REQUIREMENTS OF A HARD FORMATIONS EARLY DETECTION SYSTEM IN OPENCAST LIGNITE MINES

WYMAGANIA SYSTEMU WCZESNEGO WYKRYWANIA TWARDYCH FORMACJI SKALNYCH W ODKRYWKOWYCH KOPALNIACH WĘGLA BRUNATNEGO

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One of the frequent problems that needs to be addressed when mining coal deposits is the occurence of cohesive materials of high mechanical strength in relation to the other materials of the series. This problem is of particular importance in Europe where lignite deposits are exploited in large opencast mines utilizing Bucket Wheel Excavators (BWEs) as the main means of excavation. Often it is difficult or impossible to excavate these hard inclusions with BWEs. If their location has been determined by exploration in advance, they are usually blasted. But it is not uncommon to discover them when it is too late, that is when the BWE actually digs into them.

To proactively address this problem a clear forward warning for the presence of hard inclusions is required. However, it is impossible to detect all hard inclusions present in a coal deposit by conventional exploration methods, like drilling and geological modeling. Even the results of an exceptionally extensive exploration project would have a high level of uncertainty.

A different approach is to focus on the area where the actual problem may take place, namely the excavation face where the BWE is digging. If one could "see" a few cuts ahead of the face and detect hard inclusions, digging into them would be avoided. This can be achieved by developing a system mounted on the BWE, continuously surveying the excavation face and detecting in advance hard inclusions by using appropriate geophysical methods, thus warning for potential problems.

In this paper the requirements and components of such a system are presented, based on the typical geologic setting, the specifications of the excavating equipment, the employed working methods, and the limitations of the available geophysical methods.

Keywords: *continuous surface mining, opencast lignite mining, bucket wheel excavators, hard inclusions, real-time detection, geophysical methods, BEWEXMIN*

Jednym z częstych problemów, które należy rozwiązać przy wydobywaniu złóż węgla brunatnego, jest występowanie spoistych materiałów o wysokiej wytrzymałości mechanicznej w stosunku do innych utworów tworzących nadkład. Problem ten ma szczególne znaczenie w Europie, gdzie złoża węgla brunatnego są eksploatowane w dużych odkrywkowych kopalniach wykorzystujących wielonaczyniowe koparki kołowe (BWE) jako maszyny podstawowe. Często trudne lub nawet niemożliwe jest urobienie tych twardych inkluzji przy pomocy tych koparek. Jeśli lokalizacja wtrąceń została wcześniej określona poprzez rozpoznanie, są one zwykle urabiane z użyciem materiałów wybuchowych. Często jednak zdarzają się przypadki nie wykrycia takiej struktury do momentu, gdy koło urabiające koparki już w nie uderzy.

Aby umożliwić zareagowanie na ten problem, konieczne jest otrzymanie wyraźnego ostrzeżenia o obecności twardych inkluzji. Jednak niemożliwe jest wykrycie wszystkich twardych inkluzji obecnych w złożu węgla konwencjonalnymi metodami poszukiwawczymi, takimi jak wiercenie i modelowanie geologiczne. Nawet wyniki wyjątkowo rozległego projektu poszukiwawczego będą miały wysoki poziom niepewności.

Innym podejściem jest skupienie się na obszarze, na którym może wystąpić faktyczny problem, a mianowicie w zabierce, w której koparka wielonaczyniowa pracuje. Możliwość rozpoznania kilku pasm przed czołem zabierki i wykrycia twardych wtrąceń, pozwoliłaby na uniknięcia uderzenia w nie organu urabiającego koparki. Można to osiągnąć, opracowując system zainstalowany bezpośrednio na koparce, który będzie prowadził ciągły monitoring w przodku zabierki i pozwoli na wyprzedzające wykrycie twardych wtrąceń za pomocą odpowiednich metod geofizycznych, ostrzegając w ten sposób przed potencjalnymi problemami.

W niniejszym artykule przedstawiono wymagania i elementy takiego Systemu, oparte na typowej budowie geologicznej, specyfikacjach maszyn podstawowych, zastosowanych metodach pracy oraz ograniczeniach dostępnych metod geofizycznych.

Słowa kluczowe: *ciągły system wydobywczy, odkrywkowe wydobycie węgla brunatnego, wielonaczyniowe koparki kołowe, twarde inkluzje, wykrywanie w czasie rzeczywistym, metody geofizyczne, BEWEXMIN*

INTRODUCTION

The formation of coal takes place in a broad spectrum of depositional systems, from alluvial fan setting to strandplains and subaqueous deposition, which create the initial stratigraphic sequence and associate coal-bearing series with certain types of soils and rocks, like clay and sandstones. The final structure of coal deposits is dominated by tectonic events that follow.

