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EVALUATION OF KARST-CHASM HAZARD PROCESSES BY ELECTROPROSPECTING METHODS IN THE LOCATION OF STEBNYK POTASSIUM DEPOSIT

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Purpose. The purpose of this work is definition of potentially ecologically-hazard and karst-chasm zones and prediction of karst development near the Skhidnytsia-Pisochne highway on the area of mine No. 2 of Stebnyk potassium deposit by electroprospecting method, namely time domain electromagnetic method (TDEM). **Methodology.** The research was carried out using the TDEM method in the modification of "the contour in the contour". To study the upper part of the cross-section down to 100 meters, the digital equipment for electroprospecting "Stage" was used. For information about the depths of 50–100 meters and up to 300–400 meters, a digital electric station "Impulse 3M" was used. Field observations by TDEM methodically consisted of three phases which included: sounding on parametric wells, thus clarifying electrical parameters of the geological environment; observations along defined profiles; and creation resulting of geoelectric cross sections with the reference to the lithology of the working area. **Results.** In the northern part of research area within the sediments of the gypsum-clay cap anomalous electrical conduction zones are identified. They are associated with filtration-suffusion processes. As well an anomaly was defined in the southern part of the area in the Vorotyscha suite sediments at depths greater than 100 meters, which was associated with the formation of a depression funnel. **Originality.** The possibility of the TDEM method application for the study of karst-chasm processes on the territory of the Stebnyk potassium deposit was investigated. For the first time, using the electrical prospecting methods an estimation of the state of geological environment within the mine field No. 2 of the Stebnyk potassium deposit on the area of the Skhidnytsya-Pisochne highway was made. It is shown that the TDEM method in the complexization of two types of devices with different measurement depths allowed detailed diagnosis in the geological environment in the range of depths from 10 to 400 m with the allocation of zones of abnormal electrical resistivity, which are associated with the suffusion-filtration processes. **Practical significance.** Accordingly to the results of electromagnetic observations on the area of the highway Skhidnytsya-Pisochne in the location of the mine field No. 2 of the Stebnyk potassium deposit, the zones covered by the filtration-suffusion processes are defined. These zones are the primary objects that should be the subject of close attention for further monitoring of karst-chasm processes, and the fact of their availability should be taken into account when making administrative decisions by the authorities on the expediency of transferring the location of the highway and other infrastructure.

Key words: Stebnyk deposit; potassium salt; suffusion-filtration process; electrical prospecting; gypsum-clay cap; karst, depression.

Introduction

The intense long-term extraction of potassium salts in the Pre-Carpathians mining regions has a negative impact on the geological environment. The development of potassium salt deposits leads to a violation of geological and hydrogeological conditions in the areas of mine fields, which promotes the development of dangerous geological processes, including karst, landslides, and the formation of depression reservoirs.

To such dangerous objects belongs the Stebnyk potash deposit, where the extraction of salts occurs at the mines ST-KR-1 and ST-KR-2. Over depleted mining fields as a result of reservoir water infiltration in mining, a depression reservoir was formed, within which there is an intensive development of karst [Gajdin, & Rudko, 1998]. This is evidenced by the karst phenomena that occurred on the territory of the mine field No. 2, in particular, on September 30, 2017, a gap of about 300 m in diameter and more than 40 m in depth was formed here [Gajdin, 2017], which resulted in the collapse of the power line. Under the threat was the Skhidnytsya-Pisochne highway, which revealed asphalt covering and the formation of many numerical cracks [Maksymchuk et al., 2019].

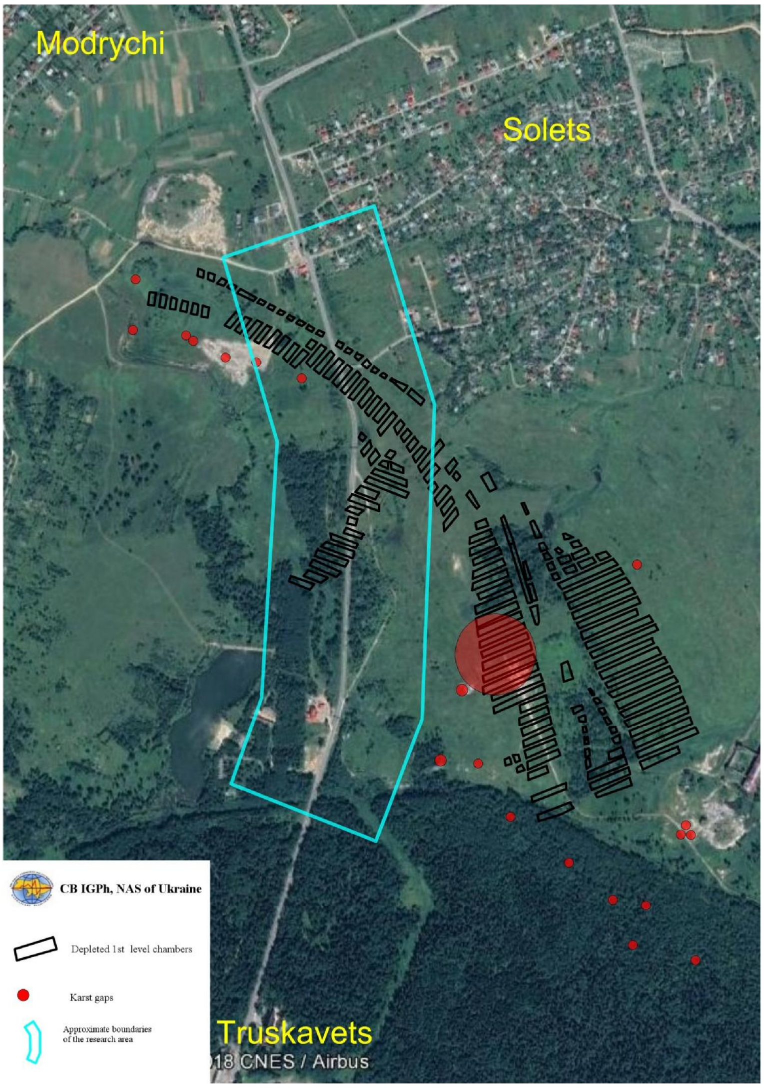

Fig. 1. Area of electricical prospecting in the limits of mining field No. 2 of Stebnyk potassium deposit

In this case the part of Skhidnytsya – Pisochne highway (Fig. 1) in the location of mine No. 2 of Stebnyk potassium deposit between cities Solets (western margin of Stebnyk city) and Truskavets is the main object of electricical prospecting for appreciation of its destruction.

Geological and geophysical situation

Stebnyk deposit of potassium salts is located in the northeastern part of the Carpathian foredeep in the basin of the Tysmenytsia River in the western part of the city of Stebnyk. The salt deposits are confined to the upper Vorotyschyn suite, which is represented by rock salt, clay, siltstones, sandstones with separate layers and lenses of potassium salts. See figure 1.

