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Detection of anomalous zones in a rock-mass, caused by past shallow extraction of zinc, lead and silver ore

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Abstract. Article discusses one of the geophysical prospecting methods (electrical resistivity method) used for solving environmental geoengineering problems. Studying bedding (rock mass) using non-invasive geophysical methods is beneficial particularly because of the ability to obtain complete and very accurate information, depending on adopted research and prospecting approach. Interpretation of geophysical data, should always include available geological, empirical and environmental information, while all results should be presented on integrated profiles and maps. This article presents the idea and the possibility of using the geophysical electrical resistivity method in order to detect anomalous zones in rock mass that may lead to formation of so called discontinuities (fractures), which are the result of past shallow ore mining operation in discussed Tarnowskie Góry area .

1. Introduction

Geophysical methods can be successfully used to solve multiple problems of environmental geoengineering. Their significant advantage is non-invasive measurement technique and the ability to conduct continuous studies on large areas (compared to "in situ" single-point measurements such as measurement holes – boreholes). The drawback of geophysical prospecting is their indirect presentation of information about structure and environmental pollution using studied physical field units. Scaling of physical field units to obtain information about geological structure or values, which characterize environmental pollution is an important process and geophysicist who interprets field images is required to have significant knowledge in that field. Results of geophysical measurements must refer to geological information related to studied area. On the other hand, it is necessary for most of the research to adopt at least two independent geophysical methods. Only then, information obtained during the research can be considered reliable enough. Unfortunately, using several different methods raises research costs and eliminates many potential contractors who have only one type of geophysical equipment available (most often, electrical resistivity equipment). These factors successfully inhibit wider development of geophysical methods in Poland, which could otherwise be used for environmental protection and broadly understood geoengineering.

The article discusses the issue of application of chosen geophysical method, i.e. electrical resistivity, which is in many cases optimal for solving different problems of environmental geoengineering. In particular, the article presents environmental hazards in areas with past mining operations, in regards to future utilization of these areas and their role in spatial planning [1, 2, 3, 4].

2. The concept of electrical resistivity method

Geophysical measurements including geoelectrical methods are based on variation of electrical parameters of studied medium. To have a full understanding of phenomena taking place when electrical current flows through soil-rock environment, one has to be aware that such medium shows resistance to current flow. According to Ohm's law, this resistance is proportional to the voltage used in relation to the current. The most basic, analyzed parameter is the electrical resistance (resistivity). That is why geoelectrical methods are equated with electrical resistivity methods. Resistivity is a characteristic of each specific material and a basis for identification of studied medium.

The essence of electrical resistivity studies is the flow of electrical current of known intensity between current electrodes (powered). Electrical potential difference generated this way, i.e. voltage measured between other two electrodes (measuring), allows for designation of resistivity of specific medium. However, only so called apparent resistivity can be measured in the field and it is reliant on true resistivity of each component of the medium.

Depending on research, following electrical resistivity surveys can be carried out:

- vertical electrical soundings 1D (PSE, SGE, VES),
- electrical resistivity profiling 1D (PE),
- electrical resistivity tomography 2D.

The essence of electrical resistivity method (geoelectrical) is the flow of electric current of known intensity between current (supply) electrodes. The potential difference created in this way, i.e. voltage measured with potential (measuring) electrodes, allows determining the resistance of a given medium. The determined resistance in the field is, however, the so-called apparent resistance, which depends on the real (specific) resistance of the individual components of the medium (figure 1).

