Acta Polytechnica CTU Proceedings **45**:20–26, 2023
https://doi.org/10.14311/APP.2023.45.0020

Published by the Czech Technical University in Prague

GEOPHYSICS FOR UNDERGROUND ENGINEERING

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Abstract. The growth of underground engineering brought a need for the use of geophysical methods for research of underground constructions rather different in approach compared to that of civil engineering. These changes relate to surface measurement on the one hand and the development of new specialised methods used for underground work on the other. The results of a complete documentation of mining work, the application of the resistivity methods used underground and also the use of 3D electrical resistivity tomography, are all presented here.

Keywords: Geophysics, underground structure, ERT.

1. Introduction

Using 2D and 3D methods in geophysical surveys is very enticing, but we must realise that even the latest mathematical procedures and possibilities of electronics have their limitations. In this paper we want to point out some problems in geophysical measurement carried out underground, including interpretation of 2D and 3D geo-electrical measurements. The paper presents the results of measurement in one mine working, between mine workings, and also between mine workings and boreholes.

2. The issue of measurement and interpretation of 2D and 3D ERT

For a greater objectivity regarding interpretation of the results of geophysical measurements, it is always suitable to process the given measured data in several ways. The same also applies to the measurement of electrical resistivity tomography. Figure 1 shows an example of how to interpret ERT measurement using the RES2DINV and ZondRes2D programs. The example manifests simple geological conditions in a survey for the construction of Motorway D35 at the municipality of Sedliště, particularly from profile 41–41'. The area of interest is formed by sedimentary rocks of the Bohemian Cretaceous Basin typical of claystone, marlstone, etc., covered by soft Quaternary sediments typical of loess, loess loam, etc.

The results of interpretations from both the programs are not identical, but they are similar. It can be declared without problems that the setup of iterative parameters in both the programs brings about larger resistivity changes than by comparing the results of both the programs mutuall [1]. In both interpretations it is possible to distinguish a near-surface layer of loams without any difficulty. The base of loams is located at a depth of about 7 m according to the RES2DINV program, and at a depth of 11 m according to the ZondRes2D program. Based on the result of drilling work, the boundary is defined at a depth of about 12 m, i.e., the interpretation comes out better from the ZondRes2D program. It is more complicated with the determination of the surface of Cretaceous clayey sediments. This geological boundary has not been determined by direct survey work (it was terminated in the Quaternary), but only by the results of vertical electrical sounding (VES). Based on VES, the boundary is located at a depth of 25 to 35 m. According to the results of RES2DINV, it is found at 30 m, and according to ZondRes2D, at about 35 m. Both the programs indicate a horizontal change in resistivity values suggesting a facies change of sediments in the second layer as well as in the third layer. This change is better evident in the uncut resistivity cross sections in the lower part of the figure.

The conditions for measuring ERT in other figures (the site of PVP/underground research facility/Bukov, testing chamber ZK-1) were opposite to that in the preceding case. Whereas in measurement from the survey for the motorway it can be said that the conditions were ideal (measurement took place on natural ground with normal moisture content, so the contact resistance values on electrodes ranged from about 200 to 1 110 Ω), underground measurement was much more complicated. From the monitoring of contact resistance values, it was detected that the contact resistance values between the electrodes and the rock massif were significantly higher. Specifically, in the studied profile (lower right, PD) contact resistance values in 2019 changed from 3 000 to 120 000 Ω. During processing, the results of such high contact resistance values on these electrodes were eliminated from further processing.

When using electrical resistivity tomography underground, we still verified the effect of the origin and version of the interpretation program on the resulting resistivity field. We carried out an extensive analysis on measurements at the beginning of cross-cut BZ-XIIJ on its left side just behind the beginning of the research facility, where copper electrodes of 10 mm

