



COMPARISON OF 2D INTERPRETATION PROGRAMS FOR ERT POROVNÁNÍ 2D PROGRAMŮ PRO INTERPRETACI ERT

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Abstract

The method of electrical resistivity tomography (ERT) is currently the most widely used geoelectric method. Generally, the processing of measured values by interpretation programs does not give conclusive results. In this paper, we compare the results of RES2DINV and ZondRes2D programs in the interpretation of ERT. For both programs, the result depends on the number of iterations and on the setting of the input parameters of the calculation. By comparing the results of both programs, it can be said that there are differences between them. These differences are of the same order of magnitude as the differences given by the calculation settings. The results show a similar structure of the field of resistivities from both programs. But the results differ in detail. In the use of the ERT method, we often encounter an approach where any minor anomaly is given importance, sometimes even fundamental. Such a style of interpretation cannot be considered correct.

Abstrakt

Metoda elektrické odporové tomografie (ERT) je v současnosti nejpoužívanější geoelektrickou metodou. Obecně platí, že zpracování naměřených hodnot interpretačními programy nedává jednoznačné výsledky. V předkládaném článku porovnáváme výsledky programů RES2DINV a ZondRes2D při interpretaci ERT. U obou programů je výsledek závislý na počtu iterací a na nastavení vstupních parametrů výpočtu. Porovnáním výsledků obou programů je možné konstatovat, že mezi nimi existují odlišnosti. Tyto odlišnosti jsou řádově stejné, jako odlišnosti dané nastavením výpočtu. Výsledky ukazují na obdobnou strukturu pole měrných odporů z obou programů. Ale výsledky se liší v detailech. V používání metody ERT se často setkáváme s přístupem, kdy jakékoli drobné anomálie je přikládán význam, někdy i zásadní. Takovýto styl interpretace není možné pokládat za správný.

Keywords

Electrical resistivity tomography, RES2DINV, ZondRes2D

Klíčová slova

Elektrické odporová tomografie, RES2DINV, ZondRes2D

1 The issue of the digital interpretation of geoelectrical measurements

The distribution of resistivity values, just as the other physical properties, in the rock mass is the matter which geophysics, including geoelectrics, seeks to describe as best as possible. With the passage of time, geophysicists acquire ever better instruments which enable the state of the rock mass to be known, using both new methods of measurement, and new methods of processing. But they are not panaceas, and without the knowledge of the theoretical basics of data acquisition and interpretation, erroneous conclusions are often drawn when using such data. This also applies to the method of electrical resistivity tomography (ERT). The depiction of the structure of the rock mass gained from such measurements and of its properties is influenced by the possibilities of measurement using this method, including the depiction of its results, and by objective conditions for its application and interpretation. The measurement in the field does not pose any problems, with apparatuses for ERT being equipped with sufficient control mechanisms which exclude gross errors of measurements. Nevertheless, if a certain value is measured with an error larger than in the other values, it can be excluded from further procedures in the first step of processing. Nevertheless, however, the acquired results can be influenced by the procedure of processing and can also be influenced by the setup of computation parameters and representation parameters.

2 The properties of program RES2DINV

Four years ago, the articles were published, dealing with complications when using the RES2DINV program (Loke, 2012). Not only the measured values of apparent resistivity, but also the setup of interpretation parameters have had an effect on the picture of the resulting distribution of resistivity values, and the use of the program for the resulting depiction of results of iterations, which affect the result of interpretation, can be summed up into the following points:

- The version of interpretation program;
- The number of iterations;
- The use of interpretation version;
- The use of the number of cells for iteration;
- The use of the type of mesh;
- The use of the interval and the number of layers;
- The use of drawing program;

- The setup of “damping factor”; and
- The use of the “standard” and “incomplete” Gauss-Newton methods and differences in the system of computation of the Jacobian and the quasi-Newton approximation.

Three of the nine parameters mentioned above, which have an effect on the resulting picture of resistivity distribution, will be presented here, which we can deem as the most important. The first of them is the difference in the resistivity field obtained by processing the measured data using different versions of the program RES2DINV. Figure 1 shows examples of outputs for program versions 3.54, 3.58 and 4.04. By comparing all the three pictures, we can find six differences. The largest differences lie in high-resistivity anomalies under the stations 48 and 88 metres. Another difference is a low-resistivity anomaly from the beginning of the profile to the station 32 metres. It is areally the most striking in program version 4.04 and the least striking in version 3.58. A partial minimum under the station 32 metres fully disappeared in the latest program version. The lowest resistivity values, however, are in version 3.54. The third different anomaly is a resistivity maximum under the station 88 metres, which has the largest anomaly in version 3.58 and the smallest in version 4.04. The fourth difference is a low-resistivity anomaly under the station 74 metres on the base of the interpreted space. It has the lowest resistivity values in version 3.58, where the minimum is concurrently areally the smallest. The highest values are in version 4.04, where the centre of the minimum is concurrently moved by five metres to the lower metres. The fifth difference is the pattern of mean resistivity values in the centre of the profile. In version 4.04, the anomaly has the smallest “thickness”. The last difference is a high-resistivity anomaly with its centre under the station 48 metres. It has the highest values in version 4.04 and the lowest in 3.58. The geological evaluation of the results of all the three program versions would not be fully different under the assumption that all the small anomalies are not explained geologically and the geological boundaries are not depicted according to the isoohms of a certain value.

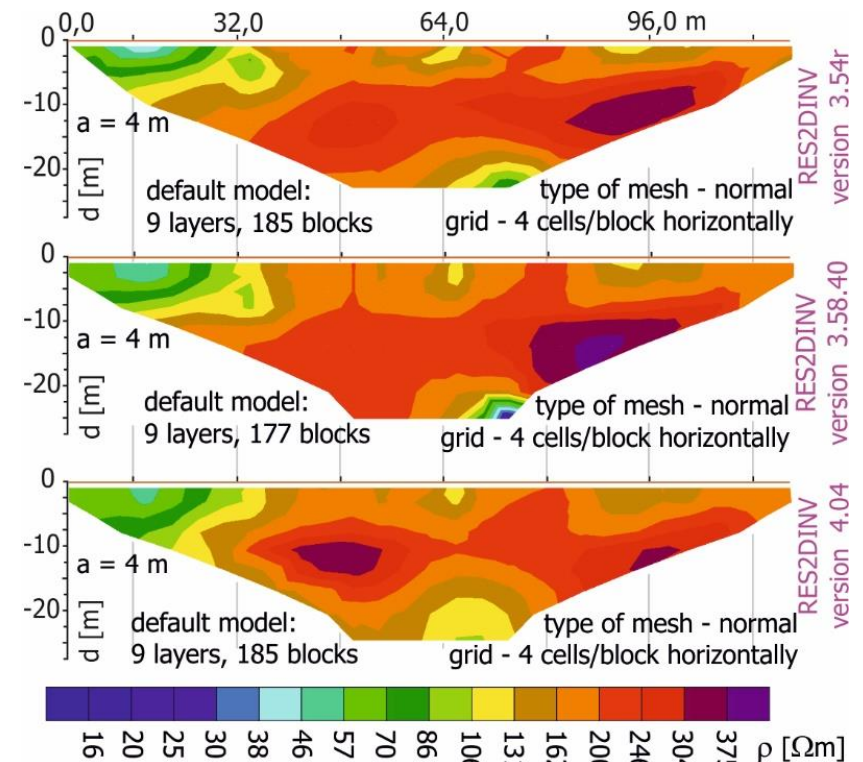


Fig. 1 Differences in ERT processing according to the version of RES2DINV program

Another parameter which quite significantly affects the output resistivity field is the so-called “damping factor”. It can be understood as a parameter which influences the “amplitude of dispersion of values”. By simplifying its value, we can achieve a larger or smaller smoothing of the resulting inverse output. When choosing the use of this method, we have two options of choice: “initial damping factor” and “minimum damping factor”. A more striking smoothing of the resulting resistivity field is yielded by the parameter “minimum damping factor”. When applying it, the fragmentation of the interpreted field of resistivity values is suppressed. By increasing the value of “minimum” damping factor, the number of depicted partial structures diminishes and they are merged into larger units. The model thus actually becomes simplified. It is well evident, e.g., in the conductive zone in the left part of the profile (Fig. 2), which is more or less discontinuous in the original model, formed by individual more or less isolated anomalies. Even if the series of individual anomalies is likely to be interpreted geologically as a single geological structure, there are examples in the literature, which interpret it differently. By simplifying the damping factor, it is achieved that the partial anomalies are merged into a single unit, which is simpler and chiefly more illustrative for geological interpretation. By changing the damping factor, the data become smoother, and thus the extreme values are suppressed, both low as well as high values. It can be declared that this procedure will prevent the occurrence of “bead-shaped” anomalies. If the value of both parameters is set higher, then the smoothing is fairly striking, with anomalies often disappearing at the lower margins of the quadrangle of the resistivity field. This is an indisputable advantage for the essential knowledge of the geological structure. By choosing a very high damping factor, however, the resistivity field can be completely changed, and thus the resulting model as well (Fig. 3). The question is how much the possibility of detailed interpretation is reduced by this procedure!