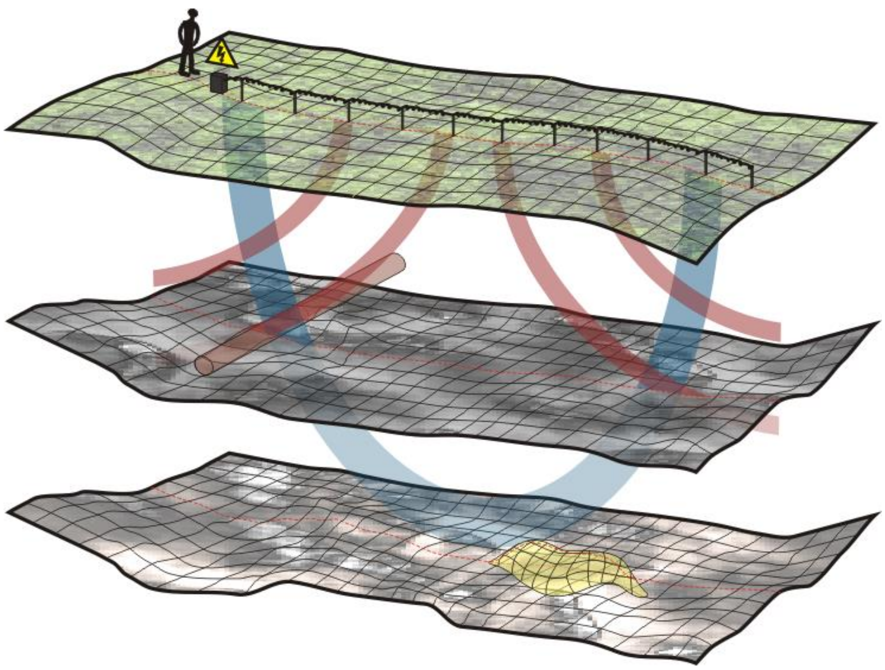

Figure 1. Scheme of electrical resistivity method (geoelectrical) research.

Choosing the method and specific measurement system relies on type and shape of surveyed structure, expected resistivity contrast, amount of noise and capabilities of equipment owned. Additionally, different measurement systems are characterized by various degree of profile covering, vertical and horizontal resolution and depth range. Surveys result in vertical profiles, cross sections and maps of resistivity variation along with their geological and engineering interpretation. Electrical resistivity method (geoelectrical) with utilization of techniques mentioned above is widely used for: identifying ground-water conditions and geological structure, localization of mining cavities (especially as a result of shallow mining operation), control of the efficiency of cavity filling and loosening the rock mass in shallow mining operation areas, localization of ground water level, water layers and underground water deposits or localization of faults [5, 6, 7].

3. Typical hazards in mining and post-mining areas

Mining and post mining areas are characterized by occurrence of hazards that are not present in any other part of the country. As a result of that, geophysicists, geologists and geotechnicians working in such areas are required to inform about the scale of these specific problems, danger that these problems can be for future generations, price of these research, cost of securing the areas, potential economic loss as a result of insufficient recognition of hazards and their detailed evaluation in areas of future investments. Many geologists, builders and geotechnicians who do not work in mining and post-mining areas might be unaware of the scale of certain geodynamic phenomena in these areas. Local authorities are quite aware of the hazard caused by shallow, old mining operation and possibility of formation of cavities, depressions and discontinuities. In some areas with investment plans, geological and geophysical surveys are conducted to detect and possibly fill underground cavities or check the efficiency of potential repairs of damaged land. Examination cavity hazards is most often performed via electrical resistivity method. Usually geophysical studies are designed with consideration for available geological and hydrogeological data and information from old mining maps (based on geological-mining expertise), which allows to choose optimal measurement techniques. Cavities may cause or are still causing, significant hazard to investment areas where mining operation took place in the past, which may generation of discontinuities mentioned above [8, 9].

4. Analysis of chosen example

Analyzed geophysical surveys were conducted on 690/44 and 691/44 lots, area 0004 located near Nowa street in Tarnowskie Góry where were location of designed buildings (figures 2 and 3). Area subjected to geophysical, electrical resistivity surveys included measurement field of total surface of 1575 m^2. Surveys were performed in order to detect possible cavities in Triassic formations, loosening of Quarternary formations and identification of potential hazard cause by past ore mining operation.

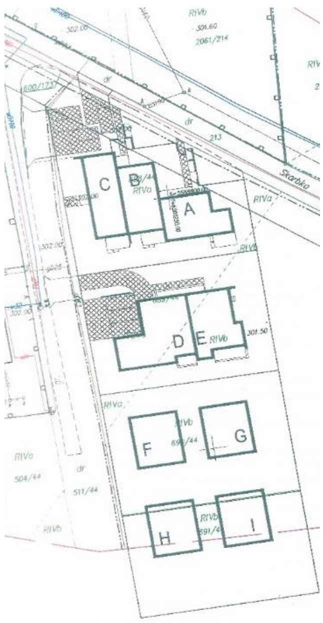

Figure 2. Location of designed buildings (segment: F; G; H; I).

