ASSESSMENT OF GEOPHYSICAL METHODS FOR THE DETECTION OF HARD ROCK FORMATIONS IN LIGNITE MINES EMPLOYING BUCKET WHEEL EXCAVATORS. THE CASE OF SOUTH FIELD LIGNITE MINE, MACEDONIA, GREECE

OCENA GEOFIZYCZNYCH METOD WYKRYWANIA TWARDYCH FORMACJI SKALNYCH W KOPALNIACH WĘGLA BRUNATNEGO WYKORZYSTUJĄCYCH KOPARKI WIELONACZYNIOWE KOŁOWE. PRZYPADEK KOPALNI WĘGLA BRUNATNEGO SOUTH FIELD, MACEDONIA, GREECE

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In this paper the preliminary evaluation of the potential of geophysical methods for the detection of geological formations of high cutting resistance and hard rock inclusions during the excavation by bucket wheel excavators (BWEs) is presented. The assessment of the geophysical methods for such applications was based on the findings obtained from the literature review, as well as on simulations and field tests. The field tests were conducted at South Field mine Kozani Greece and employed electrical, electromagnetic and GPR methods. Simulations were performed in 2D and 3D, in order to examine the response of GPR in a stratified geological structure consisting of several layers and boulders of various sizes at different depths.

Keywords: *lignite mines, hard rock formations, bucket wheel excavators, geophysical methods*

W artykule przedstawiono wstępną ocenę możliwości zastosowania geofizycznych metod wykrywania formacji geologicznych o wysokiej odporności na skrawanie jak i wtrąceń nieurabialnych, podczas normalnej pracy koparek wielonaczyniowych kołowych. Ocena metod geofizycznych dla takich zastosowań została oparta na wynikach uzyskanych z przeglądu literaturowego, a także na symulacjach i testach terenowych. Testy terenowe przeprowadzono w kopalni South Field, Kozani w Grecji, gdzie przeprowadzono badania z wykorzystaniem metod elektrycznych, elektromagnetycznych i GPR. Symulacje przeprowadzono w 2D i 3D, w celu określenia odpowiedzi GPR w niejednorodnej strukturze geologicznej składającej się z kilku warstw litologicznych i wtrąceń skalnych o różnych rozmiarach na różnych głębokościach.

Słowa kluczowe: *węgiel brunatny, twarde formacje skalne, koparka wielonaczyniowa, metody geofizyczne*

INTRODUCTION

Coal formations originate from a broad spectrum of depositional environments, from alluvial fans to strand plains and subaqueous deposition systems. In this geologic setting one of the frequent problems, when mining coal deposits, is the presence of cohesive materials of high mechanical strength in relation to the other materials of the series. These are generally called "hard formations" or "hard inclusions" and are in the form of either continuous layers or boulders. This problem is of particular importance in Europe where lignite deposits are mainly exploited in large opencast mines utilizing Bucket Wheel Excavators (BWEs) as the main means of excavation.

Due to the random spatial distribution of hard rock formations in the subsurface and grid spacing in relation to their size, it is impossible to detect all hard inclusions present in a coal deposit by conventional exploration methods, like drilling and geological modeling. An alternative approach is to focus on the excavation face where the BWE is digging. If one geophysical detector, continuously working, mounted on the BWE could "see" a few cuts ahead of the face and detect hard inclusions, digging into them would be avoided.

In this paper the preliminary evaluation of the potential of geophysical methods for the detection of geological formations of high cutting resistance and hard rock inclusions during the excavation by BWEs is presented. The assessment of the geophysical methods for such applications was based on the findings obtained from the literature review, as well as on simulations and field tests.

Geophysical field tests were conducted at the South Field mine Kozani Greece, to assess the capability of the most appropriate geophysical methods in mining conditions. The geophysical investigation involves the following methods: Electrical Resistivity Tomography (ERT), Slingram ElectroMagnetic (EM) method and Ground Penetrating Radar (GPR).

GEOPHYSICAL METHODS APPROPRIATE FOR ON LINE MEASUREMENTS

The GPR method with shielded antennas facing only ahead to the ground is a very accurate geophysical method for detecting high resistivity hard rock layers or local bodies. Overmeyer et al. (2007) tested the GPR measuring device on the mine face with a complex system supporting it, but real field data have not been presented in order to prove the usefulness of the method. The GPR method main disadvantage is that it loses its effectiveness in an environment with conductive material like clay minerals.

The electrical resistivity method can detect both local bodies and stratigraphy, since compact materials usually exhibit higher resistivity compared to loose clayey ones. Electrodes in contact with the ground and isolated by the rest of the steel structure of the BWE can be attached to the bucket. A three electrode setup mounted on a bucket has already been implemented as is reported by Overmeyer et al. (2007). However, sufficient field results have not been presented to evaluate the performance of the setup in the conditions existing in a typical opencast mine.

The electromagnetic method and the use of a conductivity meter is another way of measuring the apparent resistivity, a cumulative identity of the material. It provides similar results with the resistivity methods. There is no need of electrodes in contact with the ground. The conductivity meter can be attached to a vehicle while detecting the ground with great accuracy.

