RGNZ/MGPB

Determination of Lakebed Sediment Distribution based on Underwater Electrical Resistivity Tomography Data

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
UDC: 550.8:622.1
DOI: 10.17794/rgn.2024.2.9

Original scientific paper

Jasna Orešković[1]; Saša Kolar[2]; Ana Brcković[3]; Ivica Pavičić[4]

[1] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia, https://orcid.org/0000-0001-9813-2586*

[2] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia*

[3] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia, https://orcid.org/0009-0004-1915-3266*

[4] *University of Zagreb, Faculty of Mining, Geology and Petroleum Engineering, Pierottijeva 6, Zagreb, Croatia, https://orcid.org/0000-0003-3786-274X*

Abstract

Electrical resistivity tomography (ERT) in an aquatic environment is usually measured using two basic systems. One system uses floating electrodes, which is usually applied in shallow water, and the other uses underwater cables with integrated electrodes, which is often carried out as a mobile system. The aim of this research was to test an underwater ERT measurement with floating cables on the water surface, but with electrodes submerged at the water bottom. This type of cable spread makes it possible to lay all the electrodes vertically to the bottom without the distance between them being reduced by the uneven topography and various underwater obstacles. Prior to the field survey that was conducted in a 40 m – deep lake, the response of common electrode arrays was tested using synthetic models. Two models were used that correspond to the geological condition in the field, higher resistivity bodies in a lower resistivity environment and a model with inverse relationship of resistivity to the first one. The Wenner-Schlumberger and dipole-dipole arrays resolved the resistivity range, size and shape of the bodies very well and were therefore used in the field. The field data quality was very good and it was shown that ERT measurements in freshwater depths of more than 40 metres can provide very good results. As expected from the modelling, the dipole-dipole array led to a high-resolution resistivity model that enabled the characterisation of the lakebed sediments.

Keywords:

underwater ERT; resistivity modelling; inversion, gravel deposit

1. Introduction

The electrical resistivity tomography (ERT) geophysical method is widely used in land surveying and ERT in aquatic environment has been used with different objectives and design of measurement (e.g. **Dahlin et al., 2018; Maillet et al., 2004**). The common aquatic measurements use the bottom-laid electrodes or floating electrodes on the water surface (water-borne measurement). Regarding the environment, underwater ERT measurements were performed in a marine environment or in freshwater, lakes and rivers. However, the focus was on the implementation of underwater ERT using a different measurement concept, namely a stationary floating cable with electrodes at the lake bottom. The aim of the study was to characterize the near-bottom sediments down to a depth of several tens of meters.

The ERT in an aquatic environment is a method that is still being tested and developed to better understand the range of potential uses in aquatic surveys (**Crook & Rucker, 2017**). To date, ERT has been successfully used in submarine investigations focussing on submarine sediments and bedrock (**Befus et al., 2014**). **Lile et al. (1994)** successfully detected fracture zones beneath the seabed as an investigation for a tunnel construction. In **Dahlin & Loke (2018)**, underwater ERT was used in a project for a new line of the Stockholm Metro. Submerged cables were used to investigate the thickness of the bottom sediments, rock quality and weak zones in the bedrock.

Orlando (2013) analysed the resolution of the ERT method in the case of floating and submerged electrode cables for the detection and characterisation of the thin near-bottom sediment layers. Numerical simulations by **Loke & Lane (2004)** demonstrated that the water layer has a large effect on the measured apparent resistivity values as it usually has a lower resistivity than the subsurface. Besides, their research indicated that the use of floating electrodes for electrical resistivity imaging surveys in water-covered areas reduces the subsurface

Corresponding author: Jasna Orešković
e-mail address: jasna.oreskovic@rgn.unizg.hr

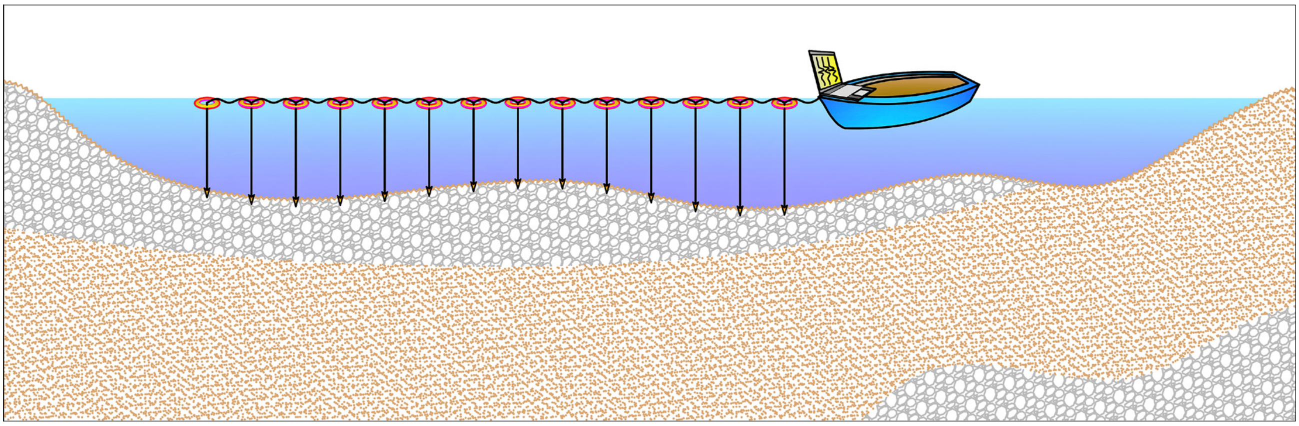

Figure 1: Underwater survey layout designed for the current research. The electrodes, attached to the cable on the water surface, are submerged to the bottom.

depth of investigation by an amount at least equal to the water depth.

