4D investigation of water infiltration in waste dumps using electrical resistivity (Elatsite mine, Bulgaria)

Aleksey Benderev^{1*}, Asen Mitev², Grigor Hlebarov³, Simeon Valtchev¹,
Ivan Vasilev³, Aleksandar Grigorov³

¹ Geological Institute, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 24, 1113 Sofia, Bulgaria; e-mails: alekseybenderev@yahoo.com; simeonvaltscheff@hotmail.co.uk

² Geophysics Engineering EOOD, Residential area Strogoziya, Bl. 113, 5800 Pleven, Bulgaria; e-mail: geophysics_engineering@abv.bg

³ Ellatzite-Med AD, 2086 Mirkovo, Bulgaria; e-mails: grigor_hlebarov@abv.bg; i.vasilev@ellatzite-med.com; a.grigorov@ellatzite-med.com

(Received: 02 August 2021; accepted in revised form: 30 August 2021)

Abstract. The objective was to investigate how water infiltrated into waste dumps at a mine site. The electrical resistivity method of field geophysics was applied to produce 4D imaging of progressive water infiltration into the waste dump. The goal is to test a method for investigating how rain water infiltrates unconsolidated materials in mine waste dumps. This is an important problem when evaluating the water balance in waste dumps and understanding the conditions for contamination of the water flowing through the waste materials. The trial was carried out in one of the two large dumps at Elatsite mine, which are composed of rocks with various fragment size and diverse mineral composition. The investigation was undertaken by discharging salt solution into the waste dump and taking geophysical measurements on a rectangular electrode grid at certain time intervals. The grid consisted of 64 electrodes forming 10×5 m cells and covering a 70×35 m area. As a result, it was possible to record how the infiltration and dispersion of the salt solution developed in space and time. In the last one of the seven surveys, 40 hours after the start of the trial, it was established that the salt solution reached a depth of approximately 40 m. The results could be used for predicting the interaction between water and waste material.

Benderev, A., Mitev, A., Hlebarov, A., Valchev, S., Vasilev, I., Grigorov, A. 2021. 4D investigation of water infiltration in waste dumps using electrical resistivity (Elatsite mine, Bulgaria). *Geologica Balcanica* 50 (2), 53–68.

Keywords: electrical resistivity tomography, infiltration, mining waste dumps, unsaturated zone.

INTRODUCTION

Mining activities always result in disturbance of the natural surface topography and geological conditions. An essential factor for this is the creation of dumps of barren rock waste material that can be of considerable volume and area. From an ecological point of view, it is particularly important to understand the pathways for rain water infiltration into the

dumps. The investigation of this process, especially using monitoring boreholes, could be very difficult, considering that the accumulated material is unconsolidated and often with a variable grain size, unevenly distributed in the volume of the dumps. Therefore, other investigative approaches are often needed to obtain the information required for the purpose of the relevant study. One such possibility is the application of geophysical investigations,

which often can assist in solving different hydrogeological problems (Dobecki and Romig, 1985; Ward, 1990; Kirsch, 2006). Electrical geophysical methods are most widely used. Some of them allow for clarifying the groundwater flow, often related to understanding the spatial distribution of contamination, sea water intrusion, or the impact of mining (see Zonge *et al.*, 1985; Meiser, 1991; Buselli *et al.*, 1998, Ustra *et al.*, 2012). Such investigations have also been carried out in Bulgaria (Gyurov and Stoyanov, 2004; Stoyanov and Gyurov, 2004; Shanov *et al.*, 2011; Dimovski *et al.*, 2017, Stoyanov *et al.*, 2017, 2019; Stoyanov and Dimovski, 2018, 2020). Recently, geophysical methods have more frequently been used for recording temporal changes in hydrogeological parameters (Wilkinson *et al.*, 2010; Sarkheil and Habibi Rad, 2015; Lesparre *et al.*, 2019). Cross borehole electrical resistivity tomography has been used in studying water flow in the unsaturated zone (Daily *et al.*, 1992).

The purpose of the present investigation is to propose and test a method for describing the infiltration of surface water and its subsequent dispersion into the unsaturated zone of mine waste dumps, by using electrical resistivity techniques. Applying this method in different parts of mine waste dumps

would allow describing the groundwater flow conditions within them, which is important for solving many ecological problems. The test site, where the investigation was carried out, is in the eastern waste dumps at the Elatsite open-cast mine.

