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DETERMINATION OF RESOLUTION LIMITS OF ELECTRICAL TOMOGRAPHY ON THE BLOCK MODEL IN A HOMOGENOUS ENVIRONMENT BY MEANS OF ELECTRICAL MODELLING

ODREĐIVANJE GRANICA RAZLUČIVOSTI ELEKTRIČNE TOMOGRAFIJE NA MODELU BLOKA U HOMOGENOJ SREDINI POMOĆU ELEKTRIČNOG MODELIRANJA

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Key words: electrical tomography, resolution, electrical modelling, geological models

Ključne riječi: električna tomografija, rezolucija, električno modeliranje, geološki modeli

Abstract

The block model in a homogenous environment can generally serve for presentation of some geological models: changes of facies, changes of rock compactness-fragmentation, underground cavities, bauxite deposits, etc. Therefore, on the block model of increased resistivities in a homogenous environment of low resistivity, the potentials of the electrical tomography method were tested for the purpose of their detection. Regarding potentials of block detection, resolution methods depend on: depth of block location, ratio between block resistivity and the environment in which it is located as well as applied survey geometry, i.e. electrode array. Thus the analyses carried out for the most frequently used electrode arrays in the investigations are the following: the Wenner, Wenner-Schlumberger, dipole-dipole and pole-pole arrays. For each array, maximum depths at which a block can be detected relative to the ratio between block resistivity and parent rock environment were analyzed.

The results are shown in the two-dimensional graphs, where the ratio between the block resistivity and the environment is shown on the X-axis, and the resolution depth on the Y-axis, after which the curves defining the resolution limits were drawn. These graphs have a practical use, since they enable a fast, simple determination of potentials of the method application on a specific geological model.

Sažetak

Model bloka u homogenoj sredini općenito može poslužiti za predočavanje nekih geoloških modela: promjena facijesa, promjena kompaktnosti-raspucanosti stijena, podzemnih šupljina, ležišta boksita i dr. Zato su na modelu bloka povišenih otpornosti u homogenoj sredini niskih otpornosti ispitane mogućnosti metode električne tomografije u njihovom otkrivanju. Mogućnost otkrivanja bloka, rezolucija metode ovisi o: dubini smještaja bloka, omjeru otpornosti bloka i sredine u kojoj se nalazi i primijenjenoj geometriji snimanja, to jest elektrodnom rasporedu. Zato su analize načinjene za najčešće korištene elektrodne rasporede u istraživanjima: Wennerov, Wenner-Schlumbergerov, dipolni i dvoelektrodni. Za svaki raspored analizirane su maksimalne dubine na kojima se može otkriti blok u ovisnosti o omjeru otpornosti bloka i matične sredine.

Rezultati su prikazani na dvodimenzionalnim grafovima gdje se na apscisi nalazi omjer otpornosti bloka i sredine, a na ordinati maksimalna dubina razlučivosti, pa su izvučene krivulje koje definiraju granice razlučivosti. Ovi grafovi imaju praktičnu primjenu, jer omogućuju vrlo brzo i jednostavno određivanje mogućnosti primjene metode na određenom geološkom modelu.

Introduction

The block model in a homogenous environment, i.e. block of higher or lower resistivities in relation to the environment in which it is located, can serve for the presentation of some geological models: changes of facies (lithological changes), changes of rock compactness-fragmentation, underground cavities, underground caverns, bauxite deposits, etc. Sand and gravel lenses in clayey deposits, or clay lenses in gravel or sand, is a geological model found in sedimentation basins. Compact blocks in fragmented carbonates, or fragmented blocks in relatively compact carbonates are located in the geological models on our karst terrains as a part of geotechnical, geological engineering and hydrogeological investigations. These investigations are frequently aimed at underground cavities as well, since they influence the geotechnical characteristics of rocks which have to be defined for the purpose of infrastructure construction, or of other larger facilities, but also in groundwater investigations. Investigation targets in other investigations, such as archaeological investigations, are also underground cavities, mostly underground caverns and burial sites resulting from the human activity.

Due to the differences in physical characteristics, the mentioned geological models can be investigated by a series of geophysical methods: seismic refraction and reflection, georadar, gravimetry, electromagnetic methods, etc. Most methods can even detect the presence of an underground cavern, although its shape is generally very difficult to define, depending mostly on its size, location depth and the geological model in which it is located. According to the up-to-date experiences, it seems that, better than any other geophysical method, electrical tomography can contribute to the potential determination of the mentioned geological models.

Electrical tomography appeared in the last two decades and enabled investigations of relatively complex geological models which could not be investigated in more detail by means of classic electrical methods, electrical sounding and profiling (Griffiths and Barker, 1993). From the very beginnings, it has been also used in Croatia, and very soon became the main method not only in groundwater investigations on karst terrains (Šumanovac and Weisser, 2001; Šumanovac et al. 2003), but also in investigations of construction material deposits (Šumanovac et al., 2006). This paper therefore uses electrical modelling for the analysis of resolution of the method on a block model in a homogenous environment, and gives graphical presentations of resolution limits for the most frequently used survey geometry of the two-dimensional electrical tomography.

Electrical tomography method

Brief overview of method development

The development of electrical tomography started with the appearance of the multi-electrode systems (Griffiths and Turnbull, 1985) with equally spaced electrodes and equally spaced pseudo-depths. Computer-controlled data acquisition can provide highly efficient and cost-effective field measurements. A somewhat different system, which has been applied for continuous electrical sounding, was presented by van Overmeeren and Ritsema (1988). This system has made possible a roll-along mode of field measurement and was later applied in 2-D electrical imaging by Dahlin (1996).

