APPLICATION OF ELECTRICAL TOMOGRAPHY FOR THE STUDY OF NEAR-SURFACE GEOLOGICAL SECTION

Stefan Dimovski, *Ph.D., University of Mining and Geology "St. Ivan Rilski", Bulgaria*
Radi Radichev, *Ph.D., University of Mining and Geology "St. Ivan Rilski", Bulgaria*
Emil Hristov, *D.Sc ., University of Mining and Geology "St. Ivan Rilski", Bulgaria*

ABSTRACT. Electrical tomography surveying can be successfully applied for the detailed study of the near-surface geological section. The approach and the basic elements of the methodology for data acquisition, processing and interpretation are revealed on the example of the performed electrical tomography surveying in the region of "Marichin valog" – a potential site for long-term storage of radioactive waste products. Field measurements are performed along 10 profiles. The distribution of the electrical resistivity along the profiles and the obtained zoning of the geoelectrical section are illustrated. Structural map of one well-distinguished geoelectrical boundary is achieved. The obtained results confirm the high geological efficiency of the electrical tomography surveying.

Introduction

Geophysical methods can be successfully applied for the detailed study of the near-surface geological section (Dimovski and Radichev, 2002). They fulfill the results from the borehole investigations and allow correct interpolation of the general behavior of the present geological formations. Electrical resistivity methods have wide application for the detailed mapping of the near-surface geological section. Their geological efficiency is connected to the rocks differentiation according to electrical resistivity. For a precise geoelectrical section the rocks electrical resistivity is tied to the existing preconditions for presence of ionic conductivity.

Electrical tomography can be effectively applied for obtaining a detailed picture of the geoelectrical differentiation in the near-surface section. This method is based on the use of modern equipment, optimal measuring techniques, and computer processing of acquired data (Gyurov and Stoyanov, 2004; Ivanov et al. 2005; Dimovski et al. 2007).

The approach and the basic elements of the measuring techniques and of the data processing and interpretation are presented on the example of a electrical tomography surveying performed in the area of "Marichin valog" – a potential site for long-term storage of low-level radioactive waste.

The field measurements were performed along ten profiles (each with a length of 235 m) having a total length of 2350 m. The processing of the acquired data and the interpretation of the obtained results are completed by the Department of Applied Geophysics, University of Mining and Geology "St. Ivan Rilski", Sofia.

Basic elements of the electrical tomography surveying technique

Electrical tomography is a new and rapidly evolving technology for the non-invasive imaging of the shallow subsurface. This technique for imaging the subsurface electrical structure is using conduction currents. From a series of electrodes, low frequency electrical current is injected into the subsurface, and the resulting potential distribution is measured. A large variety of different source and receiver positions are used to sample the target section (2-D electrical tomography). This electrical resistivity surveying method is performed with a big number of electrodes connected to a compound cable (Griffiths and Barker, 1993). The exact four electrodes necessary for each measurement (two current and two potential) are selected through a mechanical or an electronic device.

In Figure 1a is illustrated a typical 2-D measuring scheme that comprises 20 electrodes, located along the surveying line at one and the same distance “**a**”. When the Wenner array is applied, the process includes consecutive measurements with electrode spacing “**n.a**”. In the first stage all possible measurements with electrode spacing “**1a**” are performed. For each measurement the precise combination of two current and two potential electrodes is selected. For a measuring scheme composed of 20 electrodes are available 17 possible measurements with electrode spacing “**1a**”. After accomplishing the measuring cycle with distance “**1a**” between adjacent electrodes is started the next cycle of successive measurements with electrode spacing “**2a**”. This measuring process is repeated with spacing between adjacent electrodes “**3a**”, “**4a**”, “**5a**” и “**6a**”. The number of possible measurements for a fixed spacing “**n.a**” decreases with the increase of the distance between adjacent electrodes. The number of possible measurements for specific electrode spacing and for fixed count of electrodes along the surveying line depends on the applied measuring array. Among all types of arrays used in 2-D electrical resistivity tomography, the Wenner array provides the smallest number of possible measurements, but it has the highest signal-to-noise ratio among the conventional arrays.