This process results in coal deposits that are characterized, on the one hand, by relatively few material types present as overburden or intercalations but, on the other hand, of a usually complex structure.

In this geologic setting one of the frequent problems that needs to be addressed 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 exploited in large opencast mines utilizing Bucket Wheel Excavators (BWEs) as the main means of excavation.

Often it is difficult or impossible to excavate these hard inclusions with BWEs. If their location has been determined by exploration in advance, they are usually blasted. But it is not uncommon to discover them when it is too late, that is when the BWE actually digs into them. BWEs are typically designed to excavate materials of an "earthy" texture with low mechanical strength. Dynamic and stochastic impact loads exerted on a machine during these encounters are the most common causes of major BWE component failures leading to downtime, production disruption, and high-cost repairs.

There are two approaches of addressing the problem: proactively and reactively.

In proaction the objective is to prevent the BWEs from digging into the hard formations. To achieve this, a clear forward warning for the presence of hard inclusions is required. However, it is impossible to detect all hard inclusions present in a coal deposit by conventional exploration methods, like drilling and geological modeling, due to: (i) the random spatial distribution of hard inclusions in the subsurface, and (ii) grid spacing in relation to their size. Even the results of an exceptionally extensive exploration project would have a high level of uncertainty.

A different approach is to focus on the area where the actual problem may take place, namely the excavation face where the BWE is digging. If one could "see" a few cuts ahead of the face and detect hard inclusions, digging into them would be avoided. In the case of a BWE operating in terrace cut mode, the scope of such a system is illustrated in Figure 1.

Hence, a proactive approach could be the development of a system that mounted on the BWE would continuously survey the excavation face and detect in advance hard inclusions by using appropriate geophysical methods, thus warning for potential problems.

In the reactive approach the objective is to adapt the BWEs to excessive cutting resistance and to monitor in real-time the loads applied on the machine, thus recognizing any conditions that potentially could lead to failure.

In this paper the requirements and components of a hard formations early detection system are presented, based on the typical geologic setting, the specifications of the excavating equipment, the employed working methods, and the limitations of the available geophysical methods. The work was conducted in the context of the BEWEXMIN research project and included an extensive literature review, the collection and analysis of relevant data, and the evaluation of geophysical methods through field tests in the actual operational environment.

OPERATIONAL ENVIRONMENT

The requirements of a hard formations early detection system are set by the environment in which it is expected to operate. In order to delineate this operational environment, six opencast lignite mines were asked to provide relevant information pertaining to general mine data, geological data, mine configuration, installed monitoring infrastructure, excavated material data, material difficult to excavate, and bucket wheel excavators. Table 1 lists the mines for which data were submitted.

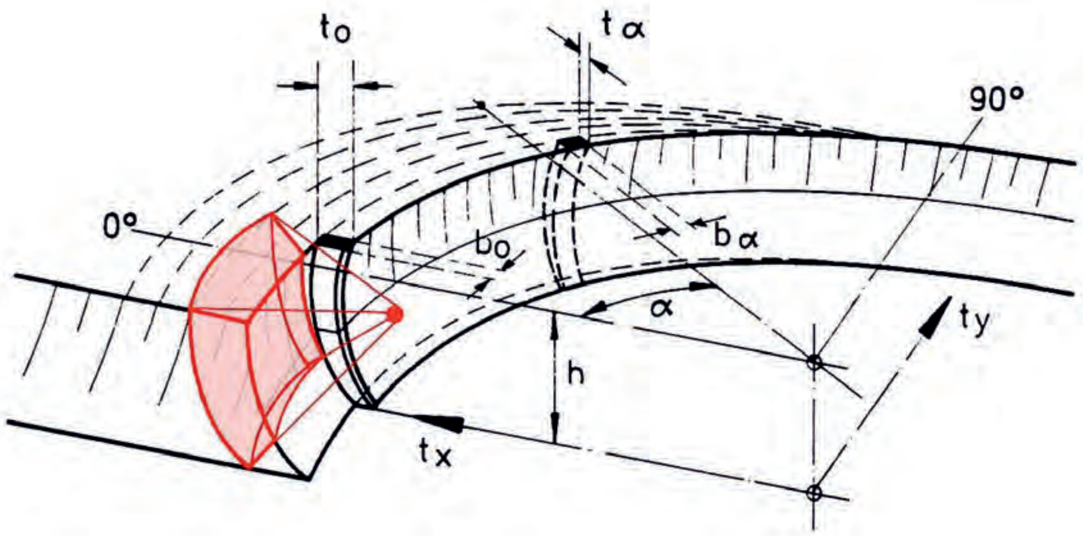

Fig. 1. Scope of the hard inclusions detection system (background drawing from Durst and Vogt, 1988)
Rys. 1. Zakres wykrywania twardych wtrąceń skalnych (rysunek w tle pochodzi z Durst and Vogt, 1988)