Electrical tomography data can be interpreted using appropriate inversion techniques. There are three approaches: one-dimensional, two-dimensional and three-dimensional inversions. One-dimensional inversion is usually based on automatic interpretation of electrical sounding data. The pseudo-section is regarded as a series of closely spaced electrical soundings, which have been extracted one after another. After automatic interpretation of each sounding, the interpreted data is merged to form a quasi 2-D section. One-dimensional inversion is usually based on Zohdy's automatic interpretation of electrical sounding (Zohdy, 1989).

This technique is useful in stratified earth models, meaning basin conditions with slight or gradual lateral resistivity variations, and gradual changes of layer thickness. But in a complex environment it can only be used to acquire a general overview of the subsurface resistivity distribution. The second approach uses true 2-D inversion of the data. The smoothness-constrained, least-squares inversion method, presented by Loke and Barker (1995; 1996a), is widely used. In recent years, three-dimensional inversions are more often used (Dey and Morrison, 1979; Sasaki, 1994; Loke and Barker, 1996b; etc.). It is now feasible to collect 3-D data and 3-D inversions are becoming more common.

Electrode arrays

Any available electrode array can be applied in measurements; the most frequently used, however, are the following: the Wenner, combined Wenner-Schlumberger, dipole-dipole and pole-pole arrays (Fig. 1). The Schlumberger array is used in combination with the Wenner array since the Wenner array must be used for the shallowest depth in a multi-electrode system, while the Schlumberger array is used for all other depths. The Wenner array requires more space for certain lateral coverage as compared with all other arrays. The Schlumberger array and the dipole-dipole and pole-pole arrays in particular, can achieve a better lateral coverage for deeper targets, and can penetrate to greater depths in the same multi-electrode system. A better lateral resolution is achieved by these arrays due to a relatively short distance between potential electrodes in comparison with relatively large distances in case of the Wenner array, which cause the smoothing of data, particularly in case of larger depth investigations and larger spacing between electrodes.

On the other hand, the main advantage of the Wenner array is the highest signal-to-noise ratio of all arrays. If high noises are expected in the investigated area, be they geological-geophysical or urban, the Wenner array is the best choice to achieve the satisfactory quality of the measured data. The Schlumberger array and the dipole-dipole array in particular are significantly more sensitive to noises and surface inhomogeneities due to a short spacing between potential electrodes. With the pole-pole array, difficulties may be caused by large distances between current and potential electrodes and by coverage of more different electrical means. Inversion of data inversion cannot be accurately performed if data are contaminated by high noise levels; moreover, in some cases inversion may become unstable, i.e. lead to a divergence of interpreted resistivity models.

