Recognition of the flysch substrate using the electrical resistivity tomography (ERT) method to assess the effectiveness of the injection process

Michał Ćwiklik[1], Bernadetta Pasierb[2], Sławomir Porzucek[3]

[1] *Cracow University of Technology, Faculty of Environmental and Power Engineering, Krakow, Poland, e-mail: michal.cwiklik@doktorant.pk.edu.pl, ORCID ID: 0000-0002-3206-2877*
[2] *Cracow University of Technology, Faculty of Environmental and Power Engineering, Krakow, Poland, e-mail: bpasierb@pk.edu.pl, ORCID ID: 0000-0001-5616-7289*
[3] *AGH University of Krakow, Faculty of Geology, Geophysics and Environment Protection, Krakow, Poland, e-mail: porzucek@agh.edu.pl; ORCID ID: 0000-0002-8250-2703*

Received: 21 February 2023; accepted: 19 April 2023; first published online: 10 May 2023

Abstract: During the construction of a section of the S-7 Lubień – Rabka-Zdrój dual expressway, located in the area of the Carpathian flysch (Carpathian Flysch Belt, South Poland), damage to the embankment was observed, as well as cracks and depressions in the new pavement. An analysis of the geological and engineering conditions in the area of the road section under construction showed the existence of a complex tectonic structure of the flysch formations, a shallow groundwater table, and numerous landslides. In order to stabilize the road substrate, it was decided to carry out injections, and the locations of these injections were initially geotechnically tested. However, due to the high variability of the geological structure, the target method employed was electrical resistivity tomography (ERT), which performed the survey in two stages. In Stage I, the geoelectrical/geochemical structure of the near-surface zone was identified, and the probable causes of road damage were indicated. This stage was completed by performing the stabilization and sealing process of the ground with an injection mixture. In Stage II, studies were carried out to evaluate the effectiveness of the injection process. The ERT method effectively identified the shallow geological structure and, in particular, delineated the zone of strong fractures in the flysch and areas associated with faults. Using the electrical resistivity tomography method, it was also possible to determine the injection mixture's approximate penetration depth and the loosening zone's degree of filling.

Keywords: electrical resistivity tomography (ERT), monitoring, Carpathian flysch, injection

INTRODUCTION

The degree of complexity of geological engineering conditions depends on three factors: the alignment and structure of the subsurface layers, the location of the groundwater table, and the possibility of adverse geological processes and phenomena. Therefore, the determination of geological and engineering conditions and the associated natural and/or anthropogenic hazards involves the identification of the current state of the geological medium and a forecast concerning the possible hazard zone (Majer et al. 2018). Non-invasive geophysical methods characterized by high efficiency and relatively short measurement times are very helpful in this regard. In contrast to point methods for geotechnical engineering, these methods can provide continuous information about the medium studied. Geophysical methods make it possible, among others, to identify the geological structure and hydrogeological conditions, assess the risk of landslide processes, identify underground technical infrastructure, detect tectonic deformations, and estimate the physical and mechanical parameters of a given medium (Martínez-Pagán et al. 2013, Pasierb et al. 2019). In the case of construction projects located in complex geological-engineering conditions (for example, a shallow groundwater table or the presence of soils with low bearing capacity, the presence of faults or landslides), geophysical methods can also be used to conduct monitoring, which allows, among others, an inspection of the subsoil before and after stabilization works, such as injection or cementing (Kremer et al. 2018, Gutiérrez-Martín et al. 2021). One of the most commonly used geophysical methods in such cases is ERT (electrical resistivity tomography) (Dahlin 1996, Loke 2010). It allows the identification of near-surface layers in areas with a complex geological structure, where conventional invasive survey methods cannot guarantee complete reconnaissance and the supply of the requisite information to determine the foundation conditions of the object (Jouen et al. 2018, Hasan et al. 2021). The ERT method is used to determine the electrical resistivity of the subsoil. This resistivity is influenced by several variables, such as the texture, structure, porosity and physical parameters of the geological medium formations that depend on water content, temperature, and soil solution concentration (Archie 1942, Samouëlian et al. 2005). The interaction between water and the subsoil is one of the most important factors and mechanisms that cause unfavourable processes and phenomena in terms of construction to occur, such as displacement caused by the formation of loosening zones in the subsoil or subsidence of the ground surface due to the formation of voids caused by karstification or suffusion (Apuani et al. 2015). To prevent these phenomena, the process of soil consolidation is carried out by injecting an injection mixture, which, combined with the soil skeleton, results in the improvement of the geotechnical properties of the construction site subsoil, i.e. strengthening the soil, increasing its strength, bearing capacity and stiffness, and preventing subsidence of the subsoil.