In the case of an environment consisting of materials of various grain sizes or relatively inhomogeneous, the GPR radargram is cluttered with reflections and it is difficult to clear the signal and identify the targets. On the contrary, the electromagnetic induction and resistivity methods see the formations as a whole, thus discriminating the boulders from the matrix of various coarse and fine materials.

GEOLOGICAL SETTING AT SOUTH FIELD LIGNITE MINE, GREECE

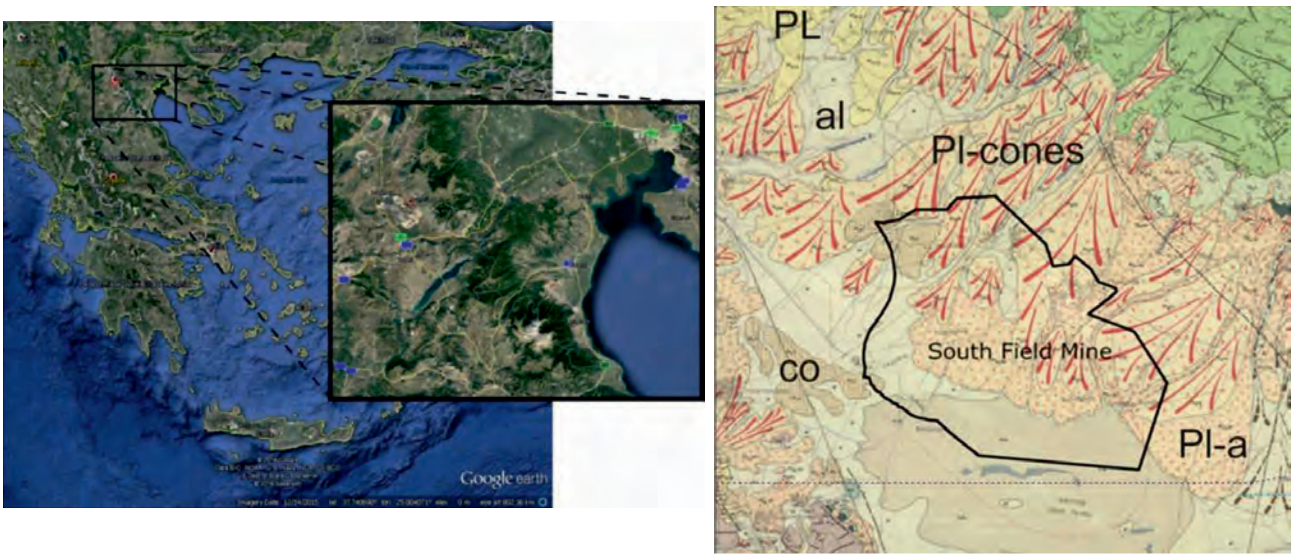
The Southern Field Lignite Mine (SFLM) is the largest of the four operational surface mines at the Lignite Center of Western Macedonia (Figure 1a), covering an area of 24 km^2. The mine exploits a portion of the Ptolemais–Kozani lignite deposit.

The SFLM lies within the Ptolemais-Kozani Basin (Koukouzas et al., 2010). The basement underlying the basin includes Paleozoic schists and granites, as well as Mesozoic dolomitic limestones and flysch of the Pelagonic Structural Zone. The basin is filled with Tertiary and Quaternary sediments up to 1000 m thick mainly Miocene to Pliocene sand, sandy clay, lignite, and marl, mainly of fluvial to lacustrine origin (Figure 1b). The main faults in the area of SFLM, have NW-SE and NE-SW directions. The former of these are considered as the marginal faults which formed the original tectonic graben, while the later formed subgraben and horsts which give today's picture of lignite basin. Younger faults with direction E-W are also observed inside the basin and at its margin (Anastopoulos & Koukouzas, 1972). The overburden material consists mainly of clay, sand, mixed formations of sand and gravels, marl and layers of semi-hard to hard rocks (sandstones, marls and conglomerates). The average thickness of overburden material is 90m (Kavouridis & Agioutantis, 2006, Kavouridis et. al., 2008).

The series of the overburden rocks of the SFLM consists of the following groups:

• Red to brown clastic sediments: This group consists mainly of clays, conglomerates and limestone gravels. The thickness of the whole formation is about 25 m, while the average thickness of hard material is approximately 10 m.

• Gray to yellow clastic sediments: This group consists of clay, sandstones, sand, conglomerates and siltstones. The average thickness of the whole formation is 25 m, while the average thickness of the hard material is 11 m.