DESCRIPTION OF THE TEST SITE

The Elatsite mine is the largest open-cast mine in Bulgaria and one of the largest in Europe. It is located in the Western Balkan Mountains, not far from the town of Etropole (Fig. 1). The ore deposit was explored in 1956–1968, and mining has been going on since 1976 (Hristov and Vasilev, 2017). A large pit was excavated and its depth and volume are continuously increasing. The excavated material is accumulated in two areas: Eastern Dumps and Western Dumps. Currently in use are mainly the Western Dumps, while the Eastern Dumps are being reinstated. The dumps consist of excavated unsorted material with various particle size and mineral composition corresponding to the host rock varieties (Georgiev, 2004). The rock types include low-grade metamorphic rocks of Paleozoic age (phyllite, hornfelse, grained and banded schist)

Fig. 1. Elatsite mine and location of the trial test.

and Mesozoic (Upper Cretaceous) magmatic rocks: quartz-monzodiorites (sienodiorites), porphyrites and granodiorite porphyrites.

The flat areas were considered suitable for undertaking the test trial as there was no work undertaken at the time, the conditions were stable, and the experiment would not interfere with the mining operations. Initial walkovers were undertaken to familiarize with the conditions on site and to select appropriate locations for the experimental setup in order to obtain results applicable in subsequent assessments. The main problems were related to the extremely inhomogeneous material in the different parts of the dumps. The size of the rock pieces varied in the range from millimeters to decimeters, and no regularity could be established due to the method of material dumping and buildup. In the process of tipping, the material is distributed down the slopes of the dumps, with coarse fragments rolling further down, while finer fractions are retained in the higher levels, near the tipping platforms. As a result, the layering that formed was irregular and subsequently disturbed with the growth of the tips and with change of tipping direction. Furthermore, the movement of the heavy trucks results in forming a wide range of compactness of the material in different parts of the dumps. The level platforms on the dumps are characterized by a very compact surface layer, which contains more fine material as compared to the deeper levels and slopes. In the process of buildup, such platforms had been formed and subsequently buried, thus forming numerous low-permeability layers in the dumps. Typical features on these platforms are puddles retaining water for long time and leaving clear footprints on the surface (Fig. 1). The sub-horizontal layers and the layering down the steep slopes form a structurally intricate system, where it is impossible to distinguish characteristic anisotropy. The selected test site is located at 1,300 m above sea level.

METHODOLOGY

The problem of investigating water intrusion into the dumps was approached by discharging saline solution into a trial pit. Because of its low resistivity, the saline solution is a medium contrasting with the materials in the dump. The three-dimensional models obtained at different times allow tracing the spatial distribution of the saline water solution and its vertical advancement. The models were created by recording the change in values after discharging the saline water as compared to the baseline meas-

urement. As a result, zones of decreased resistivity could be distinguished, assuming that the solution had passed through those zones.

Electrical resistivity tomography was the main method applied to obtain full coverage of the studied area and to create three-dimensional model for tracing the infiltrating water solution. The experimental setup was selected depending on the objectives and the actual geological conditions. The resistivity measurements were carried out in pole-pole, pole-dipole and dipole-dipole arrays (Loke, 2002). Other types of arrays cannot provide sufficient information and coverage of the investigated area as required to obtain a full 3D model. The electrodes were arranged on a grid. Ideally, the electrodes would be arranged in a square grid; however, other arrangements are also applicable depending on the specific conditions, surface topography, and technical capabilities.

The measurements were carried out with ATIGEO-200, single-channel equipment for electrical resistivity survey with direct current, including:

- 200 W power generator;
- 1 A maximal output current;
- 450 V (900 V P-P) maximal output voltage;
- 150 operating frequencies (0.25–15 Hz);
- 24-bit analog-to-digital converter;

Fig. 2. Change of electrical conductivity and resistance with increasing NaCl concentration (laboratory test results).

- personal computer and UART interface for setting the working positions of the electrodes;
- four multicore cables with 16 electrodes each, 10-m electrode spacing;
- 2×500 m cables for the pole-pole array;
- 64 operative electrodes.