The article presents the application of the electrical resistivity tomography (ERT) method to identify the shallow geological structure in the complex geological and engineering conditions of the Carpathian flysch and to determine the causes of road damage. The study was carried out to select the optimal location of the injection wells, after which the effectiveness of the subsoil stabilization work was evaluated.

STUDY AREA

Measurements using the ERT method were carried out in a section of the construction of the S-7 Lubień – Rabka-Zdrój dual expressway under construction, located south of the city of Krakow, Poland (Fig. 1). All of the geotechnical data used in the paper was obtained from confidential documents of the Salini Impregilo road building company.

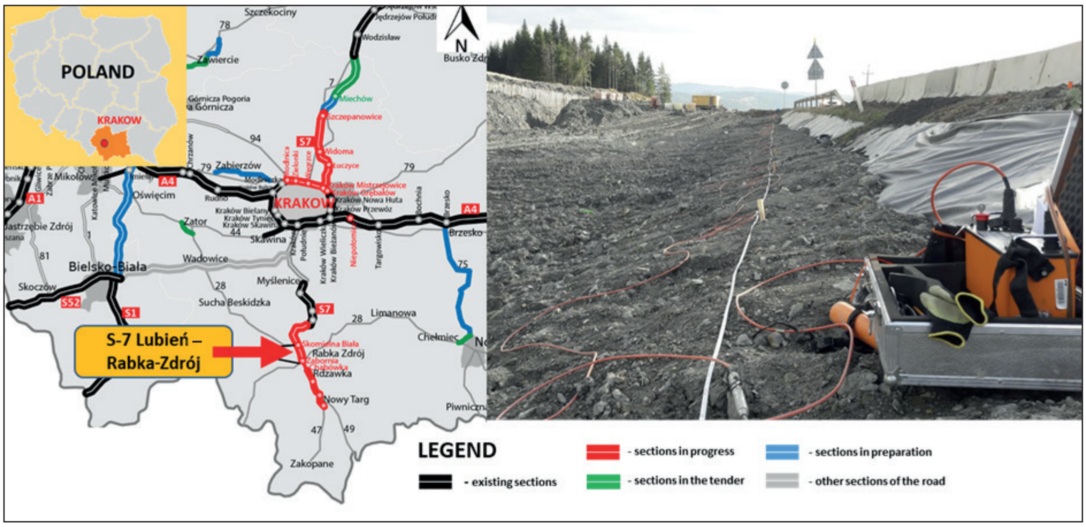

Fig. 1. Location of the study area (www.archiwum.gddkia.gov.pl/pl/aprint/34768/)

A retaining wall consisting of DFF (designed for flysch) piles with steel cores was erected on the surveyed section of the road. A year after its construction, a deviation of part of the wall from the vertical was noticed, which increased, reaching 87 cm after the next year. Cracks in the asphalt and the lowering one of the road lanes by 5–10 cm were also observed.

The analyzed section of the road is located in an area with a complex geological (the Carpathian flysch) and tectonic structure (a fault was located nearby). The shallow geological structure of the study area was determined on the basis of data from boreholes and geotechnical probes. The Carpathian flysch in the immediate subsurface is composed of clayey shales, siltstones, and weakly compacted sandstones which are mostly weathered. The dips of the rock beds ranged between 60 and 80°, and the groundwater table is shallow, at a depth of 0–1.5 m below sea level.