(a) (b)

Fig. 1. (a) Location of the lignite deposit (source: Google Earth). (b) Geological map with PPC's South Field mine final pit limits (Source: IGME and PPC). PL: Pliocene formations, al: aluvium, Pl-cones: Pleistocene cones, co: Pleistocene conglomerates, Pl-a: Pleistocene marly formations

Rys. 1. (a) Lokalizacja złoża węgla brunatnego (źródło: Google Earth). (b) Mapa geologiczna z zasięgiem wyrobiska eksploatacyjnego kopalni South Field należącej do PPC (Źródło: IGME i PPC). PL: Formacje pliocenu, al: aluwium, Pl-cones: stożki plejstocenu, co: konglomeraty plejstoceńskie, Pl-a: plejstoceńskie formacje margliste

Tab. 1. Physical and mechanical properties of excavated formations
Tab. 1. Właściwości fizyczne i mechaniczne urabianych utworów

Geological description	Moisture as received (%)	Uniaial compressive strength (MPa)
Conglomerates	0,98	11,00
Breccia	0,25	12,10
Argillaceous Marls	26,46	1,10
Clay	38,28	0,16

Tab. 2. Average resistivity values of the subsurface formations at PPC open pit mine. (Meladiotis, 2000)
Tab. 2. Średnie wartości rezystywności utworów przypowierzchniowych w kopalniach węgla brunatnego należących do PPC (Meladiotis, 2000)

Formation	Resistivity of samples as recieved (Ωm)
Conglomerates	1270
Sands	540
Argillaceous Marls	54
Sandy Clays	19
Lignite	5

• Green-grey clay, sand and silt sediments: The thickness of this formation varies from 25 m to 50 m. No hard material has been found in this formation.

Although the average thickness is enough to easily detect the hard formation, this referred to cumulative thickness and not to one or two constant seams. A lot of seams are a few centimetres and spread along the whole overburden formations. Except their small size can be found in various positions and shapes, this two special characteristics determines their detection difficulty.

Table 1 (Papageorgiou & Pakas, 1997) summarizes the mechanical and physical properties of the hard rock (conglomerates and breccia) and the easily excavated material consisting mainly of clays and argillaceous marls.

EXISTING GEOPHYSICAL DATA

The available information for open pit lignite mines in Western Macedonia consists of data and sections from two geophysical surveys. A geophysical survey at South Field mine employed Syscal 2 for the vertical electrical sounding (Meladiotis, 2000). Table 2 summarizes the average resistivity values of the formations of interest at PPC open pit mine deduced from the geoelectrical survey. A SIR system GSSI with 80 MHz and 100 MHz antennas was also employed to image hard rock layers.

Another geophysical investigation at PPC's Aminteon field mine, belonging to the Lignite Center of Western Macedonia, employed electrical and seismic tomography (Melidis, 2008). By comparing the seismic tomography velocity distribution with the geoelectrical section and borehole data, higher resistivity layers are attributed to sands and gravels. The geophysical survey could not image very thin layers of hard rock formations attributed to hard rock formations (conglomerates).

GPR SIMULATIONS FOR THE DETECTION OF HARD FORMATIONS

Several techniques have been developed for simulating propagation of electromagnetic wave fields in the earth. In forward modeling the wave field is generated by solving the wave equation. In order to gain an acceptable geological model, comparisons are often made between the synthetic and observed radargrams.

Irving and Knight (2006) solved numerically a first order system for Terrain model (TM)-mode using an explicit finite difference method. A leap-frog, staggered grid approach involves offsetting the electric and magnetic field components in both space and time such that the FD approximations of the partial derivatives in each equation are centered on the same spatio-temporal location. All spatial derivatives are approximated using fourth-order-accurate FD expressions. The time derivatives are approximated with second-order-accurate expressions. In this (2, 4) scheme the conduction current density term is modeled using a semi-implicit approximation.

To introduce an electric field source into the grid during First Difference Terrain Domain (FDTD) modeling, a source pulse function is added to update the electric field component at the desired spatial location. This amounts to adding the source function to the current density term in Maxwell's equations.

The size of the models in wave propagation simulations depends on the available computer memory. In the boundary regions both incoming and outgoing waves are present. A boundary condition is required to minimize the incoming waves from the artificial boundary reflections. Only 3 explicit boundary conditions have to be considered: the 3 sides of the model. Perfectly Matched Layer (PML) boundary regions allow propagating waves to be absorbed.

Tab. 3. EM velocity and resistivity values for layers and boulders (Galetakis et al, 2016)
Tab. 3. Prędkość rozchodzenia się fali elektromagnetycznej oraz oporność warstw geologicznych i głazów (Galetakis et al, 2016)

Layer	L1	L2	L3	L4	Boulders
Velocity (m/ns)	0.07	0.08	0.07	0.06	0.10
Resistivity (Ωm)	200	500	1000	2500	10000

Tab. 4. Coordinates and size of the boulders
Tab. 4. Współrzędne i rozmiary głazów

Center			
x(m)	y(m)	z(m)	Size (m^3)
2.5	1.7	1.5	1.5x1.5x1.5
1	1.6	3	0.5x0.5x0.5
1	4	3	1x1x1