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In the upper part of cross-section the rocks of the upper Vorotyschenska suite are covered with eluvial deposits of the gypsum-clay cap, which were formed as a result of salts leaching and are represented by clay, gypsum, partly soups, and breccia sandstones. Thickness of a gypsum- clay cap is from 20 to 120 m. The content of gypsum-anhydrite component from 20 to 60 %, and salinity can range from 1.3 to 43 %. Between the bottom of the GCC and the covering Vorotyscha suite sediments is developed an area of leaching – over-salt water. The upper part is represented by Quaternary deposits of loams and sand.

Purpose

The purpose of this work is definition of potentially ecologically-hazardous and karst-chasm zones and prediction of karst development near the Skhidnytsia-Pisochne highway in the area of mine No. 2 of Stebnyk potassium deposit by electroprospecting method, namely the time domain electromagnetic method (TDEM).

Methodology

Theoretical background

Geophysical methods are used predominantly to determine the zones of karst and suffusion-filtration processes development. Particularly high attention in monitoring studies in the Pre-Carpathians conditions is given to the method of electromagnetic field formation.

To solve the actual engineering-geological and ecologic problems in relation to the appreciation of the upper part of the geological cross-sections of the media, the detection and study of dynamics of karst, filtration-suffusion, landslide, pollution of underground waters, and other negative processes which mainly are developing at depths up to 100–200 m, by the Carpathian Branch in the 90's was created and worked out in problem areas of the region (Yavoriv, Stebnyk, Kalush, etc.) [Deshchytsya, & Shamotko, 2005] and subsequently upgraded hardware and software high-speed complex, which allows to perform small-scale classical electromagnetic (EM) sounding of the geological environment in the near-field source of the field and modification of this method at the maximum high frequencies, when the bias currents can still be neglected. Accordingly with the spatial distribution of electrical conductivity, all important elements of the corresponding geological cross-sections, as well as changes caused by processes of degradation or consolidation of the environment, are confidently defined.

Ecologically dangerous geological processes, caused by natural and man-made factors, are mainly developed in near-surface geo-environments and reach up to 200 m depth. Activation of karst processes in old mine fields leads to losses of stability in covering sediments over mine working areas and the formation of failing funnels [Deshchytsya et al., 2016]. The processes of decomposition, filtration, and suffusion in dams soils and dams are accompanied by a weakening of the strength of soil structural bonds, decreasing of stability and breakthrough of constructions. Excessive wetting of sediments, overload and cutting of slope activates landsliding in mountainous areas. These processes correspond to specific geoelectric conditions, which determine the requirements for the technical characteristics of the devices, intended to detect and study such processes.

At the initial stage of the mentioned negative processes (dissolution, increased filtration, etc.) their development does not cause changes in the physical and mechanical state of the medium, but significantly affects the electrophysical characteristics of the last one. Thus, relatively small changes in the porosity volume of near-surface soils by 1–5 % are accompanied by a change in specific conductivity in the range of 35–70 %. As a result of negative processes development in the active area they appear spatially coinciding with it electrical heterogeneities. Exact determination of electrical parameters and the geometric characteristics of the formed inhomogeneities at the level of quantitative characteristics allow us to interpret the data of field observations, and define the degree and scale of geological environment degradation. Table 1 shows the typical geoelectric conditions for individual objects, determined on the base of available field data, obtained from TDEM method in the "contour in contour" modification with the generator circuit Q and the receiving q.

For the detection and monitoring of environmentally hazards, DC methods have long time been widely used and improved [Loke, 2014; Stacey Robert W., 2006]. Mostly they are based on standard equipment, geometric soundings of environment by electrical installations (eg. type A-M-N-B) of different sizes and periodic measurements of apparent resistance (ρ_a) and its temporal changes in potentially dangerous areas. But because of low resolution and localization, classical direct current methods give limited information about spatial characteristics of the processes, since the subsurface geological cross-sections are the most heterogeneous in structure and electrical properties. Geo-radar systems have high resolution [Kyoto Lizuka, 1984]. Their action is based on the division of a geological environment with different resistance and dielectric permeability by reflected high-frequency electromagnetic signals. Under favorable conditions, high-altitude environments (dry soils, permafrost), the depth of sounding by the best georadars can reach 20–30 m or more, but in conditions of moist clay and loam, the maximum depth of sounding due to the increasing of electrical conductivity in the medium does not exceed 6-10 m. At high mineralization of the humidifying liquid phase, their application becomes impossible.

In the 1970s the method of electromagnetic sounding, suitable for division of the strata with low-ohmic and high-ohmic horizons that are impervious to direct current was developed [Sidorov, 1969]. Its possibilities to date are not exhausted. Today there is a significant positive experience in using the above-mentioned developments in solving practical, mainly engineering-geological and ecological problems, which confirms high geological informative and efficiency of electromagnetic sounding method.

Table 1

Typical parameters of geological media for problem objects

No.	Hazard processes. Search objects	Search parameters			Optimized devices parameters (m^2)
		H, depth (m)	h, thickness (m)	ρ, resistivity (Ohm·m)	
1	Salt karst (Kalush, Stebnyk). Cavities.	20–60	>5	0.5–20	Q = 60×60, q = 30×30
2	Soils of the dam tails (Kalush, Stebnyk). Dissolution areas.	2–30	0.5–10	1.2–10	Q = 10×10, q = 5×5
3	Sulfate karst (Novoyavorivsk, Lviv region). Cavities	25–40	3.5–10	2.3–20	Q = 30×30, q = 20×20
4	Pollution areas (Kalush). Anomalous conductive zones.	0.5–20	0.5–10	0.5–2.5	Q = 10×10, q = 5×5
5	Landslides (Volovets, Kopashnevo, Transcarpathians). Layer of dynamic deformations	2.5–10	0.5–2.5	2.5–10	Q = 5×5, q = 3×3

Along with the developed survey complex for the upper part of the geological cross-sections standard equipment for deep sounding ("Impulse 3M") was used. On the base of obtaining electrical parameters of the geological environment it allowed solving a number of problems:

– detection and mapping of environmentally hazardous areas over mining zones and beyond their borders throughout the mining territory;

– determination of the karst development processes degree and definition of the most dangerous areas, where probable breakthroughs of high-salt waters and brines in minings, subsidence of soils, development of suffusion-karst processes;

–- studying of environmentally hazardous processes dynamics for prediction and prevention of catastrophic phenomena.

Successful resolution of such problems was achieved by the introduction of electromagnetic diagnostics of geoenvironments diagnostic technology and predicting environmentally hazardous processes (technogenic karst) based on impulse sounding of geological cross-sections by TDEM methods, compelled with field observations with mathematical and physical modeling of complex geoelectric situations.