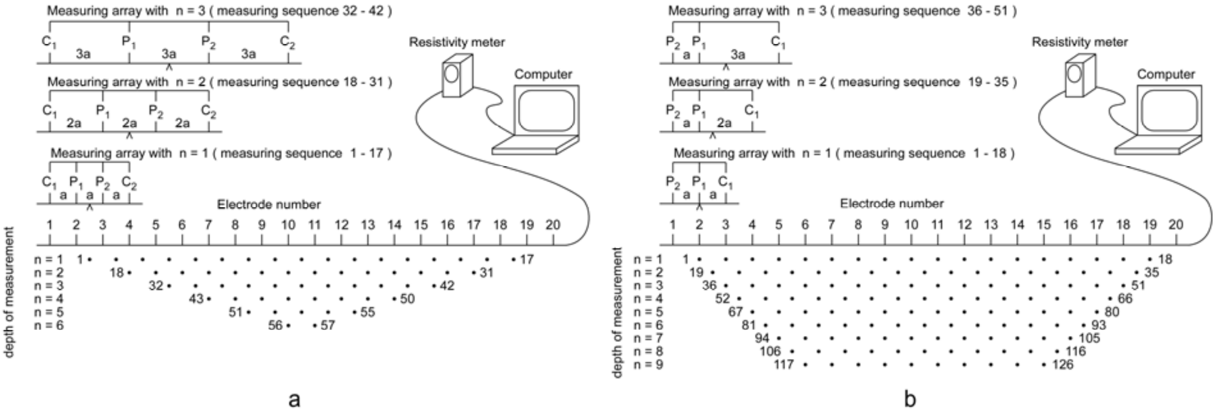

Figure 1. Illustration of a typical 2-D measuring scheme that comprises 20 electrodes, located along the surveying line at one and the same distance “a”, possible measuring sequences and arrangement of data points in the pseudosections for the Wenner array (a) and the pole-dipole array (b)

The pole-dipole array provides not only a very good horizontal and vertical coverage of the section, but is also very sensitive towards local non-uniformities. In figure 1b is illustrated a possible measuring sequence for a pole-dipole array that comprises 20 electrodes. The spacing between each two adjacent electrodes along the surveying line is “**a**”. In this array the second current electrode (C2) is located far enough, so that C1 can be regarded as point current source. The first measurement is performed selecting electrodes 1, 2, and 3. Electrode 1 is the second potential electrode P2, electrode 2 is the first potential electrode P1, and electrode 3 is the first current electrode C1. In the second measurement electrodes 2, 3, and 4 are selected as P2, P1, and C1, respectively. This procedure is repeated until electrodes 18, 19, and 20 are utilized in the last measurement with electrode spacing “**1a**”, i.e. when the dipole separation factor “**n**” is set to 1 (the distance between the current electrode C1 and the potential electrode P1 is usually an integer multiple of the distance between the potential electrode pair P1-P2). For a pole-dipole array composed of 20 electrodes are available 18 (20-2) possible measurements for **n = 1**. After accomplishing the measuring cycle with distance “**1a**” between electrodes C1 and P1 is started the next cycle of successive measurements when the dipole separation factor “**n**” is set to 2 (**n = 2**), i.e. with distance “**2a**” between electrodes

C1 and P1. In the first measurement of this cycle are selected electrodes 1, 2, and 4. This procedure is repeated until electrodes 17, 18, and 20 are utilized in the last measurement with dipole separation factor "**n**" set to 2. For a pole-dipole array composed of 20 electrodes are available 17 (20-3) possible measurements for distance "**2a**" between electrodes C1 and P1. In the next measuring cycles the dipole separation factor "**n**" increases until it reaches its maximum value of 9. After this stage the measured potential differences become relatively small and it is difficult to acquire reliable data. In order to expand the depth of the survey, the distance between the potential electrode pair P1-P2 is increased to "**2a**" and new measurement cycles are performed for different values of dipole separation factor "**n**".

If the number of electrodes is not sufficient to cover the entire length of the surveying line, then a special procedure is performed in order to increase the horizontal coverage of the scheme. In this case after each set of measurements the compound cable is moved towards the end of the studied line by a step that is an integer multiple of the spacing between two adjacent electrodes. All combinations where one ore more electrodes in new positions are included are measured and thus a complete coverage of the line under study is ensured. In Figure 2 is illustrated the movement of a measuring scheme composed of 20 electrodes towards the end of the studied line by a step of "**2a**". Arrangement of the new data points in the pseudosection is also shown.

