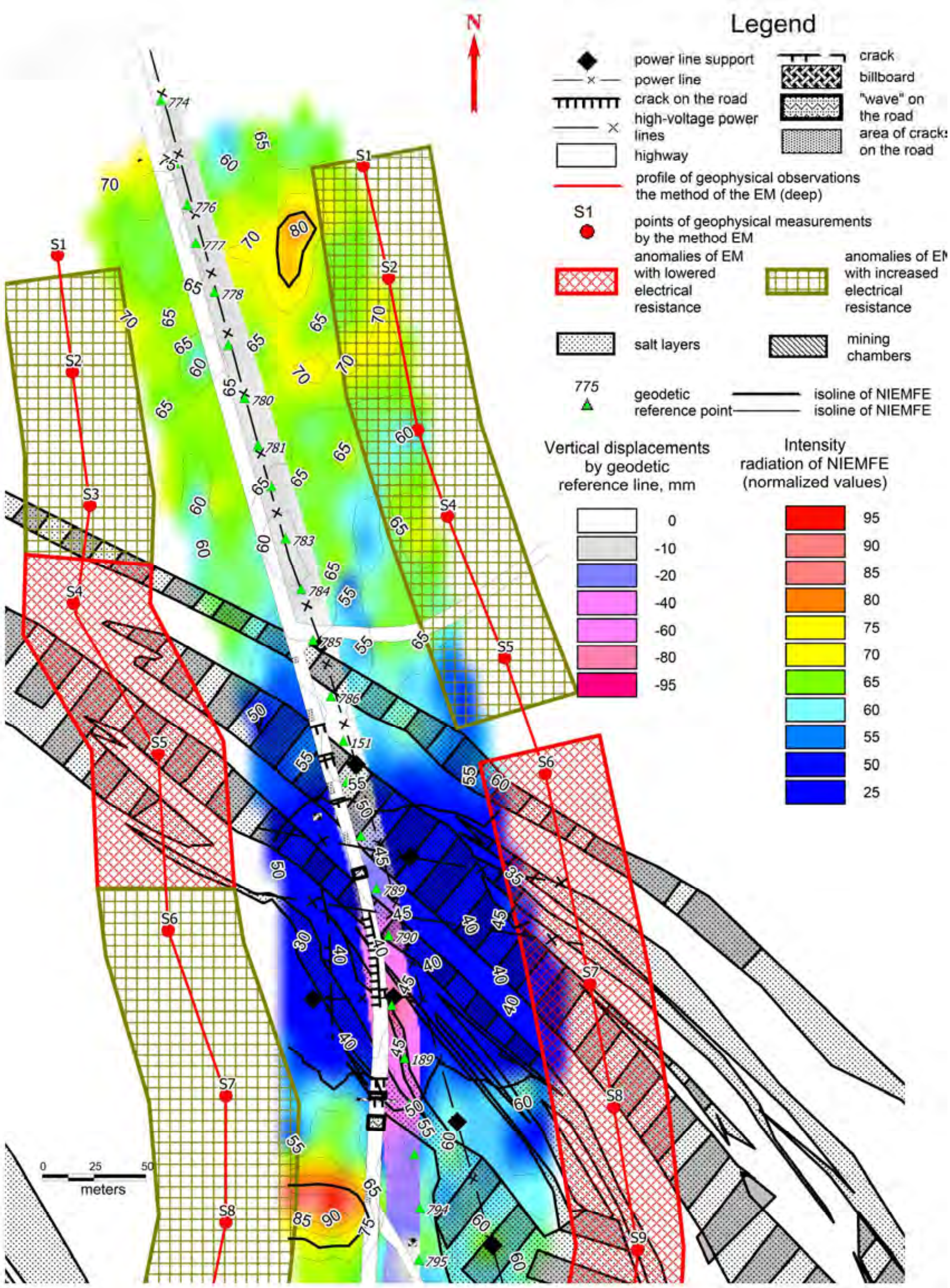

Fig. 7. Plane distribution of abnormalities by the methods of the TEM, NIEMFE, and geodetic surveys

In addition, in the special conditional sector, in the center of which there is a lubber geodetic line, the zones of intensive subsidence are indicated. All abnormal areas, that is, the decrease in the intensity of the natural electromagnetic field, low values of electromagnetic resistance, and significant subsidence, all coincide or adhere to each other. The general abnormal zone extends from the north-west to the south-east, while the boundaries of the abnormalities of the TEM and NIEMFE basically coincide. As result, a single geophysical abnormality is formed (Fig. 7).