In the case of water-borne ERT measurements, at least four floating electrodes are laid along the line on the water surface. The electrodes are in direct contact with the water, and measurement along the line is done by towing the electrode array, while different depths are reached by increasing the separation between electrodes. The measured voltage-to-current ratio is dependent on the resistivities beneath the electrode array and therefore also on the water resistivity and depth. Such ERT data are interpreted by standard 2D inversion algorithms by incorporating the water column (its resistivity and depth) as an additional layer in the model.

Water-borne ERT surveys with floating electrodes have been used in the characterization of lake sediment. **Hoppenbrock et al. (2021)** presented the water-borne ERT measurement with 13 floating electrodes, dragged by a motorboat. Prior to the interpretation of ERT data, inversion of the synthetic 2D models constructed from the obtained resistivity parameters showed that the model with a water depth of 10 m revealed the bottom layers, both sediment and bedrock, while the model with 21 m of water depth showed only weak change in resistivity below the water layer.

In our research, the maximum depth of the lake bottom was measured at approximately 40 m, and the idea of floating electrodes was discarded because it would not provide sufficient depth of measurement. To meet the requirements of the research, the method with electrodes on the lake bottom was used. Instead of an electrode cable laid on the lake bottom, we implemented the survey design with electrode cable floating on the water surface and electrodes that are lowered to the bottom at each take-out. The results of synthetic modelling were used prior to the field measurements to test the electrode array arrangement under actual conditions, as the array types have different characteristics concerning depth of investigation, sensitivity to resistivity changes, data coverage and signal strength (**Loke, 2016**).

2. Methodology

Electrical resistivity tomography (ERT) is a geophysical method that measures the electrical resistivity of the subsurface to map the structures beneath the ground. Analysis of the data can provide an understanding of sedimentary layers or geological structures both on land and in a water environment (**Loke, 2004; Maillet et al., 2004; Simyrdanis et al., 2015**).

2.1 ERT method in the aquatic environment

For two-dimensional ERT measurements on land, the electrodes used to inject current and measure the potential are most often hammered into the ground, while there are different methods for measurement in water. In a water environment, the electrodes can also be placed on the bottom, but more commonly, mobile systems are used where a cable with electrodes is dragged along the bottom, or floating electrodes are used on the water surface (**Nyquist et al., 2009; Epting et al. 2012, Kwon et al, 2005**). Combined surveys with some electrodes on land and some underwater are also used (**Loke and Lane, 2004**). In the current research we have used a different static system, with a cable on the water surface and electrodes submerged to the bottom (see **Figure 1**). The cable spread used in the research allows all electrodes to be laid correctly vertically to the bottom without the distance between them being reduced by the uneven topography and various obstacles (wires, concrete blocks, branches, etc.).

The electrodes can be arranged in different ways during the measurement. Each type of electrode array has different characteristics in terms of depth of investigation, sensitivity to changes in subsurface resistivity, data coverage and signal strength (**Loke, 2016**). **Szalai and Szarka (2008)** classified 92 geoelectric arrays in terms of penetration depth and sensitivity to lateral and/or vertical resistivity changes. In practice, the most common electrode arrays for 2D ERT measurements are Wenner, Wenner-Schlumberger, dipole-dipole, pole-pole and pole-dipole, and their properties on land measurements are well known. As described in **Loke (2016)**, the Wenner array is generally relatively sensitive to vertical resistivity changes in the subsurface below the centre of the array and is therefore good for resolving horizontal structures. Compared to other arrays, the Wenner array has a moderate depth of investigation. On the other hand, the dipole-dipole array is very sensitive to horizontal changes in resistivity, and is well suited for mapping vertical structures, but relatively poor for mapping sedimentary layers. The depth of investigation depends on both, the unit spacing (*a*) and the factor *n*. The horizontal data coverage is better than for Wenner array, which is why the dipole-dipole array has a better horizontal resolution. The Wenner-Schlumberger array is moderately sensitive to both horizontal and vertical structures, and the median depth of investigation is about 10% greater than the Wenner array for the same distance between the outer electrodes. The Wenner-Schlumberger array has a slightly better horizontal resolution than the Wenner array. Unlike the other common arrays, the pole-dipole array is an asymmetrical array, and over symmetrical structures it is expected that anomalies would be asymmetrical. The effect of asymmetry can be eliminated by combining the measurements in the forward and reverse manner. The horizontal coverage for the pole-dipole array is very good and similar to the dipole-dipole array it is more sensitive to vertical structures.

As far as the ERT measurement on land is concerned, the properties of electrode arrays in different geological models are quite well known. **Dahlin and Loke (1998)** investigated the resolution of the Wenner array used in 2D resistivity imaging. The modelling was carried out for several geological models and led to the conclusion that the resolution depends significantly on the data density and the inversion technique. **Dahlin and Zhou (2004)** compared the resolution for 10 different electrode arrays through 2D modelling for five synthetic geological models simulating a buried channel, a narrow conductive dike, a narrow resistive dike, dipping blocks and covered waste ponds. They concluded that pole-dipole, dipole-dipole and gradient arrays provide high-resolution images, with the final choice of array depending on the expected geology and resistivity contrast. **Dominković Alavanja (2006)** investigated the resolution of the most commonly used electrode arrays (Wenner, Wenner-Schlumberger, dipole-dipole and pole-pole) on the block model with increased resistivity in a homogeneous low-resistivity environment. The results showed that the dipole-dipole array provides the highest resolution and the Wenner array the lowest. In addition, the maximum detectability depth was defined for each electrode array (**Šumanovac and Dominković Alavanja, 2007**).

In an aquatic environment, the resolution of a 2D resistivity image will depend on the water properties and the type of underwater measurement, in addition to the geological model beneath the water bottom, the background noise and the data density. The water will be an additional layer in the resistivity model, defined by two basic parameters, water resistivity and depth. These two parameters can be rather easily obtained; water resistivity directly by conductivity measurements and water depth from bathymetry data.