METHODS

Measurements were performed with the use of electrical resistivity tomography (ERT) methods in two sessions in two years. Field measurements were realized with the use of an Ares I resistivity meter manufactured by GF Instruments S.R.O. The Wenner–Schlumberger array was applied with the basic electrode spacing $\Delta x = 3$ m. The array was chosen on the basis of the beneficial signal-to-noise (S/N) ratio. The lengths of the current and potential dipoles were $a = 1\Delta x$ and $3\Delta x$ and the separation factor n, which is the relationship between the current and potential dipole, equals $n = 1, 2, 3, \ldots, 9\Delta x$ (Loke 2010). These parameters resulted in the proper depth and resolution for the investigations.

The apparent resistivity data sets obtained were inverted using Res2dinv from Geotomo Software. During the mentioned process, information about terrain morphology data was taken into account. The inversion methods were tested. The first was the L_1 norm (robust and blocky) and the second was the L_2 norm (smooth). Finally, the results presented were obtained from the L_1 norm option, which is typical use in situations where sharper boundaries between resistivity zones are expected (Loke et al. 2013). It should be noted that both the acquisition and inversion processes were the same in all sessions.

In the contextual interpretation phase (geology and engineering geology) of the inverted data, geological maps, borehole information, and results of the DPH (dynamic probing heavy) tests were considered (Majer et al. 2018).

RESULTS AND DISCUSSION

In the first step of the geophysical interpretation (Stage I of the study), it was found that the geoelectric/geological medium generally consists of two layers, i.e. a near-surface, low-resistivity layer of relatively low thickness and a higher-resistivity deeper layer.

The resistivity values of the low-resistivity layer vary in a narrow range from approximately 5 to 20 Ωm, indicating that it is relatively homogeneous in terms of lithology (Fig. 2). This was confirmed by the results of the geotechnical DPH probing tests, one of the most important tools for testing soil compaction and geotechnical analysis of the subsoil (Czado & Pietras 2012, Sokołowska et al. 2017) conducted at points B1, B2, and B3 (Fig. 2). Within the low resistivity layer, the number of strokes needed to deepen the geotechnical probe by 0.1 m did not exceed 10.

The relatively high resistive layer of the substrate is characterized by resistivity values in the range of 40 to 60 Ωm. The boundary of the high-resistivity and low-resistivity zones correlates with the results of the DPH tests. In the geotechnical probing curve, there is a clear spike in the number of strokes, especially evident in the case of point B2 (Fig. 2). It is noteworthy that the high-resistivity layer is not homogeneous in terms of resistivity distribution; three zones (Zones 1, 2 and 3) of reduced resistivity are clearly marked in the layer. The decrease in resistivity is of the order of about 30–80% (Fig. 2). The heterogeneity of the layer is confirmed by data from the DPH test at point B3, where below an altitude of about 590 m above sea level, alternating increases and decreases in the number of strokes needed to deepen the probe are evident. Therefore, it can be assumed that the decrease in resistivity for Zones 1, 2, and 3 is related to the weakening of the ground under investigation. This weakening can be associated with the tectonics of the studied area, i.e., the existence of local tectonic cracks or even faults.

The geological interpretation of the electrical resistivity cross-section (Fig. 2) was carried out on the basis of the data from the boreholes. These were located within 200 m of the ERT profiles.

The results obtained from Stage I of the ERT study were used to identify the optimal injection points located between the ERT profiles beginning and its 105 running meter. The rock material from the cores shows that the relatively low-resistivity, near-surface layer corresponds to clay loam formations. In contrast, the deeper high-resistivity zone can be interpreted as the Paleogene siltstones and shales of the Carpathian flysch. In this layer, zones of decrease in resistivity can be observed, which are most likely related to water infiltration into highly fractured (weathered) rocks. Therefore, it can be concluded that the infiltration of water into deeper parts of the rocks had weakened the medium, resulting in damage to the surface of the road and its embankment.