Laboratory tests were performed in advance to determine the appropriate concentration of the salt solution (Fig. 2). It was concluded that at least 10 g NaCl per 1 L of water should be added in order to reduce the resistivity by two orders of magnitude.

The data were processed using RES3DINV software, which is capable of evaluating the spatial distribution of electrical resistivity (Li and Olden-

burg, 1992; White *et al.*, 2001). The method of least squares was applied to analyze the output data). Visualization of the results was produced using RockWork software.

The experimental setup included one 2×2×1 m trial pit in the center of a 70×30 m electrode grid formed by 64 electrodes arranged in 10×5 m cells (Fig. 3). The setup allowed for complete coverage of the subsurface volume in which the water solution infiltrated from the trial pit. The water solution discharged in the trial pit was prepared by dissolving 40 kg NaCl in 4 m³ of water. Preliminary calculations indicated that the electrical resistivity in the water solution dropped almost three times, signifi-

Fig. 3. Electrode grid on the surface and selected cross-section lines AA¹ and BB¹.

cantly decreasing the electrical resistivity of the saturated volumes in depth. The results were produced by calculating anomalous values in space and time after comparing electrical resistivity measurements to baseline conditions, which were recorded before the release of the water solution. The first measurement was undertaken 20 min after the release of water solution, then followed by six more measurements with reducing frequency over 40 hours.

RESULTS AND DISCUSSION

The experiment began on 13 August 2017. The baseline survey was completed to define the volume where the saline solution was expected to infiltrate (Fig. 4).

Subsequently, 10 kg NaCl were added into four containers of 1 m³ water, and the solution was discharged into the trial pit within 20 minutes (Fig. 5). The water level in the trial pit did not change noticeably while the water was being released, and af-

ter the full volume was poured in it infiltrated very quickly into the ground. The first measurement began immediately after discharge and subsequent measurements continued for two days, gradually becoming less frequent (Table 1).

To visualize the infiltration of the saline solution, 2D and 3D models were created, showing the anomalous values based on the results (Figs 6–13).

It was observed that, after infiltrating into the ground, the water dispersed like a cloud and was being retained in the dump materials. A good three-dimensional picture was obtained, showing the infiltration at different time intervals and allowing to estimate the exact time of reaching given points in the dump (Fig. 14). Within approximately 40 hours, the salt solution reached 45–50 m depth, from approximately 90 m total depth of the waste dumps. Based on the experimental data, the conductivity of the ground was estimated to be 0,0003 m/s. The infiltration velocity of the salt solution varies with depth (Fig. 15), and it is related to the type of waste material in the dumps. It was highest in the top lev-

Fig. 4. 3D model of the electrical resistivity distribution in the investigated volume before infiltrating NaCl solution.

Fig. 5. Discharging saline solution into the trial pit.

Table 1
Time of measurement after discharge of the saline water solution

No.	Date	Time	Start of measurement after discharge (min)
1	13.8.2018	17h 35min	0
2	13.8.2018	19h 10min	95
3	13.8.2018	20h 05min	195
4	14.8.2018	1h 25min	470
5	14.8.2018	6h 25min	770
6	14.8.2018	10h 25min	1010
7	14.8.2018	15h 2min	1305
8	15.8.2018	9h 3min	2395

els, where the material is least compacted, and decreased with approximately one order of magnitude at a depth of 10–15 m. The general trend of decreasing conductivity continued with depth, with some local aberrations as a result from irregular tipping of material of different rock composition.

CONCLUSION

The results indicate that the applied method provides very clear representation of how water infiltrates unsaturated material in waste dumps. It makes it possible to obtain actual picture of dispersion and

Fig. 6. Electrical resistivity immediately after discharge of NaCl solution: a) 3D model; b) 2D model along cross section A–A¹; c) 2D model along cross section B–B¹.

Fig. 7. Electrical resistivity immediately after discharge of NaCl solution, $t = 95$ min: a) 3D model; b) 2D model along cross section A-A'; c) 2D model along cross section B-B'.

Fig. 8. Electrical resistivity immediately after discharge of NaCl solution, $t = 195$ min: a) 3D model; b) 2D model along cross section A-A'; c) 2D model along cross section B-B'.