Loke and Lane (2004) used modelling to investigate the influence of water layers 1 m, 2 m and 5 m thick for two types of underwater measurements. One is a measurement with the bottom electrodes and the other is a measurement with the floating electrodes. These tests showed that the water layer reduces the depth of investigation of sub bottom sediments and that the data collected using a floating electrode arrangement is significantly degraded compared to the data collected with bottom-laid electrodes.

Due to the measurement environment with a much deeper water layer than in the example above, bottom-laid electrodes in this research were used, and to investigate the influence of the water layer in the current environment, synthetic modelling prior to field survey was carried out.

3. Results and interpretation

3.1 Synthetic modelling of underwater survey

The aim of the modelling was to test common electrode arrays and select the one that would best define the boundaries of the subsurface structures in this particular investigation. During synthetic modelling, the apparent resistivity is calculated that would be measured above the defined theoretical model. The modelling was carried out using RES2DMOD software (**Loke, 2016**), which applies the finite-difference or finite-element method. The finite-difference method is based on **Dey and Morrison (1979)** with a modification by **Loke (1994)** and the finite-element method is based on **Silvester and Ferrari (1990)**. A modelling method and mesh used to model the water layer and subsurface in underwater surveys is described in more detail in **Dahlin and Loke (2018)**.

The modelling was carried out on two theoretical models, one with blocks of higher resistivity in a medium of low resistivity and in the other the resistivity relationship is reversed. Both models consisted of a water layer 40 m deep because in the field survey along almost the entire profile, the depth is approximately 40 m (see **Figures 2a** and **6**). The water resistivity is 20 Ωm, as measured in the real case. Below the bottom there are two blocks of higher resistivity (400 Ωm), representing gravel deposits, within sediments of lower resistivity (40 Ωm) in the first model (see **Figure 2a**), and blocks of low resistivity (40 Ωm) presenting clay lenses within a coarse-grained sediments of higher resistivity in the second model (see **Figure 3a**). The first block is 50 m wide

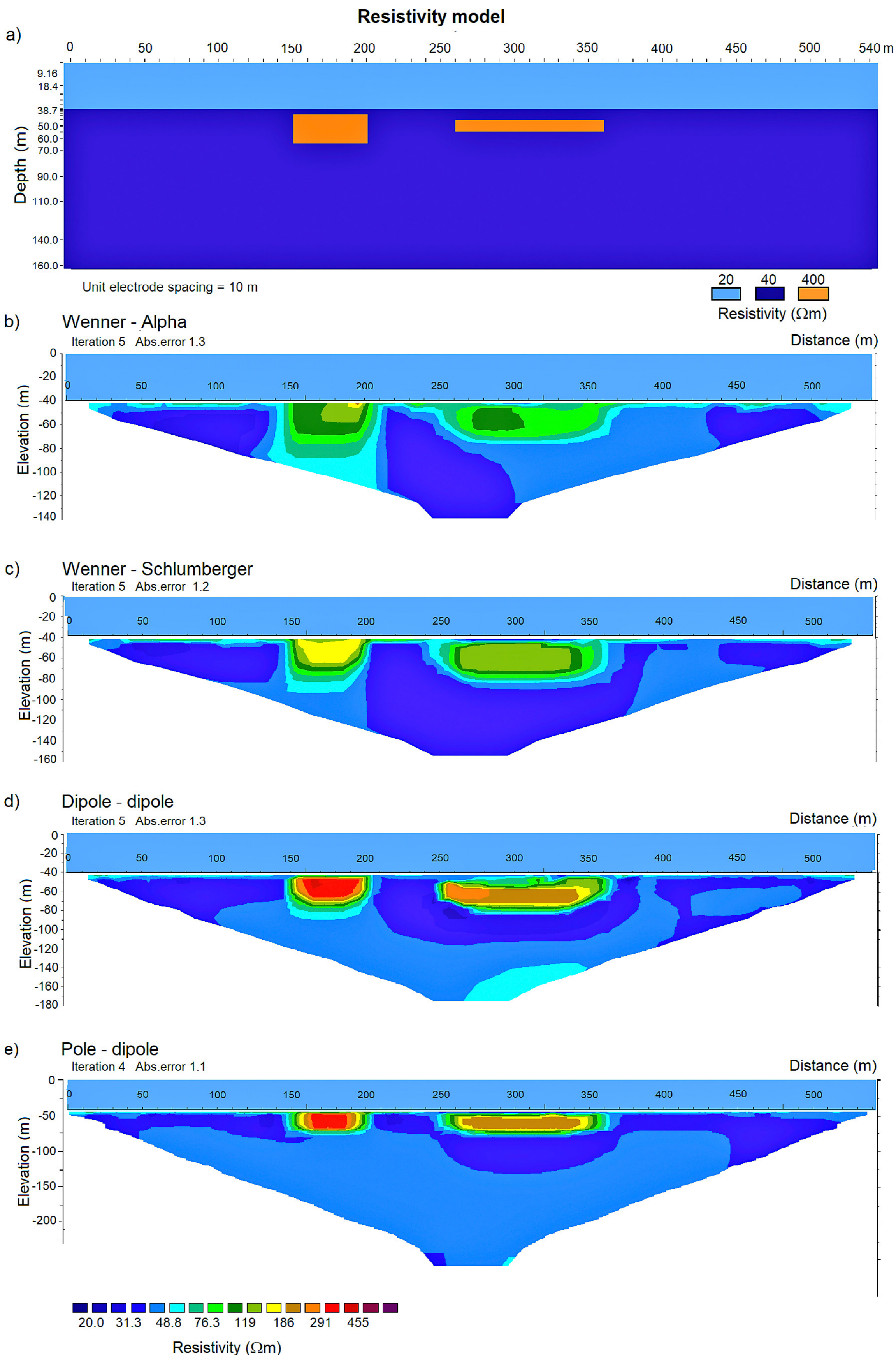

Figure 2: Synthetic resistivity model with 40 m deep water layer and higher-resistivity blocks within low-resistivity medium (a). Inverted resistivity models for underwater measurement with bottom electrodes for the Wenner array (b), Wenner-Schlumberger array (c), dipole-dipole array (d) and pole-dipole array (e).