At the initial stage of negative processes (karst, filtration-supersonic, landslide) development, when the reduction of structural relations and deformations of the soil are not yet noticeable and are not stated by direct (piezometry) methods, in the essentially potentially dangerous areas of the geological environment significant changes in its electrical characteristics already occur. In particular, the electrical conductivity of these areas increases as a result of increasing penetration and saturation of the environment with mineralized waters. Such anomalies of electrical conductivity are the main search objects of electrometric methods when examining ecologically problematic territories in order to appreciate their condition and identification of hazardous geological processes for the timely application of precautionary measures.

The generalized geoelectric model of the upper part of the cross-section is not complicated. It corresponds to a three-layered cross-section ($\rho_1 \geq \rho_2 \leq \rho_3$, where ρ_1, ρ_2, ρ_3 are the resistivities). The upper layer is represented by pebble-loamy sediments with a thickness of 10–20 m with an electrical resistivity of 30–40 Ohm·m. Lower are the low-ohm (0.6-5 Ohm·m) alluvial sediments of GCC with 10–100 m thickness. They are enriched by brines that circulate upper high-ohm (>200 Ohm·m) native salt rocks. Last one is presented as potassium and halite rocks. The situation is complicated by the presence of the cover layer deepening. Such areas are indicated as local or extended geoelectric heterogeneities over the waste and brine-filled cells. During time, this leads to stability loss of the covering rocks over mining chambers and formation of the craters and the sudden chime of the earth's surface. The beginning of such process development is mainly due to the weak ceiling and diluted areas of the waterproofing layer above mining chambers. Rocks land slipping (upwards), in addition to the development of filtration and karst processes, other previously inactive local and extended structural and material heterogeneities of the clay-gypsum cap, as well as deposits of the aquifer, which leads to large-scale environmental problems and significant material damage, may be involved. In addition, the technologically predicted depression of the surface and the formation of a mold over the mine fields in excess of the planned norms becomes an extremely powerful source of pollution of the aquifer horizon by highly mineralized waters extruded from the chambers.

The feature of salt karst in comparison with other types (sulfate, carbonate) is the ability to repeatedly accelerate the occurrence of negative processes under the influence of number factors. Along with technogenic factors, physical and chemical properties of the material and facial composition, the character and dynamics of karst processes development is determined by structural and tectonic features of the saline deposits structure [Pavlyuk, 2012], in particular, folding and numerous disjunctive deviations along and across the extension of basic structures, steep (up to vertical) occurrence of salt layers, accelerating the development of negative exogenous geological processes. The systematic electromagnetic monitoring of the geological environment of the covering layer allows predict and timely warning of negative and catastrophic phenomena. Appreciation of the geo-environmental situation over mine fields should be carried out at all stages of the exploitation of the mines and on its completion.

Methodology and technique of field works

For solution of named problems TDEM method have been applied successfully. Its most effective modification is so named "circuit in the circuit", when in contour Q, of exiting electromagnetic field, is placed receiving contour q, which is measuring inducted electromagnetic field signal $E(t) = \partial B_z/\partial t$, as deviation from t time of magnetic induction stream vertical component B_z through measuring device.

For observations in upper layers (up to 100 m) digital electrical prospecting device was applied. This was "Stage", designed in the Carpathian Branch of Geophysical Institute of National Academy of Sciences of Ukraine. Such modification of this range "Stage" device as "contour in the contour" with geometrical dimensions of the generator Q and measuring q contour: Q = 30 m × 30 m = 900 m^2, q = 20 m × 20 m = 400 m^2, respectively, which provided at the sounding zone of the geological environment depths from 10-15 m to 60-80 m in the time range of measurements of nonstationary electromagnetic fields from 5–6 to 900 ms in with step of discrete sampling, which increased with depth from 1 to 100 microseconds. To obtain data from the upper part of the section (from 2–3 m) installation with geometrical dimensions of the contour Q = 10 m × × 10 m = 100 m^2, q = 5 m × 5 m = 25 m^2 was used. In this range, the TDEM method is characterized by a rather high resolution, which ensures the selection of electrically heterogeneous objects of the geological environment with good detail and sufficient depth for the upper part of the geological cross-section.

For information on the deeper part of the geological media (from 50-100 m to 300-400 m) a digital electric station "Impulse 3M" (Russia) was used with "contour circuitry" modification with geometric dimensions of square generator Q = 125 m × ×125 m = 15625 m^2 and receiving wires q = 20 m × × 20 m × 27 turns = 10800 m^2 with measurements of a useful signal in the range from 501 mksec to 39.8 msec with a geometric step of approximately 1.12 (a total of 39 readings).

The processing and interpretation of the sounding data is based on application of software of preprocessing and transformation of measured signals in geoelectric parameters of the media, as well as methods of visualization and geological interpretation of sounding data. Based on the interpretation of sounding, differential methods of transformation of the induced field using Sidorov V. A. algorithms were used [Sidorov, 1969], software package of Mamontov V. I. with subsequent representation of the total electrical conductivity curves $S = f(H)$ and the resistivity $\rho = f(H)$ from the depth H.

In general, the usage of such types of installations provides obtaining geoelectric information about the geological environment from a few meters up to 300–400 m. Selected devices with such measurements performed on one picket not only provide continuous data acquisition throughout the depth of research, but also, taking into account overlapping of different range of TDEM observations, can increase the reliability of the results.

Despite the possibility of rocks separating by their electrical properties (resistance or inversion – conductivity), there remains significant ambiguity in the determination of one or another sediments by the values of their electrical resistance due to its significant changes for the same rocks in different physical and geological conditions. Therefore, methodically, field-based electrical surveying observations by the TDEM method consist of three stages:

1. Carrying out of parametric sounding for a concrete area near wells with known geological cross-section and electrical characteristics in order to find out in specific geological conditions the possibilities of the method for division of geological horizons and their relation to parameters of electric resistance and conductivity;
2. Implementation of soundings along the defined profiles in a step that provides the required detail and resolution of observations;
3. Construction on the basis of their results of geoelectric sections and maps with an anchor to the lithology of the district of work, the allocation of structural and tectonic features of the research area and abnormal zones. Execution, if necessary, of additional soundings in order to specify the parameters of the selected zones.

Results

According to the tested TDEM method in the first stage of the observations to determine the conformity of the lithological boundaries and definition of sediments apparent resistance, in the well No. 137 parametrical studies were carried out. This made it possible to define the parameters of the gypsum-clay cap and the contact of above salt waters. In addition to greater depths in the well were the results of literary sources [Pavlyuk, 2012; Gajdin et al., 2014]. Observations were made by two types of installations. The results of soundings by these installations in the area of the well No.137 showed a good resolution of the method (Fig. 2). Comparison of TDEM method data, which were transformed into the media parameters with data of drilling, showed that with such types of installations we can obtain results from depths range from 14 meters up to 600 meters, which is quite sufficient for analyzing the regional geological cross-section. On the base of parametric observations near the well electrical resistances were determined. This allowed making not only a lithologic division of the geoelectric cross-section but also determining their state during profile observations (Table 2).