Fig. 9. Electrical resistivity immediately after discharge of NaCl solution, $t = 470$ min: a) 3D model; b) 2D model along cross section A–A'; c) 2D model along cross section B–B'.

Fig. 10. Electrical resistivity immediately after discharge of NaCl solution, $t = 770 \text{ min}$: a) 3D model; b) 2D model along cross section A–A'; c) 2D model along cross section B–B'.

Fig. 11. Electrical resistivity immediately after discharge of NaCl solution, $t = 1010$ min: a) 3D model; b) 2D model along cross section A-A'; c) 2D model along cross section B-B'.

Fig. 12. Electrical resistivity immediately after discharge of NaCl solution, $t = 1305$ min: a) 3D model; b) 2D model along cross section A-A'; c) 2D model along cross section B-B'.

Fig. 13. Electrical resistivity immediately after discharge of NaCl solution, $t = 2395$ min: a) 3D model; b) 2D model along cross section A-A'; c) 2D model along cross section B-B'.

Fig. 14. Plot of the penetration time of the saline solution in the dump.

Fig. 15. Hydraulic (salt solution) conductivity vs depth of the waste dump.

vertical groundwater flow velocity. The successful trial is a forerunner model for planning and undertaking further investigations designed to obtain detailed description of the groundwater flow in different parts of the waste dumps, as well as general characterization of the general hydrogeological conditions in them. The method can significantly facilitate future investigations related to water balance and regime in waste dumps, as well as change in filtration properties with depth. It could be used

as a basis for forecasting possible interaction between porous medium and water for the purpose of solving environmental problems.

Acknowledgements

This work has been carried out in the framework of the contract between the Geological Institute of the Bulgarian Academy of Sciences and the Ellatzite-Med AD.