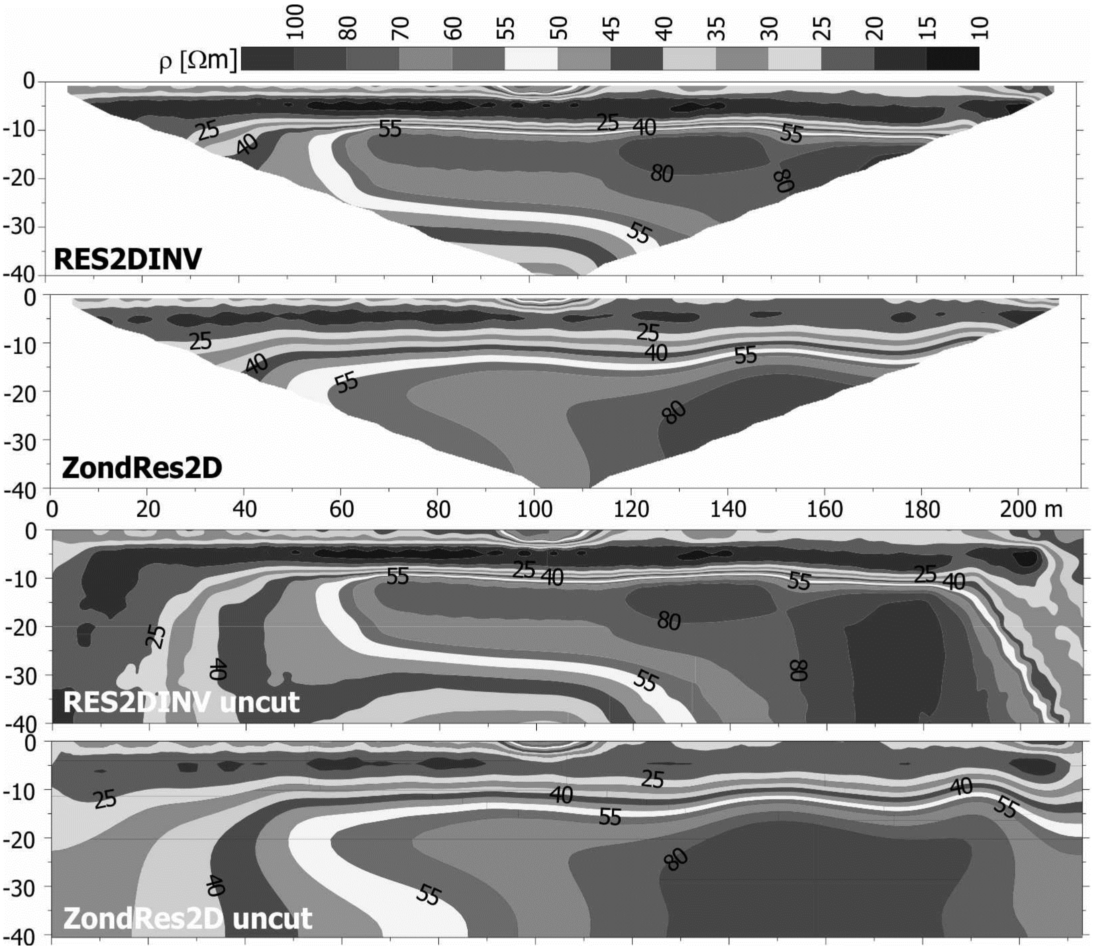

Figure 1. Comparison of ERT interpretation using the RES2DINV and ZONDRES 2D programs.

in diameter were used and sunk into the side of the mine working to a depth of 5–10 cm. The resistivity fields detected by different versions of the program are given in Figure 2.

As in the preceding example from measurement in ideal conditions, the basic geological structure identified by both the programs is the same. But the details of each anomaly are different not only by areal extension, but also by the values of resistivity. In addition to the basic environment designated "A", five anomalies "B" to "F" were detected using the ZondRes2D program; the RES2DINV program identified six anomalies "B" to "G". Anomalies "B" to "G" have relatively small dimensions and their maximum resistivity values range between four and six thousand Ω m in the ZondRes2D program, whereas in the RES2DINV program they range between four and forty thousand Ω m. The area of high-resistivity anomalies is approximately the same in both the versions. An exception is the lower limitation of anomalies "B" and "D". A larger difference is in their maxima. In the "Russian" version it is 4 200, 5 700, 5 300, 4 000 and 6 000 Ω m and in the "Danish" version it is 4 500, 4 200, 5 500, 7 000 and 30 000 Ω m. The basic environment "A" in the "Russian" version is visually more homogeneous than in the "Danish" version. This is due to the fact that the blue colours of the low-resistivity environment of the "Russian" version, in a range of 500 to 1 700 Ω m, are practically indistinguishable to the human eye. The basic environment has the values of resistivity in the "Russian" version 500 to 1 700 Ω m and in the "Danish" version 400 to 1 500 Ω m.