The third option how to influence the resulting wavelike field is the choice of using the “standard” and “incomplete” Gauss-Newton methods and differences in the system of computation of the Jacobian and the quasi-Newton approximation. In addition to the standard Gauss-Newton method, which is used

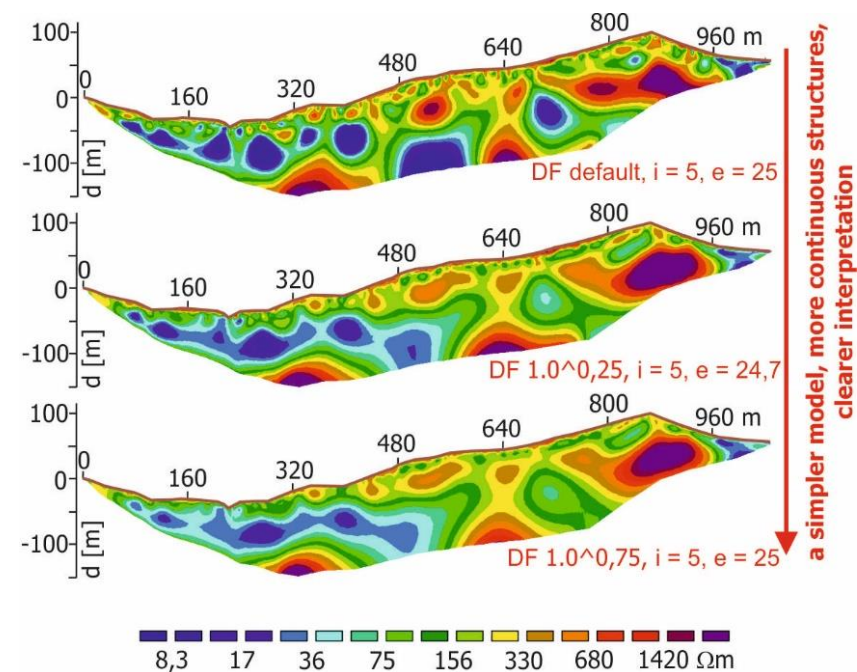


Fig. 2 Simplification of a resistivity model due to the different setup of “damping factor”

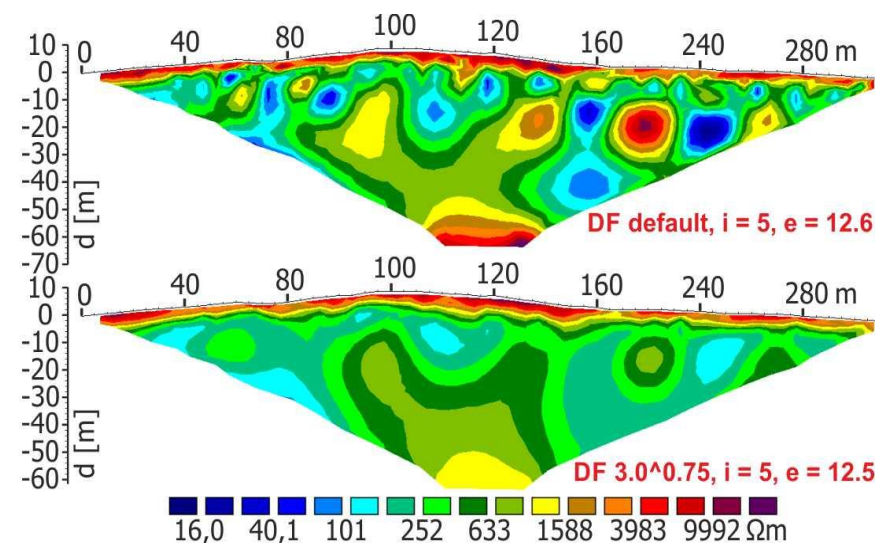


Fig. 3 The effect of change in “damping factor” on the resulting resistivity model

as a default in inversion, it is also possible in the program RES2DINV to choose the option of using the incomplete Gauss-Newton method (Fig. 4.). The choice is made before starting the inverse computation within the parameter “type of optimisation method”. It is recommended particularly for sets with a large number of measured points, or, as the case may be, with a large variation range of measured values of apparent resistivity. The program RES2DINV also offers the choice of the method of computation of the Jacobian matrix within the parameter “Jacobian matrix computation”. After each iteration, it is possible either “to recompute the Jacobian matrix”, or “to use the quasi-Newton approximation” (Loke, 2012).

3 Properties of program ZondRes2D

This program was developed at the Lomonosov University in Moscow in cooperation with private geophysical and software companies in Moscow and St. Petersburg. When working on the task “Development of Geotechnical and Geophysical Methods for Acquiring 2D and 3D Images of the Geological Structure”, the program was available to us thanks to the long-lasting cooperation between GEOTest and the company GIDROINGEO Tashkent. At the Ostrava workplace of GEOTest, we worked in a software demo version which contains most functions which the full program has, but the resulting iterated data cannot be exported from the computer. Similarly, as in the program RES2DINV, it is possible to set up the following parameters when working with the program:

- Starting height;
- Maximum depth;
- Number of layers;
- Incremental factor;
- Starting resistivity (initial resistivity of model);
- Number of nodes;
- Regular mesh;

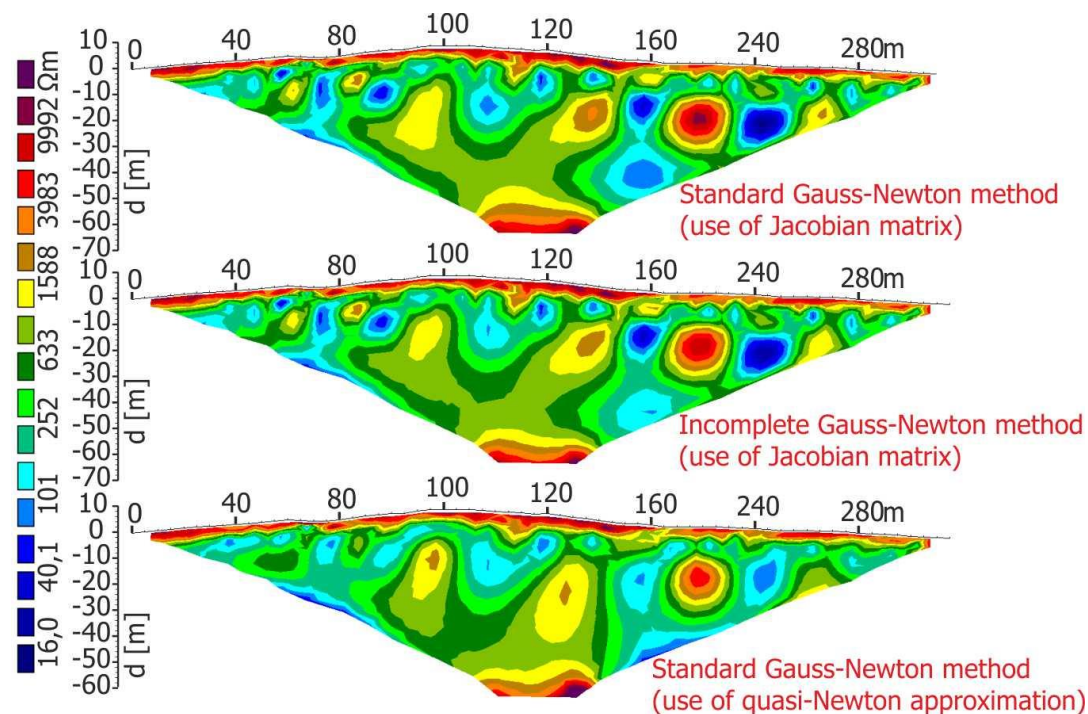


Fig. 4 Differences in the resulting model when using the “standard” and “incomplete” Gauss-Newton methods, and differences in the computation of the Jacobian and the quasi-Newton approximation

- Intermediate nodes (number of cells between electrodes);
- Method (standard Gauss-Newton method, incomplete Gauss-Newton method);
- Iteration (number of iterations);
- Inversion (defines the algorithm of an inversion problem, e.g., smoothness constrained, Occam, blocks);
- RMS error (deviation of computed resistivity values);
- Minimum resistivity;
- Maximum resistivity;
- Computation scheme;
- Automatic switch of electrodes; and
- Robust weighting scheme (with a high level of noise).