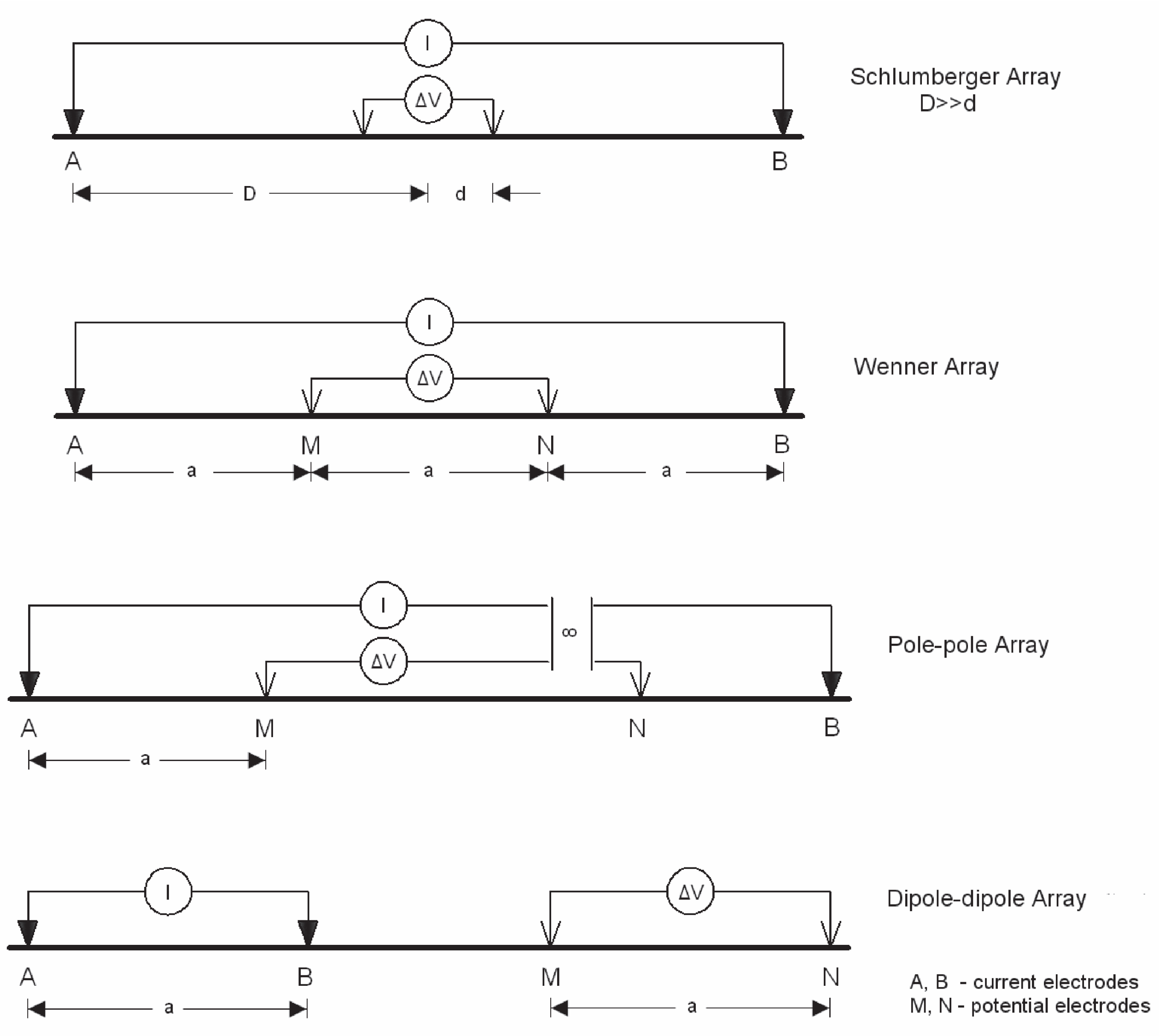

Figure 1 Electrode arrays most frequently used in the electrical tomography method

Slika 1. *Elektrodni rasporedi, ponajčešće korišteni u metodi električne tomografije*

Two-dimensional electrical modelling

In general, two approaches are applied in geophysical interpretation, as follows: forward modelling and inversion. For any given geological model, any geophysical anomaly or field, a single-valued calculation is made. However, if there is a measured geophysical anomaly or field, the solution is generally not single-valued, i.e. there are several different geological models which cause the same geophysical anomaly. This is called an ambiguity in interpretation.

For the analysis of the method resolution, both interpretation methods were used: electrical forward modelling and electrical inversion. Forward modelling enabled the calculation, simulation of measured pseudosections for any given block model in a homogenous environment, whereas by means of inversion the detectability and recognition potential for a specific block were analyzed. Forward modelling was carried out by the application of the RES2DMOD software (Loke, 1995-2001), and inversion by the application of the RES2DINV software (Loke and Barker, 1995; 1996a).

The RES2DMOD program calculates apparent resistivities, theoretical pseudosection for a given resistivity model and electrode array. The resistivity model is divided into a series of homogenous and isotropic elements, resulting in a numerical model for whose solution either the finite difference method (Dey and Morison, 1979; Loke, 1994), or the finite element method (Smith and Vozoff, 1984) can be applied. In the finite difference method, a two-dimensional underground model is divided into a network of rectangular blocks, and the calculation is performed on the node points with defined parameters. In the finite element method, a model is divided into regular elements: triangles, squares, rectangles, etc., while the parameters are defined according to the elements, thus the calculation is related to them. The advantage of the finite difference method is the easier data entry, whereas the finite element method enables a more accurate calculation for complex models with irregular limits and sudden lateral changes in resistivity.

The modelling process has certain difficulties which need mentioning. The calculated theoretical pseudosections are exposed to inversion the same as the actual measured data. However, it was observed that there appear strong deformations on the model boundaries, which depend on the input model (resistivity ratio) and the electrode array (Dominković Alavanja, 2006). These deformations are caused by applied algorithms, thus the boundary anomalies must never be interpreted as a consequence of the impact of real objects, i.e. target objects of the investigation must not belong to the boundary parts of the profile.

The resistivity of the environment in which the block is located is set at 100 Ωm, while the block is given higher resistivities, and then certain ratios between the block resistivity and the environment are observed (Table 1). The schematic presentation of the used model is given in Fig. 2, together with the theoretical pseudosection for the pole-pole array.

When considering the defined model in relation to an actual geological model, the basal rock in clastic deposits may be composed of clay, sandy clay, or clayey sand, and the block with higher resistivities may represent sand and gravel. Similar resistivity ratios can be valid for sandstone lenses in marly deposits. Flysch deposits can include isolated blocks of carbonate rocks, in which there are very high resistivity ratios between the block and the parent rock. In case of an underground cavity, the basal rock could be within clastic deposits (sandstone, shale, clayey deposits), where the cavity is characterized by significantly higher resistivities if it is empty, since air serves as insulation. However, in such rocks it is difficult to assume the existence of natural cavities, but rather those that are artificially made. Natural cavities are primarily connected to carbonate rocks, limestones and dolomites, which appear in the karstic Dinarides belt. Here the cavities of various shapes and dimensions appear much more frequently in limestones, even on the regular basis, due to their chemical weathering. The resistivity ratio of the cavity and the parent rock depends on the material contained in them. If the cavities are empty, i.e. contain air, they will be characterized by very high resistivities. Thus their resistivities will be higher than those of the parent rock, based on which they could be recognized. If the rock is fragmented, it will have lower resistivites, and with the increased level of fragmentation, the contrast between the resistivity and the cavity will be easier detected. In compact rocks, however, which are characterized by very high resistivities, cavities will be difficult to detect. If they are filled with clay or water, cavities are regularly detected in carbonate rocks due to their lower resistivities, since the resistivities of clay and water are significantly lower than the resistivity of even highly fragmented carbonate rocks.