Tab. 1. List of lignite mines
Tab. 1. Zestawienie kopalń węgla brunatnego

No.	**Country**	**Mine**	**Coordinates (degrees)**	**Data provided by**
1.	Czechia	Bílina	N50.5703544 E13.7110790	VUHU
2.		ČSA	N50.5488439 E13.5345258	
3.		Vršany	N50.4918986 E13.5552111	
4.	Greece	South Field	N40.4180833 E21.8378000	PPC
5.	Poland	Szczerców Field	N51.2466667 E19.1186111	PGE
6.	Romania	Husnicioara	N44.6702778 E22.7600000	CEO

Tab. 2. Environmental conditions
Tab. 2. Uwarunkowania środowiskowe

Mine		Bílina	ČSA	Vršany	South Field	Szczerców Field	Husnicioara
Elevation (m)		200-300			660	180	320
Climate		Cool to temperate continental			Humid continental	Humid continental	Humid continental
Annual temperature (°C)	min	-15			-1	-24	-28
	mode	15			N/A	N/A	12
	max	35			29	38	41

Tab. 3. BWE characteristics
Tab. 3. Charakterystyka koparek wielonaczyniowych kołowych

Mine	**Bílina**	**ČSA**	**Vršany**	**South Field**	**Szczerców Field**	**Husni-cioara**
Service mass (t)	5560	4360	4360	3886	8107	1452
Inverter (units × kVA)	2×1150	2×800	2×800	No	6×400	No
Motor (units × kW)	2×1150	2×800	2×800	3×700	6×200	2×630
Motor RPM	993	993	993	N/A	990	980
Motor frequency (Hz)	8.26-19.84/ 50	8.26-19.84/ 50	8.26-19.84/ 50	50	N/A	50
Motor voltage	400-690V	400-690V	400-690V	20 kV	500-690V	6 kV
BW diameter (m)	13.5	12.6	12.6	17.5	17.5	11.5
Bucket capacity (m^3)	1.3	1.3	1.3	3.7	4.6	1.8
Pre-cutters	No	No	No	Yes	Yes	Yes
Chain back	No	No	No	Yes	Yes	No
Rock deflectors	No	No	No	No	No	Yes

Tab. 4. Inverters on BWEs
Tab. 4. Zestawienie koparek według kryterium zainstalowanych falowników

Mine	**Bílina**	**ČSA**	**Vršany**	**South Field**	**Szczerców Field**	**Husni-cioara**
BWEs with inverter	12	9	9	-	5	-
BWEs without inverter	26	26	26	9	6	5
Total BWEs	38	35	35	9	11	5

Given that the early detection system will be mounted on the BWEs, it will be exposed to the elements. Thus, it is required to withstand the harsh outdoors environment of an opencast mine, which is characterized by the presence of humidity, precipitation, ice, dust, and continuous exposure to UV radiation during daytime. In addition, it is required to operate daily and annually in temperatures ranging widely from -28 to 41°C. In Table 2 data on the environmental conditions at the examined mines are provided.

In Tables 3 and 4 characteristics of selected BWEs are listed. It is observed that four out of the six investigated mines are using BWEs equipped with variable frequency drives. This modern power electronic drives consist of a filter, a rectifier, a DC link capacitor, an inverter, and an AC motor. Many small capacitive couplings exist in the motor drive systems which may be neglected at low frequency analysis but the conditions are completely different at high frequencies (Zare, 2009). Electromagnetic interference is a major problem in recent motor drives that produces undesirable effects on electronic devices, such as high-frequency interference in the range from 150 kHz to 30 MHz in input and output that may cause negative influence on ripple control signal, radio and TV signal, security systems, and radiated emissions up to 1 GHz.

Moreover, it is observed that chain-back buckets are used on BWEs in two mines, as is illustrated in Figure 2. The sensor devices can be integrated on the BWEs by placement either in the bucket wheel or next to it (Overmeyer et al. 2007). The chain-back buckets eliminate the possibility of placing the sensor devices on the bucket itself, as proposed by Mathiak et al. (2011). Thus, the sensor devices must be placed next to the bucket wheel and in a distance where electromagnetic interference is minimized, which in combination with the bucket wheel radius and the vibration of machine components define the requirements for the sensor mounting design.