Figure 3. General view of surveyed investment areas.

4.1 History of ore mining in Tarnowskie Góry area

Mining, in broadly understood Tarnowskie Góry area (along with nearby parts of Bytom and Piekary Śląskie), goes back to early medieval period, making this region one of the oldest metal ore mining centers in Europe. The oldest mention of ore mining in this area comes from 1136 and refers to silver mining near Bytom. Document, issued by duke Władysław Opolski in 1247, mentions ore mining in Repty Śląskie area, in direct vicinity of area studied in this article. Mining in Tarnowskie Góry area were carried out practically continuously since early medieval period to 1912, when Tarnowskie Góry region has been finally considered as depleted. Nowadays, area of historical metal ore mining in near Tarnowskie Góry includes 185 km of existing tunnel workings in form of tunnels, chambers, adits and huge number of remainders of historical mine workings, mainly in form of major and minor shafts in various condition, which total number has been estimated to be around 20,000. Other remainders of mining activity, which are considered significant from geotechnical point of view, are vast areas covered in anthropogenic cohesive ground from gangue and ore processing waste. Currently, in the best-preserved part of underground mine workings there is a museum Zabytkowa Kopalnia Srebra [Historic Silver Mine]. Available for tourist purposes there is also a segment of one of the draining adits called Sztolnia Czarnego Pstrąga ["Black Trout" adit]. The adaptation of historical fragments of mine workings as a museum and tourist attractions are the only underground mining activity that takes place in Tarnowskie Góry area [10].

4.2 Analysis of ore mining based on historical maps from Tarnowskieg Góry area

Considering the fact that mining activity in Tarnowskie Góry area ended in 1912, the most detailed are the geological and mining maps from that period, which contain the fullest and most current image of mining exploitation range. Fragment of historical mining and geological maps including area of studied areas on Skarbek street in Tarnowskie Góry, has been presented on figure 5. In mid-western part of studied area, mine workings have been shown, drilled behind lead and brown iron ores. Near the southern border of 690/44 lot there is the "Alter Hoffman" mine shaft, which has unknown depth and method of dismantling. Tunnel workings in galena deposits run from Hoffman shaft, in 50 m proximity from western border of the lots, covering western part of 690/44 lot. The next working starts in north-western corner of 691/44 lot and runs in south-east direction, towards exploitation workings of this deposit. Their depth can be roughly estimated at 29,5m, based on the depth of Hoffman shaft that gives access to the deposit (figure 6, workings marked in blue color). Thirty meters west from northern border of 690/44 lot there is „Nord" shaft at 39,1m depth. This shaft gives access to brown iron ore, which probably has been mined along the western border of the lots. The shaft also branches into tunnels, one of which runs from the shaft to the north-western corner of 690/44 lot (figure 6 workings marked in brown color).Considering the approximate and probably incomplete range of tunnel workings presented on the map (figure 6) it can be concluded that there can be tunnels beneath 690/44 and 691/44 in depth range of 29-40 m. To the west of studied lots there is a zone of numerous shafts and mine workings, of which closest to the lot, almost directly at its border, are brown iron ore workings, and in about 15 m ranged, galena mine workings i.e. lead ore. According to Local Spatial Development Plan (MPZP) of southern districts of the Tarnowskie Góry city (figure 4), the whole studied area of the lots is marked as a historic mining workings "remainder" zone, meaning tunnels with smaller historic value preserved to a varying degree. Orange area visible along the western border of the lots marks the zone of main mine workings of historic mine of silver-bearing deposits, which is related to the branch of mentioned Reden draining tunnel.Additionally, according to Local Spatial Development Plan of southern districts of the Tarnowskie Góry city it's clear that the lots 690/44 and 691/44 are located in a zone of old galena and brown iron ore mining activity. According to MPZP, raising buildings in this area requires a geological and mining expertise including the influence of mine workings on future construction. Old mine workings, after ending the exploitation, were usually abandoned and with time, self-filled, compressed or collapsed. However, rigid, carbonate rocks allowed for preservation of such workings in rock mass. Only long-term erosion processes (caused by surface water influence) lead to irregular and impossible to predict collapses and self-filling of these workings. Studied case refers to tunnels made in dolomite rocks related to galena prospecting.