Table 1 Used resistivity ratios for the block and the surrounding rock and results of modelling for the dipole-dipole array

Tablica 1. *Korišteni omjeri otpornosti bloka i okolne stijene i rezultati modeliranja za dipolni raspored*

Dipole-dipole array		
Block resistivity / environment resistivity		Maximum block depth (m), 40×20 m block
1.25	(125/100)	70
1.5	(150/100)	90
1.75	(175/100)	100
2	(200/100)	100
2.5	(250/100)	110
3	(300/100)	120
4	(400/100)	120
5	(500/100)	120
7.5	(750/100)	120
10	(1000/100)	130
15	(1500/100)	130
20	(2000/100)	130
30	(3000/100)	140
50	(5000/100)	140
100	(5000/50)	140
250	(5000/20)	140

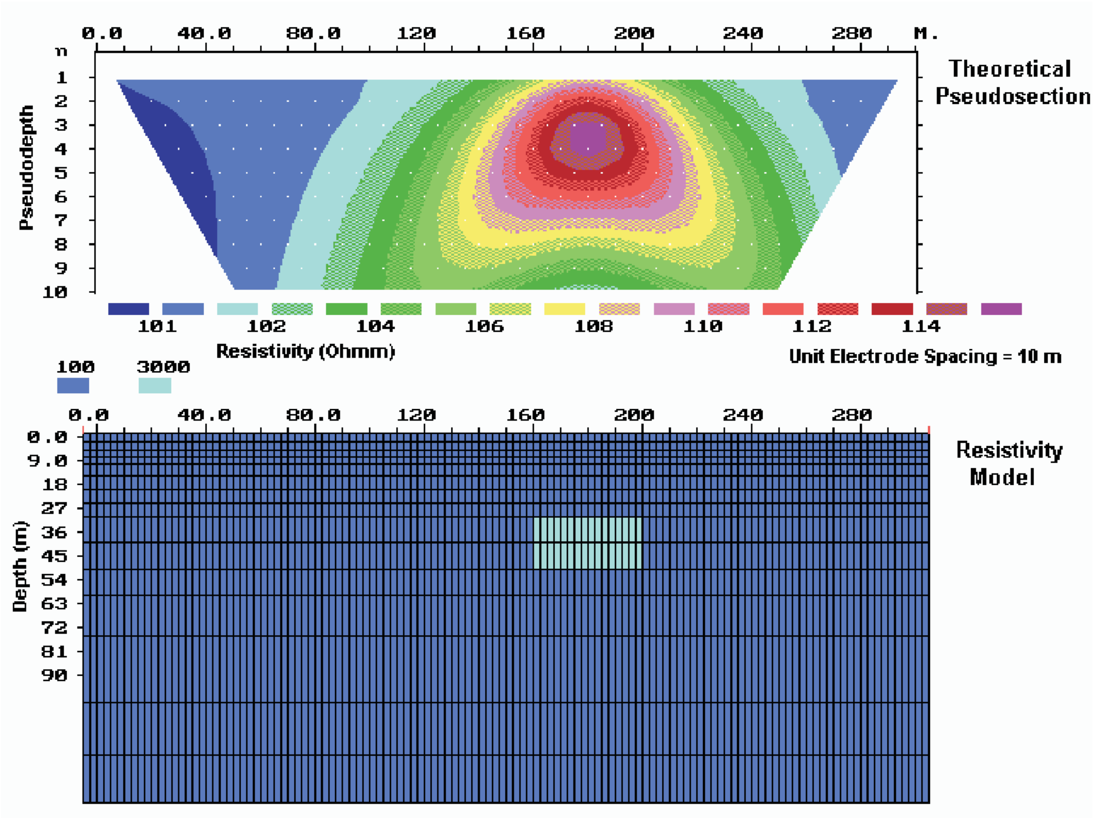

Figure 2 Model of block of higher resistivities in a homogenous environment of lower resistivities, and theoretical pseudosection for pole-pole array

Slika 2. *Model bloka većih otpornosti u homogenoj sredini manjih otpornosti i teoretska pseudosekcija za dvoelektrodni raspored*

Underground cavities in carbonate rocks are very irregular in shape, which makes their detection more difficult. Namely, the impact of an elongated underground cavity is different than that of a concentric one. The appearance of underground cavities is related to the fissure and fault zones, thus they are most frequently concentrated in such zones. Their dimensions can greatly vary, but are more often of smaller dimensions and irregular shapes. Therefore, on karst terrains, the most frequent targets are the zones in which underground cavities appear, i.e. fissure and fault zones, either as part of geological engineering or hydrogeological investigations. As they are at least partially filled with clay or water, they will be characterized by significantly lower resistivities in relation to their parent carbonate rocks.

It is generally known that the resolution decreases with depth in all geophysical methods, and that the electrical methods are characterized by a faster decrease than the seismic ones. Therefore, the size of an object must always be considered in relation to its location depth, e.g. a smaller block can be clearly detected at smaller depths, while it will not be seen at higher depths. In other words, for detection at higher depths, the size of a block must be increased. The resolution is also influenced by differences in resistivities between the block and the homogenous environment in which it is located, so their resistivity ratios must be considered. In general, resolution is better for higher resistivity ratios, i.e. higher differences in resistivities, thus the potentials for block detection with regards to resistivity ratio and location depth are considered. Table 1 shows the used ratios and results of modelling for the dipole-dipole array. Resolution for different block dimensions was analyzed, and as a representative dimension which can cover the most mentioned geological models shown in this paper, the 40x20 m dimension was determined.