Table 2

Relation between geological layers and their resistivities

Sediments type	Sediments features	Resistivity (Ohm·m)
Quaternary sediments	n/a	–
GCC	Dry	50–100
»	Dampish by water with dissolved salt in quantity 1–10 gram/liter	8–50
»	Dampish by water with dissolved salt in quantity 10–50 gram/liter	1.5–8
»	Dampish by water with dissolved salt in quantity more then 50 gram/liter	< 1.0
Vorotysche suite N_1vr	watered	5–20
»	Sealed, the cells are filled with water	40–100
»	Dense, impenetrable	>400

Profile observations along the road have been fulfilled in the north-south direction with a total of 81 observation points (OP): 44 deep (profile I-I, OP S1-1–S1-23, profile II-II, OP S2-1–S2-21) and 37 near-surface (profile I-I, OP d1–d19, profile II-II, OP d20–d37) soundings. Besides, 15 addiotional soundigs have been done (Fig. 3).

The cross-section from 4 meters up to 100 m depth was detailed accordingly to the results of near-surface soundings along the profile I-I (Fig. 4b).

The results showed that the base of the gypsum-clay cap (GCC) is at an absolute altitude of 260–240 m. According to the parameters of the resistance, the cross-section is present almost throughout the length of the profile, but the depth is strongly differentiated and divided into two zones: the upper with low conductivity (10–40 Ohm·m) and the lower conductive (5–10 Ohm·m). This suggests that the upper part of the GCC is poorly moistened with surface fresh water, and in the lower part fraction of dissolved salts in ground waters, filled with weakly permeable sediments of GCC, ranges from 10 to 50 g/l. Only in some points the concentration exceeds 50 g/l, which indicates a low resistance of less than 1 Ohm·m. The low resistance band along the entire profile in the conductive zone of the GCC shows that the groundwater level is in 305 m absolute depth. Within the observation points d2-d3, an anomalous conductive zone (resistance <1.0 Ohm·m) in the northern part of the profile is defined. It is 14 meters thick but on the PC d7-d8 it was detected at 314 meters and 10 meters in thickness. Both zones in these points are interconnected and form a conductivity anomaly with an extension angle from north to south. Additional observations were done along profiles III-III and IV-IV (Figs 4, a–c) for the detail analysis of the anomalously conducting zone on the I-I profile.

The results showed that the anomaly is present in all three profiles and deepens in the south-east direction parallel to extension and the bedding of salt layers. It is likely that such anomaly can be associated with a suffusion-filtration process, which involves not only the transfer of salts to lower hypsometric levels, but probably the redeposition of gypsum-clay material.

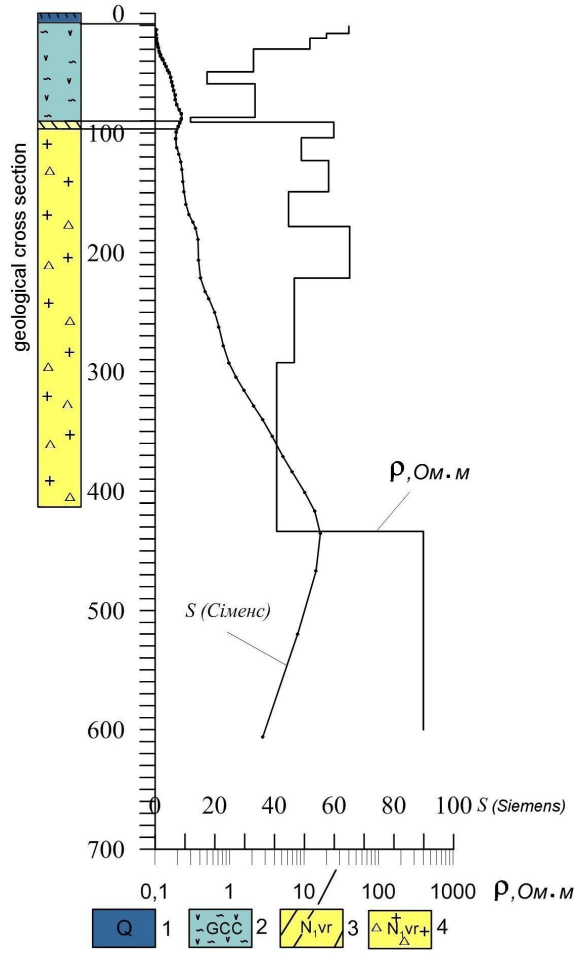

Fig. 2. Observation results by TDEM method on the parametric well No.137

1 – Quaternary sediments; 2 – sediments of gypsum-clay cap (GCC): clay, gypsum, sandstones, sandy loam, breccias; 3 – conductive zone of above-salt waters; 4 – Vorotyscha suite sediments: potassium and halite salts, clay, siltstones, sandstones

Results of near-surface soundings (research of gypsum-clay cap)

This anomalous zone was defined by us as of the result of observations in 2009 (Fig. 5). As we see in comparison with 2017 the conductivity of rocks increase. This indicates the degradation of the environment during this period. The profile II–II is located on the western side of the Skhidnytsia-Pisochne road and runs from north to south, with a length of 855 meters. Most of the profile passes in the location of the power line, pipelines, underground power and phone lines, due to which the results turned out to be not available for processing. Although in the northern part of the profile it was possible to allocate a small conductivity anomaly on an absolute altitude of 325 meters (16 meters from the surface).

Results of deep soundings (study of the Vorotysche suite N_1vr)

Profile I-I (OP s1-1–s1-23), where deep soundings were performed, is located along the eastern side of the Skhidnytsia-Pisochne road and runs in north-south direction. Its length is 1255 meters (Fig. 5). The cross-section covers the absolute altitudes from 296 m and up to -100 meters (depth from 50–70 meters).

Sediments of Vorotysche suite significantly differs in resistance values from the depths on the contact of GCC bottom and to an absolute altitude of 160 meters. The upper part is more conductive and has a resistance value 20–100 Ohm·m. Below the 160 meters resistivity increases from 100 to 400 Ohm·m. This is not observed in the edge of the profile, where it goes beyond the boundary of the trough. This indicates that this area is mainly involved and has undergone changes as a result of subsidence.

On the absolute altitude from 285 meters to 225 meters (depth 80-120 meters) stands the bedding of the GCC cap, the resistance of which is 10–40 Ohm·m. Along the boundary of the GCC, thin zone with conductivity 2–10 Ohm·m (in some cases 2–5 Ohm·m) associated with above salt waters is defined. Deposits are in general electrically heterogeneous. Within the range of OP s1-6 and to s1-14 at a depth of 200 meters are mine workings chambers (Fig. 7). Above the old cameras, the thickness of the Vorotyscha sediments is 48–60 meters. Within the OP s1-10, a local conductive zone, which reaches mining chambers, is defined. It may be related with infiltration of the above-salt waters in chambers.