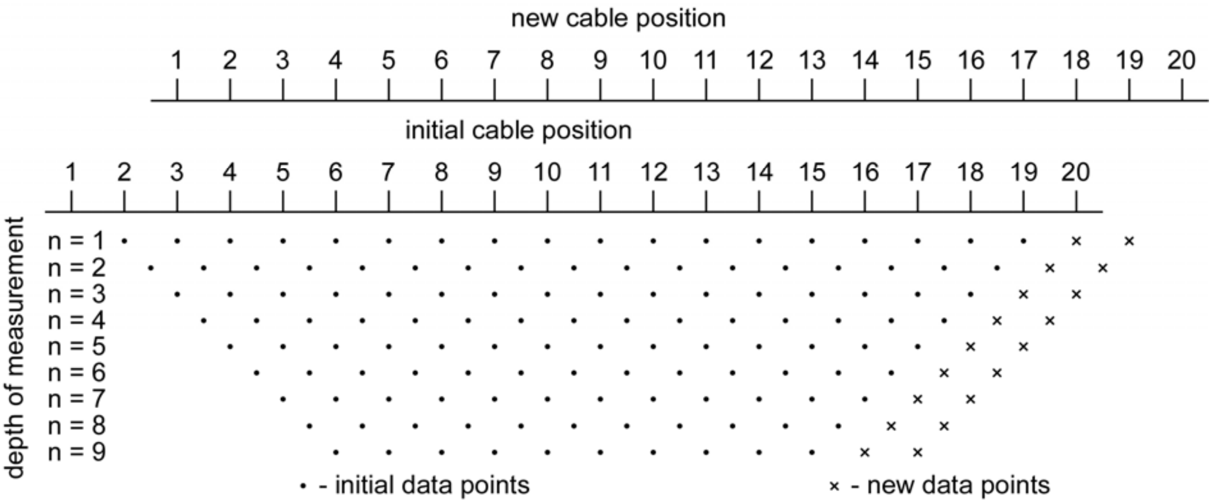

Figure 2. Movement of a measuring scheme towards the end of the studied line by a step of "2a" and arrangement of the new data points

The measuring scheme applied during the electrical tomography surveying performed in the area of "Marichin valog" consists of 24 electrodes and the spacing between two adjacent electrodes equals to 5 m. After completing a full set of measurements, the scheme was moved by a step of 60 m. The field measurements were performed utilizing a four-electrode Wenner-Schlumberger array.

The measurements were performed by Terrameter SAS 1000. This resistivity and IP instrument is produced by the Swedish company ABEM. This instrument is with integrated PC for full control of data acquisition process and storage of data. It has a built-in transmitter with maximum ±400 V (800 V peak-to-peak) and 1000 mA output. The receiver discriminates noise and measures voltages correlated with transmitted signal current (resistivity surveying mode and IP mode) and also measures uncorrelated DC potentials with the same discrimination and noise rejection (voltage measuring mode). The microprocessor monitors and controls operations and calculates results. In geophysical surveys, the SAS 1000 permits natural or induced signals to be measured at extremely low levels, with excellent penetration and low power consumption. Moreover, it can be used in a wide variety of applications where effective signal/noise discrimination is needed.

The true resistivities in the subsurface area are determined by the computer program RES2DINV (Loke, 2001). For this purpose, the resistivity values measured by the field equipment in different points (having particular electrodes location) have to be transferred into apparent resistivity values after taking into consideration the array geometry. The computer program is using as input data the information about the electrodes location on the surface and the apparent resistivity values in each measured point. On this basis the program is automatically dividing the subsurface area into a given number of rectangular blocks. Then, applying the least-squares method, the resistivity of each block is determined in such a way that the calculated apparent resistivity values for the composed model are fitting in the best possible way the measured electric field.

The computer program RES2DINV provides three vertical sections as a final result from the interpretation of the 2D electrical surveying data. These sections are: measured apparent resistivity pseudosection - made after interpolation of the apparent resistivity values derived from the field measurements in each point; calculated apparent resistivity pseudosection - composed as a result of interpolation of the apparent resistivity values calculated in each point after solving the forward problem for the model; inverse model resistivity section – created as a result of interpolation of the determined resistivity values in each rectangular block of the composed model. The comparison between the two pseudosections illustrates the reliability of the obtained model solution. The third section reveals the true resistivity distribution in the subsurface area and is providing the possibility for making qualitative and quantitative esteems.

Surveying results, analysis and interpretation

The precise location of the geophysical surveying lines in the area of “Marichin valog” – a potential site for long-term storage of low-level radioactive waste is illustrated in Figure 3. The field measurements were performed along ten profiles (each with a length of 235 m) having a total length of 2350 m.

The processing of the acquired data and the interpretation of the obtained results are performed by the Department of Applied Geophysics, University of Mining and Geology “St. Ivan Rilski”, Sofia.

The analysis of the obtained geoelectrical sections along the 10 studied surveying lines in the area of “Marichin valog” (see Figure 4, Figure 5, Figure 6, Figure 7, Figure 8, Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13) is in accordance with the geological sections recorded in boreholes MC-34XΓ, MC-35, and MC-26. These boreholes are situated on Line 3 (Figure 6), Line 4 (Figure 7), and Line 9 (Figure 12), respectively. The performed analysis gives reason the following conclusions to be made:

- The geoelectrical section along all lines is very consistent regarding the electrical resistivity distribution in depth.
- For all lines the electrical resistivity has increased values on the surface (120 – 150 Ωm) and decreases with a relatively high gradient (about -10 Ωm/m) to the values of 40 – 45 Ωm. In accordance with the geological sections recorded in boreholes MC-34XΓ, MC-35, and MC-26, the surface part of the geoelectrical section has a thickness of about 0 – 12 m and indicates the presence of soil and silty loess. The transition towards a much smaller negative gradient in the changes of electrical resistivity can be accepted as the first geoelectrical boundary. The geoelectrical section from the surface to the first geoelectrical boundary is defined as first electrical resistivity zone.
- Under this surface zone, the electrical resistivity values decrease with a negative gradient (about -2.5 Ωm/m) down to 25 - 30 Ωm where the second geoelectrical boundary is well-distinguished. The layer limited by this boundary ties with the spread of the Pleistocene loess

clays. This layer has a thickness that varies in a relatively wide range (5 – 12 m) and electrical resistivity values 25 – 45 Ωm. The geoelectrical section between the first and the second geoelectrical boundaries is defined as second electrical resistivity zone.