Based on analysis of available cartographic source material, following elements of historic mining activity in 690/44 and 691/44 area can be presented (figure 5):

- Studied lots are located in the area of historic dolomite lead ore and brown iron ore exploitation. Remainders of workings made in dolomite rocks may be present, which could have been preserved to this day and which may prove hazardous by allowing for occurrence of discontinuities.
- Studied area is located in the area of Historic Silver and Lead Ore Mine, which is one of the best-preserved and at the same time the most exploited areas of Tarnowskie Góry.
- It should also be taken into consideration that the cartographic data, regarding historical mining exploitation are often incomplete and imprecise. Exploitation maps have often been made using hand-made sketches or even verbal transmissions. There is possibility that in the area of studied lots there can be undocumented workings, which is based directly on mining situation in the area. Small errors in location of historical mining objects are especially important, considering very small distances between historical mining remainders and designed buildings. This concerns in particular "Alter Hoffman" shaft located in southern part of 690/44 lot.
- Workings related to historical exploitation of brown iron ore are located in loose geological formations, often making them unstable and lead to their fast self-filling, also under the influence of infiltrating rainwater. However, it cannot be ruled out the possibility that there are still zones where rock mass is relaxed, there are relatively small cavities, which may cause local surface discontinuities, especially when subjected to additional ground load and construction works.
- Therefore, in case of studied areas, surface discontinuity occurrence hazard cannot be excluded (in form of small surface collapses).
- Probability of such occurrences is unmeasurable. Presence of old mining activity remainders in analyzed area leads to believe that potential deformation may occur.

- Thus, it is necessary to conduct - in studied investment area – non-invasive geophysical surveys in order to confirm or eliminate the hazard of discontinuities occurrence.

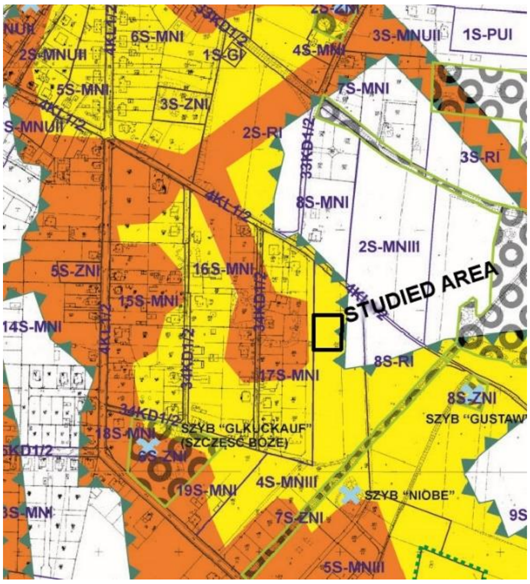

Figure 4. Fragment of MPZP map of southern districts of Tarnowskie Góry city. Marked in orange is range of main workings of historic silver mine and "Black Trout" adit. Yellow color represents zones with remainder of historic mine workings. Green line marks the border of historical protected zone.