Below the mining chambers, according to sounding data, sediments of Vorotyscha suite are detected as a consolidated medium with a resistivity of 40–100 Ohm·m.

On the southern side of the mine a powerful conductive area was defined by electromagnetic sounding (OP s1-13–s1-17). It was traced monitored from the GCC bottom to significant depths and is probably related with structural features, as the anomaly passes along the tectonic element, which divide Vorotyscha sediments from the Polyanitska suite deposits. The magnitude of this anomalous zone is amplified in particular by exogenous processes, occurring on the boundary of the deposit.

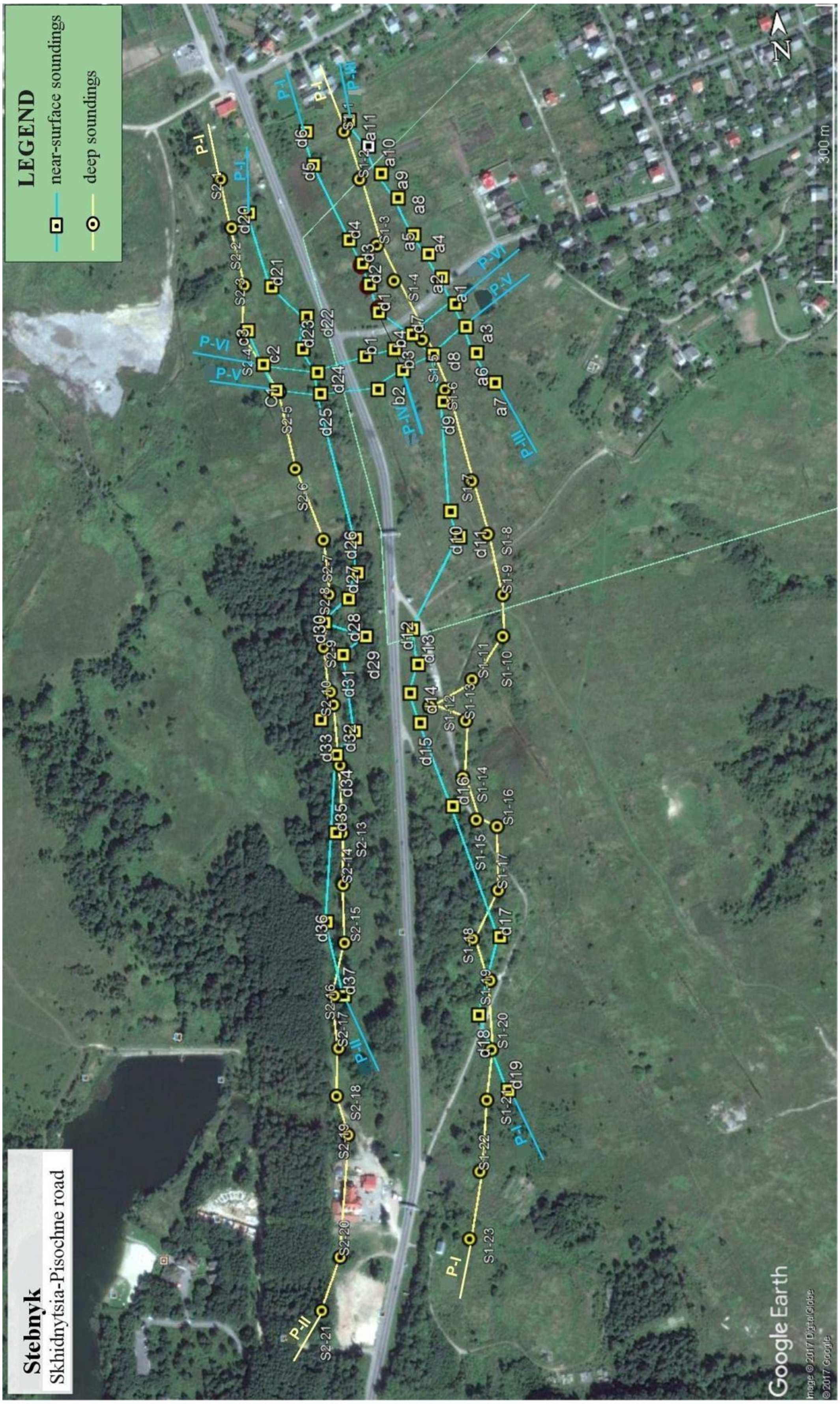

Fig. 3. Locations of profiles and observation points (OP) along Skhidnytsya-Pisochne highway