The cutting height usually varies from 50 to 70% of the bucket wheel diameter, if this is allowed by both the cutting resistance of the material and the stability of the face slope. When selective mining has to be implemented for the excavation of thin layers of material or when the cutting resistance of the material is high, the cutting height can be less than 50% of the

Fig. 2. View of a bucket wheel with pre-cutters and chain-back buckets
Rys. 2 Widok koła urabiającego z czerpakami wyposażonymi w zespoły zębów oraz z łańcuchową matą

Tab. 5. Excavation characteristics
Tab. 5. Parametry eksploatacyjne

Mine	Bílina	ČSA	Vršany	South Field	Szczerców Field	Husni-cioara
Multi-layer	Yes	No	Yes	Yes	No	Yes
Selective mining	Yes	No	No	Yes	Yes	Yes
Max block height (m)	35	32	32	33	50	22
Max block width (m)	81	75	75	57	110	50
Working method	Terrace	Terrace	Terrace	N/A		Terrace
Minimum height of cut (m)	0.6	0.6	0.6	N/A		N/A
Max typical height of cut (m)	6.7	6.3	6.3	(8.75)		4.7
Max depth of cut (m)	0.62	0.5	0.5	N/A	1.6	0.81
Max cutting speed (m/s)	3.9	3.7	3.7	3.02	5.0	2.81
Max slewing speed (m/s)	1.06	1.06	1.06	0.58	0.58	0.5
Max boom vertical speed (m/s)	0.15	0.07	0.07	0.08	0.12	0.1
Max BWE travel speed (m/s)	0.6	0.6	0.6	0.17	0.17	0.1

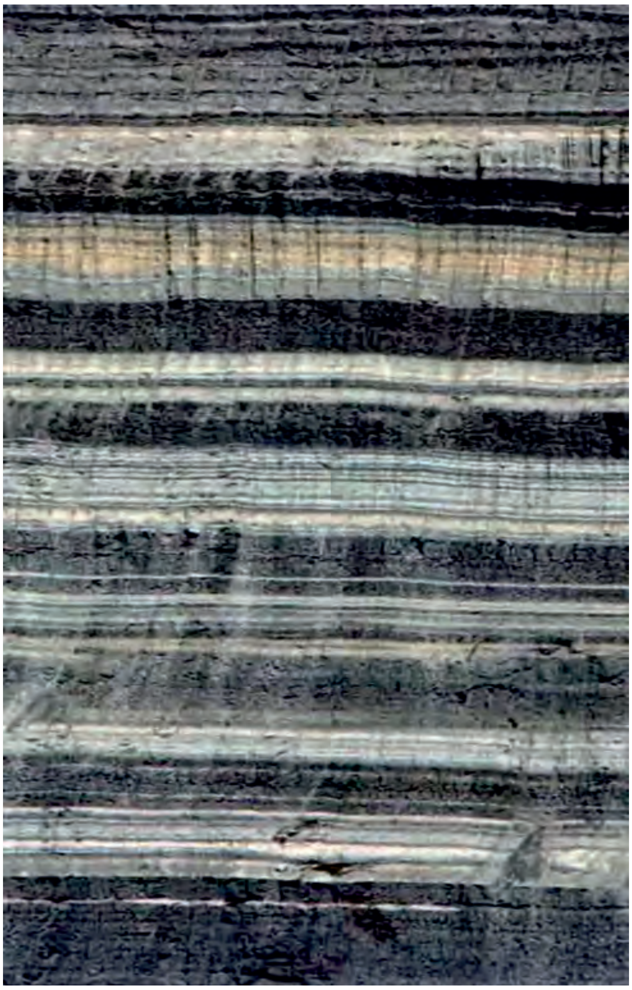

Fig. 3. Typical multi-layer stratigraphy of Greek lignite deposits (Public Power Corporation, 2010)
Rys. 3. Typowa wielowarstwowa stratygrafia greckich pokładów węgla brunatnego (Public Power Corporation, 2010)

bucket wheel diameter and as small as approximately 15 cm.

Selective mining is implemented in four of the examined mines, as can be seen in Table 5 where the excavation characteristics are listed. A special case is PPC's South Field mine where the multi-layer (zebra-like) lignite deposit consists of a series of lignite layers of thickness varying from just a few centimeters up to several meters, separated by intercalations of sandy and clayey waste materials. Figure 3 depicts a typical multi-layer stratigraphy of this deposit. Moreover, very frequently the face surface left behind the cut is undulated as is illustrated in Figure 4. This situation dictates that the sensor mounting design takes into consideration the need to: (i) rotate the sensor in the vertical plane, in order to aim at the actual material excavated at any given time, and (ii) be able to keep a constant distance between the sensor and the face surface.

The maximum recorded depth of cut is 1.6 meters. Hence, the sensor should have the ability to detect hard inclusions at a minimum distance of approximately three meters ahead of the face, which corresponds to the material to be excavated in the two following cuts.

The combination of block width, cut height, slewing speed, boom vertical speed, BWE travel speed, and type of sensor output, defines the data volume, transfer rates, and storage, as well as the computational throughput requirements.