3. Measurement and interpretation of ERT in 2D and 3D versions underground

The first example of the use of electrical resistivity tomography in the 3D version is from measurement in testing chamber ZK-1 at the site of PVP Bukov. In this chamber, several stages of repeated measurements were carried out, with six profiles being measured: two of them always on the sides of the chamber, one on the footwall of the chamber and one on its top wall. The profiles were measured both separately and on the opposite profiles, i.e., one series of electrodes was, for example, on the lower left profile (LD) and the other on the upper right profile (PH). In all, measurement in testing chamber ZK-1 took place five times, in January 2016, then in April 2017, in September 2019, in February 2020 and in May 2021. For those in September 2019 and in February 2020, measurement took place on the lower right profile (PD) always three

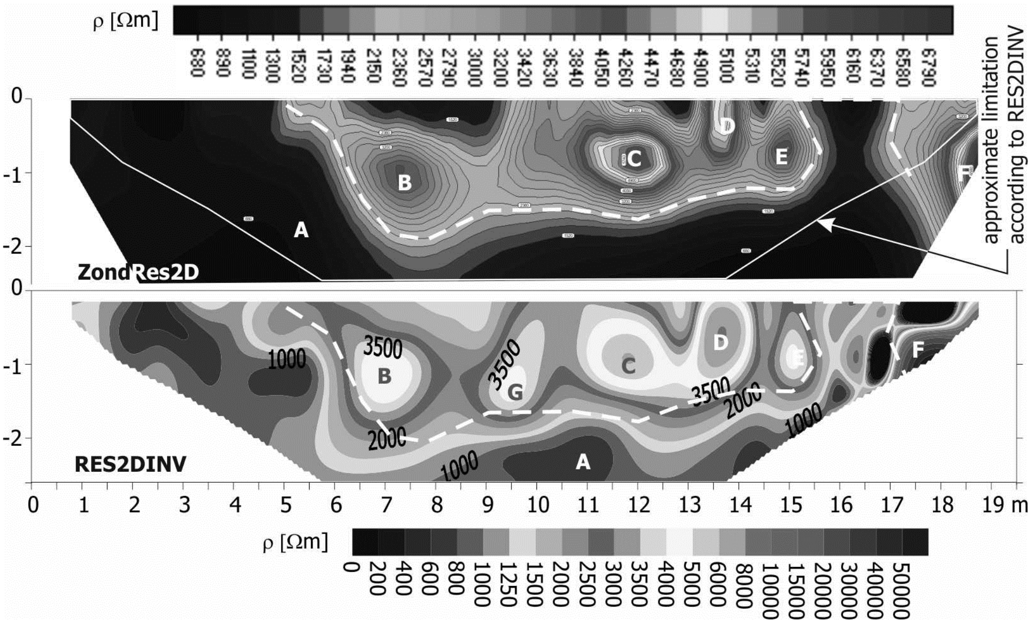

Figure 2. Comparison of the results of ERT interpretation using RES2DINV and ZondRes2D programs in ZK-1.