The resolution also depends on the applied survey geometry, i.e. applied electrode array. Therefore, the analysis was conducted for arrays which are most frequently used in practical investigations which apply electrical tomography: the Wenner, Wenner-Schlumberger, dipole-dipole and pole-pole arrays, and the results were shown in Fig. 4-7. The examples of electrical modelling for the dipole-dipole array are shown in Fig. 3. The theoretical pseudosections and inverse resistivity models are also shown, which satisfy the theoretical "measured" pseudosections within a certain RMS-error. Based on a pseudosection, it is difficult to conclude if the cause for an anomaly is a higher resistivity block, since its appearance, apart from the underground model itself, is also influenced by the applied electrode array. The inverse resistivity model is closer to the actual resistivity model, since the impact of the electrode array on "measured" data is filtered by applied inversion method. It is evident that a higher resistivity ratio of the block and the parent rock environment results in a sharper anomaly. A sharper anomaly also results if the block with the same resistivity ratio is located at a lower depth. Since data are smoothed for convergence purposes in the inversion process, the inverse model shows a spherical, concentric anomaly, although the model is formed with a rectangular block.

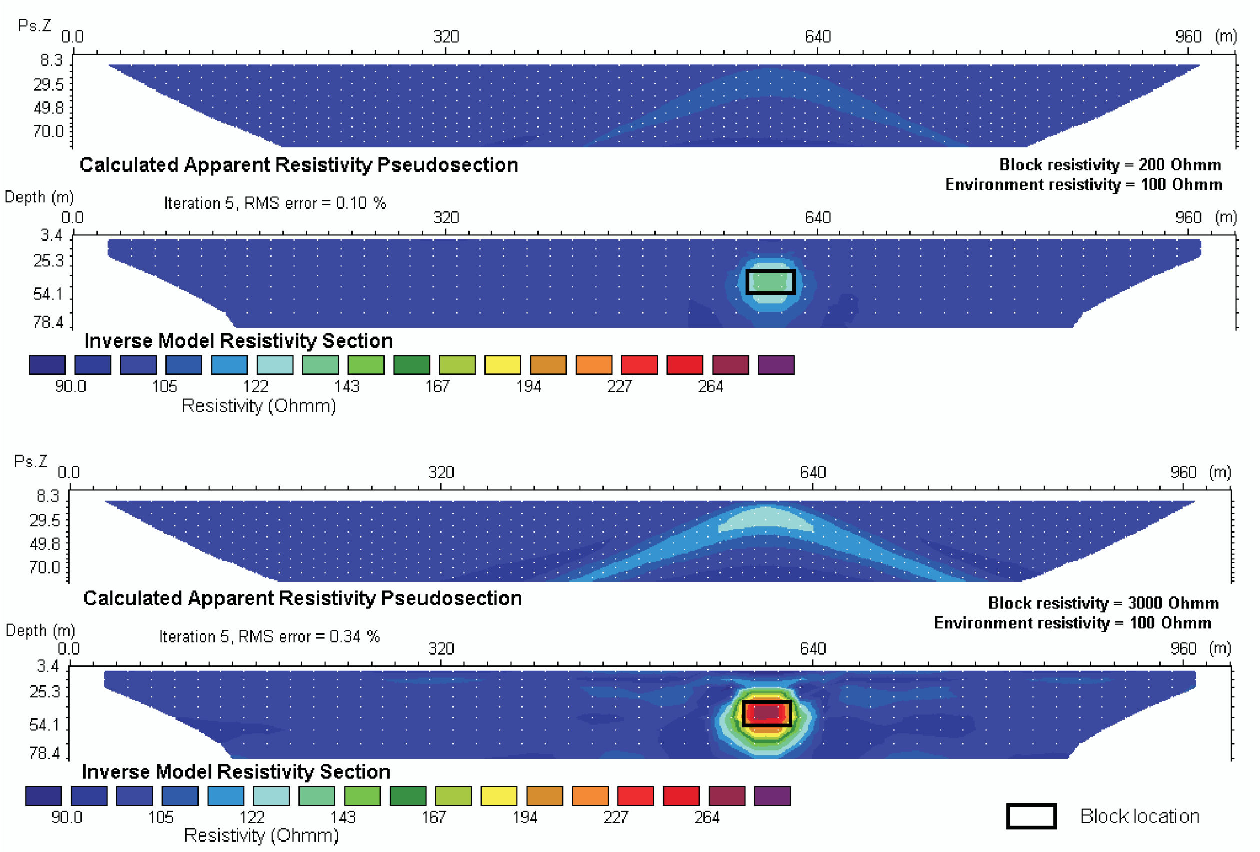

Figure 3 Examples of electrical modelling by application of the dipole-dipole array

Slika 3. *Primjeri električnog modeliranja primjenom dipolnog rasporeda*

Determination of resolution limits

Based on the results obtained by the application of the most frequently used array in investigations, i.e. the Wenner array, it was already evident that the resulting graphs for the determination of resolution limits are relatively regular (Fig. 4). The point values are entered on the graph, and those related to the limit value of resolution for a certain resistivity ratio are drawn on the X-axis, while those related to the block depth are drawn on the Y-axis. Based on the point values, a smoothed curve is drawn, showing the resolution limit. Point values do not fall ideally on the curve, which can be explained partly by the subjectivity of the assessment, and partly by a deformation caused by inversion algorithms.