- The geoelectrical section under the second geoelectrical boundary is defined as third electrical resistivity zone. It maps the Pliocene clays and clayey sands of the Brusartsi formation. The electrical resistivity values in this zone are relatively low and vary in the range of 15 – 30 Ωm.
- In the western part of the area, along all lines, is observed a zone of relatively higher resistivity values (up to about 50 – 80 Ωm). According to the section of borehole MC-35, this zone indicates presence of lime concretions in the clayey depositions of the Brusartsi formation.

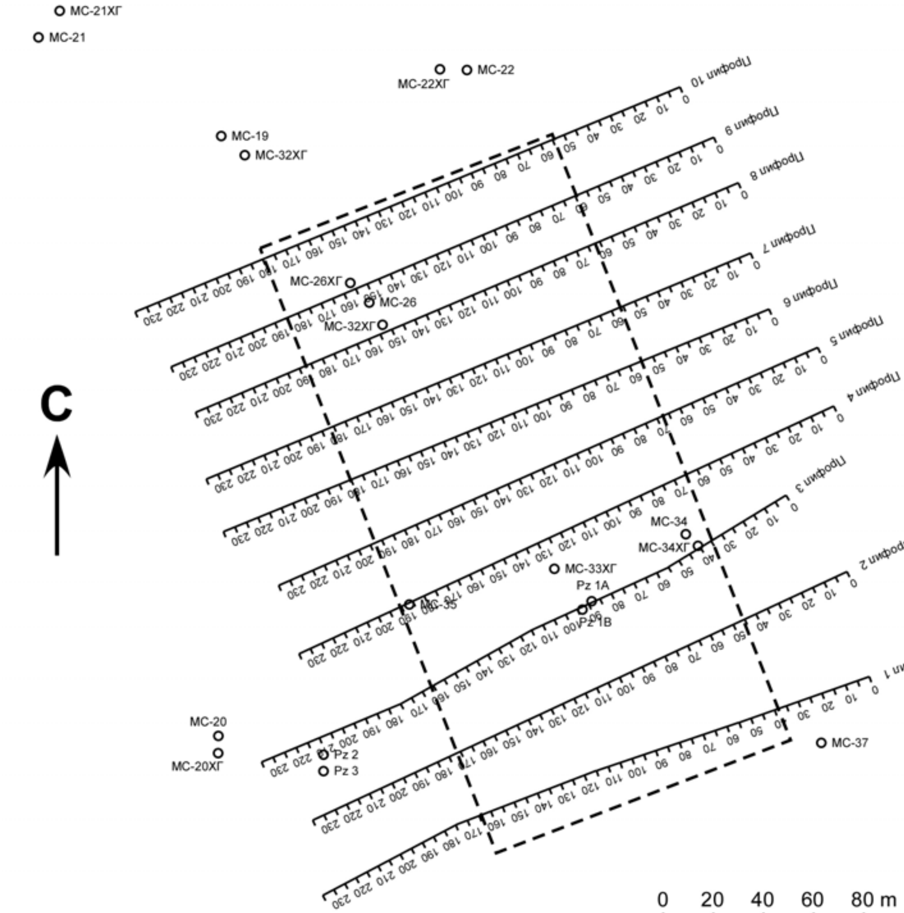

Figure 3. Location of the geophysical surveying lines in the area of “Marichin valog”

The compound analysis of the obtained electrical tomography data and the geological sections recorded in boreholes ensures the preconditions for mapping the boundaries between the distinguished electrical resistivity zones:

- The boundary between the first electrical resistivity zone (soil and silty loess) - 1 and the second electrical resistivity zone (Pleistocene loess clays) - 2 can be successfully mapped next to isolines with electrical resistivity values of about 40 – 45 Ωm.
- The boundary between the second electrical resistivity zone (Pleistocene loess clays) - 2 and the third electrical resistivity zone (Pliocene clays and clayey sands of the Brusartsi

formation) - 3 can be successfully mapped next to isolines with electrical resistivity values of about 25 – 30 Ωm.

- The forth electrical resistivity zone (presence of lime concretions in the clayey depositions of the Brusartsi formation) - 4 can be successfully mapped by isolines with electrical resistivity values of about 40 – 45 Ωm.

The obtained electrical tomography data along all ten surveying lines can be analyzed according to the derived conclusions for the specifics of the geoelectrical section and the stated basic preconditions for differentiation of the geoelectrical section.