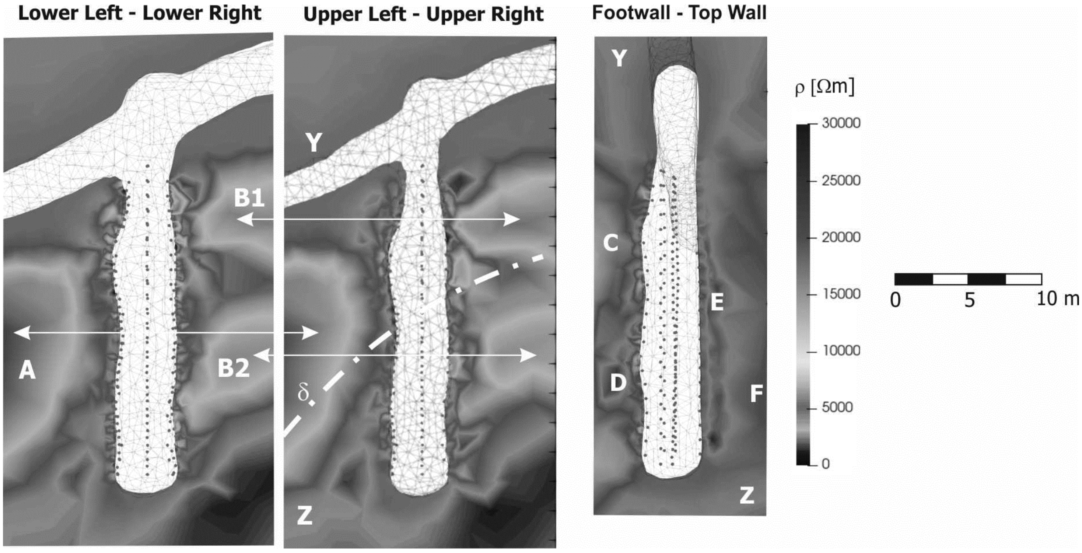

Figure 3. Resistivity cross sections through testing chamber ZK-1.

times immediately one after the other. The results of measurement from 2019 processed by the GENIE program for 3D interpretation and put together at the Technical University of Liberec, are depicted in Figure 3.

The interpreted resistivity values range from 200 to 25000 Ω m. The interpreted resistivity values are unusually (even improbably) high. On two sub-horizontal cross sections and on one vertical cross section, we can distinguish eight blocks. Blocks Y and Z lie at the margins of the measured space and cannot be considered as reliable. The reason is a very low number of measured points from which it is possible to count resistivity values. These blocks cannot be assigned a geological meaning. The other blocks by their position allow us assign their geological, or more precisely, their geotechnical meaning.

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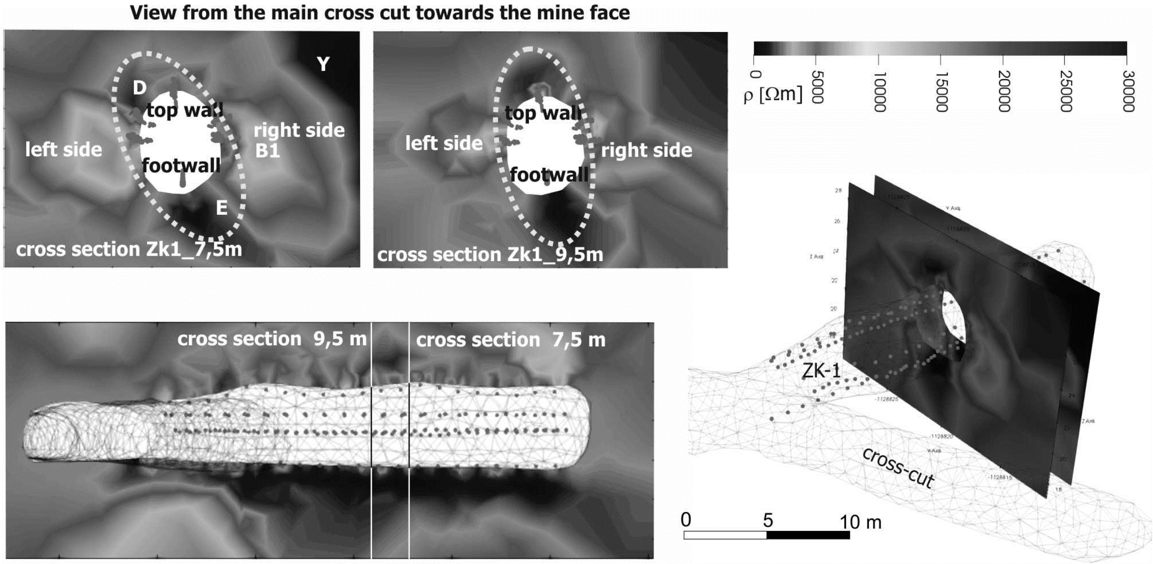

Figure 4. ERT cross sections perpendicular to ZK-1.