REFERENCES

- Buselli, G., Hwang, H.S., Lu, K. 1998. Minesite groundwater contamination mapping. *Exploration Geophysics* 29 (3–4), 296–300, <https://doi.org/10.1071/EG998296>.
- Daily, W., Ramirez, A., La Brecque, D., Nitao, J. 1992. Electrical resistivity tomography of vadose water movement. *Water Resources Research* 28 (5), 1429–1442, <https://doi.org/10.1029/91WR03087>.
- Dimovski, S., Stoyanov, N., Tzankov, C., Kisyov, A. 2017. A geophysical approach for mapping of abandoned mining workings and unconsolidated zones in coal mining areas. *Journal of Mining and Geological Sciences* 60, 99–103.
- Dobecki, T.L., Romig, P.R. 1985. Geotechnical and groundwater geophysics. *Geophysics* 50 (12), 2621–2636, <https://doi.org/10.1190/1.1441887>.
- Georgiev, G. 2004. Geology of porphyry copper deposit Elat-site, Bulgaria. *Annual of the University of Mining and Geology “St Ivan Rilski”* 47 (1), 75–82 (in Bulgarian, with English abstract).
- Gyurov, C., Stoyanov, N. 2004. Possibilities of 2D resistivity method for locating the extension of old landfills. *Proceedings of the 4th National Geophysical Conference with International Participation “Geophysics in Economic Activity, Environment and Cultural Heritage Investigations”*, Sofia, p. 131 (in Bulgarian, with English abstract).
- Hristov, V., Vasilev, I. 2017. Drainage of Ellatzite open pit (Bulgaria). *Engineering Geology and Hydrogeology* 31, 3–11 (in Bulgarian, with English abstract).
- Kirsch, R. 2006. *Groundwater Geophysics. A Tool for Hydrogeology*. Springer, Berlin–Heidelberg–New York, 493 pp., <https://doi.org/10.1007/3-540-29387-6>.
- Lesparre, N., Robert, T., Nguyen, F., Boyle, A., Hermans, T. 2019. 4D electrical resistivity tomography (ERT) for aquifer thermal energy storage monitoring. *Geothermics* 77, 368–382, <https://doi.org/10.1016/j.geothermics.2018.10.011>.
- Li, Y., Oldenburg, D.W. 1992. Approximate inverse mappings in DC resistivity problems. *Geophysical Journal International* 109 (2), 343–362, <https://doi.org/10.1111/j.1365-246X.1992.tb00101.x>.
- Loke, M.H. 2002. *A practical guide to RES2DINV ver. Rapid 2-D Resistivity & IP inversion using the least squares method*. Geoelectrical Imaging 2-D & Geotomo Software, Penang, Malaysia, 96 pp.
- Meiser, P. 1991. Geophysical investigations. In: De Breuck, W. (Ed.), *Hydrogeology of Salt Water Intrusion*. IAH, Hannover, 361–362.
- Sarkheil, H., Habibi Rad, M. 2015. 4D electrical resistivity tomography monitoring of Talesh Mahaleh-Rasht coastal aquifer polluted by Caspian seawater. *Proceedings of Near Surface Geoscience 2015, 21st European Meeting of Environmental and Engineering Geophysics*, September 2015, 1–5, <https://doi.org/10.3997/2214-4609.201413795>.
- Shanov, S., Vasilev, I., Mitev, A., Hristov, V., Mihailova, B. 2011. Electrical tomography for studies of the inner structure of dumps (Open-pit “Ellatzite”, Bulgaria). *Conference Proceedings of the 6th Congress of the Balkan Geophysical Society*, October 2011, cp-262-00020.
- Stoyanov, N., Dimovski, S. 2018. Seawater intrusion into protected area Stomoplo, Ropotamo complex (Southern Bulgaria). *Review of the Bulgarian Geological Society* 79 (3), 151–152 (in Bulgarian, with English abstract).
- Stoyanov, N., Dimovski, S. 2020. Geoelectrical approach for differentiating the hydrogeological section in the study of a tailings pond site. *Proceedings of the 6th International Scientific Conference GEOBALKANICA 2020, May 2020, Ohrid, North Macedonia*, 127–135, <https://doi.org/10.18509/GBP.2020.01>.
- Stoyanov, N., Dimovski, S., Kisyov, A. 2019. Seawater intrusion in the Alepu protected area, part of the Ropotamo complex (Southern Bulgaria). *Proceedings of the 10th Congress of the Balkan Geophysical Society, September 2019, Albena Resort, Bulgaria*, 216–220, <https://doi.org/10.3997/2214-4609.201902635>.
- Stoyanov, N., Gerginov, P., Tarabees, E., Benderev, A., Dimovski, S. 2017. State of the art and the problems of interaction between groundwater and marine waters in the Nile delta. District Rashid, Egypt. *Proceedings of the 17th International Multidisciplinary Scientific GeoConference SGEM 12*, 793–800, <https://doi.org/10.5593/sgem2017/12>.
- Stoyanov, N., Gyurov, C. 2004. Application of electrical resistivity surveying for estimating the salt water intrusion into the Quaternary aquifer in the region of Arkoutino reserve, Bulgaria. *Proceedings of the 4th National Geophysical Conference with International Participation “Geophysics in Economic Activity, Environment and Cultural Heritage Investigations”*, October 2002, Sofia, 137–140 (in Bulgarian, with English abstract).
- Ustra, A.T., Elis, V.R., Mondelli, G., Zuquette, L.V., Giacheti, H.L. 2012. Case study: a 3D resistivity and induced polarization imaging from downstream a waste disposal site in Brazil. *Environmental Earth Sciences* 66 (3), 763–772, <https://doi.org/10.1007/s12665-011-1284-5>.
- Ward, S.H. (Ed.). 1990. *Geotechnical and Environmental Geophysics: Volume I. Review and Tutorial*. Society of Exploration Geophysicists, Tulsa, USA, 398 pp.
- White, R.M.S., Collins, S., Denne, R., Hee, R., Brown, P. 2001. A new survey design for 3D IP inversion modelling at Copper hill. *Exploration Geophysics* 32 (3–4), 152–155, <https://doi.org/10.1071/EG01152>.
- Wilkinson, P.B., Meldrum, P.I., Kuras, O., Chambers, J.E., Holyoake, S.J., Ogilvy, R.D. 2010. High-resolution electrical resistivity tomography monitoring of a tracer test in a confined aquifer. *Journal of Applied Geophysics* 70 (4), 268–276, <https://doi.org/10.1016/j.jappgeo.2009.08.001>.
- Zonge, K.L., Figgins, S.J., Hughes, L.J. 1985. Use of electrical geophysics to detect sources of groundwater contamination. *SEG Technical Program Expanded Abstracts*, 147–149.