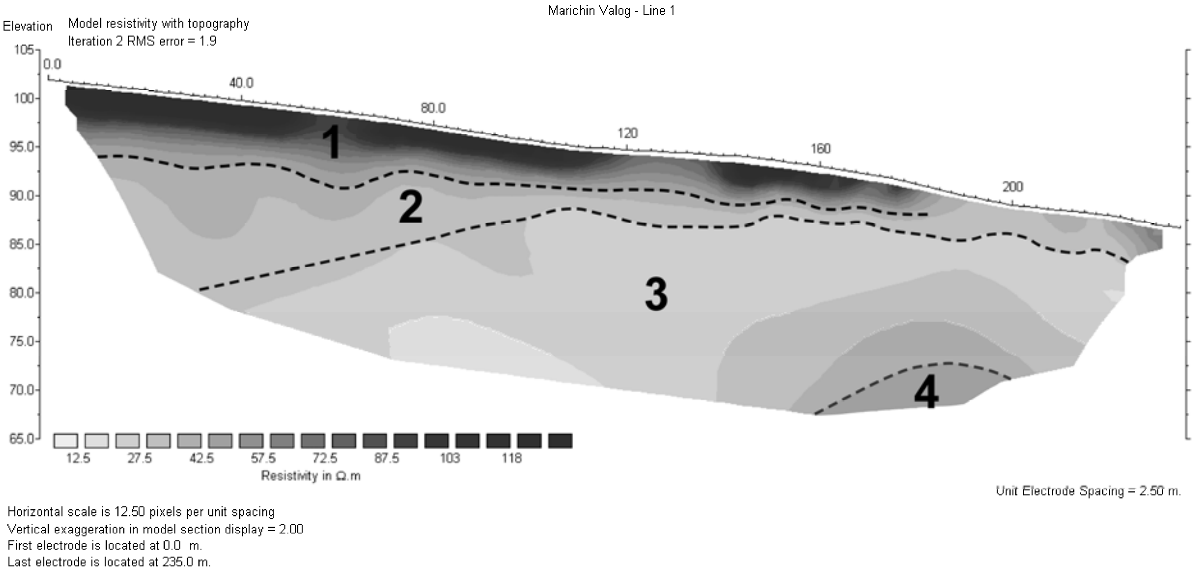

Figure 4. Electrical resistivity section along Line 1

The results from the performed electrical tomography surveying along Line 1 are presented in Figure 4.

The line begins with a relatively big thickness of the surface layer (soil and silty loess) – electrical resistivity zone 1 and of the Pleistocene loess clays – electrical resistivity zone 2. Their combined thickness is about 20 m.

The thickness of the surface layer is about 7m in the beginning of the line and gradually decreases to zero at 190 m. At the end of the line the presence of this zone is hinted again.

The thickness of the Pleistocene loess clays also decreases from the start of the line, where it is about 15 m, towards the interval between 100 m and 190 m, where this zone is about 2 – 3 meters thick. Then the thickness increases and towards the end of the line is about 4 – 5 meters.

The Pliocene clays and clayey sands of the Brusartsi formation (electrical resistivity zone 3) are distinguished without ambiguity in the whole section. They are characterized by low electrical resistivity values (10 – 25 Ωm).

In the interval between 160 m and 210 m along the line, under the hypsometry level of 75 m, is mapped the presence of a media characterized by relatively high electrical resistivity values. This media (electrical resistivity zone 4) ties with the presence of lime concretions in the clayey depositions of the Brusartsi formation.

The results from the performed electrical tomography surveying along the other nine lines in the area of "Marichin valog" – Line 2 (see Figure 5), Line 3 (see Figure 6), Line 4 (see Figure 7), Line 5 (see Figure 8), Line 6 (see Figure 9), Line 7 (see Figure 10), Line 8 (see Figure 11), Line 9 (see Figure 12), and Line 10 (see Figure 13), are more or less resembling the results and conclusions stated for Line 1.