With an increase in the resistivity contrast, there is also a continuous increase in the depth to which a block can be detected. At the minimum resistivity ratio, 1.25, a block which is located at the depths to 20 m is detectible, but already at the resistivity ratios of 1.5, a block can be detected at twice that depth (40 m). By increasing the ratio, there is also a continuous increase in depths at which a block can be detected. However, for the ratio of 30, a block can be detected at the depth of 80 m, whereas for higher ratios the resistivity contrast does not influence the depth increase, thus the depth of 80 m is practically the highest detectible block depth 40x20 m (Fig. 4).

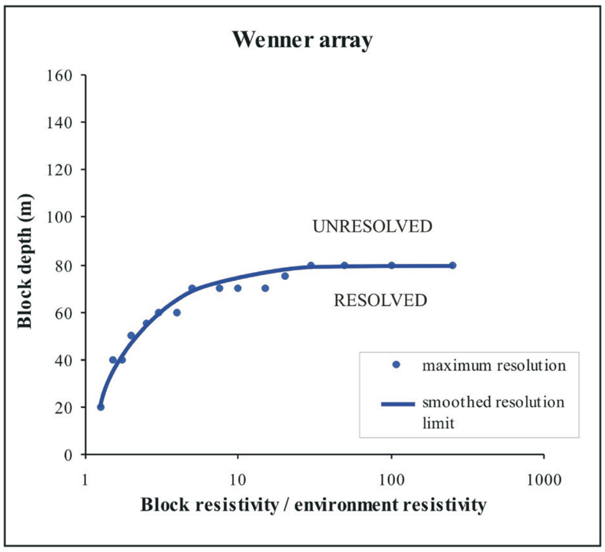

Figure 4 Graphical presentation of resolution limits for the block of 40x20 m dimension by means of the Wenner array

Slika 4. Grafički prikaz granica razlučivosti za blok dimenzija 40x20 m primjenom Wennerovog rasporeda

The application of other electrode arrays results in resolution limit curves which are similar in shape (Figs. 5, 6, and 7). The smallest resistivity contrast by the application of the Wenner-Schlumberger array enables the detection of a block at the depth of 10 m, while an increase in the resistivity ratio leads to a sudden increase of the detection depth (Fig. 5). The maximum detectability depth of 90 m is achieved already for the resistivity ratio of 10, after which a ratio increase does not affect the depth increase.

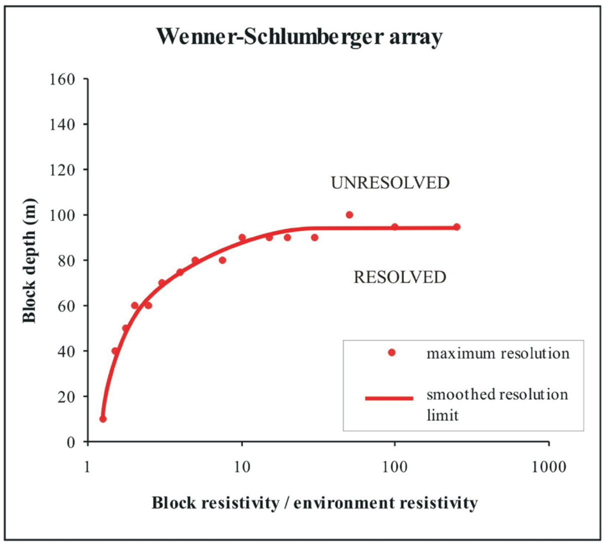

Figure 5 Graphical presentation of resolution limits for the block of 40x20 m dimension by means of the Wenner-Schlumberger array

***Slika 5.** Grafički prikaz granica razlučivosti za blok dimenzija 40x20 m primjenom Wenner-Schlumbergerovog rasporeda*

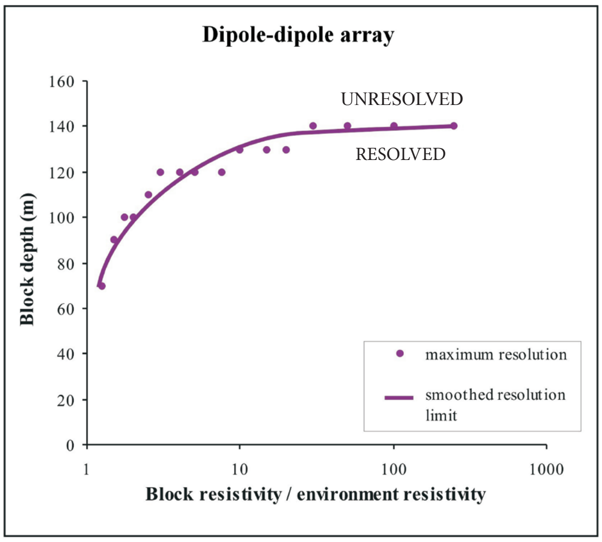

Figure 6 Graphical presentation of resolution limits for the block of 40x20 m dimension by means of the dipole-dipole array