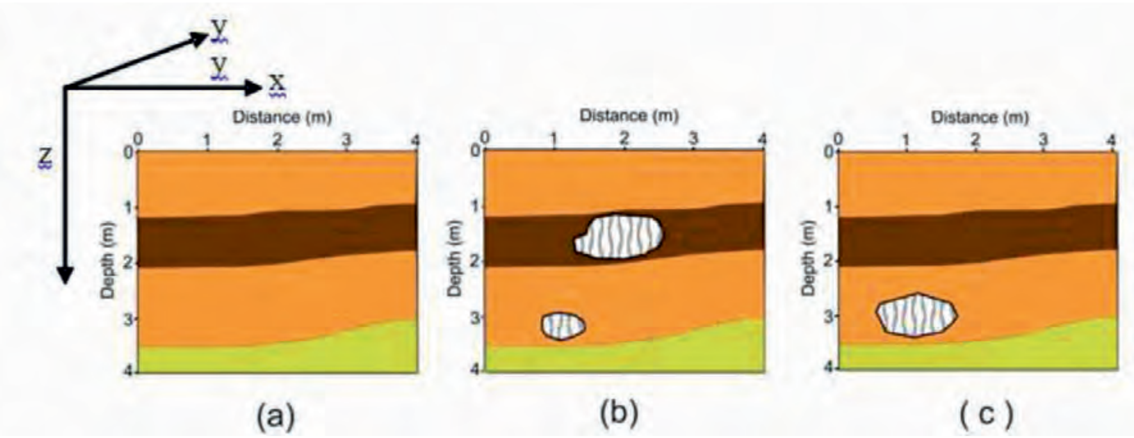


Fig. 2. Selected sections of a 3D model at y= 0 m (a), 1.6 m (b) and 4 m (c) for a stratified geological structure consisting of four layers. Boulders, whose size is 1.5x1.5x1.5 m^3, 0.5x0.5x0.5 m^3 and 1x1x1 m^3 have been placed at varying depths
Rys. 2. Wybrane przekroje modelu 3D dla y = 0 m (a), 1.6 m (b) i 4 m (c) dla pokładowej struktury geologicznej składającej się z czterech warstw. Głazy o wymiarach 1,5x1,5x1,5 m^3, 0,5x0,5x0,5 m^3 i 1x1x1 m^3 zostały umieszczone na różnych głębokościach

2D and 3D GPR simulations were performed with tools capable of modeling the behavior of boulders and the surrounding geological formations. In particular, two software packages, namely: REFLEX W (Sandmeier, 2012) and MATGPR (Irving and Knight, 2006, Tzanis, 2010), have been employed. Both software packages utilize the FD method for generating the wave field in time domain. This initial value problem requires a line or point source whose time excitation is chosen here to be a Ricker wavelet. Absorbing boundary conditions are introduced at the bottom and the sides of the model in order to eliminate side reflections.

The velocity and electrical resistivity of hard formations for each layer are given in Table 3. Various scenarios have been examined. Here, we have chosen the ones corresponding to a stratified geological structure consisting of four layers, as shown in Figure 2. Three boulders, (B1, B2, B3), have been included whose size and centers are given in Table 4.

The size of the examined 3D model is 4x4.8x4 m^3. During the simulation along a survey line, the transmitter and receiver distance is kept constant while scanning the subsurface.

Figure 3 depicts the radargrams from the simulations using the GPR 250 MHz antenna for the 3D model shown in Figure 2. Figure 3 (top) compares radargrams from the 2D and the 3D simulation for survey line at y=0 m and x=0 m (mine face).

These images depict the slanted events corresponding to reflected waves propagating along the mine face. An additional event observed at the radargrams from the 3D simulation originates from boulder B1 which is located offline. Therefore, more realistic but time consuming 3D simulations are preferable for imaging the boulders. In conclusion, a series of simulations showed that the GPR method is useful for locating hard rock inclusions at depths less than four meters.

GEOPHYSICAL SURVEY

The geophysical survey involved electrical, electromagnetic and GPR methods. The aim of the survey is to examine the potential of geophysical methods in locating hard rock inclusions.

Electrical Resistivity Tomography method

An 100 m long Electrical Resistivity Tomography (ERT) line was scanned in order to image hard rock layers. Slingram electromagnetic profiling was carried out at the mine face in order to study the electrical conductivity variation due the presence of hard rock layers. GPR scans were acquired both at the mine face and on the benches.

The geolectrical survey employed the Syscal Pro Iris system and RES2DINV software for the acquisition and processing