Fig. 4 Typical undulated face surface
Rys 4. Typowa falista powierzchnia skarpy

EVALUATION OF GEOPHYSICAL METHODS

The geophysical methods initially evaluated were:

- Geoelectric
- Electromagnetic
- Combined electromagnetic and electrical resistivity
- Ground penetrating radar (GPR)
- Seismic reflection
- Gravity
- Magnetics
- X-ray fluorescence
- Natural gamma radiation

In addition, the use of infrared detection and optical sensors, as well as body sound analysis was evaluated.

The electrical resistivity method is a fine method for detecting both local bodies and stratigraphy, since coarse materials compared to fine materials have different resistivities, as do compact materials compared to loose materials. The measuring setup of electrodes can focus on a certain depth of detection and is not influenced by bodies farther than this detection depth. The measurements themselves (apparent resistivities or impedances) can discriminate coal from other sediments, as well as boulders. The measurements can be taken with a four or three 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. Use of more electrodes may result in a finer detection, in the sense of resistivity tomography ahead of the excavation. Electrodes in contact with the ground and isolated by the rest of the steel

Fig. 5. Field test to determine the influence of the BWEs steel structure on the measured apparent conductivity
Rys. 5. Badanie terenowe w celu określenia oddziaływania stalowej budowy koparki na zmierzoną przewodność pozorną.

structure of the BWE can be attached to the bucket.

The electromagnetic (EM) 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 has to be close to the ground and at a distance from any steel structure at least two times the detection depth. With a detection depth of three meters ahead of the excavation, the EM measuring device has to be theoretically six meters far from the steel structure. However, during field tests on an operating BWE it was found that there is no significant interference for distances greater than four meters, as is illustrated in Figures 5 and 6. An additional advantage of the method is the relatively low weight of the sensor, which is less than five kilograms.

Both resistivity and electromagnetic methods can discriminate materials usually present in coal mines, with the measured values identifying the material as well.

The GPR method with shielded antennas facing only ahead to the ground is a very accurate geophysical method for detecting interfaces between mainly homogeneous fine material layers or local bodies. Layers or bodies must have different resistivities (or conductivities). Identification of layers or bodies in respect of lithology is difficult. Inhomogeneous material creates noise in GPR sections and the need of good processing is necessary for excluding all noise signals and leaving only the reflection signal identifying the boundary of a layer or a confined body. The GPR method identifies easily the layer boundaries after signal processing, but the identification of a confined boulder is more difficult. In addition, it has the problem that it loses its effectiveness in an environment with conductive material.

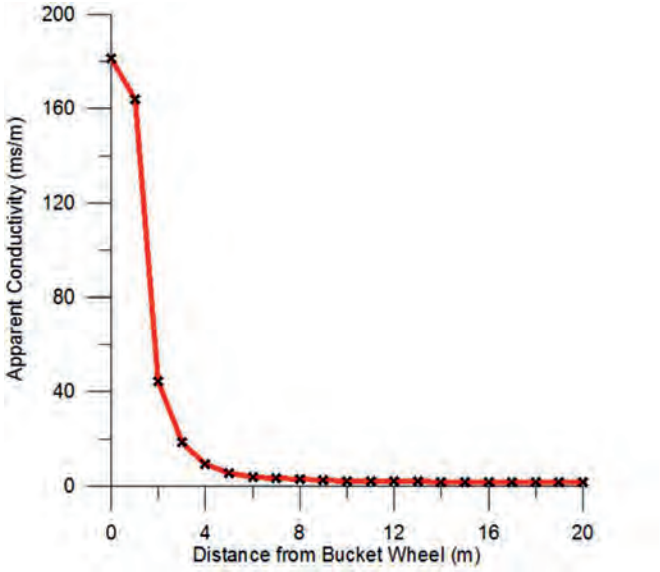

Fig. 6. Measured apparent conductivity versus the distance of the EM sensor from the bucket wheel
Rys. 6. Wykres zmierzonej przewodności pozornej w funkcji odległości czujnika EM od koła czerpakowego

The geologic setting in all six mines, as listed in Table 6 and shown in Figures 7 and 8, 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 electromagnetic (induction or GPR) methods are theoretically promising in detecting the local features. However, 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).

The geological setup with the great conductivity (resistivity) contrast between the local features and the clayey environment can easily be presented by the electromagnetic induction or resistivity methods, which, in addition, are well defining the formations lithologically. A simple 2D or 3D presentation of the measurements is adequate for outlining the local feature, unlike the GPR method where signal processing is necessary. A disadvantage of the electromagnetic induction or resistivity methods is the difficulty in discriminating under certain conditions between an isolated rigid body and a local area of very coarse material. Since both are outlined as a whole,