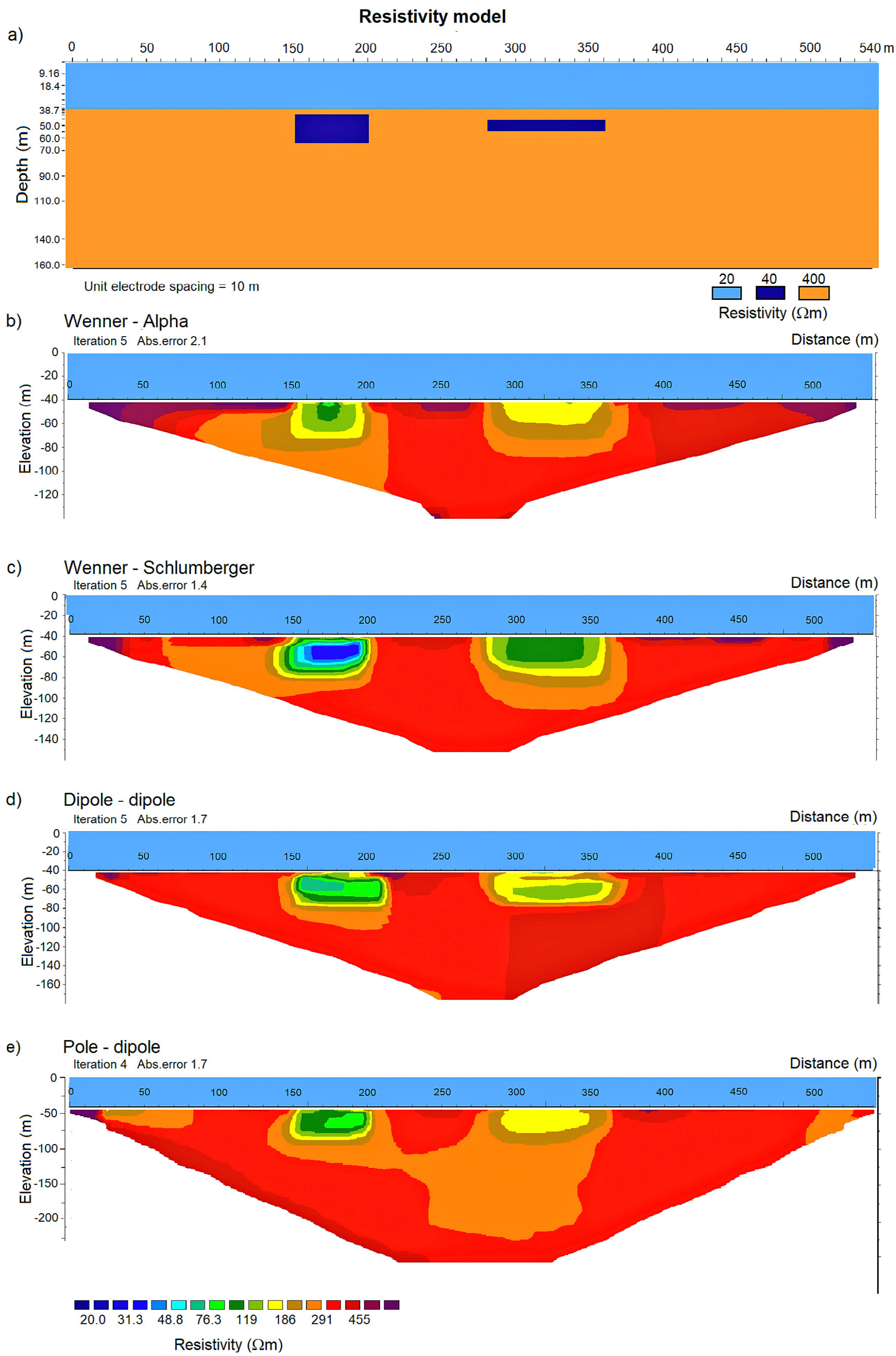

Figure 3: Synthetic resistivity model with 40 m deep water layer and low-resistivity blocks (a). Inverted resistivity models for underwater measurement with bottom electrodes for the Wenner array (b), Wenner-Schlumberger array (c), dipole-dipole array (d) and pole-dipole array (e).

and 25 m thick, and lies 5 m below the lake bottom, while the second one is 100 m wide and 10 m thick, and lies 10 m below the bottom. The low-resistivity environment represents fine-grained sediments such as sand, clayey sand and clay. The resistivities in the model have been defined according to typical resistivities of the main lithologies published in the literature (e.g. **Schön, 2011**; **Ward, 1990**), but the resistivity of the same lithology can vary over a wide range, sometimes by several orders of magnitude, depending on the rock condition, grain size and fluid content. Clay and sand, however, generally have lower resistivities than gravel.

The modelling was carried out for a line with 55 underwater electrodes and a unit electrode spacing of 10 m was used, as would be in the field survey. The model response was calculated using the finite element method and a random noise of 3% was added to the calculated resistivity values. Four electrode arrays were tested: Wenner-Alpha (i.e. Wenner), Wenner-Schlumberger, dipole-dipole and forward pole-dipole. A dataset for all possible combinations of "*n*" and "*a*" resulted in 477 points for the Wenner-Alpha array and a maximum pseudo-depth of 92 m, and for Wenner-Schlumberger 1765 data points and a pseudo-depth of 103 m. The dipole-dipole array yielded 2155 data points for $n = 10$ and pole-dipole 2545 data points with the greatest pseudo-depth of 195 metres.