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Block A lies on the right northern wall of the chamber. This block can be considered as a block of rocks in natural state, not being affected in any way by mining work or any other investigation that could have taken place in this space. Its resistivity values range between about 10 and 25 thousand Ω m. Block B can also be characterised similarly, being divided into two sub-blocks B1 and B2. Sub-blocks B1 and B2 are probably separated by a discontinuity, or by a conductive zone of fracturing of the rock mass (δ). This zone is also manifested on the right side as a boundary between blocks A and Z. The zone of fracturing defined by resistivity probably corresponds to joints of the NNW-SSE to N-S strike. According to all three resistivity cross sections, one mega-block can probably be defined, comprising blocks A, B and C and corresponding to the original rock mass.

Interesting information can be obtained from cross sections drawn perpendicular to the axis of ZK-1 (Figure 4). The cross sections were constructed only on the basis of ERT measurement in September 2019. Interpreted resistivity values in the cross sections range from 300 to 15 000 Ω m. The cross sections were constructed under the stations of 7.5 and 9.5 m perpendicular to the axis of the working. The most interesting on the perpendicular cross sections are anomalies of low resistivity values above the top wall of the chamber and beneath its footwall. These low-resistivity anomalies indicate the places of the massif loosening after the chamber excavation and the re-distribution of the stress field. We proceed from an assumption that the micro-fissures were formed in the loosened massif and filled by groundwater. The moisture content in the massif may not be at all high. It is sufficient for a decrease in rock resistivity when the fissures create a conductive network.

The drop in resistivity values is different above the top wall of the chamber and beneath its footwall. The explanation must be found in the moisture content of the rock above and beneath the working. It is possible to expect full saturation of fissures in the massif by groundwater beneath the footwall of the chamber, whereas above the top wall there remain places in which pores in the rock are not fully saturated. This fact is shown by small anomalies of low resistivity values, whereas beneath the footwall the decrease in resistivity values affects the whole massif concerned.

If we proceed from a generally accepted assumption that the fractured massif in the surroundings of the stope has the form of an ellipse in the perpendicular cross section [2], then it is possible to estimate what the ellipse definition of the fractured massif will look like in the vicinity of ZK-1. It is interesting that the ellipses do not have their long axes vertical, but that the axis of the ellipse above the top wall is turned to the north. On the cross section at 7.5 m, the ellipse is

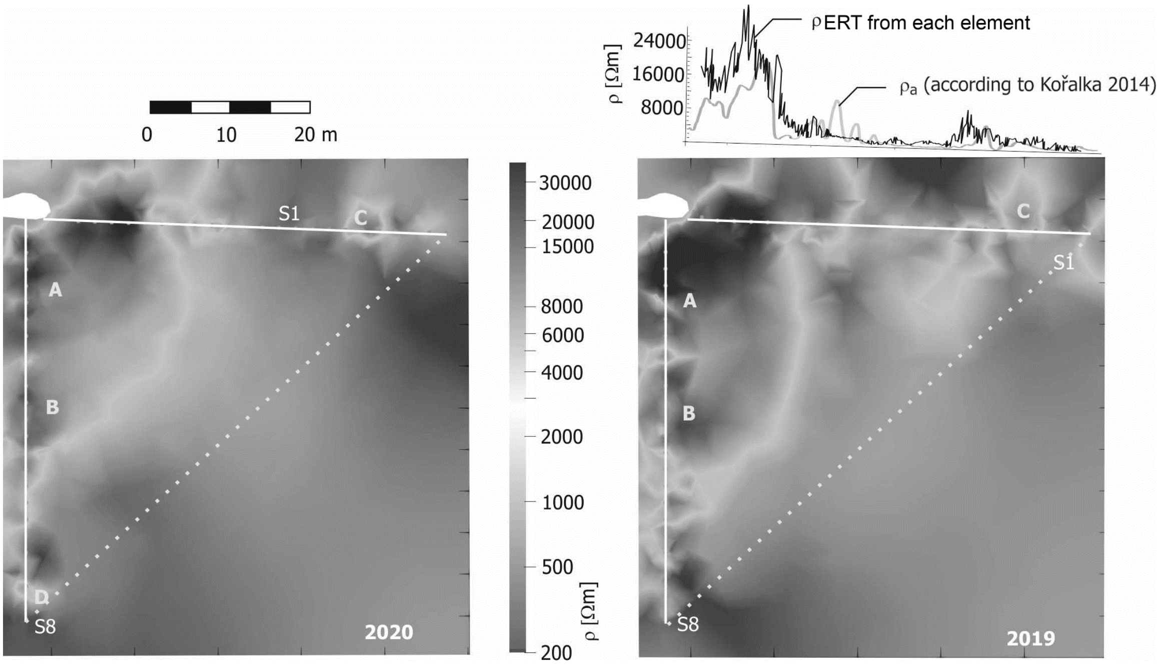

Figure 5. Cross sections from ERT between boreholes S1 and S8.