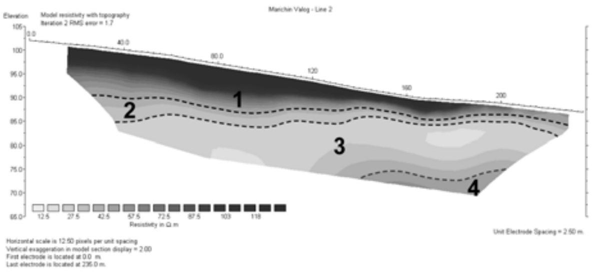

Figure 5. Electrical resistivity section along Line 2

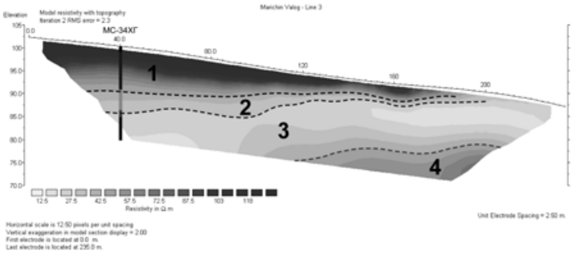

Figure 6. Electrical resistivity section along Line 3

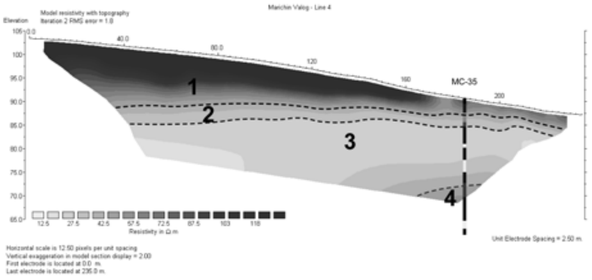

Figure 7. Electrical resistivity section along Line 4

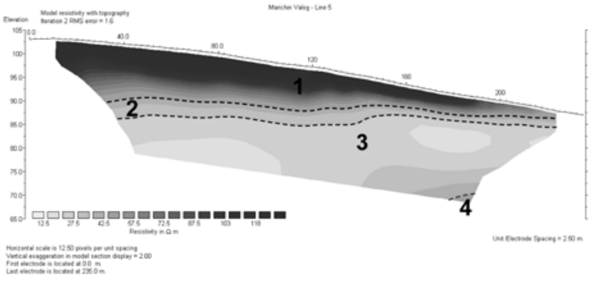

Figure 8. Electrical resistivity section along Line 5

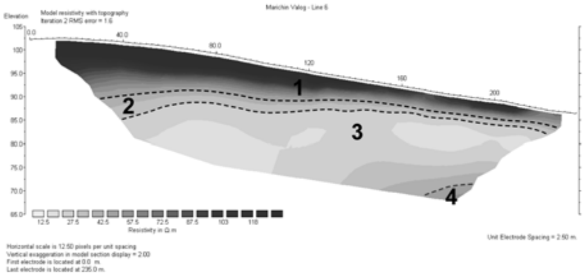

Figure 9. Electrical resistivity section along Line 6

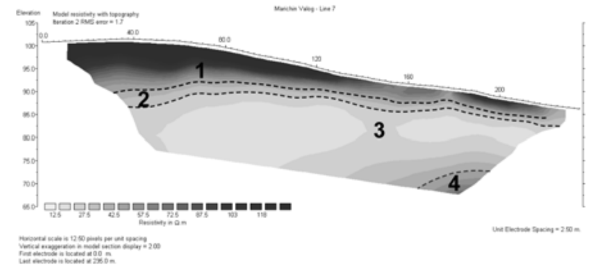

Figure 10. Electrical resistivity section along Line 7

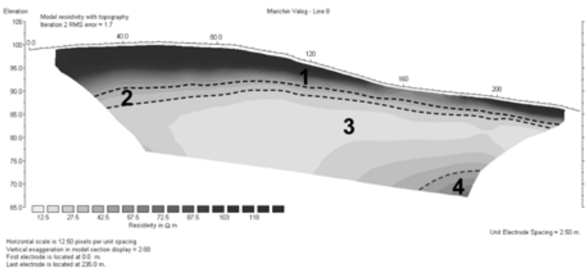

Figure 11. Electrical resistivity section along Line 8

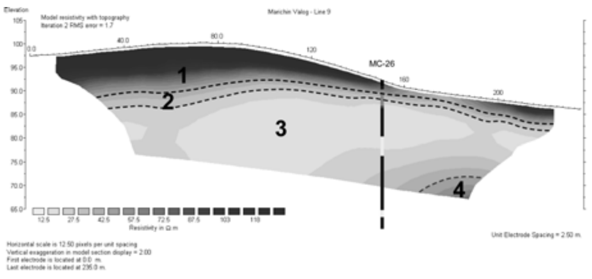

Figure 12. Electrical resistivity section along Line 9

Relatively small variations are observed in the thickness values and in the general behavior of the layer of soil and silty loess (electrical resistivity zone 1). The Pleistocene loess clays (electrical resistivity zone 2) are characterized by intermediate electrical resistivity values for the observed geoelectrical sections. They are spread along all lines and have thickness of about 2 – 5 m. The Pliocene clays and clayey sands of the Brusartsi formation (electrical resistivity zone 3) are well-distinguished along all lines. They are characterized by relatively consistent low electrical resistivity values. These clays and clayey sands spread to the bottom of the obtained sections (the depth of the study is about 25 – 30 m). In the western end of all profiles, by relatively higher resistivity values is mapped the presence of lime concretions in the clayey depositions of the Brusartsi formation (electrical resistivity zone 4).