The inversion of the Wenner-Alpha synthetic resistivity dataset shows a low-resolution model in which the thickness of the blocks appears to be greater than in the theoretical model, and their resistivities are significantly lower in the inverted model (see **Figure 2b**). The Wenner-Schlumberger array also leads to a rather poor resolution, where the thickness of the thin high-resistivity body is not well resolved (see **Figure 2c**). This array also leads to a difficult determination of the lower boundaries. In contrast, the inversion of the dipole-dipole array dataset resulted in a resistivity model that corresponds well with the theoretical model, and even the thin low-resistivity layer above the blocks is very well resolved (see **Figure 2d**). The thicknesses and positions of the blocks can be well identified, as well as the resistivity of the thicker block. The results of the pole-dipole array are very similar, and the depth of investigation is even greater (see **Figure 2e**), only the lateral boundaries of the two higher resistivity bodies are not as sharp as in the model derived from the dipole-dipole array.

In the case of the inverse resistivity relationship, the results of the modelling are presented in **Figure 3**. Both blocks of lower resistivity are reproduced in the inversion models, although for the Wenner array the size and depth of the anomalies do not reflect the blocks well, especially for the thin block. The anomaly shows a greater thickness and a significantly different resistivity (see **Figure 3b**). The actual resistivity of the block is 40 Wm, while the anomaly at the location of the thin block reaches about 190 Wm. The Wenner-Schlumberger array provides the best resistivity range, and the size and shape of the larger block are quite well resolved, but this is not the case for the thin block (see **Figure 3c**). At the location of this block, the resistivity anomaly indicates a block of greater thickness extending from the water bottom. This part of the model is well resolved by the dipole-dipole array (see **Figure 3d**). The last is a pole-dipole array that reaches the greatest pseudodepth and the anomalies are clearly visible but indicate a greater thickness and higher resistivity of the low-resistivity bodies.

Synthetic modelling shows that the data collected with the Wenner-Schlumberger array leads to the most accurate inverted resistivity model in terms of resistivity range and size of anomalies, especially for blocks of larger thickness. The dipole-dipole array produces the best resolution for thin block, and the thin layer above the blocks. For this reason, a profile in the field survey was measured using two electrode arrays, Wenner-Schlumberger and dipole-dipole, in order to obtain well-resolved structures in both cases.

3.2 Field survey

The study was carried out on a 40 m deep lake in the area of Quaternary alluvial deposits of the Drava River. The deposits underlying the lake consist of gravel, sand, silt and clay with possible occurrences of thin coal beds. The aim of the investigation was to determine the distribution of the sediments beneath the lake bottom.

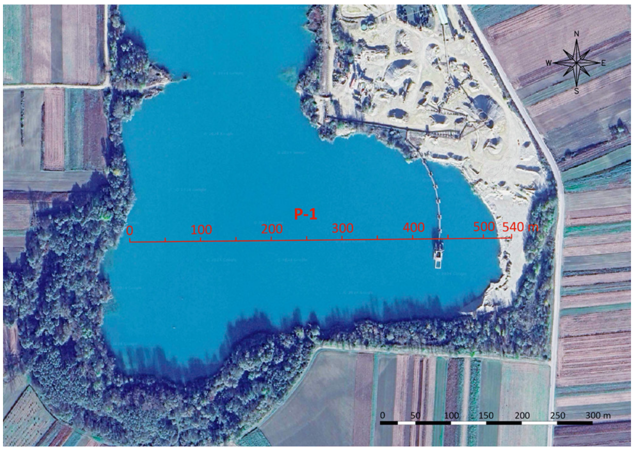

Figure 4: Location of the survey area with position of the ERT-line at the lake surface

In the study area, the thick complex of clastic deposits with an alternation of gravel, sand, silt and clay was deposited during the Middle Pleistocene by the sedimentation of dragged and suspended material from the Alps (**Babić et al., 1978**). The huge amounts of suspended loads downstream of the Alps are the result of heavy runoff after the precipitation-rich periods during the Middle Pleistocene in the Alps. The Quaternary gravels originate mostly from metamorphic and igneous rocks, and to a lesser extent from carbonate rocks, and the grains vary in size and sorting. The thickness of the unbound gravel-sand sediments increases from less than 20 metres near the Slovenian border to 80 metres towards the east, where the Mura flows into the Drava River. In addition, the grain size of the quaternary deposits decreases from north-west to south-east.

The electrical resistivity tomography survey was carried out along a 540 m long line with only the last electrode located on the land and all the others at the lake bottom. The electrode cable with 55 electrodes was fixed on the land, and take-outs were placed above the floating docks to keep them dry (see **Figure 5**). The electrode plates were submerged to the lake bottom at each take-out using an insulated wire (see **Figure 1**). A boat was used to deploy the cables and electrodes, as well as to host the instruments during measurement. The unit electrode spacing was 10 m. ERT measurements were carried out using an ABEM Terrameter Lund System and two electrode arrays, Wenner-Schlumberger and dipole-dipole, were used. The measurement was performed according to standard protocols for these electrode arrays.

The water depth data were acquired separately as part of the bathymetric survey and not as part of this study. The topography of the lake bottom along the line is shown in **Figure 6**. In the central part of the profile, the depth varies between 35 and 41 metres, while the depth changes sharply towards the coast.

Figure 5: Cable and cable take-outs deployed on the surface

The resistivity of the water column has a large influence on the inversion results, and when the thickness of the water layer is much greater than the unit electrode spacing, the effect of the water layer approaches that of a homogeneous half-space (**Loke and Lane, 2004**). Therefore, it is necessary to include information about the water resistivity in the model. The lake water conductivity (the reciprocal of resistivity) was measured on water samples. The electrical resistivity tomography data were collected at the end of December, when the average air temperature was around 6°C and small temperature differences can be expected in the water column depending on depth. Therefore, an average measured resistivity value of 20 Ωm (conductivity 495 μS/cm) was used for the inversion.