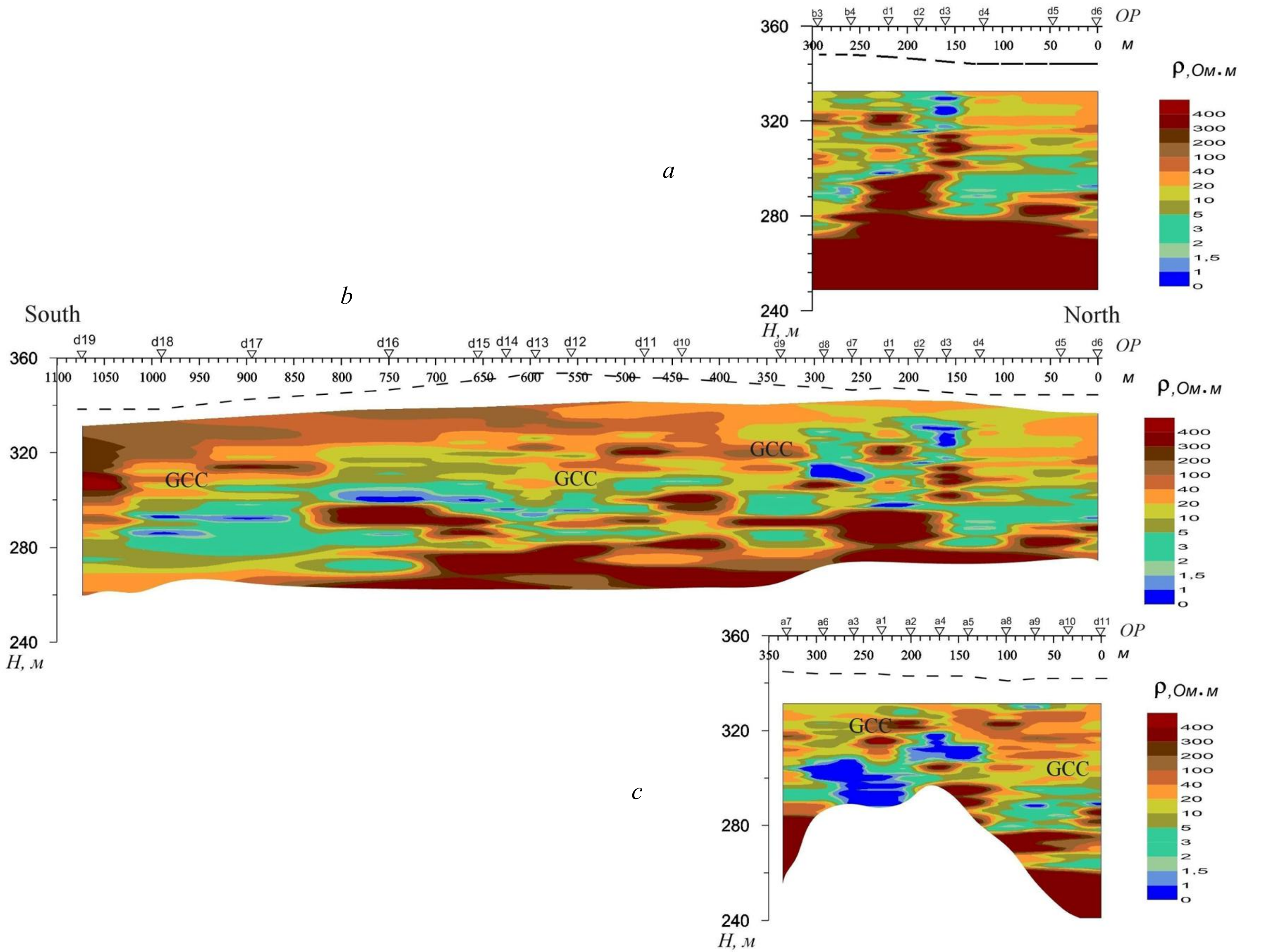

Fig. 4. Geoelectric cross-sections along Skhidnytsia-Pisochne highway: a – profile IV – IV; b – profile I – I; c – profile III - III

The same anomaly the results of electromagnetic sounding indicate on the northern side of the profile between OP s1-1 and s1-4. The intensity of this anomalously conducting zone increases in the northern direction and is explained by exogenous processes occurring on the boundary of the deposit. On the southern side, on the profile within the OP s1-18 and s1-21, a sufficiently large anomaly of conductivity at depths with an absolute altitude of 232–242 meters is allocated. The anomalous zone is located within the limits of the distribution of the trough where the subsidence of surface is more than 1.2 meters.

In its southern edge, there is a disjunction in the sedimentation of the polyanytska suite near the OP s1-17, which is associated with the trough depression [Kuzmenko et al., 2017]. The conductivity anomaly itself expands to the north (north-east) toward a powerful deep anomaly, described above, and is associated with exogenous processes at the boundary of the deposit body.

Profile II-II (OP s2-1–s2-21) is located on the western side of the Skhidnytsya-Pisochne. Its length is 1265 meters. The section covers absolute altitudes from 280 to 0 meters (from 70 meters to depths more than 350 meters).

The N_1vr sediments, as in the previous profile, differ significantly in their resistivity values from the depths adjacent to the GCC bedding to the absolute altitude of 160 meters. The upper part is more conductive and has a resistance values from 20 to 100 Ohm·m. Below the absolute altitude of 160 meters the resistivity rises from 100 to 400 Ohm·m. An exception is the southern side of the cross-section where the values of decreased resistivity reach the level of 180 meters. This is due to the fact that the southern side of the profile is located in the edge of the trough subsidence.

On the altitudes 220 meters and 240 meters (depth 90–110 m) the bedding of GCC is defined, the resistivity of which is 2–40 Ohm·m. Within the GCC, a significant section of the cross-section has a reduced resistivity within 2-–5 Ohm·m. It corresponds to the watering of the sediments in the horizon. Over-the-salt waters along the boundary of the GCC bedding in the cover of N_1vr rocks are practically not allocated, perhaps because of their low thickness.

In the area of the profile among OP s2-13–s2-14 and OP s2-3–s2-5 at a depth of 200 meters (absolute altitudes) mine chambers are located. Above the empty old chambers the thickness of N_1vr sediments is 50–60 meters. Local conductivity anomalies, which are directly above the mining area in the OP s2-13–s2-15 and beyond it in the OP s2-17 and s2-18 are probably due to structural features (fault) and an influence of subsiding trough. The anomaly, which is directly located above the mining area, significantly reduced the protective properties of the protective layer to 20–30 meters.

Studies have stated that in the northern part of the area, the surface electrical conductivity anomaly, which is located directly near the highway and covers a large area, is a result of filtration-suffusion processes. In the southern part of the geoelectric sections, a deep anomaly of electrical resistance is likely to be associated with the subsidence trough and runs directly under the Skhidnytsya-Pisochne road. The boundaries of abnormal zones are plotted on a schematic map (Fig. 8).

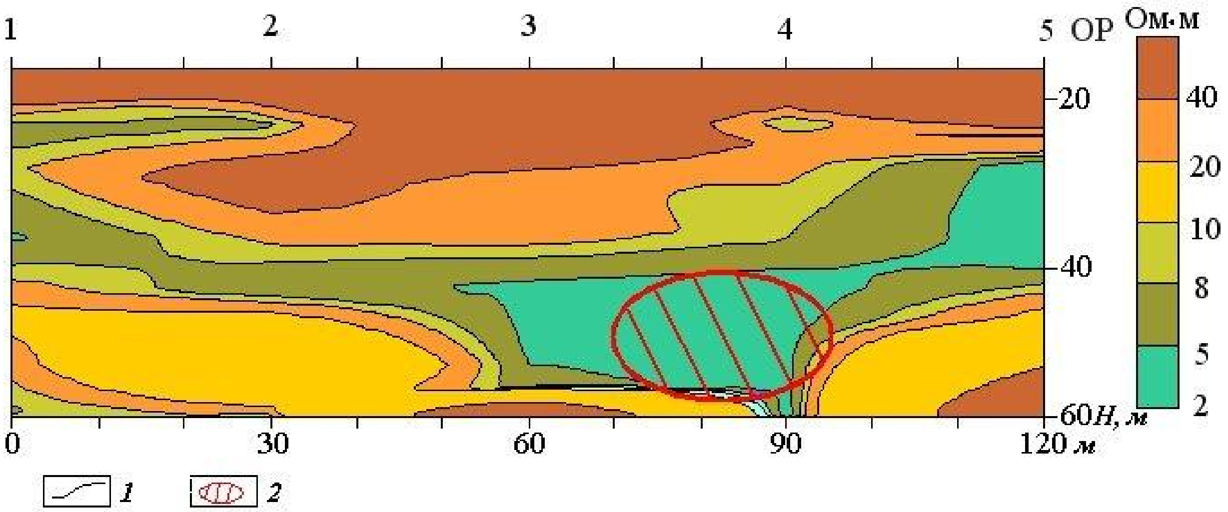

Fig. 5. Geoelectric cross-section for 2009 observations corresponds with 2017 observations on the profile I – I, OP d1–d4
1 – isooms; 2 – an anomalous zone