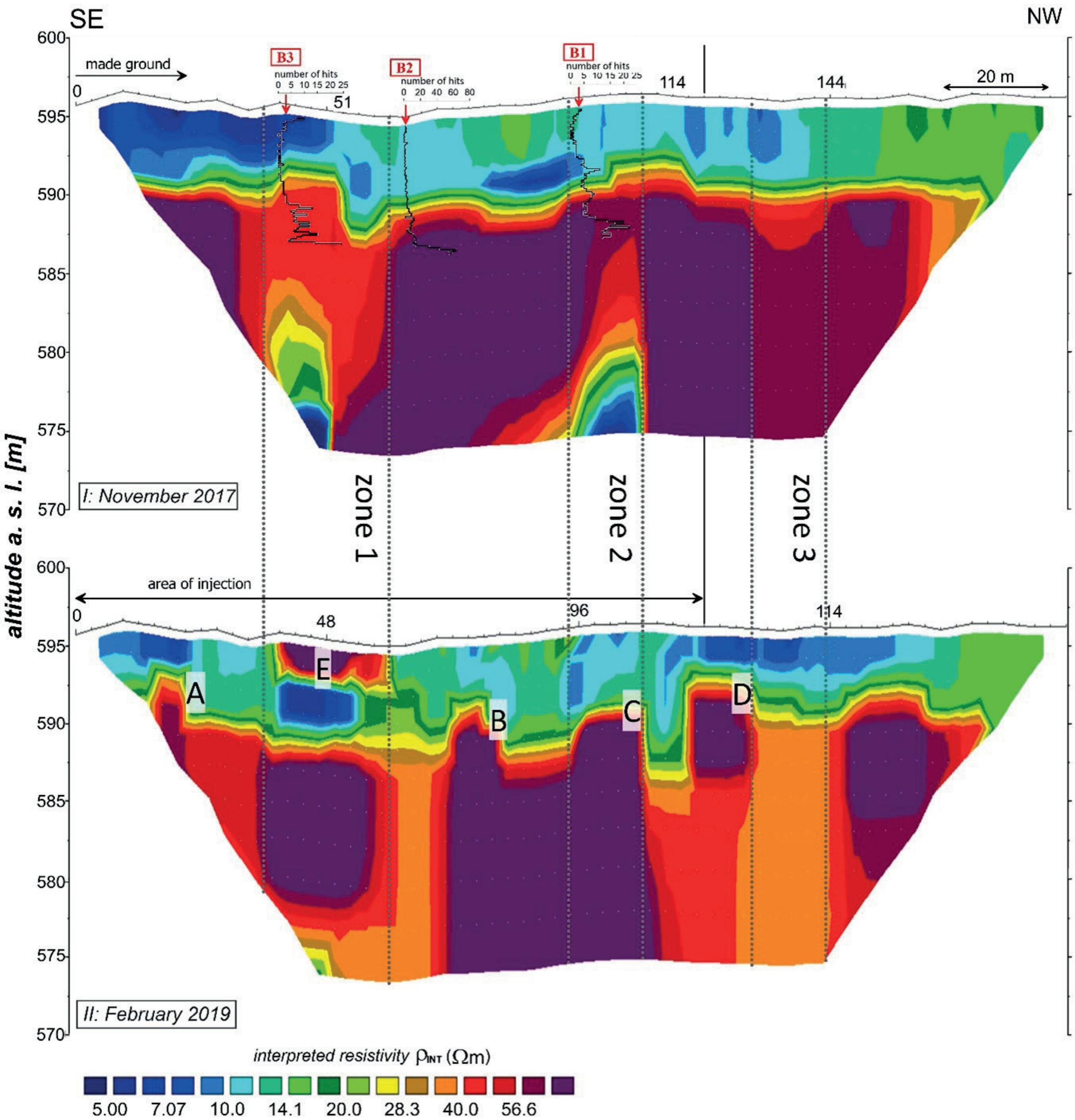

Fig. 2. 2D interpreted resistivity distribution: Stage I (iteration number = 7; RMS error = 1.98%); Stage II (iteration number = 9; RMS error = 4.26%); robust inversion

Under similar hydrological conditions, the second stage of electrical resistivity testing was carried out after injection, 15 months after Stage I. The injections caused significant changes in the image of the resistivity distribution in the flysch formations. The disappearance of the low resistivity Zones 1 and 2 (Fig. 2) was observed, probably associated with the partial filling of the fractures and cracks and blocking of the flow of water in these areas. Low resistivity values were only observed within Zone 1 and Zone 3, indicating water is still present. However, the resistivity in both of these regions after injection is much higher than previously observed in Zones 1 and 2 of Stage I of the study.