3.3. Inversion results

The inversion of apparent resistivity data was performed using the inversion software Res2dinv. A detailed description of the inversion method for underwater resistivity data can be found in **Loke et al. (2003)**. The data quality has been checked prior to inversion and was found to be of good quality. As expected, there was no high noise as there was no activity on or around the lake at the time of measurement. The Wenner-Schlumberger electrode array resulted in 546 data points, while the dipole-dipole array resulted in 588 data points. The topography of the lake bottom, the elevation of water surface and the water resistivity were included in the data files. The inversion of apparent resistivities was carried out for an underwater survey with one electrode located on land, and therefore water boundaries were defined in the data file and a surface geometric factor was used. The resistivity of the water layer in the model is kept constant at a known value. For the underwater measurement dataset, the Res2dinv software automatically uses the finite-element method (**Loke, 1996**).

The inversion resulted in models of sub-bottom resistivity distribution and the aim was to map near-surface deposits. When interpreting results, it should be taken into account that in the real environment the resolution

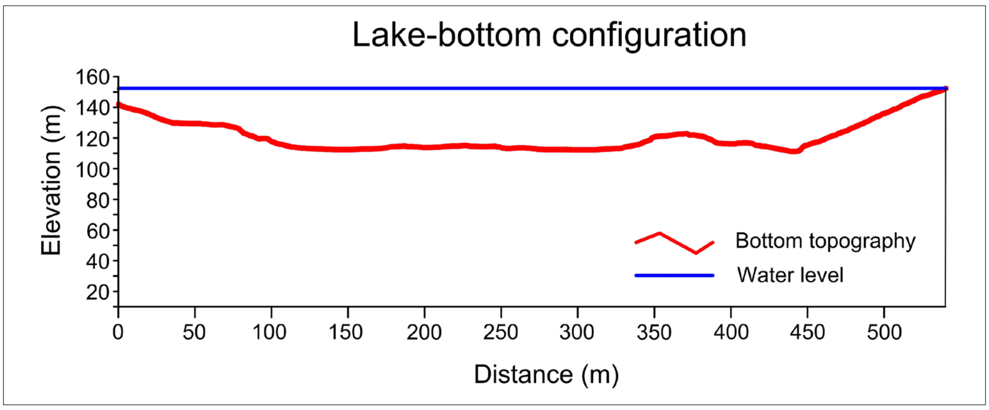

Figure 6: Lake bottom topography from bathymetric survey. Water level is at 151 m.a.s.l.

Copyright held(s) by author(s), publishing rights belongs to publisher, pp. 111-120, DOI: 10.17794/rgn.2024.2.9

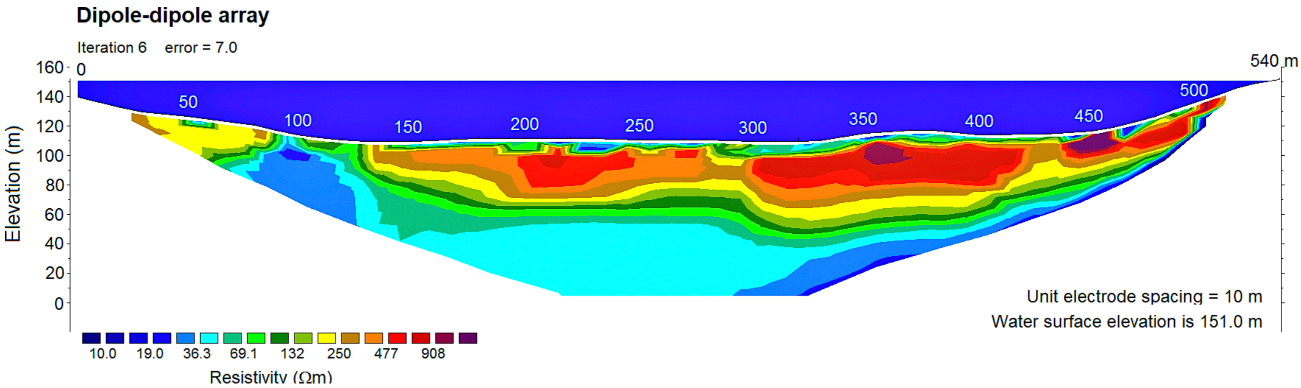

Figure 7: Resistivity model of profile measured at the lake bottom, using dipole-dipole array. Electrodes are submerged at the water bottom, only the last electrode is located on land.

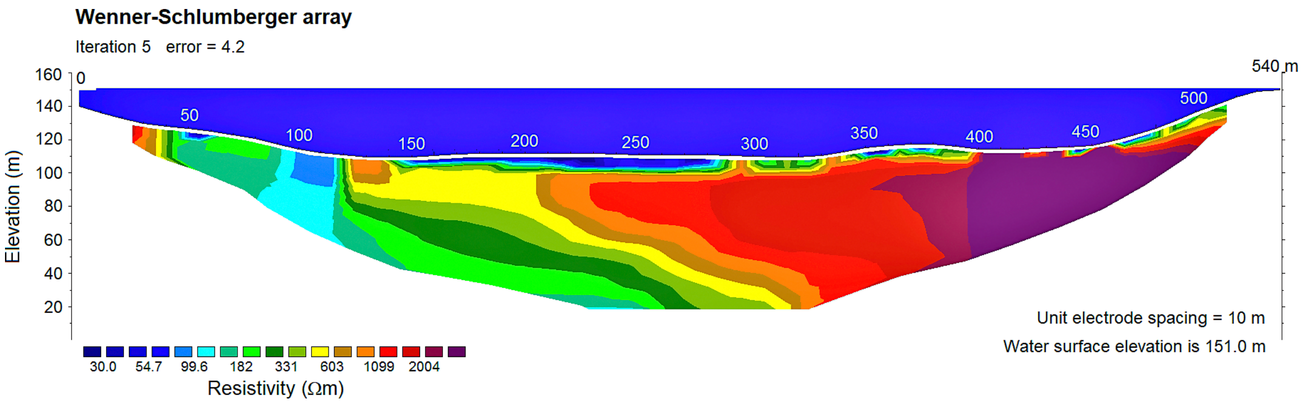

Figure 8: Resistivity model of profile measured at the lake bottom, using Wenner-Schlumberger array. Electrodes are submerged at the water bottom, only the last electrode is located on land.

of measurements is also affected by 3D effects. The models are shown in **Figure 7**, for the dipole-dipole array, and in **Figure 8** for the Wenner-Schlumberger array. The inversion resulted in an RMS error of 7% for the dipole-dipole array, and 4% for the Wenner-Schlumberger array, indicating that the data are of good quality and that the measured data and the model fit well.