The result of computation in the demo version is depicted only on the monitor of the computer. If we wanted to use the full version of this program, we always addressed Uzbek colleagues who processed data for us using the full version of interpretation by the program ZondRes2D. The input and output data were transmitted over the internet.

At our request, the results were processed in a different setup of parameters of the program ZondRes2D on selected measured data. The first tests were conducted by comparing the results of different versions of this program. Similarly, as in the program RES2DINV, in some setups the results from versions 5_2 and 6_2 are practically identical; in others they are significantly different.

The first example is from measurement at the site of Kamechy. The area of interest is located in the cadastre of the City of Brno, in the City Part of Bystrc. The territory belongs to the Brunovistulicum of the Moravian-Silesian Area of the Bohemian Massif. The basic regional unit affecting the geological structure of the area of interest is the Brno Massif formed chiefly by Proterozoic deep magmatic rocks of the type of diorite – granodiorite. The marginal parts of the Brno Massif are formed by metamorphic rocks – paragneiss, migmatite, etc. It is possible to identify the sediments of the Carpathian Fore-Deep, of the Neogene Age, overlying the eruptive rocks. They fill particularly depressions on the surface of eruptive rocks. The uppermost component of the rock environment is mainly Quaternary loamy sediments.

Measurement performed at the site of Kamechy was evaluated using both available versions of the program ZondRes2D, i. e. versions 5_2 and 6_2. For iteration, the basic setup of interpretation parameters was used, i.e., the maximum depth 27.2 m, 9 layers,

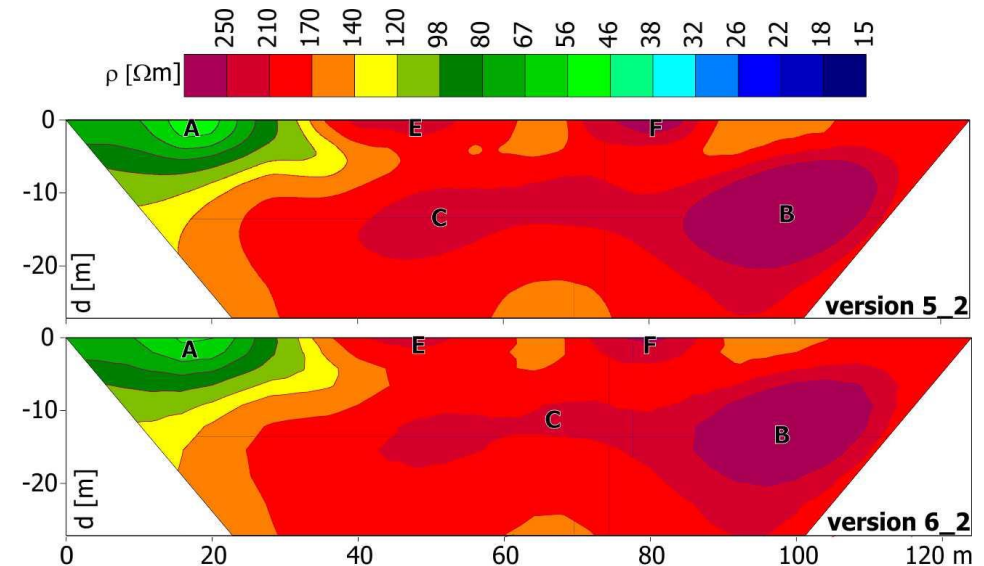


Fig. 5 Minimum changes in the resistivity field when iterating different versions of program ZondRes2D

32 nodes, intermediate nodes: 0, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , the starting resistivity 200 Ωm , 10 iterations, the computation scheme: total, automatic switch of electrodes: yes, robust weighting scheme: no. The result of iterations is depicted in Figure 5.

Figure 5 shows that the computation did not exhaust the option of dispersion of the size of resistivity values given by the setup of the program. The basic elements of the resistivity field from the results of version 5_2 are anomalies of resistivity values. The first is an area “A” of low resistivity values at depths down to nine metres under the stations 0–35 m. The opposite of this anomaly is a lens “B” of material with high resistivity values at the end of the profile. There the resistivity reaches values of even over 250 Ωm . The centre of this lens lies at a depth of 12 metres under the station practically about 100 metres. Another interesting feature is a thin layer “C” of high resistivity values emerging from the high-resistivity lens under the station about 83 m. This layer disappears under the station 40 m and its resistivity reaches values between 210 and 250 Ωm . At the surface, two more places of higher resistivity values can be found, “E” and “F”; the first one under the stations 40 to 52 m and the second one under the stations 75 to 85 m. The resistivity values of this layer rise above 210 Ωm .

If we look for differences between the individual versions, we must point out that we do not consider these differences as substantial. However, we do not mean by that that some users of electrical resistivity tomography will not consider these differences as significant. It is necessary to note that such users will not be geophysics specialists! Low-resistivity anomaly “A” at the beginning of the profile is practically identical in both versions. A minimum difference can be found in the size of high-resistivity anomaly “B”, which begins under the station 82.7 m in version 6_2, whereas in version 5_2 it begins under the station 82.2 m, which we consider as an insignificant difference. A larger difference can be found in layer “C” of higher resistivity values. It is thinner and shorter in version 6_2. We consider the differences in near-surface anomalies as irrelevant.

The second example is from measurement at the same site, and the measurement was again evaluated using both available versions of the program ZondRes2D, i.e., versions 5_2 and 6_2. For this iteration, a significantly different setup of some interpretation parameters was used, i.e., maximum depth 27.2 m, 9 layers, 249 nodes, intermediate nodes: 7, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , starting resistivity 200 Ωm , 10 iterations, computation scheme: total, automatic switch of electrodes: yes, robust weighting scheme: no. The result of iterations is depicted in Figure 6.

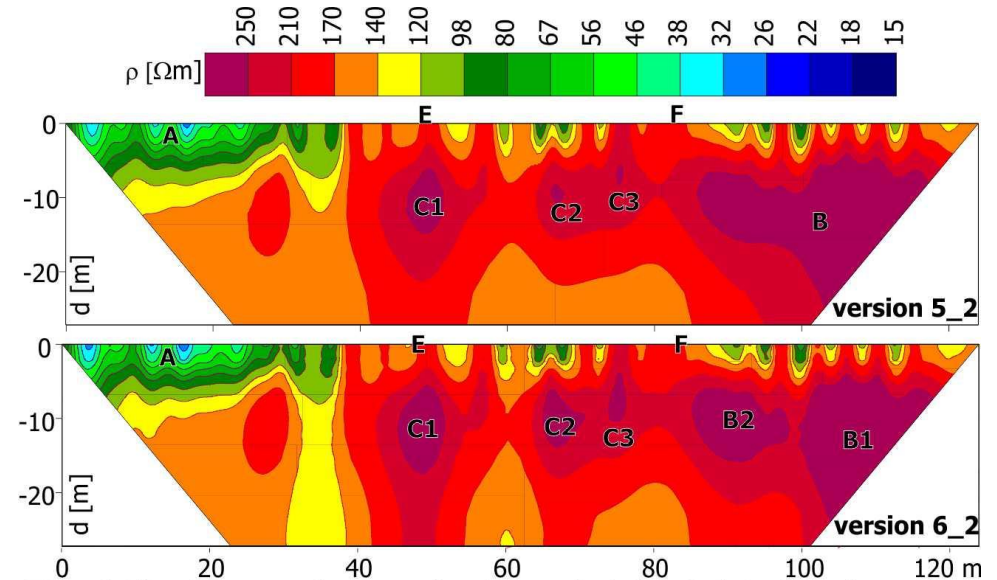


Fig. 6 Significant changes in the resistivity field when iterating different versions of program ZondRes2D