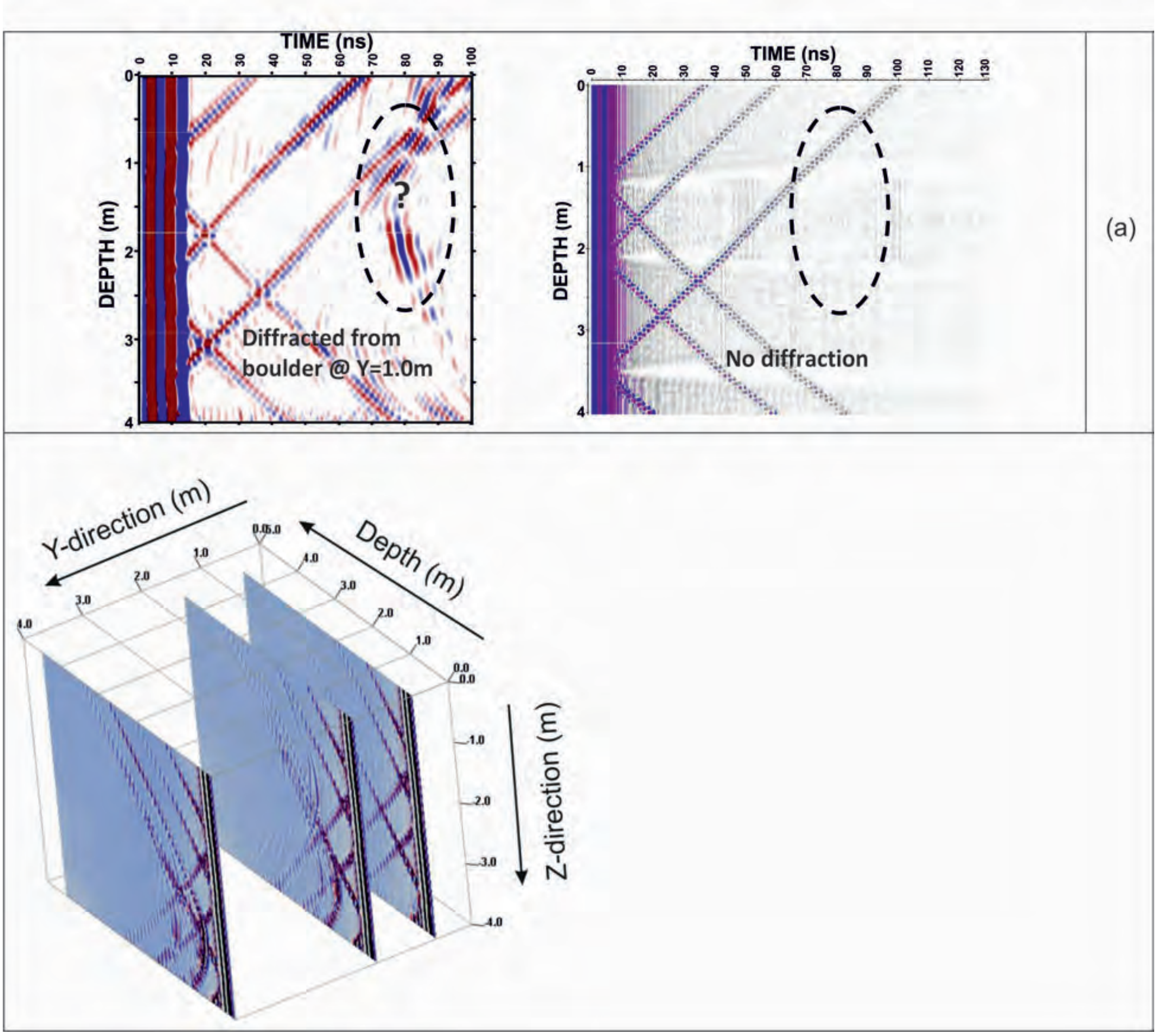


Fig. 3. (Top) Radargrams from 2D and 3D simulations for survey line at y=0 m (mine face). (Bottom) Radargrams from 3D simulation at different study lines of the 3D model at the mine face at y= 0m, 1.6 m and 4 m

Rys. 3. (Góra) Radargramy z symulacji 2D i 3D dla przekroju y = 0 m (miny). (Dół) Radargramy z symulacji 3D na różnych przekrojach badania modelu 3D na powierzchni czoła skarpy czołowej zabierki przy y = 0 m, 1,6 m i 4 m

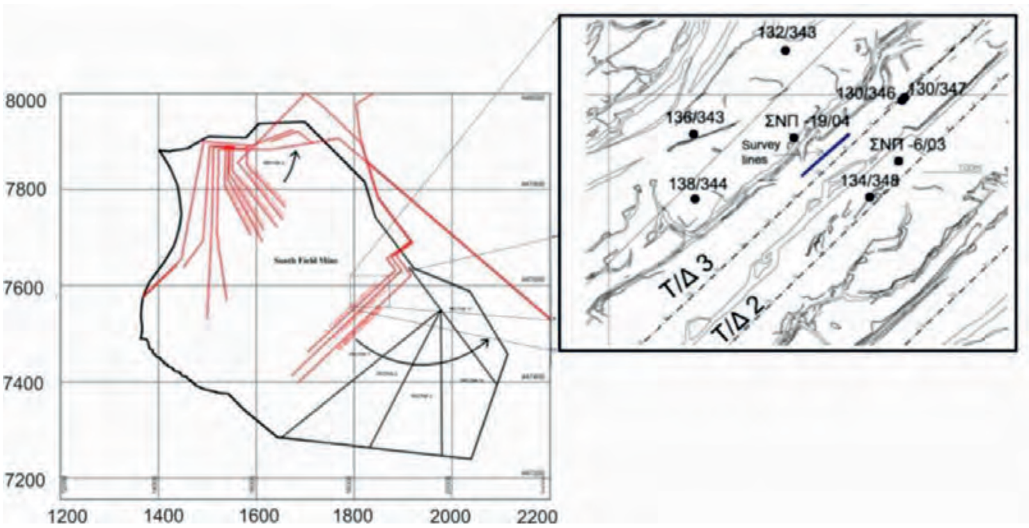


Fig. 4. Location map showing the area of the geophysical survey at PPC open pit mine in Greece. Blue line indicates the ERT line

Rys. 4. Mapa obszaru objętego badaniami geofizycznymi w kopalni odkrywkowej PPC w Grecji. Niebieska linia wskazuje linię ERT