The inverted resistivity model obtained with the dipole-dipole array shows lower resistivities at the beginning of the profile (20 – 100 Wm) which correspond to fine-grained sediments, sand and clayey sand or fine-grained gravel at the very beginning of the profile. In the distances from 130 m to the end of the profile, there are three higher resistivity anomalies (red colour in **Figure 7**), which originate from coarse gravel deposits. The thickness of the gravel deposits can be estimated to about 30 metres. In the deeper part of the model, the resistivities are low (< 60 Wm) and correspond to clay and sandy clay sediments. The lowest resistivity anomaly in blue colour at a 100 m distance represents clay lens, or silty clay sediments (see **Figure 7**).

The resistivity model obtained with the Wenner-Schlumberger array has a lower resolution than the one obtained with the dipole-dipole array, which is recognisable at first sight (see **Figure 8**). The two models are very similar up to a profile distance of 150 metres. The Wenner-Schlumberger model also shows lower resistivities up to 120 m, which represent sand and clayey sand sediments or fine-grained gravels. However, the higher resistivity anomaly from 200 m to the end of the profile has a much lower resolution, and its lower boundary can hardly be estimated. The lateral extension corresponds to the dipole-dipole model in **Figure 7** and also shows an increasing resistivity towards the end of the profile.

As expected from the synthetic modelling results, the field measurements also show that the dipole-dipole array provides a resistivity model with the highest resolution under these geological conditions. The boundaries of deposits are quite sharp and their vertical as well as lateral extent can be defined with a high degree of certainty.

4. Conclusions

The underwater ERT survey using floating cable and electrodes submerged on the lake bottom was successfully tested in the environment of a deep lake. The aim of the research was to map the sediment layers under the lake bed. The method with floating electrodes could not be used as most of the current flows within the water layer, which is 40 metres deep in the current investigation. Synthetic modelling of the underwater measurement was carried out for the most common electrode arrays. The results show that dipole-dipole and pole-dipole arrays provide the most reliable inverted models in terms of resolution and resistivity range for modelling higher resistivity blocks in a lower resistivity environment. This model is intended to present gravel deposits in a sandy and clayey-sand environment. The Wenner and Wenner-Schlumberger arrays produce a model of rather low resolution, especially concerning the lower boundary of the blocks. On the other hand, the Wenner-Schlumberger array together with the dipole-dipole array has an advantage in the model of low-resistivity blocks in a higher resistivity environment, which represent clay lenses or clay layers within gravel deposits.

Based on the modelling results and in order to obtain well-resolved structures in both cases, two electrode arrays were selected for the field investigation, a dipole-dipole and a Wenner-Schlumberger array. The measured data were of very good quality and showed that ERT measurements at freshwater depths of more than 40 m provide very good results. As expected from the modelling, the dipole-dipole array led to a high-resolution model that enabled the spatial and vertical determination of gravel deposits while Wenner-Schlumberger array provided lower resolution results.

5. References

Babić, Ž., Čakarun, I., Sokač, A. and Mraz, V. (1978): O geologiji kvartarnih naslaga porječja rijeke Drave (*Geology of Quaternary deposits of the river Drava drainage basin in Croatia*). Geološki vjesnik, 30(1), 43-61.

Befus, K. M., Cardenas, M. B., Tait, D. R. & Erler, D. V. (2014). Geoelectrical signals of geologic and hydrologic processes in a fringing reef lagoon setting. Journal of Hydrology, 517, 508-520. https://doi.org/10.1016/j.jhydrol.2014.05.070

Crook, N. and Rucker, F.D. (2017): Waterborne Electrical Resistivity of the Hypersaline Mono Lake. Journal of Environmental and Engineering Geophysics, 22 (2), 191-196. https://doi.org/10.2113/JEEG22.2.191

Dahlin, T. and Loke, M.H. (1998): Resolution of 2D Wenner resistivity imaging as assessed by numerical modelling. Journal of Applied Geophysics, 38(4), 237-249. https://doi.org/10.1016/S0926-9851(97)00030-X

Dahlin, T. and Loke, M.H. (2018): Underwater ERT surveying in water with resistivity layering with example of application to site investigation for a rock tunnel in central Stockholm. Near Surface Geophysics, 16, 230-237. https://doi.org/10.3997/1873-0604.2018007

Dahlin, T. and Zhou, B. (2004): A numerical comparison of 2D resistivity imaging with 10 electrode arrays. Geophysical Prospecting, 52, 379–398. https://doi.org/10.1111/j.1365-2478.2004.00423.x

Dey, A. and Morrison H.F. (1979): Resistivity modelling for arbitrary shaped two-dimensional structures. Geophysical Prospecting, 27, 106-136. https://doi.org/10.1111/j.1365-2478.1979.tb00961.x

Dominković Alavanja, S. (2006): Određivanje rezolucije metode 2D električne tomografije (*Determination of resolution limits of 2D electrical tomography*). Magistarski rad, Rudarsko-geološko-naftni fakultet, Zagreb. (*in Croatian*)

Epting, J., Wüest, A. and Huggenberger, P. (2012): Investigating sediments and rock structures beneath a river using underwater ERT. Open Geosciences, 4(1), 81-93. https://doi.org/10.2478/s13533-011-0052-0

Hoppenbrock, J., Bücker, M., Gallistl, J., Flores Orozco, A., de la Paz, C.P., García García, C.E., Razo Pérez, J.A., Buckel, J. and Pérez, L. (2021): Evaluation of Lake Sediment Thickness from Water-Borne Electrical Resistivity Tomography Data. Sensors, 21, 8053. https://doi.org/10.3390/s21238053

Kwon, H., Kim J., Ahn H., Yoon J., Kim, K., Jung, C., Lee, S. and Uchida, T. (2005): Delineation of a fault zone be-neath a riverbed by an electrical resistivity survey using a floating streamer cable. Exploration Geophysics, 36, 50–58. https://doi.org/10.1071/EG05050

Lile, O.B, Backe, K.R., Elvebackk, H. and Buan, J.E. (1994): Resistivity measurements on the sea bottom to map fracture zones in the bedrock underneath sediments. Geophysical Prospecting, 42(7), 813–824. https://doi.org/10.1111/j.1365-2478.1994.tb00242.x

Loke, M.H. (1994): The inversion of two-dimensional apparent resistivity data. PhD thesis, The University of Birmingham.