***Slika 6.** Grafički prikaz granica razlučivosti za blok dimenzija 40x20 m primjenom dipolnog rasporeda*

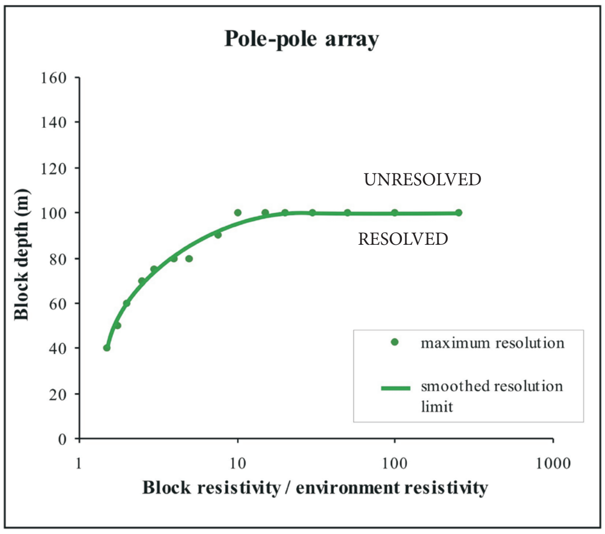

Figure 7 Graphical presentation of resolution limits for the block of 40x20 m dimension by means of the pole-pole array

***Slika 7.** Grafički prikaz granica razlučivosti za blok dimenzija 40x20 m primjenom dvoelektrodnog rasporeda*

The dipole-dipole array enables the block detection at a significantly higher depth (70 m), in comparison with previous arrays, if the resistivity ratio is minimal (Fig. 6). The curve growth is slower in comparison with other arrays, and the maximum depth significantly higher, equalling 140 m, which was achieved for the ratio 30. The pole-pole array enables the block detection at a smaller depth (40 m) for the smallest resistivity ratio. The maximum detectability depth is 100 m, smaller than in case of the dipole-dipole array, but is achieved already for the ratio of 10 (Fig. 7).

A comparative presentation of resolution limits for all applied electrode arrays and differences in resolution can be more clearly seen in Fig. 8. The curves are generally parallel, side from the area of the smallest resistivity ratios (1.25, 1.5 and 1.75). The lowest resolution limits are achieved by the application of the Wenner array, which indicates the smallest resolution in the block detection. Somewhat higher, but very similar resolutions are enabled by the Wenner-Schlumberger and pole-pole arrays, with the maximum depths of the block location from 90 to 100 m. The highest resolution, significantly higher than in case of other electrode arrays, is enabled by the dipole-dipole array. Thus all that falls below the curve of the Wenner array can be defined as resolvable on inverse models. All that falls above the curve of the dipole-dipole array, however, is not resolvable, while a wide area between the curves is conditionally resolvable, depending on the applied array (Fig. 8).

The method resolution in the actual field conditions, however, is influenced by a series of other parameters as well, which must be taken into account and which can affect the decision on selecting the appropriate electrode array. These are as follows: available space, target depths and noises. One must primarily consider urban and other noises to which electrode arrays are sensitive to a different level, and where the Wenner array has an advantage thanks to its lowest sensitivity.

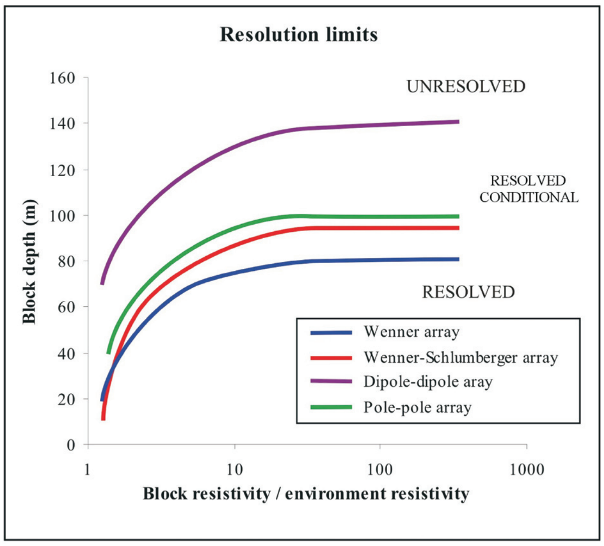

Figure 8 Comparative presentation of resolution limits for applied electrode arrays

Slika 8. *Usporedni prikaz granica razlučivosti za primijenjene elektrodne rasporede: Wennerov, Wenner-Schlumbergerov, dipolni i dvoelektrodni*

Investigation example

An example of underground cavities related to a fault zone in electrical tomography investigations can be found in the area of the Obrh spring at Ozalj. The measurements were conducted by the application of the Wenner electrode array, with a unit spacing of 10 m, on the profile with the length of 360 m. The Obrh spring is related to a reverse fault at the contact of Jurassic dolomites and limestones (Fig. 9). The profile was set over the spring, which is located at the position 220 m, nearly vertically to the direction of the structures. According to the Base Geological Map, the terrain is built of Jurassic Foraminiferal-algal limestones ($J_3^{2,3}$), Jurassic dolomites (J_1^{1+2}), as well as Plio-Quaternary and Quaternary clastites (Bukovac et al., 1983). The Upper Triassic limestones are fragmented, karstified and well water-permeable, whereas dolomites are very poorly permeable and pose a barrier to groundwater flow.

The highest resistivities are found at the beginning of the profile, resulting from relatively fresh dolomites. In the end part of the profile, a mountainous area with a very steep slope, there are somewhat lower resistivities caused by karstified limestones. On the dry surface part, the resistivities are relatively high, and decrease with depth due to their probable water saturation. These limestones are characterized by vertical water flow. At the position 305 m, a strong vertical decrease in resistivity is clearly evident, probably caused by the presence of underground cavities and fissures, which are at least partly clayey. In the central part of the profile, the area of the spring itself, which slopes towards the mountain under the general angle of 45º, there is a wide zone of decreased resistivities. The resistivities in the central part of the zone fall to about 40 Ωm, i.e. freshwater resistivity level. These resistivities are caused by a very wide fault zone, as determined by drilling (Dragičević, 2001). In the drillhole located in the spring area, which is the area with the lowest resistivities on the tomographical profile, strongly karstified, fragmented dolomites were identified. At the depths from 18 to 20 m, due to falling in of tools during drilling, a cavern was identified.