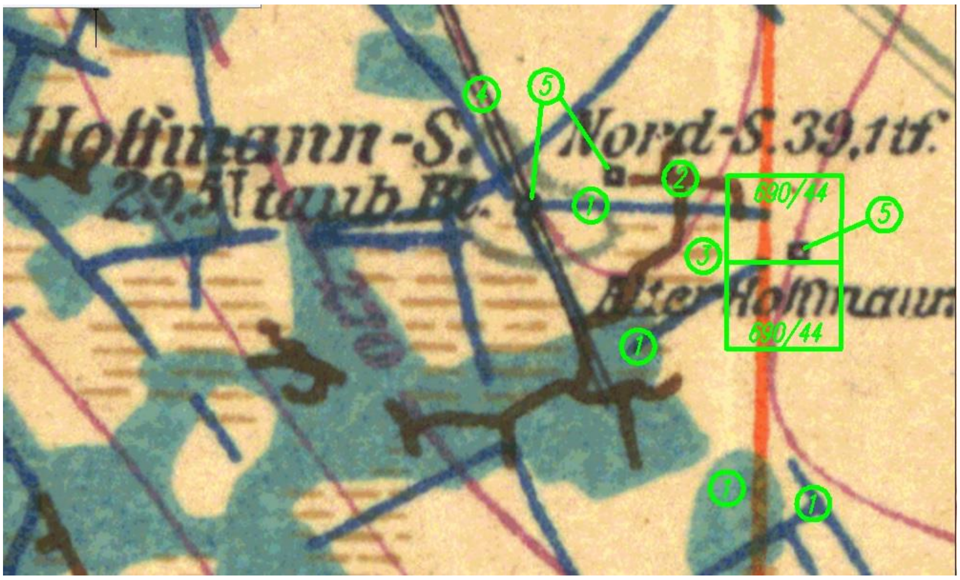

Figure 5. Ore excavation map of Upper Silesia region from old Central Mining Department in Wrocław, published in Berlin in 1911, (Erzkarte) sheets No 6 and 7 [11]. 1 – tunnel and excavation workings of galena deposits (blue), 2 – access tunnels in brown iron ore deposits (limonite) (brown), 3 – probable location of excavation workings in brown iron ore deposits (brown dotted line), 4 – water tunnel, which is a branch of Reden crosscut, 5 – major and minor ore shafts.

5. Methodology of field surveys

Based on the above, it has been proposed to perform non-invasive geophysical surveys. Geophysical surveying for possible discontinuities, as well as detecting cavities in Triassic formations and potential loosening of Quarternary formations after finished exploitation of coal deposits, was performed using medium gradient electrical resistivity profiling. Electrical resistivity method is based on variation of resistivity between anomalies such as cavities, caverns, fracture zones etc. and surrounding rock mass [12, 13].

Measuring system generates artificial electrical field in the medium and allows for mearing of its voltage in specific segment of surface. Results are basis for evaluation of apparent resistivity of the ground. The choice of depth range (choosing specific measuring system) is conditioned by specific, often complicated, geological-mining situation. Depth range of electrical resistivity method is dependent on the distance between powered electrodes stuck in the ground (in geoelectrical methods marked as current electrodes A and B) and lithology of given area [3, 8, 14]. Potential variation is measured between measuring electrodes (marked as M and N). To perform the task that is a subject of the article, area was measured using two setups, AB = 90 m and AB = 150 m in a 5 m grid and measuring intervals of 5 m. The grid has been adjusted to fit measuring field dimensions. To supplement the survey, additional setup AB = 150 m has been done perpendicularly to the previous one in 5 x 5 m grid. First measuring setup AB = 90 m has been done to check the rock mass conditions in depth range of the first shallow mining operation of iron ore. Its depth range, based on long, experimental research has been determined to be around 18 – 22,50 m. Second measuring setup AB = 150 m has been chosen based on deeper ore exploitation. Depth range of AB = 150 m electrode setup is around 30 – 37,50m [15].

6. Geophysical survey interpretation

Electrical resistivity method has been chosen to determine condition of rock mass, which helps to evaluate potential threats to a surface. Basic notion of resistivity profiling interpretation is that, no matter the method, the results have common characteristic, which is the possibility to view resistivity as a sum of "background" and anomalies. Background can be understood as a value of resistivity obtained in case of uniform rock mass or a rock mass built of uniform horizontal layers. When we talk about physically diverse system (cavities, fissures, fractures, water), then the resistivity curve of such rock mass has variable course. Any distortions, exceeding the value of the background are called anomalies. Their intensity is dependent on dimensions and intensity of distortion. Absolute values of resistivity in anomalous zones also rely on resistivity of surrounding rocks, fracturing intensity caused by mining activity, water levels etc. Results of study, based on field survey interpretation, allowed for creation of apparent resistivity map and anomalous zone map for each measuring setup used (figures 8-11). The main criteria for designating anomalous zones on measuring field was average value of apparent resistivity (table1). Any deviation from average resistivity value in studied rock medium, in form of significant growth or reduction is considered the anomalous zone (place). Table 1 shows compilation of resistivity values obtained as a result of electrical resistivity surveys [15, 16, 17].