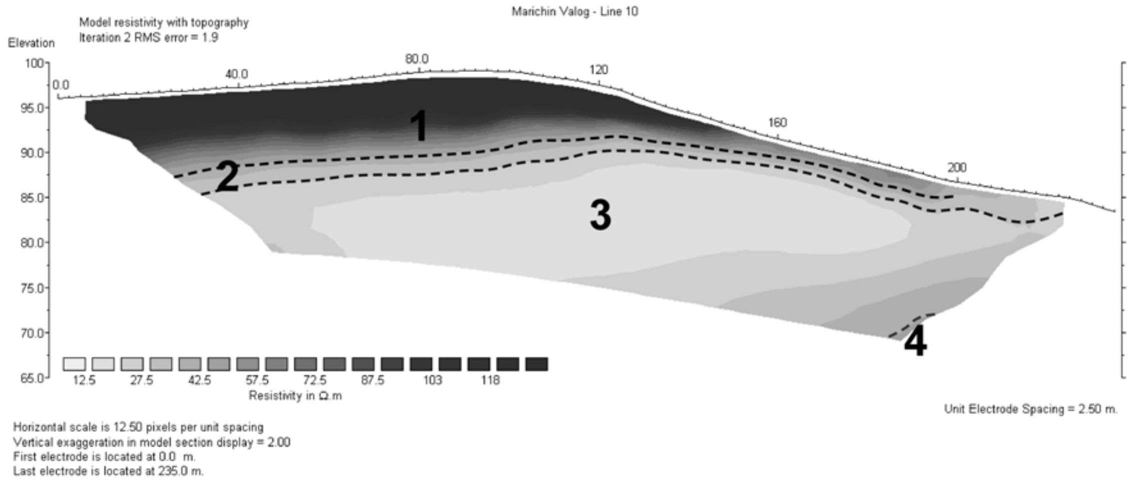

Figure 13. Electrical resistivity section along Line 10

On the base of the results from the performed electrical tomography surveying along the studied ten lines in the area of "Marichin valog" is elaborated one structural scheme that illustrates the behavior of the second geoelectrical boundary. It is tied to the contact between the Pleistocene loess clays (electrical resistivity zone 2) and the Pliocene clays and clayey sands of the Brusartsi formation (electrical resistivity zone 3). The behavior of this boundary is illustrated in Figure 14.

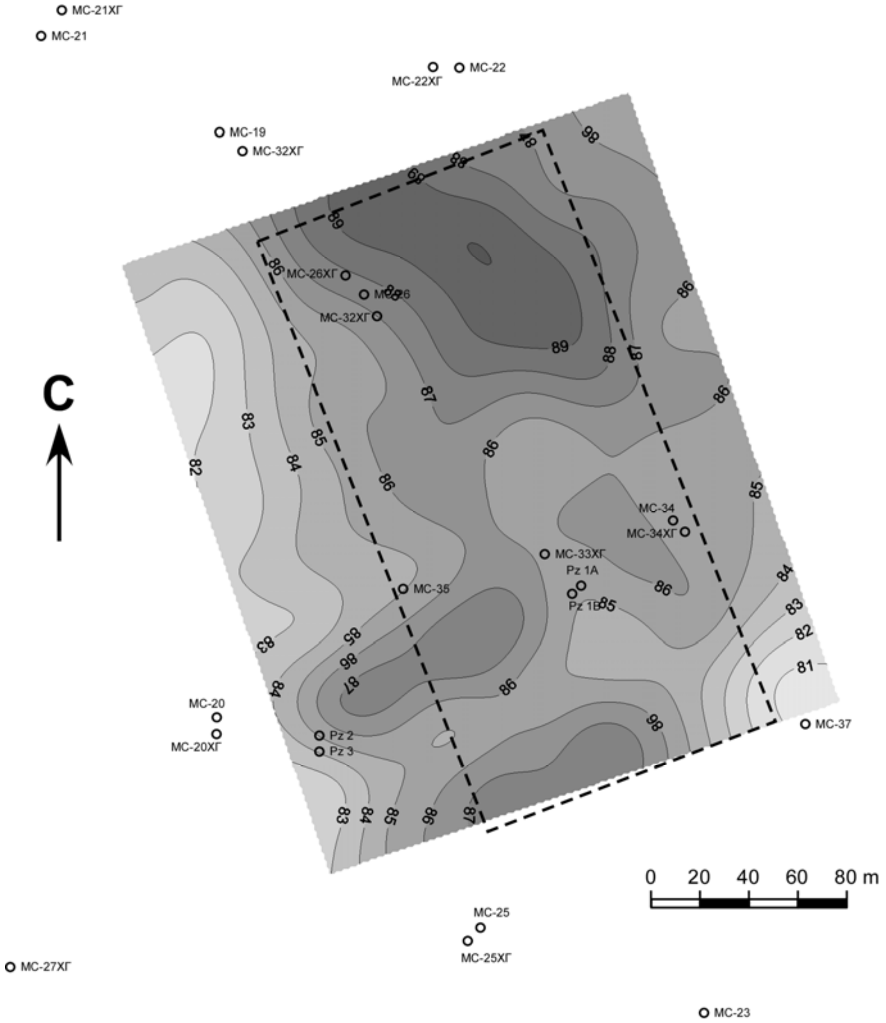

Figure 14. Structural scheme of the top of and the Pliocene clays and clayey sands of the Brusartsi formation