turned by about 25 ° and on the cross section at 9.5 m by 10 °. In relation to the possibilities of the method, the given numbers cannot be taken as absolute numbers, but it can be stated that the ellipse is turned by roughly 15 ° to the north. Similarly, the stress should also be turned. Interesting is the ratio of semi-axes of the ellipse. The resistivity data show that the ratio of semi-axes of the outlined ellipses of fracturing is about 1:2.

Another testing of possibilities of 3D ERT and a new program for 3D interpretation of ERT (GenieERT) took place on the results of measurement between boreholes S1 and S8 at the same site. In this case, all electrodes were placed in the borehole. In relation to the conditions of measurement, it was an ideal situation. The electrodes in the borehole have a minimum contact resistance that changed from 930 to 6 500 Ω.

The comprehensive interpretation of measurement in boreholes S1 and S8 comprises the processing of electrical resistivity tomography (2019), resistivity logging (carried out by Aquatest, a.s.) and the resistivity values obtained from ERT. The grey curve depicts the interpreted resistivity values of the first series of ERT elements from the sections of one metre size. The outcome of this comparison of all results is shown in Figure 5. The interpreted resistivity values range between 300 and 20 000 Ω m. On the cross section between boreholes S1 and S8, it is possible to identify four blocks A to D2. The high resistivity values characterise blocks A and B. The other radiographed area is characterised by low resistivity values. Blocks A and B are of special significance, differing from the other blocks by their area and the size of the maxima of resistivity values, which reach about 20 000 Ω m. The delineation of the blocks is also evident in the results of down-hole logging. These anomalies constitute blocks of rocks which are not practically affected by fracturing. The pictures of distribution of the interpreted resistivity values obtained in 2019 and 2020 bring factually the same results. Certain differences can be found in the form of anomalies between 2019 and 2020. The anomalies in 2019 are in area larger and the margins of anomaly A in 2019 are not so rugged. Anomalies C and D in 2019 are smaller than was the case in 2020.

5. Physical documentation of mine walls

Below the RQD output in Figure 6, graphs of the results of measurement using “speedy” methods are presented one after another, i.e., measurement of temperature, radioactivity and magnetic susceptibility. The results of “speedy” methods provide valuable results, particularly in comparison with other measurements, e.g., resistivity methods. On the curves of dose rate, certain increases of values are evident, located under the stations between about 9 and 18 m, having a significant response in ERT measurement (the last graph). The extent of the “radioactive” anomaly is very close to the extent of the resistivity anomaly. An interesting fact appears that a local significant decrease in the values of interpreted resistivity occurred in the inflection point of the resistivity elevation (under the station of about 13.5 m). Another interesting fact is a correlation of magnetic susceptibility with ERT under the stations of about 3.5 and 17 m, which have a response in resistivity minima on the curves of ERT measurement. Whereas the geomagnetic anomalies are in.