By comparing Figures 5 and 6 we see that the essential character of the distribution of the resistivity field did not change, but the differences between both versions are significant. Figure 6 shows that the computation did not exhaust, similarly as in Figure 5, the option of dispersion of the size of resistivity values. The basic element of the resistivity field from the results of version 6_2 is also anomaly “A” of low resistivity values at depths down to nine metres under the stations 0–35 m. Unlike the preceding iteration, the boundaries of each resistivity zones are intensely undulated. Similarly, as in Figure 5, the opposite of low-resistivity anomaly “A” is anomaly “B” with high resistivity values at the end of the profile. Unlike the preceding scenario of computation, the high-resistivity anomaly is areally more extensive. The resistivity there again reaches values of over 250 Ωm . The centre of this lens lies deeper, now at a depth of 15 metres under the station practically 100 metres. This layer “C” of higher resistivity values breaks down into three partial anomalies which show a greater thickness. Anomaly “C” disappears under the station 40 m and its resistivity reaches values between 210 and 250 Ωm . At the surface, two places of higher resistivity values can be found, “E” and “F”. In general, it can be declared that in scenario 2 the vertical features of the geological structure are strongly applied.

By comparing the results of versions 5_2 and 6_2, we can state that there are larger differences in the resistivity field in version 6_2 than it was in the basic setup (version 5_2). The largest difference is the fragmentation of lens “B” into two partial lenses “B1” and “B2”. At the surface, anomalies “E” and “F” fully disappeared; they were replaced by a set of small anomalies with a wide fluctuation of resistivity values.

Other tests show how the resistivity field changes when parameters for iteration are changed. Version 6_2 of the program ZondRes2D was used for all the following computations. It is natural that the number of such changes can be endless. This part of the report will present two examples in which changes in parameters lead to a more significant change in the resistivity field and one example in which it is not so. In the first example in Figure 7, the basic setup of interpretation parameters was chosen for computation, i.e., the maximum depth 27.2 m, 9 layers, 32 nodes, intermediate nodes: 0, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , starting resistivity 200 Ωm , 10 iterations, computation scheme: total, automatic switch of electrodes: yes, robust weighting scheme: no. The first view of the resistivity field already suggests significant changes which are due to the number of nodes used. The essential structure, i.e., the low-resistivity minimum, the high-resistivity lens and the medium-resistivity layer is similar to the structure in Figures 5 and 6 also in these resistivity cross-sections.

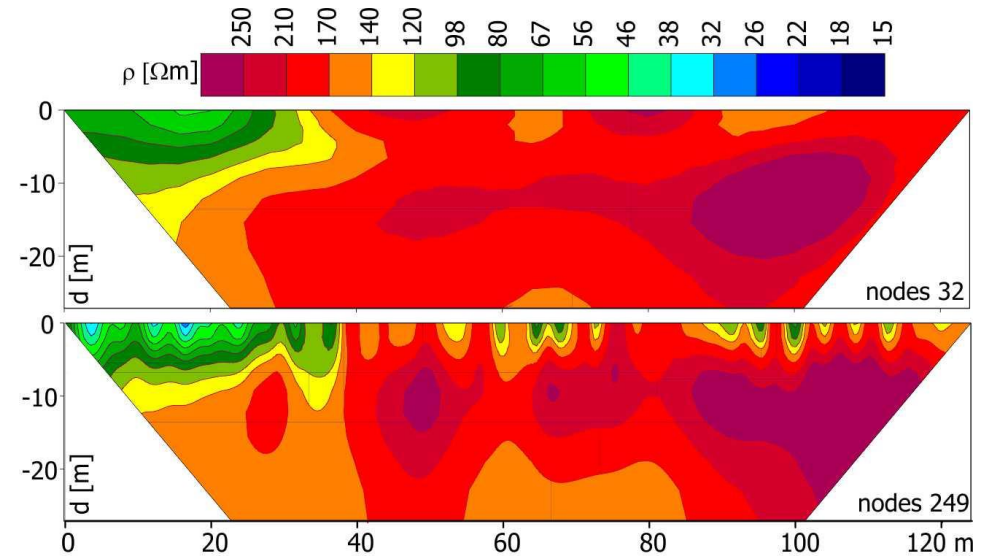


Fig. 7 The effect of change in the “number of nodes” on the resulting resistivity model of program ZondRes2D

Figure 5 and the upper part of Figure 7 correspond with a small number of layers used. The result is a picture of a simple geological structure without a significant number of partial anomalies and with gradual resistivity boundaries. A completely different situation is in the lower part of Figure 7, in which the following setup was used: maximum depth 27.2 m, 9 layers, 249 nodes, intermediate nodes: 7, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , starting resistivity 200 Ωm , 10 iterations, computation scheme: total, automatic switch of electrodes: yes, robust weighting scheme: no.

Here, similarly as in Figure 6, the main medium-resistivity layer disintegrates and a number of minor anomalies occur at the surface with no practical significance. The same holds true that in this case the boundaries between the individual resistivity layers widely fluctuate.

Figure 8 shows a case with a change in the number of layers. The first picture represents a model with a lower number of layers and with the following setup: maximum depth 27.2 m, 9 layers, 249 nodes, intermediate nodes: 7, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , starting resistivity 200 Ωm , 10 iterations, computation scheme: total, automatic switch of electrodes: yes, robust scheme: no.

The second picture illustrates a model with a higher number of layers as well as with a lower depth which is caused by reducing the incremental factor to value 1: maximum depth 24 m, 24 layers, 249 nodes, intermediate nodes: 7, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , starting resistivity 200 Ωm , 10 iterations, computation scheme: total, automatic switch of electrodes: yes, robust weighting scheme: no.

The differences in the individual models are not as significant as with a change in the number of nodes, but certain changes are well documented. It is interesting that changes in the near-surface layers are striking, with the intensity of changes decreasing with depth.

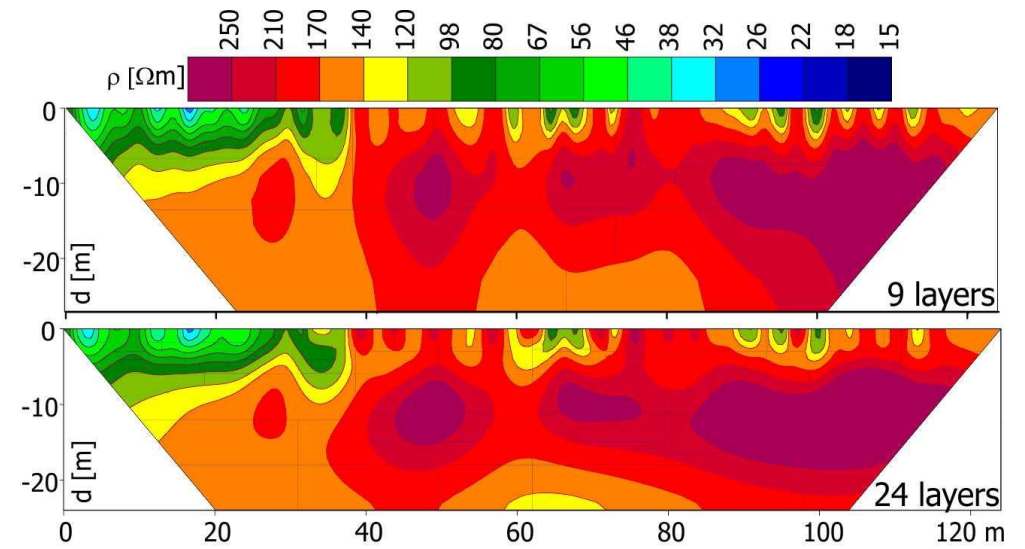


Fig. 8 The effect of change in the “number of layers” on the resulting resistivity model of program ZondRes2D