Conclusions

The compound analysis of the results from the performed electrical tomography surveying along the studied ten lines in the area of “Marichin valog” gives reason the following conclusions to be made:

- The geoelectrical section along all lines is very consistent regarding the electrical resistivity distribution in depth. Four geoelectrical zones are well-distinguished on the sections:

- The first geoelectrical media includes the surface part of the section and indicates the presence of soil and silty loess (zone 1). It is characterized by relatively high electrical resistivity values (50 – 150 Ωm).
- The second geoelectrical media ties with the spread of the Pleistocene loess clays (zone 2). It is characterized by relatively lower electrical resistivity values (25 – 45 Ωm) if compared with the first geoelectrical zone.
- The third geoelectrical media maps the Brusartsi formation (zone 3). These are Pliocene clays and clayey sands characterized by a well-expressed and relatively consistent ionic conductivity and low electrical resistivity values (in the range of 15 – 30 Ωm).
- In the western part of the area, in the third geoelectrical media is observed the presence of rocks with relatively higher resistivity values (up to about 50 – 80 Ωm). This media (zone 4) indicates presence of lime concretions in the clayey depositions of the Brusartsi formation.

- The following assumptions can be made for the area of “Marichin valog” – a potential site for long-term storage of low-level radioactive waste:

- The electrical resistivity shows consistent behavior in the distinguished geoelectrical zones. This is a sign for homogeneity in the lithological-facial characteristics of the rocks that are attached to the respective zones.
- The thickness of the surface layer of soil and silty loess decreases from the beginning of the lines towards their end, i.e. from northeast to southwest. This trend is opposite to the changes of surface hypsometry.
- The layer of Pleistocene loess clays is relatively consistent. Its thickness has predominant values in the range of 3 – 5 m.
- The top of the Brusartsi formation presented by Pliocene clays and clayey sands is situated at hypsometry level of 83 – 91 m. This fundamental third geoelectrical zone continues its spread under the depth of the study, i.e. 25 – 30 m below the surface.
- In the western part of the area, along all lines, is observed a zone of relatively higher resistivity values (up to about 50 – 80 Ωm). According to the section of borehole MC-35, this zone indicates presence of lime concretions in the clayey depositions of the Brusartsi formation.

References

1. Daniels F., R.A. Alberty. 1966. *Physical chemistry*. John Wiley and Sons, Inc.
2. De Groot-Hedlin, C., S. Constable. 1990. *Occam's inversion to generate smooth, two-dimensional models form magnetotelluric data*. Geophysics, 55, 1613-1624.
3. Dimovski, S., R. Radichev. 2002. *Prognostication of natural and technogeneous risks by the application of geophysical surveying.* Environmental Management and Health. Vol. 13, No. 3, 249-262.

4. Dimovski, S., N. Stoyanov, Ch. Gyurov. 2007. *Efficiency of electrotomography surveying for geoelectrical mapping of near-surface geological section.* BULAQUA Journal, No. 4, 47-55.
5. Griffiths, D. H., J. Turnbull, A. I. Olayinka. 1990. *Two-dimensional resistivity mapping with a computer-controlled array*. First Break, 8, 121-129.
6. Griffiths, D. H., R. D. Barker. 1993. *Two-dimensional resistivity imaging and modeling in areas of complex geology*. Journal of Applied Geophysics, 29, 211-226.
7. Gyurov, Ch. N. Stoyanov. 2004. *Possibilities of 2D resistivity method for locating extension of old landfills* – Proceedings of the 4th National Geophysical Conference with International Participation , Session 3, "Geophysics and Environment", Sofia, 4-5 October, 128-131
8. Ivanov, R., N. Stoyanov, S. Dimovski, Ch. Gyurov, A. Kerezov. 2005. *Methods for spatial monitoring of possible leaks in soil and groundwater caused by landfills.* First International conference with technical exhibition on water resources, technologies and services "BULAQUA 2005", 344 – 353
9. Keller G.V., F.C. Frischknecht. 1966. *Electrical methods in geophysical prospecting*. Pergamon Press Inc., Oxford.
10. Loke, M. H., R. D. Barker. 1996. *Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method.* Geophysical Prospecting, 44, 131-152.
11. Loke, M.H. 1999. Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D surveys. Penang, Malaysia, p. 57.
12. Loke, M.H. 2001. A practical guide to RES2DINV ver. 3.4; Rapid 2-D Resistivity & IP inversion using the least-squares method. Geotomo Software, Penang, Malaysia, p. 96