Average, registered values of apparent resistivity are similar, which means that there is no significant lithology variation at studied depth range. Considering that in case of electrical resistivity profiling, the measured value is the apparent resistivity and not true resistivity any details about layers that rock mass consists of, cannot be determined. In the light of data obtained from setups AB = 90 and AB = 150 used, high resistivity anomalous zones have been designated (figures 6-9). Additionally, low resistivity anomalous zones have also been detected and are characterized by significant reduction of resistivity values, which were found near gravel road. These anomalies may have been caused by road's foundation, which have lower conductivity value causing distortion of the results or a mound left after construction of neighboring buildings. Places with high resistivity values are drained, dry areas or areas filled with air such as loosened ground, fractures or cavities where anomalous values reach maximum.

Table 1. Compilation of electrical resistivity values.

Area	Measuring field surface and dim. 1575 m^2 45 x 35 m	Measuring field surface and dim. 1575 m^2 45 x 35 m	Measuring field surface and dim. 1575 m^2 45 x 35 m
Measuring setup	AB = 90 m Profiles direction E-W	AB = 150 m Profiles direction E-W	AB = 150 m Profiles direction N-S
Minimum apparent resistivity (Ω·m)	49	55	41
Maximum apparent resistivity (Ω·m)	217	204	229
Average apparent resistivity (Ω·m)	138,3	141	145,5

As mentioned earlier, surface discontinuities are related to the occurrence of physical discontinuities in layers of rock mass and their form is dependent on physical and mechanical characteristics of the system. If the overburden is loose and free flowing, then conical depression is usually formed, if its rocky and fragile – irregular depression, while when the overburden is plastic (cohesive soils) - regular depressions. According to archival mining maps that on the border of studied lots, mining shaft Alter Hoffmann (figure 5) could have been located, which was around 35 m deep. The last information about anthropogenic structures located in place of this shaft come from 1911 and say it was mining waste dump. On 1958-1961 maps, the shaft is not marked (in contrast to other shafts) in any way and was not visible in the field then and is not visible today. Old ore mining shafts are hazardous to surface structures because of the lack of information about their deconstruction. Northeast of possible location of shaft's entry hole, there is a high resistivity anomaly on AB = 150 m setup (N-S profiles, figure 8) along with resistivity maximum, which can point to a potential hazard caused by inappropriate deconstruction of the shaft. There is no anomaly in place where shaft was located based on 1911 map. AB = 150 m setup covers depth range where location of mine access tunnels, which allowed excavation using nearby shafts. Registered anomalies do not have linear continuity that points towards unsecured tunnels, however, they have few points range and can be a remainder of incorrectly dismantled goaf or can be a result of loosening of the ground. In the area of the access tunnel itself, the anomalies are not present. General map of studied investment area along with geophysical measurements results summary – electrical resistivity method, presented on (figure 9). However, mining maps do not always show the real geological and mining situation. Deformations cause by mining occur where there shouldn't be any and it is a result of e.g. shallow mining operation, expertize based on incomplete archival material, incorrect location of excavations and mining infrastructure on maps. In the light of conducted research, designated anomalous zones, especially their maximum values marked with yellow outline were presented in form of resistivity distribution maps, show zones threatened by potential occurrence of surface deformations.

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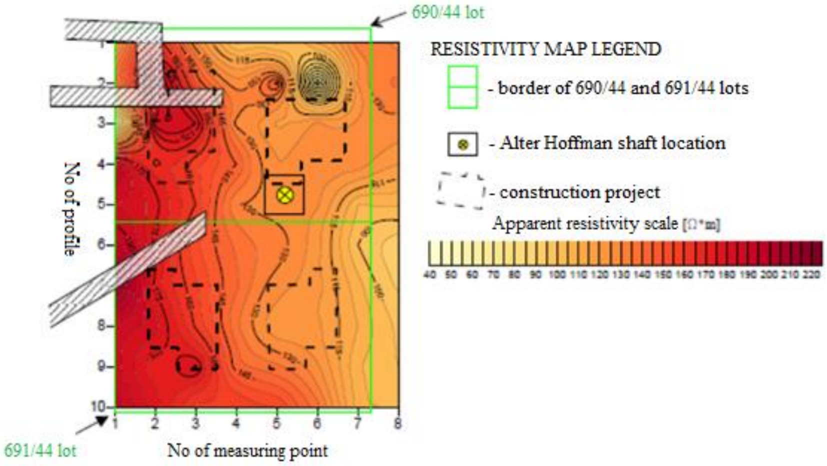

Figure 6. Apparent resistivity distribution map AB = 90m profiles direction E-W.