Analyzing the ERT cross-section from Stage II of the study (Fig. 2), one can also see changes in the distribution of the resistivity and an irregular course of the boundary between the subsoil and the overburden. The demarcated zones of higher resistivity, A, B, C, and D (Fig. 2), indicate that the injection mixture had not penetrated the highly resistive flysch bedrock. Thus, it can be concluded that much of the flysch substrate was not cracked or weathered, and the few loosening areas were mostly filled in. The interpreted high resistivity anomaly in Zone E, located near the ground surface, is probably related to the retention of the injection mixture.

The question of the resistivity of the injection mixture obtained after inversion of the ERT test data in relation to the actual resistivity values is a matter of debate. After Stage II, the resistivity in the injection mixture-filled zones is several tens of ohm-meters (Fig. 2), while its theoretical literature value according to Cheytani & Chan (2021) is several thousand ohm-meters. Such a large discrepancy between the theoretical resistivity and the interpreted resistivity at the injection sites is probably associated with the complex geological structure of the subsoil and the influence of the inversion algorithm, which does not allow for a correct representation of the actual resistivity (the resistivity is underestimated).

The Carpathian flysch is built of alternating thin layers, consisting of different rocks (sandstones, conglomerates, claystone) which, as a rule, differ in resistivity. The resistivities of these formations compared to the theoretical value of the average resistivity of the mixture are not high. The resistivity distribution obtained from the survey does not reveal this structure, since the vertical resolution of the ERT method decreases markedly with depth (Dahlin 2001, Loke et al. 2013). Therefore, this is undoubtedly one of the reasons for the underestimated resistivity values obtained from the inversion. It is also important to highlight the fact that in reality the geological medium is three-dimensional, while the data obtained are from the surveys conducted in 2D geometry. Also, the direction of the surveys conducted is important due to the arrangement of the layers in the flysch. Thus, the results obtained are only a 2D approximation of a three-dimensional medium.

CONCLUSIONS

The construction of the S-7 Lubień – Rabka-Zdrój dual expressway was carried out under difficult ground conditions. These were mainly due to the complex tectonic structure of the flysch formations, the shallow occurrence of the groundwater table, and numerous landslides. The ERT studies aimed to identify the shallow geological structure and determine the causes of deformation. The research showed that, from the perspective of geoelectric research, the medium is two-layered. The first, low-resistivity layer correlates well with the near-surface formations of clay loam character. The low resistivity variability of these formations indicates a relatively homogeneous lithological layer, which was confirmed by geotechnical probing tests of the DPH. The lower layer of higher resistivity could be identified with Paleogene siltstones and clay shales of the Carpathian flysch. This layer is not homogeneous, which was also confirmed by the DPH test results, showing alternating increases and decreases in the number of strokes needed to deepen the probe. The various resistivity zones recorded in it were formed as a result of water infiltration into the fractured/weathered geological medium. This phenomenon could be considered to have been the cause of the damage to the road embankment and cracking of the road surface. On the basis of the ERT studies, the zones of injection were identified to stabilize the subsoil. The second stage of the research was performed to assess the condition of the geological medium after injection.

The results generally showed an increase in the resistivity within the loosened areas, indicating their sealing. Local zones of high resistivity were also observed at the subsoil-overburden boundary and they could be associated with an excess of the injected mixture.

In conclusion, the electrical resistivity tomography method can be effective for identifying the highly layered flysch geological medium and an effective tool for monitoring the injection process.

The work was financed through the statutory activity Ś-2/235/2017/DS and DS/2021-Ś1 (Faculty of Environmental Engineering and Energy, Cracow University of Technology).

REFERENCES

Apuani T., Giani G.P., d'Attoli M., Fischanger F., Morelli G., Ranieri G. & Santarato G., 2015. Assessment of the efficiency of consolidation treatment through injections of expanding resins by geotechnical tests and 3D electrical resistivity tomography. *The Scientific World Journal*, 2015, 237930. https://doi.org/10.1155/2015/237930.

Archie G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of AIME*, 146(01), 54–62. https://doi.org/10.2118/942054-G.