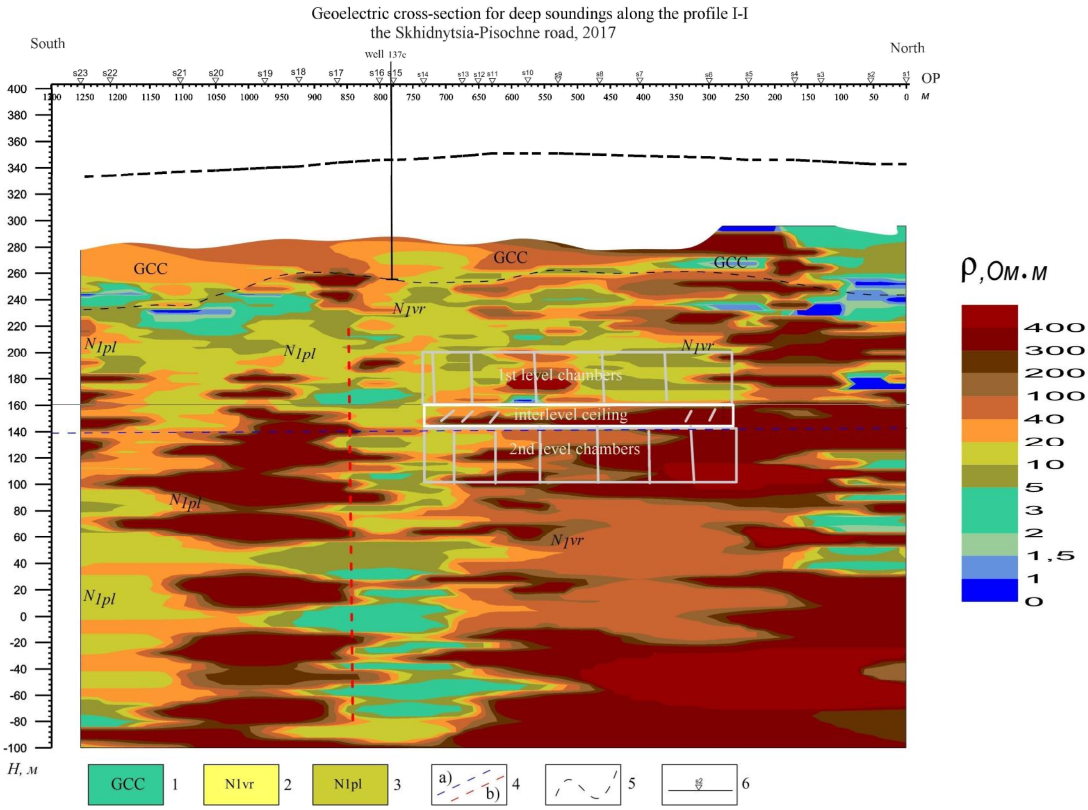

Fig. 6. Geoelectric cross-section for deep soundings along the profile I–I
1 – GCC sediments; 2 – Vorotyscha suite sediments; 3 – Polyanytsia suite sediments; 4 – lithological boundaries; 5 – Earth's surface; 6 – OP

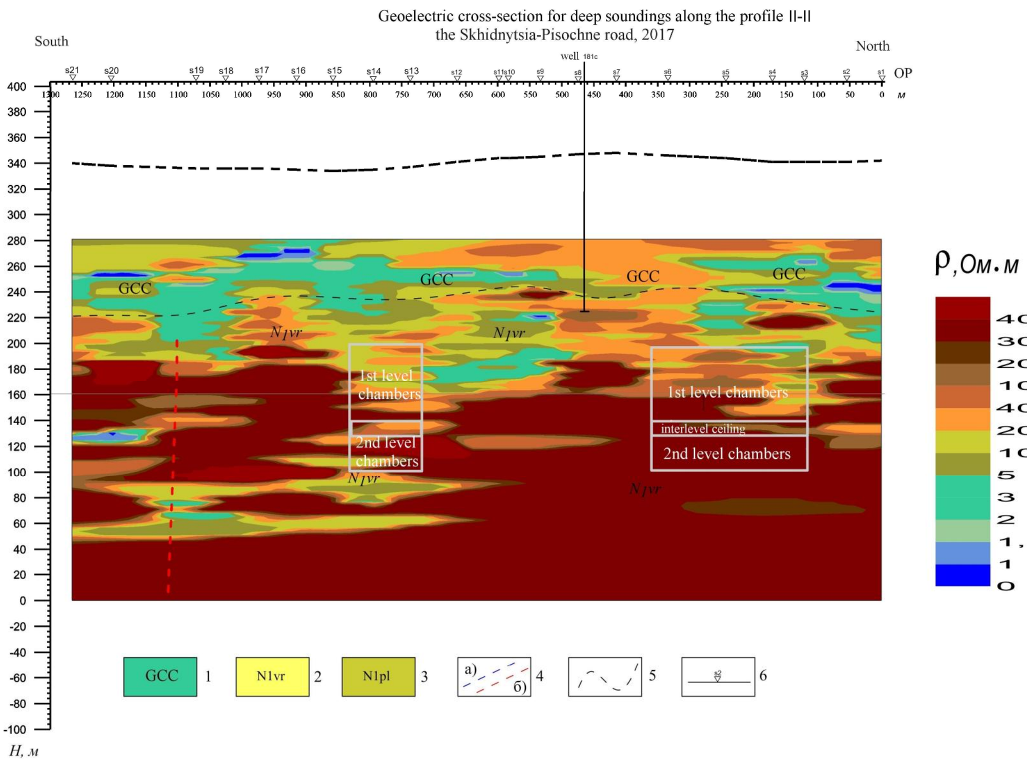

Fig. 7. Geoelectric cross-section of deep soundings along the profile II – II.
1 – GCC sediments; 2 – Vorotyscha suite sediments; 3 – Polyanytsia suite sediments; 4 – lithological boundaries; 5 – Earth's surface; 6 – OP