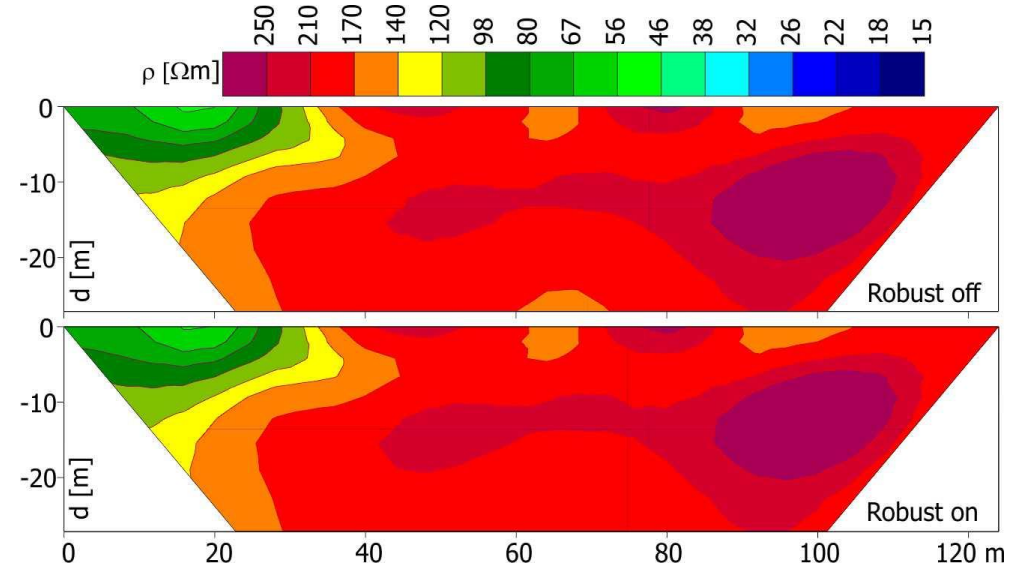


Fig. 9 Changes in the resistivity field when turning on the function “Robust”

The last example of the effect of the setup of the computation parameter is in Figure 9, describing the effect of the turning-on of the function Robust on the interpreted resistivity field. The given pictures clearly show that in this case both the resulting resistivity fields are practically identical. For inversion, the basic setup of interpretation parameters was used in both cases with such a difference that the function Robust was turned on in the second model, i.e., maximum depth 27.2 m, 9 layers, 32 nodes, intermediate nodes: 0, inversion: smoothness constrained, the range of resistivity values 1–1000 Ωm , starting resistivity 200 Ωm , 10 iterations, computation scheme: total, automatic switch of electrodes: yes, robust weighting scheme: no (yes in the second case).

5 Comparison of the results of interpretation using the programs RES2DINV and ZondRes2D

For the greater objectivity of interpretation of the results of geophysical measurements, it is always suitable to process the given measured data in several manners. The same also applies to the measurement of electrical resistivity tomography. Therefore, we used the option to let our data interpret in Tashkent with the use of the program ZondRes2D and to compare them with our interpretation using the program RES2DINV. We began this program by comparing measurements in simple geological conditions and subsequently we passed into more complicated conditions.

The first illustration in Figure 10 is from a survey for the construction of motorway D35 in a section between Dzbanov and Litomysl, specifically from profile 41-41. The geophysical profile was located in the cadastre of the municipality of Sedliste. The area of interest is formed particularly by sedimentary rocks of the Bohemian Cretaceous Basin, of the types of claystone, marlstone, etc., overlain by loose Quaternary sediments of the types of loess, loess loam, etc. In the surroundings of watercourses, or valleys, as the case may be, also fluvial floodplain sediments are deposited.

The results of both interpretations are not identical, but similar. It is possible to declare without problems that greater resistivity changes are made by setting up interpretation parameters in both programs than are the differences between the programs themselves.

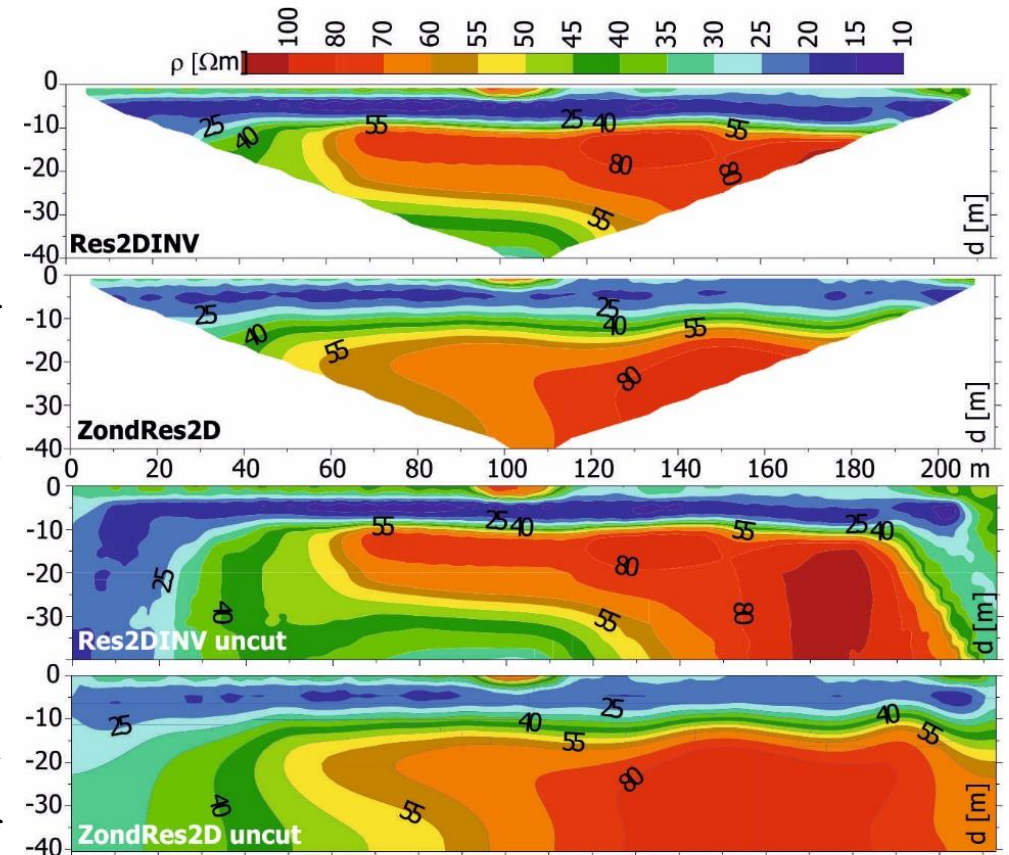


Fig. 10 Comparison of the results of ERT interpretation at the site of motorway D35 using programs RES2DINV and ZondRes2D

In both interpretations it is possible without problems to distinguish a near-surface layer of loam. The base of loam is found at a depth of about 7 m according to the program RES2DINV, and at a depth of 11 m according to the program ZondRes2D. According to the results of drilling work, the boundary is defined at a depth of about 12 metres, i.e., interpretation is better yielded from the program ZondRes2D. It is more complicated with the determination of the surface of Cretaceous clayey sediments. This geological boundary was not identified by using direct exploratory work, but only by vertical electrical sounding (VES). According to VES, the boundary is located at a depth of 25 to 35 m; according to the results of RES2DINV, at a depth of 30 m, and according to ZondRes2D, at a depth of about 35 m. The horizontal change in resistivity values in both programs suggests facies change in sediments in the second and third layer. This change is better evident in the uncut resistivity cross-sections in the lower part of the picture.

The first evaluation of the size of resistivity values indicates that the resistivity values from the program ZondRes2D are higher than those from the program RES2DINV. An example can be a lens of high resistivity values, which lies under the stations 122–145 m at a depth of around 15 m in the program ZondRes2D, or 25 m in the program RES2DINV. In order to better assess such differences, we identified the distribution of resistivity values for the results of both programs. The results of this comparison in the form of frequency distribution are shown in Figure 11.

Y-axes in this picture are deliberately chosen in different scales for each program. The result of iteration in each program yielded different numbers of points in which resistivity was determined. In order that both curves could be better mutually comparable, the curve for the “Russian” version was chosen in a half scale. The first view of the picture shows that the resistivity values determined by the program ZondRes2D are higher than those from the program RES2DINV, namely by about 25%.