Cheytani M. & Chan S.L.I., 2021. The applicability of the Wenner method for resistivity measurement of concrete in atmospheric conditions. *Case Studies in Construction Materials*, 15, e00663. https://doi.org/10.1016/j.cscm.2021.e00663.

Czado B. & Pietras J.S., 2012. Rozpoznanie geotechniczne podłoża przez sondowania statyczne i dynamiczne – porównanie oporów penetracji stożka [Geotechnical soil testing by CPT and dynamic probing – comparison of the cone penetration resistances]. *Czasopismo Techniczne. Budownictwo*, 109(20), 3-B, 21–33.

Dahlin T., 1996. 2D resistivity surveying for environmental and engineering applications. *First Break*, 14(7), 275–283. https://doi.org/10.3997/1365-2397.1996014.

Dahlin T., 2001. The development of DC resistivity imaging techniques. *Computers & Geosciences*, 27, 1019–1029. https://doi.org/10.1016/S0098-3004(00)00160-6.

Gutiérrez-Martín A., Yenes J.I., Fernández-Hernández M. & Castedo R., 2021. Stabilization methodology in foundation soils by ERT-3D application in Estepona, South Spain. *Applied Sciences*, 11(10), 4455. https://doi.org/10.3390/app11104455.

Hasan M., Shang Y., Meng H., Shao P. & Yi X., 2021. Application of electrical resistivity tomography (ERT) for rock mass quality evaluation. *Scientific Reports*, 11, 23683. https://doi.org/10.1038/s41598-021-03217-8.

Jouen T., Clément R., Henine H., Chaumont C., Vincent B. & Tournebize J., 2018. Evaluation and localization of an artificial drainage network by 3D time-lapse electrical resistivity tomography. *Environmental Science and Pollution Research*, 25(24), 23502–23514. https://doi.org/10.1007/s11356-016-7366-x.

Kremer T., Vieira C. & Maineult A., 2018. ERT monitoring of gas injection into water saturated sands: Modelling and inversion of cross-hole laboratory data. *Journal of Applied Geophysics*, 158, 11–28. https://doi.org/10.1016/j.jappgeo.2018.06.001.

Loke M.H., 2010. *Rapid 2D Resistivity & IP Inversion Using Least-Squares Method*. Tutorial Geotomo Software. http://www.geotomosoft.com/downloads.php [access: 1.09.2022].

Loke M.H., Ackworth I. & Dahlin T., 2003. A comparison of smooth and blocky inversion methods in 2D electrical imaging surveys. *Exploration Geophysics*, 34(3), 182–187. https://doi.org/10.1071/EG03182.

Loke M.H., Chambers J.E., Rucker D.F., Kuras O. & Wilkinson P.B., 2013. Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics*, 95, 135–156. https://doi.org/10.1016/j.jappgeo.2013.02.017.

Majer E., Sokołowska M. & Frankowski Z. (red.), 2018. *Zasady dokumentowania geologiczno-inżynierskiego (w świetle wymagań Eurokodu 7)*. Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy, Warszawa.

Martínez-Pagán P., Gómez-Ortiz D., Martín-Crespo T., Manteca J.I. & Rosique M. 2013. The electrical resistivity tomography method in the detection of shallow mining cavities. A case study on the Victoria Cave, Cartagena (SE Spain). *Engineering Geology*, 156, 1–10. https://doi.org/10.1016/j.enggeo.2013.01.013.

Pasierb B., Grodecki M. & Gwóźdź R., 2019. Geophysical and geotechnical approach to a landslide stability assessment: a case study. *Acta Geophysica*, 67(6), 1823–1834. https://doi.org/10.1007/s11600-019-00338-7.

Samouëlian A., Cousin I., Tabbagh A., Bruand A. & Richard G., 2005. Electrical resistivity survey in soil science: a review. *Soil and Tillage Research*, 83(2), 173–193. https://doi.org/10.1016/j.still.2004.10.004.

Sokołowska M., Chada M., Roguski A. & Majer E., 2017. Ocena badań geologiczno-inżynierskich wykonanych na potrzeby inwestycji drogowych w latach 2007–2016. *Przegląd Geologiczny*, 65(10/2), 672–677.