Loke, M.H. (1996): Tutorial: 2-D and 3-D electrical imaging survey. Geotomo Software (rev. 2023). Available at: http://www.geotomosoft.com/downloads.php

Loke, M.H. (2016): RES2DMOD ver 3.03, Rapid 2D resistivity and I.P. forward modeling using the finite-difference and finite-element methods. Geotomo Software.

Loke, M.H., Acworth, I., and Dahlin, T. (2003): A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. Exploration Geophysics, 34, 182–187. https://doi.org/10.1071/EG03182

Loke, M.H. and Lane, J.W.Jr. (2004): Inversion of data from electrical resistivity imaging surveys in water-covered areas. Exploration Geophysics, 35, 266–271. https://doi.org/10.1071/EG04266

Maillet, G. M., Rizzo, E., Revil, A. and Vella, C. (2004): High Resolution Electrical Resistivity Tomography (ERT) in a Transition Zone Environment: Application for Detailed Internal Architecture and Infilling Process Study of a Rhône River Paleo-channel. Marine Geophysical Researches, 26 (2-4), 317-328. https://doi.org/10.1007/s11001-005-3726-5

Nyquist, J.E., Heaney, M.J. and Toran, L. (2009): Characterizing lakebed seepage and geologic heterogeneity using resistivity imaging and temperature measurements. Near Surface Geophysics, 7, 487-498. https://doi.org/10.3997/1873-0604.2009022

Orlando, L. (2013): Some considerations on electrical resistivity imaging for characterization of waterbed sediments. Journal of Applied Geophysics, 95, 77-89. https://doi.org/10.1016/j.jappgeo.2013.05.005.

Schön, J.H. (2011): Physical Properties of Rocks - A Workbook, Vol. 8: Handbook of Petroleum Exploration and Production, Cubitt, J. (Ed.). Elsevier, Netherlands, pp. 273-335.

Silvester, P.P. and Ferrari R.L. (1990): Finite elements for electrical engineers (2nd. ed.). Cambridge University Press.

Simyrdanis, K., Tsourlos, P., Soupios, P., Tsokas, G., Kim, J.H. and Papadopoulos, N. (2015): Surface-to-tunnel electrical resistance tomography measurements. Near Surface Geophysics, 13(4), 343–354. https://doi.org/10.3997/1873-0604.2015019

Szlai, S. and Szarka, L. (2008): On the classification of surface geoelectric arrays. Geophysical Prospecting, 56, 159–175. https://doi.org/10.1111/j.1365-2478.2007.00673.x

Šumanovac, F. and Dominković Alavanja, S. (2007): Determination of resolution limits of electrical tomography on the block model in a homogenous environment by means of electrical modelling. Rudarsko-geološko-naftni zbornik, 19, 47-56.

Ward, S.H. (1990): Resistivity and Induced Polarization Methods. Geotechnical and Environmental Geophysics, Volume I: Review and Tutorial, 147-190. DOI: 10.1190/1.9781560802785.ch6

SAŽETAK

Određivanje rasprostiranja sedimenata dna jezera na temelju podataka podvodne električne tomografije

Prilikom mjerenja električnom tomografijom (ERT) u vodenome okolišu najčešće se primjenjuju dva osnovna sustava. Prvi sustav koristi se elektrodama na površini i obično se primjenjuje u vodi male dubine, a drugi sustav koristi se podvodnim kabelima s integriranim elektrodama, koji se često izvodi kao mobilni sustav. Cilj ovoga istraživanja bio je testirati podvodno ERT mjerenje s plutajućim kabelima na površini vode, ali elektrodama uronjenim do dna. Prije samoga terenskog istraživanja koje je provedeno u jezeru dubine oko 40 m testirali smo odziv najčešće korištenih elektrodnih rasporeda postupkom modeliranja. Korištena su dva modela koja odgovaraju geološkim uvjetima na terenu: blokovi veće električne otpornosti u sredini niže otpornosti i model s obrnutim odnosom otpornosti. Rezultati pokazuju da dipolni i Wenner-Schlumbergerov elektrodni raspored daju odličan odziv u smislu raspona otpornosti, veličine i oblika blokova i stoga su korišteni prilikom testiranja u terenskim uvjetima. Mjerenjem su dobiveni podatci vrlo dobre kvalitete te se pokazalo da ovakva ERT mjerenja mogu dati vrlo dobre rezultate u slatkovodnim okolišima s dubinama većim od 40 metara. Kao što su pokazali i rezultati modeliranja, dipolni elektrodni raspored dao je model otpornosti visoke rezolucije koji je omogućio karakterizaciju sedimenata jezerskoga dna.

Ključne riječi:
podvodna električna tomografija, modeliranje otpornosti, inverzija, ležište šljunka

Author's contribution

Jasna Orešković (1) performed the field work, provided ERT forward modelling, final data interpretation and presentation of results. **Saša Kolar (2)** defined the measurement design, performed the field work, data processing and participated in the interpretation of the results. **Ana Brcković (3)** performed the field work, data processing and ERT inversion. **Ivica Pavičić (4)** provided the geological setting and participated in the interpretation of the results.

 pp. 111-120, DOI: 10.17794/rgn.2024.2.9