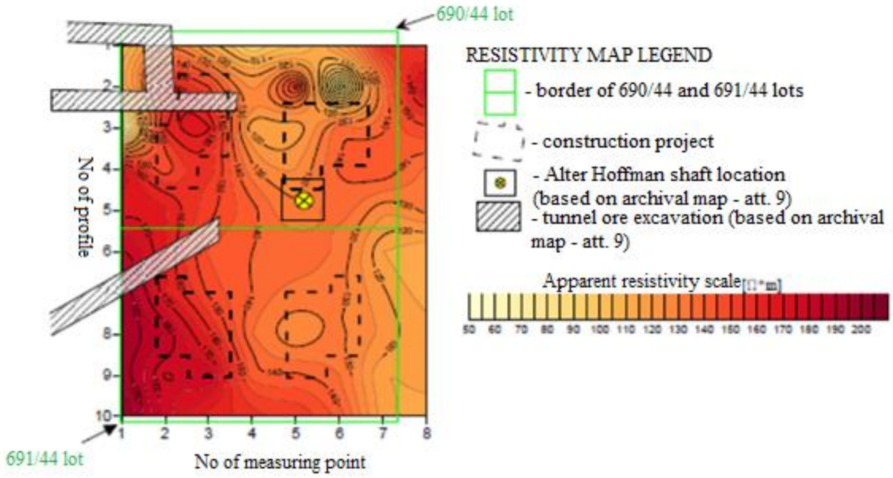

Figure 7. Apparent resistivity distribution map AB = 150m, profiles direction E-W.

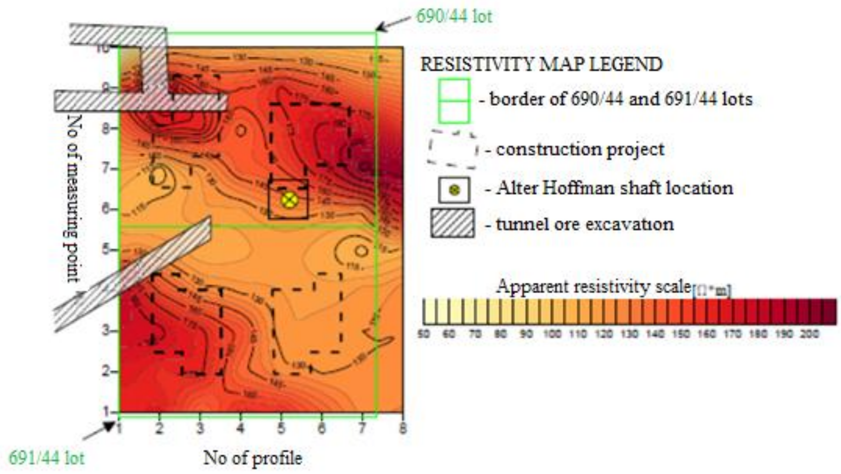

Figure 8. Apparent resistivity distribution map AB = 150m, profiles direction N-S.