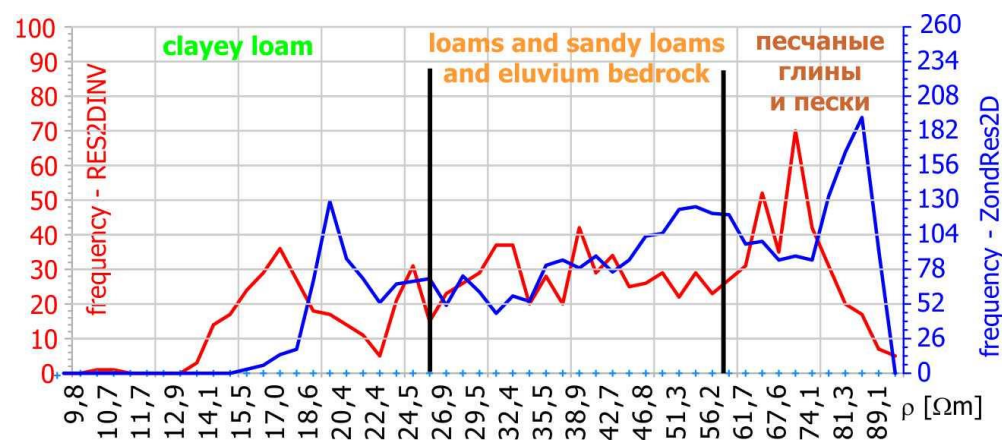


Fig. 11 Distribution of resistivity values at motorway D35 in cross section 41

According to the histograms of resistivity values, the boundaries of individual lithological units can be determined approximately. The boundaries are delineated in the curves of resistivity distribution and were determined for the interpretation using the program RES2DINV. If we also wanted to determine this boundary for the program ZondRes2D, then the values of boundary resistivity values will be by about 25% higher. It is natural that the boundary values cannot be taken as absolutely valid, but it is necessary to define a certain useful guideline for determining the lithological character of individual resistivity layers.

The second example in Figure 12 shows a comparison of surface ERT measurements made on the Tyubegatan deposit of potash salts in Uzbekistan. The upper picture is the original of interpretation using the program ZondRes2D with a direct output of the depicted field of

resistivity values. The lower picture is a conventional output of the “Czech” method, in which the result of iteration is converted to the field of resistivity values using the external graphic program SURFER.

Surprising in the results is that the resistivity values are very low. This situation is caused by the penetration of surface water into the deposit. The high transitional resistivity values (3000 Ωm to 80 000 Ωm) were caused by the geographic location of the deposit, i.e., by the essential effect of the arid climate and by the minimum moisture of surface loam. The geological structure in this profile can be described as having three layers. The surface layer is formed by a layer with relatively higher resistivity values, which is formed by three partial elements “A”, “B” and “C”. Relatively small anomaly “A” is actually a continuation of layer “B”, but it is not clear from the results of measurement what the cause of its division is. The only possible explanation seems to be the existence of a small low-resistivity anomaly which is better evident in the “Czech” interpretation. The drop of resistivity values can be caused by the infiltration of surface water into the sediments with an admixture of potash salts. A similar effect can be seen under the station 210 m where such an anomaly divides layer “B” into two parts. This feature can again be better seen in the “Czech” interpretation, where we can even consider

a possibility of further observation of underground saline water through an environment with relatively higher resistivity. This anomalous place lies beneath a surface watercourse, so in this place we can assume a sufficiently large recharge of the rock mass by surface water.

Middle layer “F” shows a conductive layer which, however, does not maintain steady resistivity along the profile. What the cause of this feature is cannot be deduced from available measurements. Resistivity values in this layer do not exceed about 7 Ωm . The third layer is formed by underlying sediments with higher resistivity reaching about 40 Ωm according to the results of “Czech” interpretation, and 30 Ωm in the “Russian” version.

The conditions for ERT measurement in other pictures were opposite from what it was in the preceding cases. In measurement conducted during a survey for motorways, it can be stated that the conditions were ideal. Measurement took place on the natural ground with moisture, so the transitional resistivity values on electrodes ranged between 200 and 1110 ohms. Measurement on the deposit of potash salts now approached the conditions of measurement underground.

Other examples are from measurement in the PVP Bukov in testing chamber ZK-1. When observing transitional resistivity values during the whole task, they were the highest in this place. Specifically in the profile (in the lower right-handed part) studied in 2019,

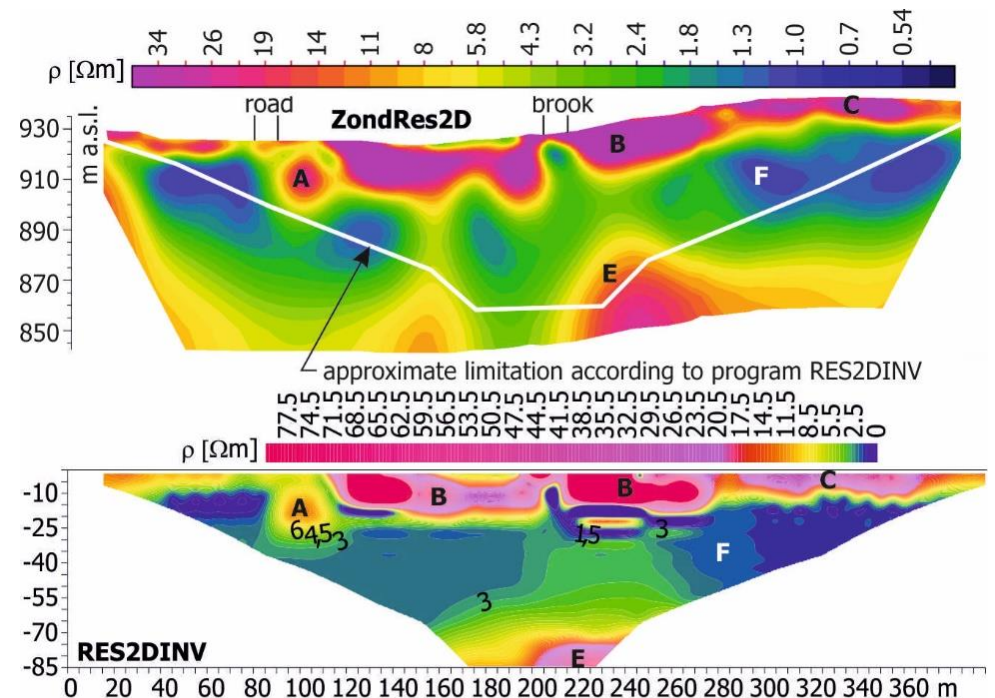


Fig. 12 Comparison of the results of ERT interpretation at the site of Tyubegatan

transitional resistivity values changed from 3000 to 120000 ohms. When processing them, the results of such higher transitional resistivity values on these electrodes were excluded from further processing.