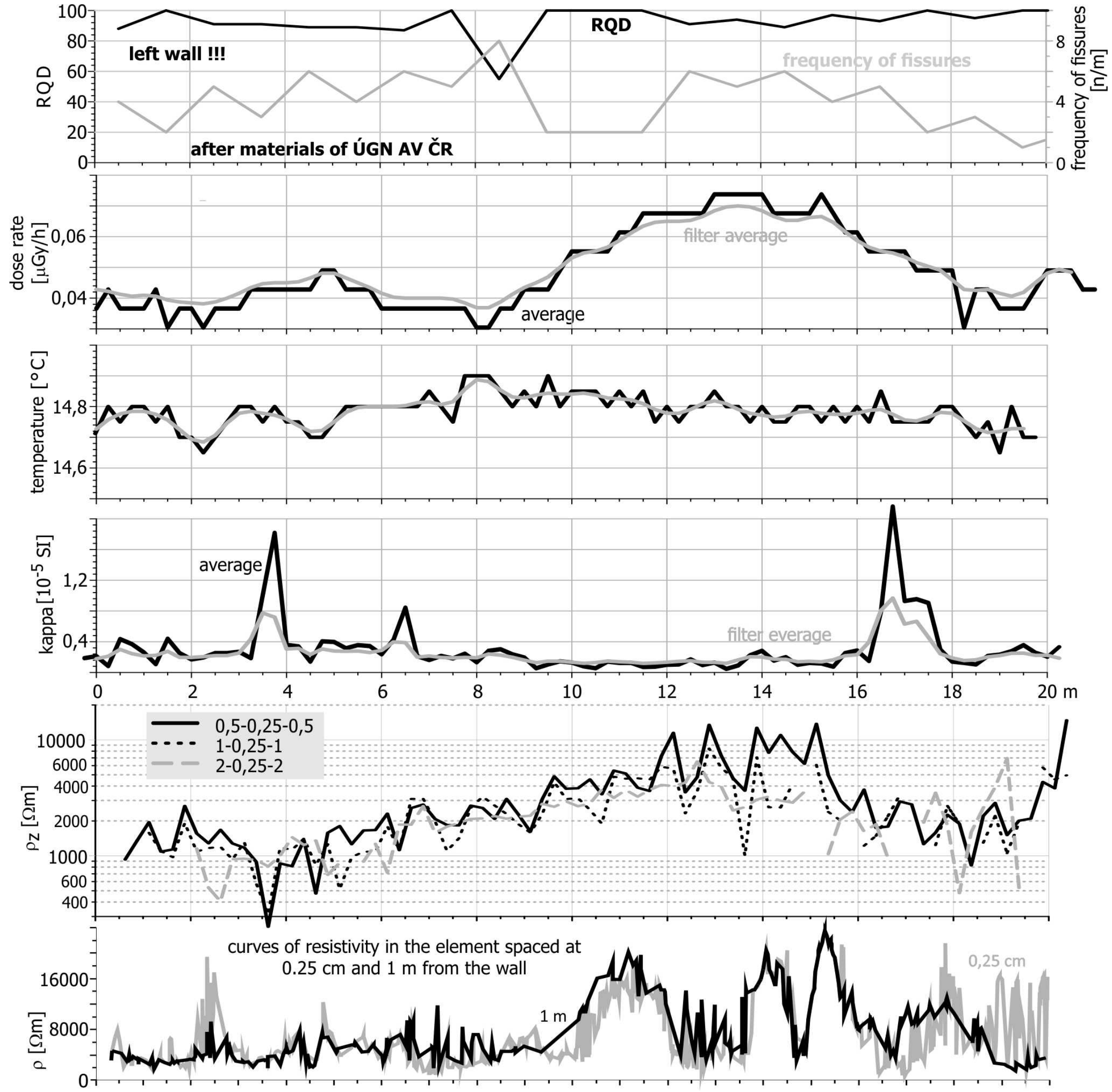

Figure 6. Physical documentation of a mine wall.

Figure 6 presents the results of 2D and 3D geophysical and geotechnical measurements on the wall of chamber ZK-1. The first graph illustrates the mechanical state of the rock environment on the left side of the working, represented by the RQD (Rock Quality Designation) coefficient, and also expressed in the form of the frequency of fissures per the unit of distance. Both measurements were conducted by geomechanics from the Institute of Geonics of the Czech Academy of Sciences (IG CAS). The RQD coefficient expresses the quality of rock and is usually determined on drill cores. Geomechanics of the IG CAS developed procedures to determine RQD from measurement on the surface of mine workings. When viewing the shape of curves, it is evident that the quality of the measured rocks is good to excellent. An exception is a section under the stations between about 7.5 and 9.5 m, where the value of RQD diminishes from about 95–100 % to about 55 %, i.e., the quality of rocks is classified by a medium grade. The given fact probably indicates the existence of structural discontinuities. The RQD value 55 accompanies a higher frequency of fissures (joints).