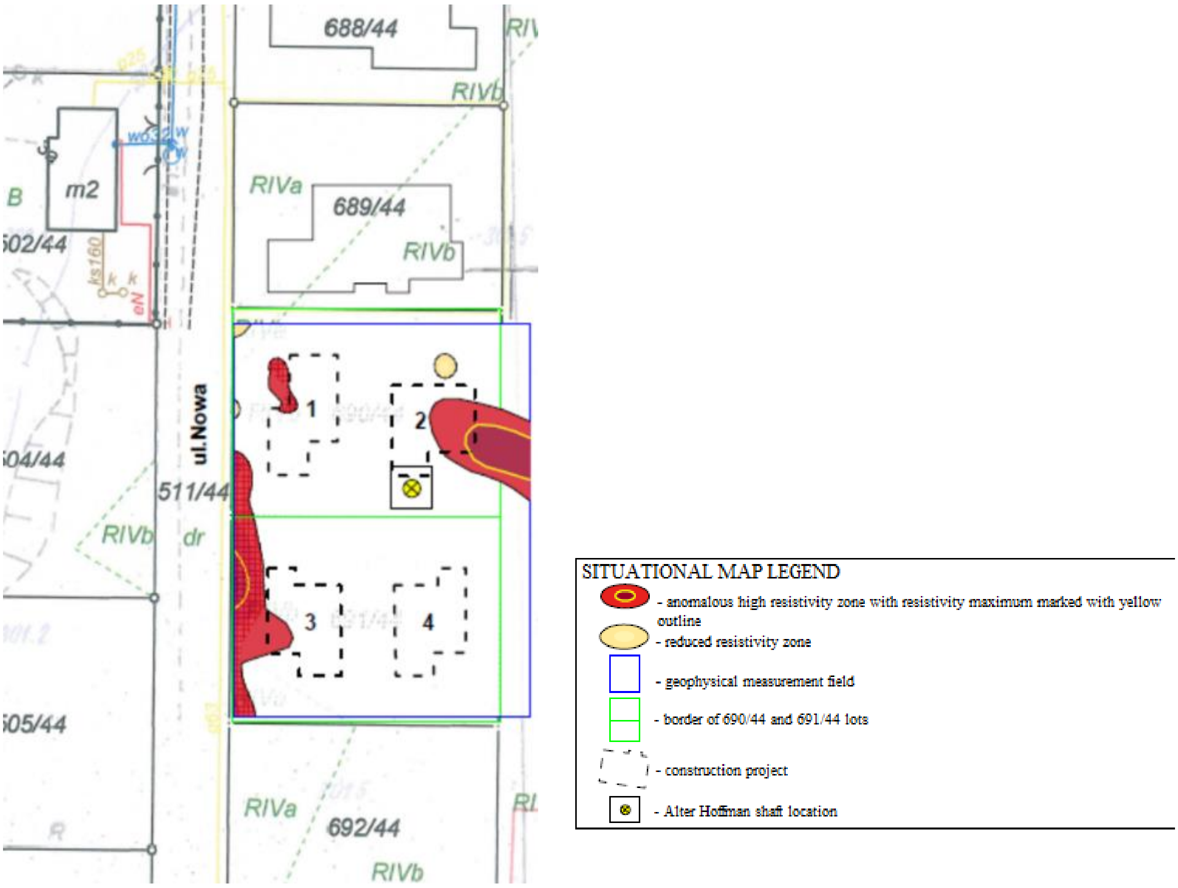

Figure 9. Situational map of studied investment area along with geophysical measurements results summary – electrical resistivity method.

7. Summary

To complete the task, which was the subject of this article, two-level medium gradient electrical resistivity profiling has been conducted. Field surveys performed on measurement field used two different measuring setups AB = 90 m and AB = 150 m in 5 m grid at 5 m intervals. To supplement the survey, additional setup AB = 150 m has been done perpendicularly to the previous one in 5 x 5 m grid. First measuring setup AB = 90 m has been done to check the rock mass conditions in depth range of the first shallow mining operation of iron ore. Its depth range, based on long, experimental research has been determined to be around 18 – 22,50 m. Second measuring setup AB = 150 m has been chosen based on deeper ore exploitation. Depth range of AB = 150 m electrode setup is around 30 – 37,50 m (figures 6-9). In the light of data obtained from setups AB = 90 and AB = 150 used, high resistivity anomalous zones have been designated. In the light of conducted research, designated anomalous zones were presented in form of resistivity distribution maps, show zones threatened by potential occurrence of surface deformations. Places with high resistivity values are drained, dry areas or areas filled with air such as loosened ground, fractures or cavities where anomalous values reach maximum. In the light of conducted research, designated anomalous zones, especially their maximum values marked with yellow outline were presented in form of resistivity distribution maps, show zones threatened by potential occurrence of surface deformations. Considering the planned investment it is absolutely necessary to ensure the underground pipelines are watertight (waste, water etc.) and that water is not gathering (e.g. rain water from the roof). Potential leaks in the system may cause water to migrate into the rock mass, which leads to deformation of the surface.

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