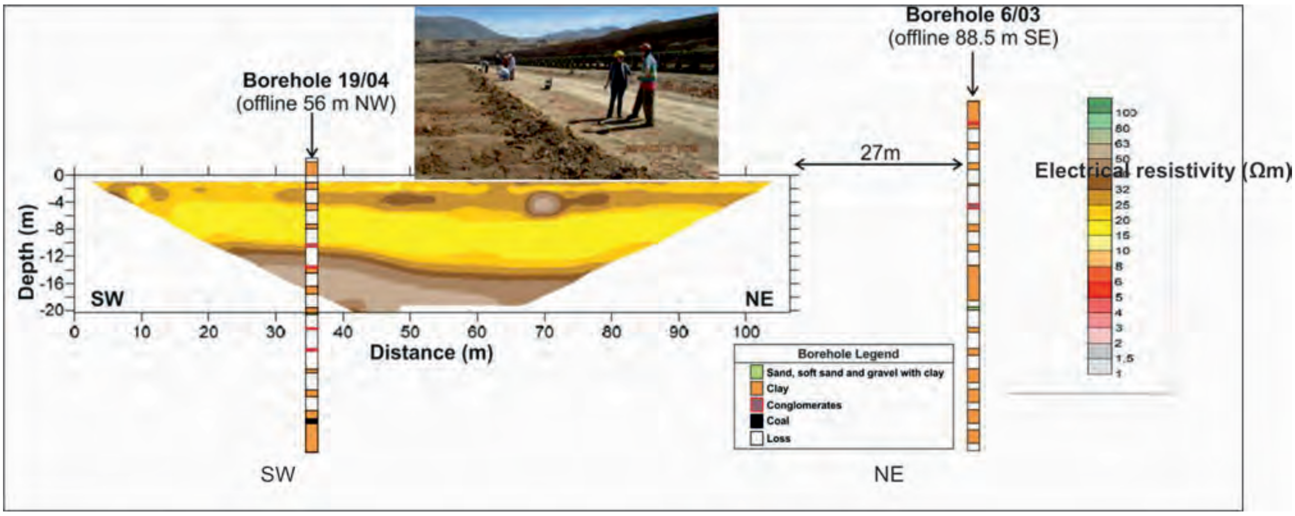


Fig. 5. Boreholes' 19/04 and 6/03 logs in comparison with the Geoelectrical sections at the PPC open pit mine for the dipole-dipole. Logs of boreholes after enlargement

Rys 5. Profile odwiertów 19/04 i 6/03 w porównaniu z sekcjami geoelektrycznymi w kopalni odkrywkowej PPC dla dipol-dipol. Logi odwiertów po powiększeniu

of the apparent resistivity data. The measurements were taken with a four electrode setup and the apparent resistivity or impedance is a cumulative identity of the material in a volume of certain size, dependent on grain size and compactness. More specifically we use more electrodes in both Dipole-dipole (DD) and Wenner-Schlumberger (WS) configurations which resulted in a finer detection, in the sense of resistivity tomography ahead of the excavation. The DD array enhances lateral variation of the electrical resistivity, while the WS array is more suitable to describe the vertical variation of the electrical resistivity.

Figure 4 shows the position of the surveyed Electrical Resistivity Tomography (ERT) line whose electrode spacing, 1.5 m and maximum depth, 20 m. Electrical tomography detects two higher resistivity layers (Figure 5). The superposition of boreholes 19/04 and 6/03 on the ERT sections indicate that the high resistivity zones are attributed to boulders.

Slingram Electro Magnetic (EM) method

The Slingram Electro Magnetic (EM) method was employed in order to estimate the electric properties of the formations (Kaczor and Weymouth, 1981). Vertically polarized sinusoid oscillations are transmitted and received. The transmitted alternating primary field is induced in rocks with dissimilar electric resistivities eddy currents or secondary fields. The electromagnetic induction instrument measures the inphase and quadrature components of the secondary electromagnetic field. The quadrature component depends on soil conductivity. Thus, from the quadrature component measurements, the soil conductivity is estimated. The measured apparent conductivity of ground (in millisiemens per meter) gives information e.g. about the rock type or soil.

During data acquisition, measurements were collected along three lines on two slopes at the overburden of the PPC South Field mine using the GF-Instruments CMD. The height of one slope is less than 4 m, while the height of the other one is approximately 19 m. Figure 6 displays the range of the measured apparent conductivity values. For comparison reasons the data from the bigger slope were coded using a color scale and were displayed next to the photo of the slope (Figure 6), indicating that hard rock layers consisting of conglomerates exhibit lower apparent conductivity values.

Thus, presentation of the measurements is adequate for outlining the local feature.

Ground Penetrating Radar (GPR)

GPR measurements, using a Mala Ramac system with two antennas (250 MHz and 100 MHz) were collected on two benches and two slopes of the overburden formations at PPC South Field mine. The acquisition and processing parameters are depicted on Table 5.