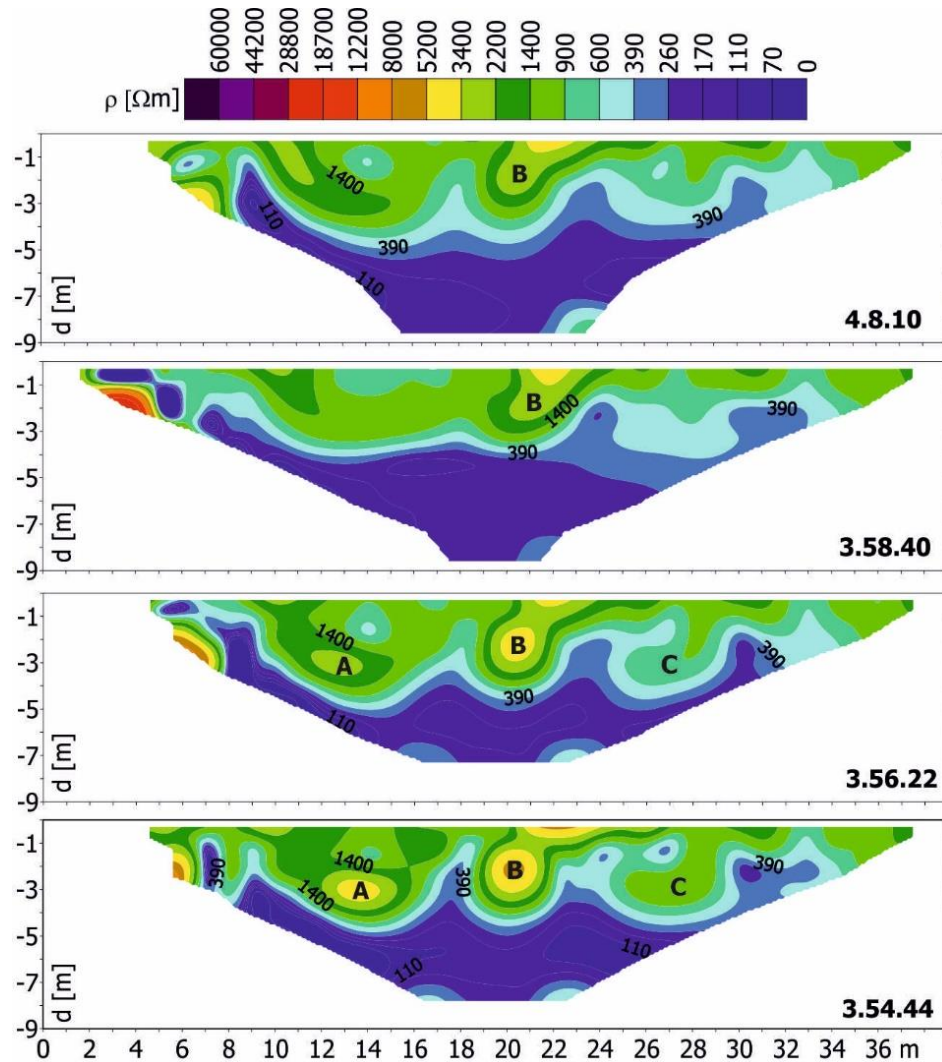


Fig.14 Comparison of the results of ERT interpretation using different versions of program RES2DINV - from measurement made in 2013

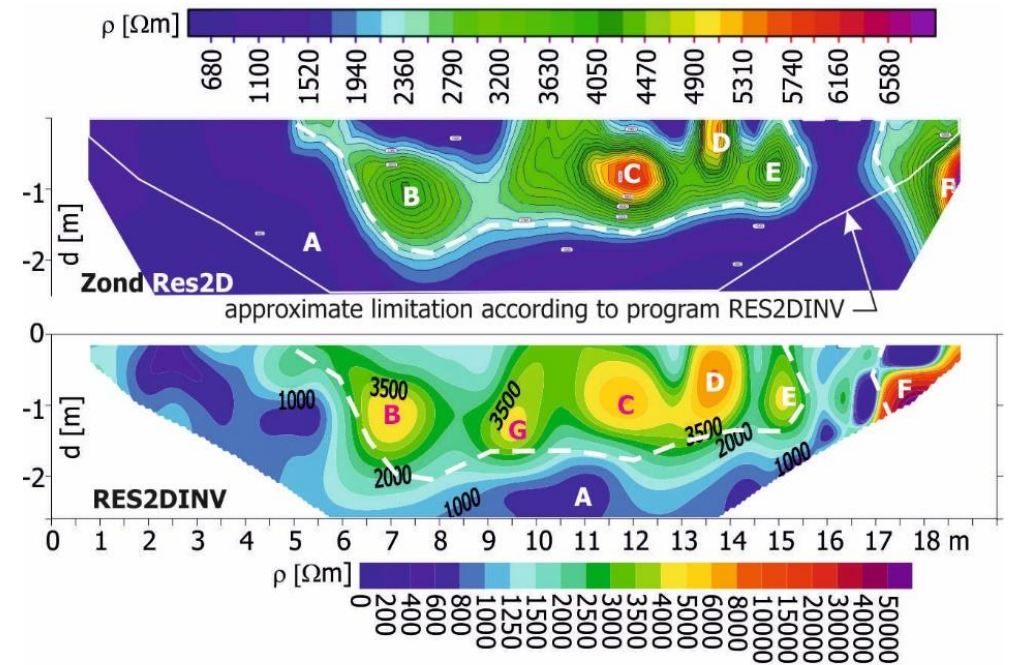


Fig. 13 Comparison of the results of ERT interpretation using programs RES2DINV and ZondRes2D in ZK-1

The result of a comparison of inversion from both programs is shown in Figure 13. In this case, the colour scale of depiction of resistivity values is different. It is due to the fact that we received the resistivity contours from the program ZondRes2D directly from Tashkent. In most cases, we constructed the resistivity contours in GEOTEST using the program SURFER. Similarly, as in the preceding examples of measurement under ideal conditions, the basic arrangement of the geological structure identified with the use of both programs is the same. The individual anomalies differ in details, not only by their areal extension, but also by the values of resistivity.

In addition to the basic environment marked as “A”, five anomalies “B” to “F” were discovered using the program ZondRes2D and six anomalies “B” to “G” using the program RES2DINV. All anomalies “B” to “G” have relatively small dimensions and their

maximum resistivity values range between four and six thousand ohm-metres in the “Russian” version, whereas in the “Czech” version they range between four and forty thousand ohm-metres. The area of high-resistivity anomalies in the “Russian” version is approximately the same as in the “Czech” version. An exception is the lower delineation of anomalies “B” and “D”. A large difference is in the maxima of anomalies. In the “Russian” version they reach 4200, 5700, 5300, 4000 and 6000 Ωm and in the “Czech” version they reach 4500, 4200, 5500, 7000 and 30000 Ωm . Basic environment “A” in the “Russian” version is visually more homogeneous than in the “Czech” version. This is due to the fact that the blue colours of the low-resistivity environment in the “Russian” version in a range of 500 to 1700 Ωm are practically invisible to the naked eye. The basic environment in the “Russian” version has resistivity values in a range of 500 to 1700 Ωm and in the “Czech” version in a range of 400 to 1500 Ωm . When using electrical resistivity tomography underground, we verified the effect of the versions of interpretation program on the resulting resistivity field. We made extensive analysis on measurements at the beginning of cross cut BZ-XIII on its left side just behind the research facility, where copper electrodes of a diameter of 10 mm were used, inserted into the side of the mine working to a depth of 5–10 cm. We used the following versions of the program RES2DINV for interpretation: 3.54.44, 3.56.22, 3.58.40 and 4.8.10. For testing, first we used the results of measurement made in 2013; they were obtained using the apparatus ARES I. The resistivity fields detected by the different versions of the program are shown in Figure 14.

The resistivity fields in all versions suggest a two-layer environment. The lower layer probably corresponding with the undisturbed rock mass shows resistivity values reaching about 300 Ωm and lower. In the upper layer to depths of around five metres, three anomalies “A”, “B” and “C” with higher resistivity were distinguished, reaching values of up to 8000 Ωm . However, it is interesting that these anomalies can be found more easily in the previous versions of the program Res2DInv. For example, anomaly “A” in version 3.54.44 has its maximum reaching