It is necessary to note the regularity in plane or linear sizes of abnormalities. The largest area is the abnormality NIEMFE. It is about two hundred meters wide in the direction of the north-east – south-west, and its length obviously extends beyond the boundary of the survey along the salt formation. The large area of the abnormality and the significant decrease in the intensity of the field (almost half), along with significant subsidence at the central point (185 mm, including 85 mm in 2017), suggest that this is a section of destructive deformations. The peripheral part of the abnormalities, where the subsidence is insignificant, characterizes the zone of initial deformation, which in the future will develop into the active stage. Thus, applying the NIEMFE method, we can observe abnormalities that correspond to the activation of the stress-strain state at different stages of deformation. The outline of the abnormalities of the TEM, defined along the profiles, are within the limits of the NIEMFE abnormalities. This is explained by the fact that in order to form an abnormality of the lower resistance, more substantial dissolution is required than for the formation of abnormalities of NIEMFE. The smallest size, in comparison with the abnormality of NIEMFE (along the line of geodetic datum line), has sections of within the formation of which a significant dissolution of rocks is required, which is associated with the development of karst-sulphosity processes and the deformation of the near-surface layer.

Scientific novelty

The scientific novelty lies in the experimentally proven efficiency and high informativeness of the complex application of the TEM and NIEMFE methods for researching the state of the geological environment involved in the karst sinkhole processes within the deposits of potassium salts.

Practical significance

The practical significance consists in the necessity to determine the primary complex of geophysical methods for non-destructive control of the state of the rock masses at the exhausted salt deposits with the subsequent plane forecast of the destructive processes in order to prevent the consequences of the development of emergency situations of a geological nature. The efficiency of this set of methods is demonstrated on the basis of the research in the area of development of natural and human-caused salt karst in the Stebnytsky potassium salt field in the Precarpathian region.

Summary

Thus, we arrive at the conclusion that it is effective to combine the plane NIEMFE and the profile TEM techniques. Then, the method of NIEMFE clearly confirms the deep nature of subsidence and sinkholes as well as forecasts the limits of their further development. With the help of the method of TEM, the development of salt leaching processes to the depths is observed, and the differentiation of the rocks by electrical resistance and the degree of dissolution and zones of active filtration of groundwater are established. The TEM method has certain limitations due to the methodological features and cost, so separate profiles should be placed based on the data of the NIEMFE plane survey. The results of the TEM is the information for establishing the centers for changing the stress-strain state of rocks, that is, they are necessary for the interpretation of the causes of the occurrence of the abnormalities of NIEMFE.

A comprehensive approach to forecasting the subsidence and collapses allows reproducing the spatial picture of the dynamics of changes in the rock masses as a result as well as the natural and human-made factors. An important factor is the availability of regular geodetic observations for confirmation of the danger of the development of deformation processes and the final determination of the deformation stage of the rock mass.

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КОМПЛЕКСУВАННЯ МЕТОДІВ ЕЛЕКТРОРОЗВІДКИ У ЗАДАЧАХ ПРОГНОЗУВАННЯ ТЕХНОГЕННИХ ПРОСІДАНЬ І ПРОВАЛІВ НА РОДОВИЩАХ СОЛІ ПЕРЕДКАРПАТТЯ

Мета. Метою роботи є дослідження ефективності комплексу методів природного імпульсного електромагнітного поля Землі (ПІЕМПЗ) та зондувань становленням електромагнітного поля (ЗС) для попередньої оцінки ступеня стабільності гірничих масивів у межах родовищ калійних солей Передкарпаття, а також прогнозування розвитку деформаційних процесів у приповерховому шарі геологічного середовища. **Методика**. Проведення площівних та профільних спостережень методами ПІЕМПЗ та ЗС на території шахтних полів родовищ калійних солей та побудова моделей геоелектричних розрізів, визначення зон з аномальними значеннями електричної провідності та інтенсивності природного електромагнітного випромінювання. **Результати**. За результатами профільних електрометричних методів (ЗС) та площівних спостережень ПІЕМПЗ на території шахтного поля рудника № 2 Стебницького родовища калійних солей виявлено та оконтурено зони аномальних значень електропровідності та аномалії інтенсивності електромагнітного випромінювання. На основі комплексної інтерпретації виділено зони підвищеної карстопровальної небезпеки на ділянці автодороги Трускавець – Пісочне. Зроблено висновок про високу інформативність та ефективність комплексу методів ЗС і ПІЕМПЗ для оцінки ступеня карстопровальних процесів у зонах розроблення корисних копалин. **Наукова новизна.** Полягає в експериментально підтвердженій ефективності та високій інформативності комплексного застосування методів ЗС і ПІЕМПЗ для вивчення стану геологічного середовища, охопленого карстопровальними процесами у межах родовищ калійних солей. **Практична значущість.** Запропонований комплекс геофізичних методів ЗС і ПІЕМПЗ дає змогу з високою достовірністю спрогнозувати зони ймовірних карстових провалів та здійснити запобіжні заходи для мінімізації наслідків розвитку карстопровальних геологічних ситуацій.

Ключові слова: Стебницьке родовище; калійна сіль; суфозійно-фільтраційний процес; електророзвідка; гіпсо-глиниста шапка; карст; депресія.

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