GPR measurements acquired on the slopes were collected without a wheel encoder which records the relevant position of each trace. GPR traces on these sections cor-

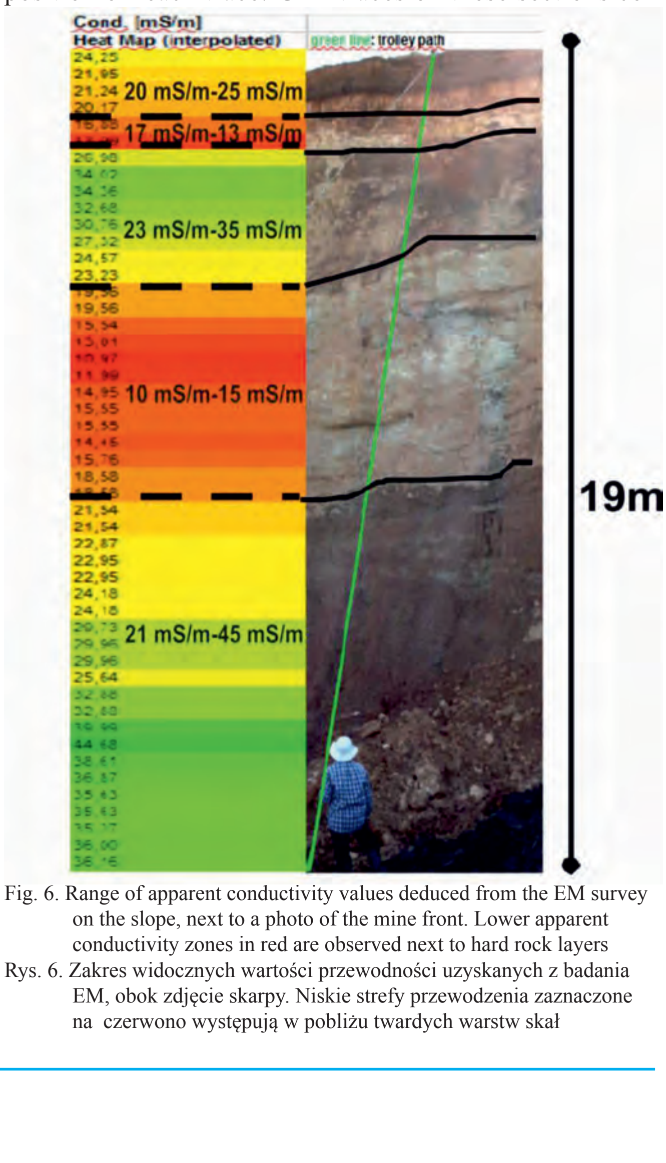


Fig. 6. Range of apparent conductivity values deduced from the EM survey on the slope, next to a photo of the mine front. Lower apparent conductivity zones in red are observed next to hard rock layers

Rys. 6. Zakres widocznych wartości przewodności uzyskanych z badania EM, obok zdjęcie skarpy. Niskie strefy przewodzenia zaznaczone na czerwono występują w pobliżu twardych warstw skał

Tab. 5. Acquisition parameters for the GPR experiment at PPC open pit mines. Basic processing includes dewow, trim time window and background noise removal. K-L (X) denotes K-L transform employing X eigenvectors
Tab. 5. Akwizycja danych dla eksperymentu GPR w kopalniach odkrywkowych PPC. Podstawowa obróbka obejmuje wygaszanie, strojenie i usuwanie szumów tła. K-L (X) oznacza transformację K-L wykorzystującą wektory własne X

Line number	135	139	140	141	142	143
Dominant Frequency (MHz)	250	250	250	250	100	100
Time interval (ns)	0.3937	0.3937	0.3937	0.3937	0.9263	0.9263
Space interval (m)	0.04943	-	-	-	0.09886	0.09886
Antenna offset (m)	0.31	0.31	0.31	0.31	0.5	0.5
Processing	Basic K-L (2)	Basic K-L (2)	Basic K-L (2)	Basic K-L (2)	Basic K-L (1)	Basic K-L (1)

respond to time as the GPR device was fixed to measure a trace each second. The GPR position deduced from photos, the trace number and the relevant recorded time were integrated in order to extract the trace position. The 250 MHz GPR section at the bench images the hard rock inclusion present at the smaller slope at a depth of 1.8m (Figure 7).

DISCUSSION OF THE RESULTS

Geophysical methods have been evaluated in terms of their ability to detect geological formations of high cutting resistance and hard rock inclusions during the excavation by BWEs in typical geologic environment of lignite mines in Northern Greece.

Simulations were performed in 2D and 3D, in order to examine the response of GPR in a stratified geological structure consisting of four layers and boulders of various sizes. Two scan setups, against the mine face and below the bucket wheel, as well as GPR antennas of 100 and 250 MHz were used in the simulations.

The resulting radargrams showed that in all examined scenarios the presence of boulders and seams was detected at depths less than four meters. Thus, the simulations verified the potential of the GPR method and justified further investigation through field tests that will be performed in the context of developing a real-time hard inclusions detection system attached to the excavator.

The geophysical survey conducted at South Field mine Kozani Greece employed electrical, electromagnetic and GPR methods. The electrical tomography detected two higher resistivity layers, attributed to conglomerates. The Slingram EM method detected hard rock layers consisting of conglomerates exhibit lower apparent conductivity values.