Tab. 6. Formations hard to excavate.
Tab. 6 Formacje trudno urabialne

Mine	Bílina	ČSA	Vršany	South Field	Szczerców Field	Husnicioara
Continuous layers	Yes	Yes	No	Yes	Yes	No
Boulders	Yes	Yes	Yes	No	Yes	Yes
Boulder material	Quartz Siderite Ankerite Kaolinite	Clayey siderites	Quartz Ankerite Siderite Kaolinite	N/A	N/A	Sandstone
Matrix material	Claystone Sand	Claystone	Claystone Sand	N/A	Sand Gravel Clay Loam	Claystone Sand
Size	0.2-15 m	0.1-1 m	0.2-3 m	N/A	0.1-10 m^3	0.5-15 m
Shape	Spherical	Slab	Spherical	Irregular	Oval	Irregular
Density (kg/m^3)	2200	2300	2200	2400-2700	N/A	2340
Compressive strength (MPa)	15-20	10-35	15-25	15-143	N/A	40-45

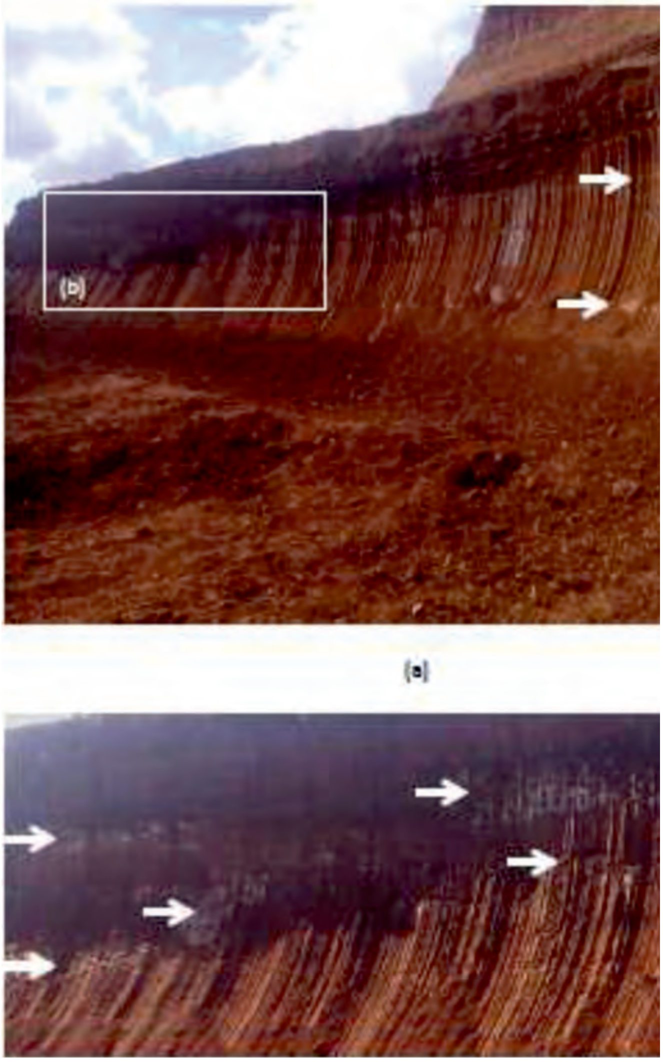

Fig. 7. Hard formations at PPC's South Field mine
Rys. 7. Twarde formacje skalne w kopalni South Field należącej do PPC

the measurement is in these cases inadequate for material discrimination. In any case, either a rigid body or an area of very coarse material of similar size are both outlined well.

In the GPR method focusing on the ground is not affected by the BWE's metallic structure. In contrast, the electromagnetic induction and resistivity methods are affected and the strength of the signal is severely decreased.

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.

In final comparison, 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.

Fig. 8. Boulder at the Husnicioara mine
Rys. 8. Wtrącenie skalne w kopalni Husnicioara

The seismic reflection method is good for detecting layer interfaces. In a quite environment it can be used for detecting layer boundaries. The detection of bodies is dependent on depth. However, the echo signal is severely influenced in noisy environments, thus the method cannot be applied by any technique with a device attached on a BWE.

Gravity and magnetics are reconnaissance methods for surveying wide fields of mining interest. They cannot accurately focus in a certain depth in the conditions of an operating opencast mine or when attached on a BWE.

X-ray fluorescence devices require firm placement on the target and cannot be used remotely, which makes them inappropriate for the given purpose.

Natural gamma radiation is limited to mines with shale as host rock and needs frequent calibration (Maksimovic and Mowrey, 1995).

Infrared detection and optical sensors cannot be used to see ahead of the face. However, they could be used for assisting material detection and calibration of other methods based on the optical properties of the excavated materials. Moreover, they can be used for providing the background on which a measurements map is overlayed, thus facilitating visual warning when the bucket wheel is approaching a hard formation.

Similarly, *body sound analysis* cannot be used to see ahead of the face. However, it could be used for assisting material detection and calibration of other methods based on characteristic vibration frequencies that may be associated with certain materials.