Relatively narrow, the decrease in apparent resistivity values is more gradual and more extensive in the measured line. It is possible that this concerns the manifestations of local lithological changes (veins penetrating the base rock perhaps?), but for explanation it is again necessary to have more information of a non-geophysical character.

The next-to-last graph in Figure 6 shows graphs of already mentioned resistivity measurements. Specifically, these are profiling curves of spacings A0,5M0,25N0,5B; A1M0,25N1B; A2M0,25N2B. The data were extracted from a cloud of values obtained by the ERT method, carried out with a detailed interval (0.25 m) and to a sufficient extent (about 22 m). The curves of resistivity profiling enable the basic quasi-homogeneous blocks to be delineated; they are characterised by the extent and value of apparent resistivity.

The resistivity curves are similar by their character to the curves obtained from the measurement of dose rate, where a small difference was recorded only in the initial part of the profile – a local minimum under the station of about 2.5 m on the curve of dose rate has the equivalent shifted to the station of about 3.5 m on the resistivity curves. This difference is probably determined by the oblique course of the plate (vein), which then causes the anomaly. It is necessary to realise that the dose rate characterises the space theoretically to 0.5 of a metre, but in reality even less. The range of geoelectrical measurement can be many times higher. The remaining sections correlate very well.

In the last cross section, two resistivity curves are plotted, each of them from a different depth level, indicating the assumed state of the rock environment. The grey curve reflects the resistivity situation at the level to 0.25 m behind the wall of the working and the black curve to 1 m behind the wall of the working. The given values, however, are only indicative because the determining parameters are the size and shape of cells from the 3D model, which are not the same. The displayed data, however, are sufficiently representative for orientation and the basic distribution of the values of resistivity along the wall of the working.

6. CONCLUSIONS

The comparison of programs for 2D interpretation of electrical resistivity tomography (RES2DINV and ZondRes2D) has brought forth a number of interesting findings. We proceeded from our previous knowledge that the resulting resistivity field was not only a picture of distribution of resistivity values in the rock mass, but it could also be affected by the setup of input parameters for iterations. We have obtained for testing the ZondRes2D program in a functional demo version, and thanks to the cooperation of Czech and Uzbek specialists, a possibility has arisen to use both the programs to their full extent [3] and [4], During testing work, it appeared that it was possible to change the resulting resistivity field, similarly as in the RES2DINV program, by setting up parameters in the ZondRes2D program as well.

When evaluating digital programs of interpretation, we must be aware that we are trying to solve mathematically a not quite correct problem. In this case, we determine a substantially larger number of parameters than the input data we actually have. When comparing the results of both the programs, we began with the interpretation of results in simple geological conditions. In this case, the results were satisfactory because the differences in interpretation using both the programs were comparable with the differences which are obtained when changing the setup of input parameters of iteration. In more complicated surface conditions, the differences in interpretation were higher, but still comparable with changes given by the setup of programs. The largest difference occurred in the application with mine conditions. There, the differences between both the programs even increased, and we even recorded an example where interpretation by the ZondRes2D program was more reliable and the calculated model approached the reality more than in the case of the output from RES2DINV.

Geophysical measurement using the system of 3D and its 3D evaluation brings quite new possibilities when describing the rock mass in general and this also applies to special conditions underground. In mine workings, the possibility to choose the arrangement of profiles and points of measurement on profiles is limited as compared to surface applications of geophysical measurements. To find a suitable system of points measurement is usually very difficult and requires many compromises. An advantage of 3D processing of geophysical measurements is the spatial information on the geological structure of the area of interest. A disadvantage is the problem of obtaining a sufficient number of high-quality data for a 3D interpretation to bring reliable results. This paper describes several successful examples of the use of 3D geophysical measurement in different lithological types of rocks.

ACKNOWLEDGEMENTS

Geophysical work published in this paper was largely carried out in the underground research facility (PVP) Bukov. It was constructed, and is operated by, the Radioactive Waste Repository Authority (SÚRAO). To accomplish any activity in the spaces of the deep mine is relatively costly, complicated and requires a coordination of many professions and activities (working facilities, technical support, etc.). Thanks to the coordination with SÚRAO, which supports research activities in PVP to the maximum extent possible in the form of technical support and by providing services, it was possible to manage very well the planned measurements and all the other activities. For all this our thanks and appreciation are due to SÚRAO.

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