GPR measurements, using a Mala Ramac system with two antennas (250 MHz and 100 MHz) were collected on two benches and two slopes at the overburden formations of the PPC South Field mine. The GPR sections at the slopes showed

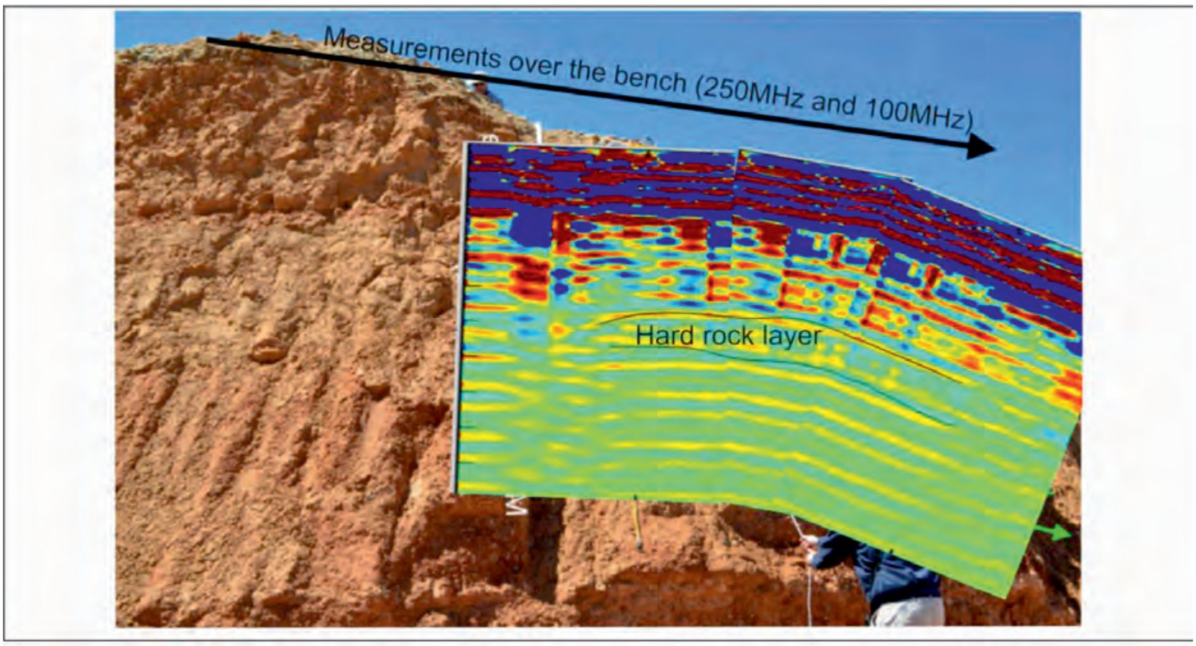


Fig. 7. GPR section at the upper bench (line 135) using the 250 MHz antenna is superimposed on the photo of the mine face of the bench. Velocity analysis by diffraction hyperbola on this section indicates that V=0.08 m/ns
Rys. 7. Sekcja GPR z pomiarów wykonywanych na górnej półce (linia 135) z zastosowaniem anteny 250 MHz została nałożona na zdjęcie badanej skarpy. Analiza prędkości na podstawie hiperboli dyfrakcyjnej na tym odcinku wskazuje V = 0,08 m/ns

changes on the direct wave arrival time and shape between the hard and soft rock layers. The 250 MHz GPR section at one of the benches images properly the hard rock inclusion which is seen at the smaller slope at a depth of 1.8 m.

Both resistivity and electromagnetic methods can discriminate materials usually present in coal mines, with the measured values identifying the material as well. The application of these two methods is found to be reliable in the operating conditions of an opencast mine and a BWE. Small-scale field tests of the resistivity, electromagnetics and GPR geophysical methods proved their effectiveness in opencast mines for detection of the ground ahead of the excavation face. The geologic setting in PPC mine is dominated by fine grained materials, generally of a clayey character with an intermediate compaction. These form the matrix where local bodies of much greater compaction and size are found. This situation is very well discriminated by the geophysical parameter of conductivity or its inverse, resistivity. Therefore, the electrical or EM (induction or GPR) methods are the most promising in detecting the local features.

A uniform clayey environment gives in general no signal in the GPR method due to attenuation by the highly conductive material, thus it is difficult to enter into deeper horizons as is reported by Francke (2012). However, an isolated rigid body or a local area of very coarse material will show a high amplitude signal or a multiple reflections area, generally outlining the body or the coarse material respectively. The reflections of EM wave in the GPR method may be originated also by some difference in compaction of the fine grained material. Thus, in the generally similar geologic environment of the examined mines the electromagnetic induction and resistivity methods are able to outline lateral inhomogeneity, while the GPR method can do so if the signal can pass through the conductive clayey materials before facing the hard formations.

CONCLUSIONS

Geophysical methods have been evaluated through field tests in terms of their ability to detect geological formations of high cutting resistance and hard rock inclusions during the excavation by BWEs. The ERT is a powerful method for detecting hard rock layers whose thickness is greater than the electrode spacing. The EM method provides useful information about the hard rock inclusion. This feasibility study identified that in the typical geologic environment of lignite mines such as the South Field PPC's open pit mine in Northern Greece, the electromagnetic (induction or GPR) methods are the most promising in detecting local features such boulders and seams.

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