Finally, as already mentioned, an issue of great concern is electromagnetic interference from motors and drives. Of the presented methods the mostly affected by electromagnetic interference is the electromagnetic method because the frequencies used are rather low (10-20 kHz). Countermeasures to minimize interference of harmonics should be considered by modifying the geometry of the sensor and the frequency, shielding of cables and electronics, and the development of appropriate digital filters.

In conclusion, t*he electromagnetic (EM) method and the use of a conductivity meter* is the most suitable geophysical method for the given operational environment.

AUXILIARY COMPONENTS

Sensor mounting

The sensor is carried by an arm mounted on the bucket wheel boom. Based on the operational environment and the selected geophysical method it must have the following characteristics:

- Variable pitch controlled by the cut height.
- Variable length controlled by the face undulations.
- Material not interfering with the electromagnetic sensor.
- Distance between the sensor and the bucket wheel always greater than four meters.
- Manually retractable for sensor protection.
- Easily detachable from the BWE when it is not needed.

Visualization

The output of geophysical measurements may be comprehensible in the eyes of an experienced geophysicist but provides little or no information to the layman. The system is required to provide information on the materials anticipated to be encountered in the next few cuts of the face that is displayed in real-time and in a visually meaningful way on a monitor installed in the BWE's operator cabin.

In this regard, each geophysical method has a certain type of output that defines and confines what can be done. Measurements with the apparent resistivity and apparent electromagnetic conductivity methods are a single numerical value for each surveyed point and therefore can be easily overlayed on a map of the face. The measured numerical value is stored in a database record along with its spatial coordinates. The data records are used to provide a color-coded layer on an image or drawing of the excavated face. This layered image is refreshed in real-time or near-real-time (e.g. every five seconds) and a change in conductivity color warns the BWE operator about the presence of hard formations or local features. Hence, the visualization subsystem is required to integrate images and measurements of various modalities and fuse them in one consistent image of the 2D projection of the cut face. In this integration process, key points on the source images must be detected and geometrically registered, aligned, and blended through image stitching.

Positioning

The precise position and heading of the geophysical signal source in 3D space are required for determining the location of the material volume that corresponds to the measured apparent conductivity. The information is used for producing the measurements map and overlaying it on the face image, thus facilitating the visualization of the conditions ahead of the face.

This can be achieved by triangulation using a Global Navigation Satellite System (GNSS) that is equipped with at least three antennas installed on the BWE, providing the position and heading of the bucket wheel in terms of its absolute spatial coordinates, roll, pitch, and yaw. For the position and pitch of the geophysical sensor itself, a tilt sensor and a linear displacement measuring device can be used for providing its coordinates and heading relative to the bucket wheel.

Signal processing and analysis

In the typical application of geophysical methods, the acquired dataset is processed and analyzed in a second stage where time is normally not a dominating factor. This is not the case in real-time processing and analysis of continuously arriving datasets, which is a highly demanding task requiring high data transfer rates and computational throughput.

Real-time signal processing and analysis is usually based on algorithms involving some kind of parallelism, such as data parallelism and functional parallelism. Multiple identical or different processors, each operating on a different data subset, work concurrently to realize the required high-throughput. The parts of the application involving different kinds of information processing are implemented using dedicated and specific hardware architectures well supporting the required kinds of processing. In other words, efficient real-time signal processing and analysis requires heterogeneous computation platforms (Jozwiak, 2015).

High-performance embedded computing (HPEC) systems provide such a computing capacity in a scalable modular architecture, with a rugged design, small size, and low energy consumption. They are used in mission-critical real-time military applications like radar signals processing, moving target detection, image matching, and unmanned aerial vehicles guidance (GE, 2010).

Graphic processing units (GPUs) and central processing units (CPUs) combined in accelerated processing units (APUs) are the main components of HPEC systems, providing specialized capabilities for each task. Backplanes are used for high-speed data traffic management between individual function modules.

In the case of the formations detection system an added complexity to the signal processing and analysis is due to the need of visualizing in real-time the geophysical measurements. To this end, embedded vision technology has to be used.

Embedded vision is the technology that executes vision algorithms or vision system control software (Embedded Vision Alliance, 2016). The typical computer vision pipeline is shown in Figure 9.

Different types of processor architectures are used for embedded vision usually combined in heterogeneous computing environments. Common processor architectures are:

- General purpose CPUs. They are best suited for heuristics, complex decision-making, network access, user interface, storage management, and overall control. A general purpose CPU may be paired with a vision-specialized device for better performance on pixel-level processing.

- Graphics Processing Units. They deliver massive amounts of parallel computing potential and can be used to accelerate the portions of the computer vision pipeline that perform parallel processing on pixel data.

- Digital Signal Processors (DSPs). They are preferred for processing image pixel data as it streams from a sensor source.