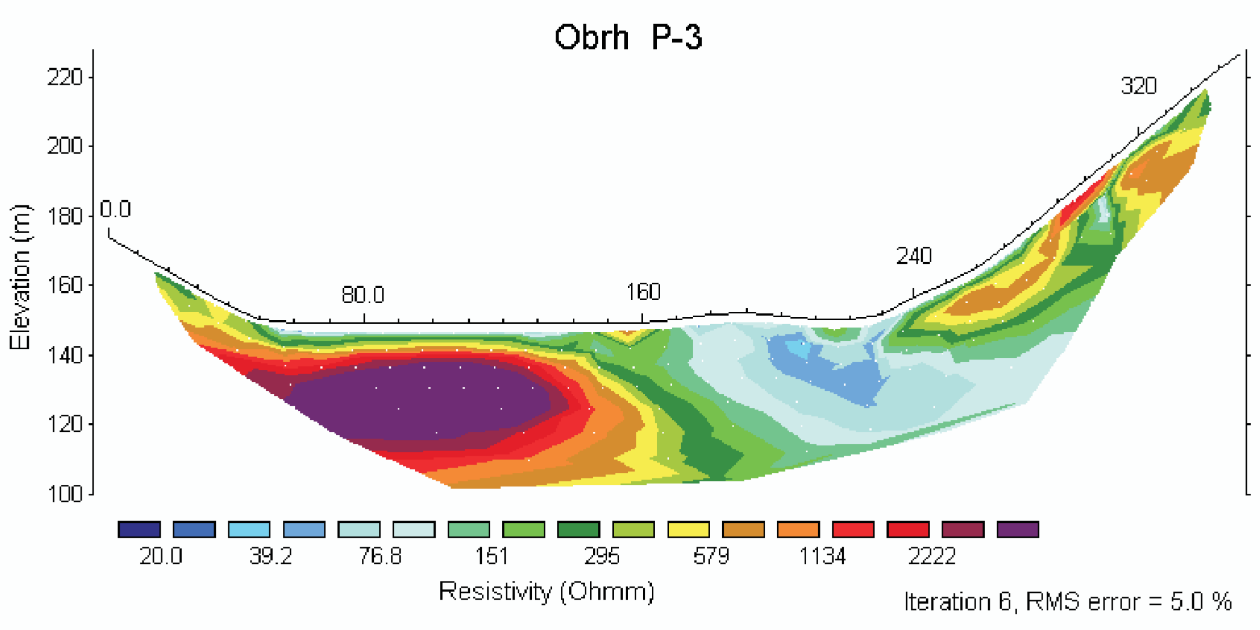

Figure 9 Inverse resistivity model for electrical tomography profiles measured in the area of the Obrh spring at Ozalj, where investigative drilling in the profile centre detected underground cavities of smaller dimensions in the fault zone

Slika 9. *Interpretirani model otpornosti profila električne tomografije, koji je mjeren na području izvora Obrh kod Ozlja, gdje su u rasjednoj zoni u središtu profila istraživačkim bušenjem otkrivene podzemne šupljine manjih dimenzija*

Conclusions

Two-dimensional electrical modelling was used for analysis of electrical tomography potentials in the detection of the higher resistivity block in a homogenous environment of lower resistivities. This model can represent several geological models, which are the target of many investigations, since they influence the geomechanical characteristics of a terrain in case of construction of infrastructure facilities and in groundwater investigations on karst terrains. As a representative, a block of 40x20 m dimensions was elected, and the maximum block location depths at which it can be detected were analyzed. Block detection potentials as well as the resolution method depend on the ratio between the resistivities of the block and its environment, thus the detectability depths were defined in this relation, and shown in the graphical overviews. The results also depend on the applied electrode array, so the analysis was performed for the most frequently used arrays: the Wenner, Wenner-Schlumberger, pole-pole and dipole-dipole arrays. The resolution graphs for individual arrays enable a very fast, simple definition of the potentials of a method application on a concrete geological model, thus having a significant practical use.

The resolution limit curves are similar in shape for all arrays, and, in general, the detectability depth increases with the increased contrast and resistivity ratio until it reaches a maximum detectability depth. The highest resolution is enabled by the dipole-dipole array and the lowest by the Wenner array. Between them are the pole-pole and Wenner-Schlumberger arrays, with very similar resolutions. At the very low resistivity ratio of 1.5, the dipole-dipole array enables detection to the depth of 90 m, and all other arrays to the depth of 40 m. The maximum detectability depth for the Wenner array is 80 m, achieved for the ratios equal or higher than 30, whereas the Wenner–Schlumberger array achieves the maximum depths of 90 m already for the ratio of 10. Somewhat higher depths of block detection are enabled by the pole-pole array, 100 m at the 10 ratio, and the highest by the dipole-dipole array. When it is applied, blocks can be detected at depths to 140 m for resistivity ratios over 30. In concrete investigations, environmental geophysical, geological and urban noises influence decrease in these theoretical resolutions. As electrode array sensitivity to them varies, they will also influence the decision on selecting the most optimal electrode array. The Wenner array is the least noise sensitive, which is advantageous in comparison with other arrays.

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