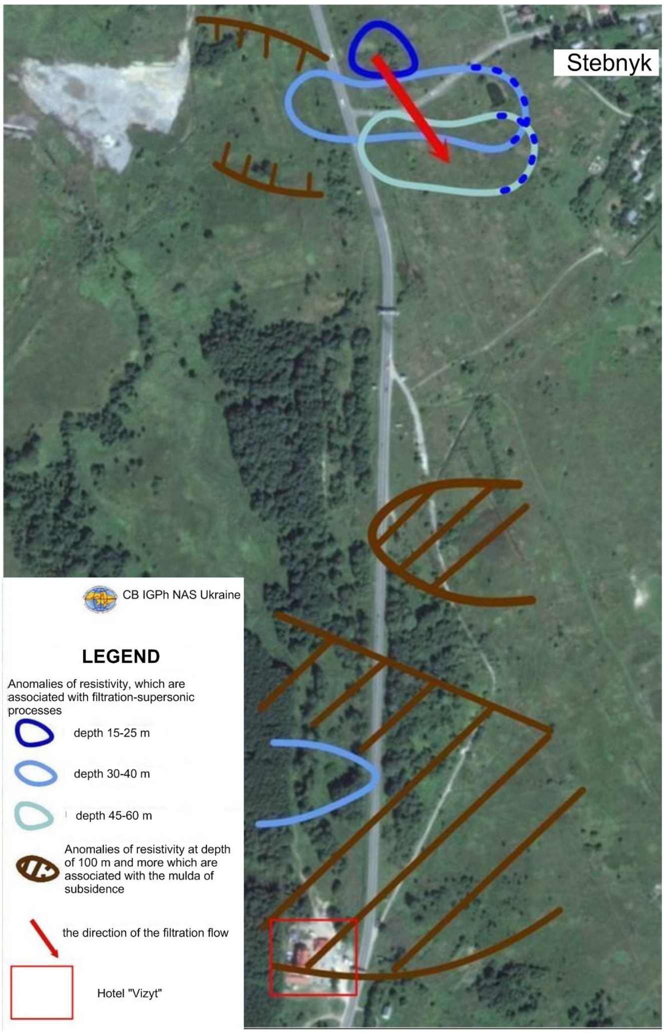

Fig. 8. Scheme of anomalous zones location for electromagnetic soundings along Skhidnytsia-Pisochne highway

Originality

The possibility of the TDEM method application for the study of karst-chasm processes in the territory of the Stebnyk potassium deposit was investigated. For the first time, using the electrical prospecting methods an estimation of the state of geological environment within the mine field No. 2 of the Stebnyk potassium deposit on the area of the Skhidnytsya-Pisochne highway was made. It is shown that the TDEM method in the complexization of two types of devices with different measurement depths allows us to diagnose in detail the geological environment in the range of depths from 10 to 400 m with the allocation of zones of abnormal electrical resistivity, which are associated with the suffusion-filtration processes.

Practical significance

Accordingly to the results of electromagnetic observations on the area of the highway Skhidnytsya-Pisochne in the location of the mine field No. 2 of the Stebnyk potassium deposit, the zones covered by the filtration-suffusion processes are defined. These zones are the primary objects that should be the subject of close attention for further monitoring of karst-chasm processes, and the fact of their availability should be taken into account when making administrative decisions by the authorities on the expediency of transferring the location of the highway and other infrastructure.

Conclusions

Summing up the TDEM method works results on the site adjacent to the highway Skhidnytsya–Pisochne, within the south-eastern section of the mining field of the Stebnyk potassium salt deposit mine No. 2, the following should be noted.

An appreciation of the geological environment state in the range of depths from 4 to 400 meters is made. This interval of depth is sufficient for a detailed study of exogenous geological processes that can affect the state of the road.

On the basis of observations near the highway, two zones of anomalous conductivity are defined: in the northern part of the study area and in the southern part.

In the northern part of the site there is a surface anomaly of electrical conductivity, which is located directly near the highway and covers a large area. The detected anomaly is associated with the filtration-suffusion processes, which cover the sediments of the GCC at depths from 10 to 50 meters. In the location of electrical prospecting profiles the anomaly is about 18 thousand square meters and has volume – 350 thousand cubic meters. The filtration-suffusion processes, on the base of sounding data, are oriented towards the occurrence of salty layers. The main part of this zone is located in east area of the highway, but it is also directly below the road, where it can be traced with about a 4 m thickness at a depth of 33–37 meters from the surface. The outlining of the anomalous zone boundaries in the direction of the city of Stebnyk requires additional observations. Typically, suffusion-filtration processes are a result of degradation of the geological environment with the subsequent formation of karst

In the southern part of cross-sections deep electric resistance anomaly is defined. It is 250–300 meters wide with maximum thickness near 60 meters (absolute altitude 188–250 meters). Probably it relates with trough depression and locates directly under the Skhidnytsya-Pisochne highway.

Defined anomalous zones along the highway indicate existence of hazardous processes, which can cause destruction of the highway.

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ОЦІНКА КАРСТОПРОВАЛЬНОЇ НЕБЕЗПЕКИ У МЕЖАХ СТЕБНИЦЬКОГО КАЛІЙНОГО РОДОВИЩА МЕТОДАМИ ЕЛЕКТРОРОЗВІДКИ

Мета. Мета роботи – виявити потенційно еконебезпечні карстопровальні зони та спрогнозувати розвиток карсту на ділянці автодороги Східниця–Пісочне у межах впливу полів рудника № 2 Стебницького родовища калійної солі електророзвідувальним методом зондувань становленням електромагнітного поля (ЗС). **Методика.** Дослідження виконувались за допомогою методу ЗС у модифікації “контур у контурі”. Для вивчення верхньої частини розрізу до 100 метрів застосовано цифрову електророзвідувальну апаратуру “Стадія”. Для отримання інформації про глибини від 50–100 м і до 300–400 м використано цифрову електророзвідувальну станцію “Імпульс 3М”. Польові спостереження методом ЗС методично складались з трьох етапів, до яких входили: проведення зондувань на параметричних свердловинах, завдяки чому уточнюються електричні параметри геологічного середовища; проведення спостережень вздовж визначених профілів та побудова за отриманими результатами геоелектричних розрізів з прив’язкою до літології району робіт. **Результати.** На ділянці досліджень у північній її частині у відкладах гіпсо-глинистої шапки виділено зони аномальної електропровідності, природа яких пов’язується з фільтраційно-суфозійними процесами, а також аномалію виявлено у південній частині ділянки у відкладах Воротищенської свити на глибинах понад 100 метрів, що пов’язується з утворенням депресійної лійки. **Наукова новизна.** Досліджено можливості методу становлення електромагнітного поля для вивчення карстопровальних процесів на території Стебницького родовища калійної солі. Вперше за допомогою електророзвідувальних методів зроблено оцінку стану геологічного середовища у межах шахтного поля рудника № 2 Стебницького родовища калійної солі на ділянці автодороги Східниця–Пісочне. Показано, що метод ЗС при комплексуванні двох типів установок різної глибинності дозволяє детально діагностувати геологічне середовище у діапазоні глибин від 10 до 400 м з виділенням зон аномального електричного опору, що пов’язуються з суфозійно-фільтраційними процесами. **Практична значущість.** За результатами електромагнітних спостережень на ділянці автодороги Східниця–Пісочне у межах шахтних полів рудника № 2 Стебницького родовища калійних солей виділено зони, охоплені фільтраційно-суфозійними процесами. Зазначені зони є першочерговими об’єктами, які повинні бути предметом пильної уваги для подальшого моніторингу карстопровальних процесів, а факт їхньої наявності необхідно враховувати при прийнятті управлінських рішень органами влади про доцільність перенесення місць розташування автомагістралі та інших об’єктів інфраструктури.

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

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