- Field Programmable Gate Arrays (FPGAs). They simultaneously accelerate multiple portions of a computer vision pipeline.

- Application-Specific Standard Products (ASSPs). Vision-specific processors and cores are specialized, highly integrated chips tailored for specific applications or application sets.

Heterogeneous computing environments are used for accelerating image processing because the data rate and algorithm complexity are not constant when traversing the processing pipeline. The pipeline starts with ultra-high data rates and low algorithm complexity to end in low data rates and high algorithm complexity, while the total computational load varies between 10 and 100 billion operations per second (Vissers, 2014). This transition is shown in Figure 10. To address this issue a combination of processing elements is typically used:

- CPU for complex decision-making, network access, user interface, storage management, and overall control.

- High-performance DSP for real-time, moderate-rate processing with moderately complex algorithms.

- Highly parallel engines for pixel-rate processing with simple algorithms.

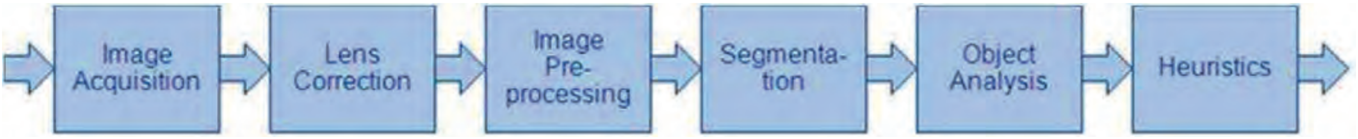

Fig. 9. The typical computer vision pipeline (Embedded Vision Alliance, 2016)
Rys. 9. Typowy przykład przetwarzania potokowego (Embedded Vision Alliance, 2016)

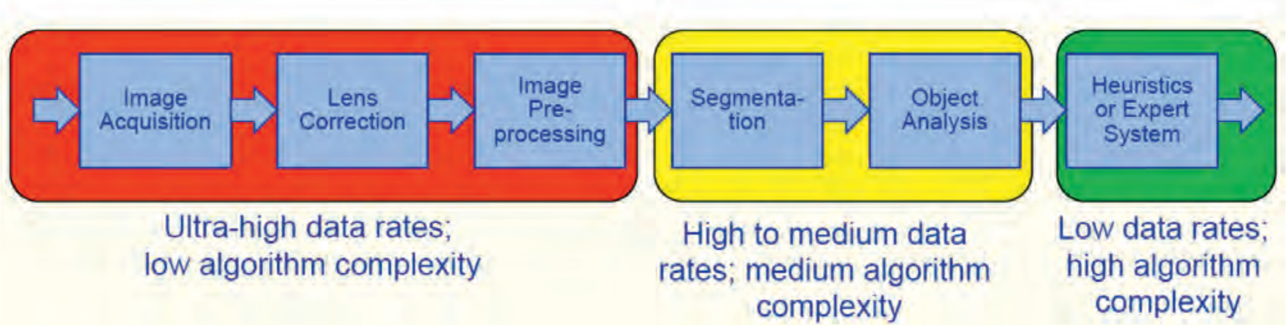

Fig. 10. Data rate and algorithm complexity in the image processing pipeline (Vissers, 2014)
Rys. 10. Szybkość przesyłania danych i złożoność algorytmu w potoku przetwarzania obrazu (Vissers, 2014)

CONCLUSIONS

In this paper the requirements of a hard formations early detection system in opencast lignite mines using BWEs are presented. The system is mounted next to the bucket wheel and continuously monitors the ground ahead of the excavation face as the bucket wheel is traversed.

For the given operational environment and geologic setting that is dominated by fine grained materials, generally of a clayey character, which form the matrix where hard formations occur, the electromagnetic method and the use of a conductivity meter is the most suitable geophysical method. The system detects layer interfaces, local features and their material, and provides in real-time a clearly comprehensible warning to the BWE operator when hard inclusions difficult to excavate are identified.

The approach is to focus on the area where the actual problem of digging into hard inclusions may take place, namely the excavation face of the BWE. The goal is to extract and visualize useful information on the existing ground conditions from geophysical data for a few cutting depths ahead of the face, typically in the range from one to three meters.

Critical issues that must be dealt with are:

- The harsh mining environment. Extreme temperature variations, humidity and precipitation, dust, UV radiation, machine vibrations, massive steel structures, and electromagnetic interferences impose the need for rugged equipment that can withstand these conditions and remain operational and reliable.

- High data volume and transfer rates.

- High computational throughput is needed for processing the raw data by using high-complexity algorithms in a relatively short amount of time.

- Precise positioning is required for minimizing the margin of error.

- Different data modalities have to be fused into spatially located information and simple, comprehensible visual and audio messages.

Finally, the system must be able to adapt to the highly variable operational conditions dictated by the geology and the excavation methods.

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