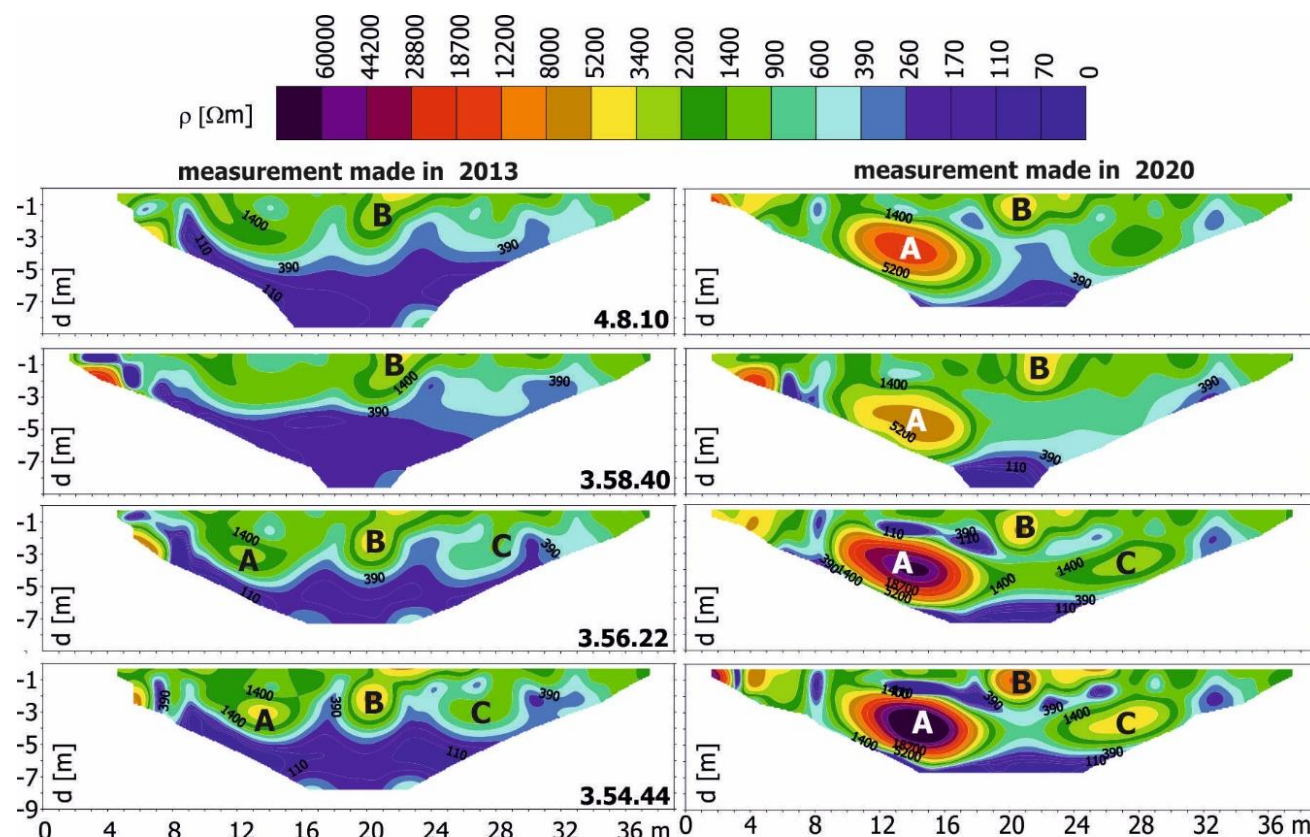


Fig. 15 Comparison of the results of ERT measurement using different versions of program RES2DINV - from measurement made in 2013 and in 2020

about 5000 Ωm , in version 3.56.22 it decreases to 3000 Ωm and in newer versions of the program it was no longer interpreted. The same applies to anomaly “C”. Anomaly “B” gradually decreases its maximum and in the latest version 4.8.10 it merges with a small surface anomaly. And in this latest version, the depth range of higher resistivity values decreases by about one metre.

During research into the use of geophysical methods underground, a question arose in the matter of their use for time changes in the rock mass. Within the project “Development of Geotechnical and Geophysical Methods for Obtaining 2D and 3D Images of the Geological Structure”, this option was also investigated when using the ERT method. The results of measurements repeated over time yielded surprising findings. Their depiction is shown in Figure 15.

For evaluation we again used four versions of the program RES2DINV similarly as it was in Figure 14. The resistivity fields identified by measurement made in 2013 and in 2020 are fairly different at first sight. A particularly conspicuous difference lies in the values of resistivity. Its maximum values rose up to 60000 Ωm . In closer investigation it can be found that basic anomalies “A”, “B” and “C” remained in place. But their amplitudes changed significantly. The smallest changes are visible in anomaly “B”. It remains roughly the same positionally and areally, but its maximum value increased - the most in versions 3.54.44 and 3.56.22. Resistivity values in these resistivity anomalies increased by one zone, i.e., by about 50%. Higher changes were identified in anomaly “C”, which increased areally in versions 3.54.44 and 3.56.22. The maximum of the anomaly in version 3.54.44 increased by three resistivity zones, i.e., about five times. The largest changes were identified in anomaly “A”. It increased significantly both areally and with its amplitude. The maximum resistivity values in this place increased about ten times. The smallest changes were detected in version 4.8.10.

From the geological point of view, it was very difficult to find a logical explanation of such changes. A decrease in moisture content to practically zero was fairly improbable. For this reason, we interpreted both measurements using also the program ZondRes2D. The results of such tests are shown in Figure 16.

At first viewing Figure 16 it is evident that better results are yielded by interpretation using the program ZondRes2D. In no case can be found such differences in its results between the years 2013 and 2020. Interpretation using the program RES2DINV yields different results from measurements of the year 2020 than it is in the other interpretations. Anomaly “B” is absolutely clearly detectable in the results

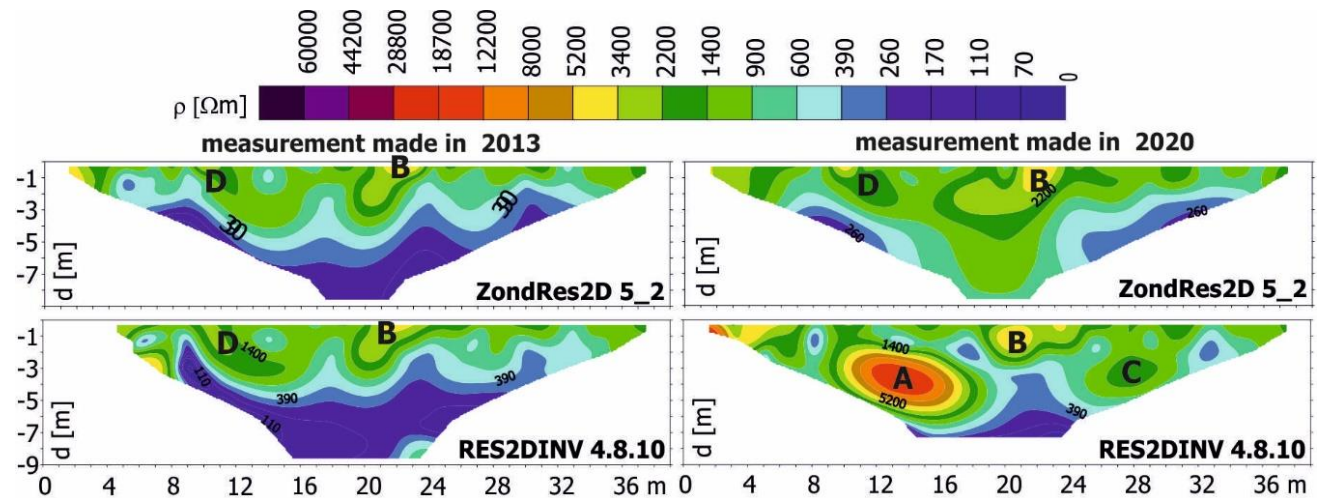


Fig. 16 Comparison of the results of ERT interpretation using programs RES2DINV and ZondRes2D - from measurement made in 2013 and in 2020

of interpretation. Anomalies “A” and “C” are not visible in any of the measurements in the “Russian” interpretation. In 2013, anomalies “B” and “D” are detectable in both programs. It can be deduced from these findings that the program RES2DINV yields not quite reliable results in difficult conditions of measurement. If we evaluated time changes of the resistivity field from the results of the program ZondRes2D, then we could see that in 2020 resistivity values had increased. These changes can be explained by a decrease in moisture content in the rock mass.

6 Conclusion

The comparison of programs for the 2D interpretation of electrical resistivity tomography (RES2DINV and ZondRes2D) has yielded a number of interesting findings. We proceeded from our prior knowledge that the resulting resistivity field was not only a picture of the distribution of resistivity values in the rock mass, but it could also be influenced by the setup of input parameters for iterations. When we had the program ZondRes2D in a demo version at our disposal, and ultimately also thanks to the cooperation with Uzbek colleagues, we had an opportunity to use it in the full extent. During testing work it was evident that it was possible to change the resulting resistivity field, similarly as the program RES2DINV, by setting up parameters of the program ZondRes2D.

When evaluating the digital programs of interpretation, we must be aware that we solve a mathematically not quite correct problem. In this case, we determine a substantially larger number of parameters than are the results of measurement. When actually comparing the results of both programs, we began with the interpretation of results in individual geological conditions. In this case, the results were satisfactory because the differences in interpretation using both programs were comparable with the differences which are obtained by changing the setup of input parameters of iteration. In complicated surface conditions, the differences in interpretation were higher but still comparable with the changes given by the setup of programs. The largest difference occurred in the application to mining conditions. There the differences between both programs still increased, and we even recorded an example in which interpretation using the program ZondRes2D was visually more acceptable.

Acknowledgement

Comparison of programs RES2DINV and ZondRes2D involved the results of ERT measured at the Underground Research Facility (PVP) Bukov, established and operated by the Czech Radioactive Waste Repository Authority (SURA). The implementation of any activities in the spaces of the deep mine is relatively costly, complicated and requires a coordination of many professions and activities (facilities, technical support, etc.). Thanks to the coordination with SURA, which supports research activities in the PVP to the extent possible in the form of technical support and by providing service, the planned measurements and all the other activities were successfully very well managed. Our appreciation and thanks are due to SURA for everything it has done for us.

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