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APPLICATION OF SELF POTENTIAL METHOD IN THE AREA CONTAMINATED WITH OIL DERIVATIVES

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ABSTRACT

Oil derivatives contamination of soils effects in changes of many physical properties of soil such as: electrical resistivity, conductivity and self potential (SP) as well. Thus the measurable anomalies of these properties are possible to detect with geoelectrical measurements.

SP geoelectrical measurements were carried out in the area of controlled oil spill. The oil was spilled into vadose zone of dry sands. The first underground water level was observed at the depth of 10 m. The measurements were carried out along 20 m long profile situated above 3 m long contaminated zone. The part of contaminated zone (1.5 m) had been subjected to bioremediation process with yeasts *Yarrowia lipolytica* since 4 months. In the border of contaminated zone and biodegradated one chemical gradient was developed and significant increase of self potentials values can be observed.

The measurements were carried out with potential gradient method. Lund Imaging System equipment and non-polarizable electrodes ($Cu/CuSO_4$) were applied.

Above contaminated and biodegraded zone distinct SP anomaly (10-20 mV) was measured. The anomaly correlates with results of EM, resistivity imaging and induced polarization investigations.

KEYWORDS: self potential (SP), resistively imaging, electromagnetic survey, oil contamination, bioremediation

INTRODUCTION

In all cases when changes in our environment are hazardous and are due to human activity we are forced to undertake the affective remediation to reduce its degradation. The effectiveness of applied action depends on how rapid is our detection of polluted areas and on how quick we can identify the source of pollution. In case of the shallow subsurface soil contamination with non-aqueous phase liquids (NAPL) we can use the geophysical methods in most cases they allow for quick and inexpensive evaluation of contamination level and the range of the environment degradation. The geoelectrical methods seem for these aims excellent and are noninvasive what is also important.

Contaminations with oil derivatives products generate, in various way, corresponding changes of physical rock properties e.g.: electrical resistivity, electromagnetic conductivity, self and induced potentials. The level of changes depends in large degree on the concentration of contaminants. A lot of papers present the results of the detection and of monitoring of polluted areas with resistivity and electromagnetic methods (Mazáč et al., 1990; Monier-Williams, 1995; McNeill, 1997; Sauck et al., 1998; Riser-Roberts, 1998; Mareš et al., 2000; Sauck, 2000; Cassidy et al., 2001; Marcak, 2001; Buselli and Lu, 2001; Atekwana et al., 2002; Shevnin et al. 2003; Werkema et al., 2003; Atekwana et al., 2004; Żogała et al., 2005; Che-Alota et al., 2009; Żogała et al., 2009a; Żogała et al., 2009b; Gołębiowski et al., 2010). A few papers only indicate on the effective application for this purpose the self potential methods also (Atekwana and Atekwana, 2010).

The aim of this paper is to present the obtained results of the application of self potential method for the observation of the process of bioremediation with *Yarrovia lipolityca* yeasts of polluted area with oil derivatives. The results of observed self potential above the contaminated plume have been compared with other results obtained with resistivity imaging and electromagnetic methods.

GEOLOGY

The studied area is located in the former fuel base in Borne Sulinowo. The town together with the fuel base is situated at the Pile Lake belonging to the Szczecinek lake district (NW Poland) (Fig. 1). Geologically the area is belonging to the Kujawsko-Pomorski rift. The Cenozoic sediments are deposited

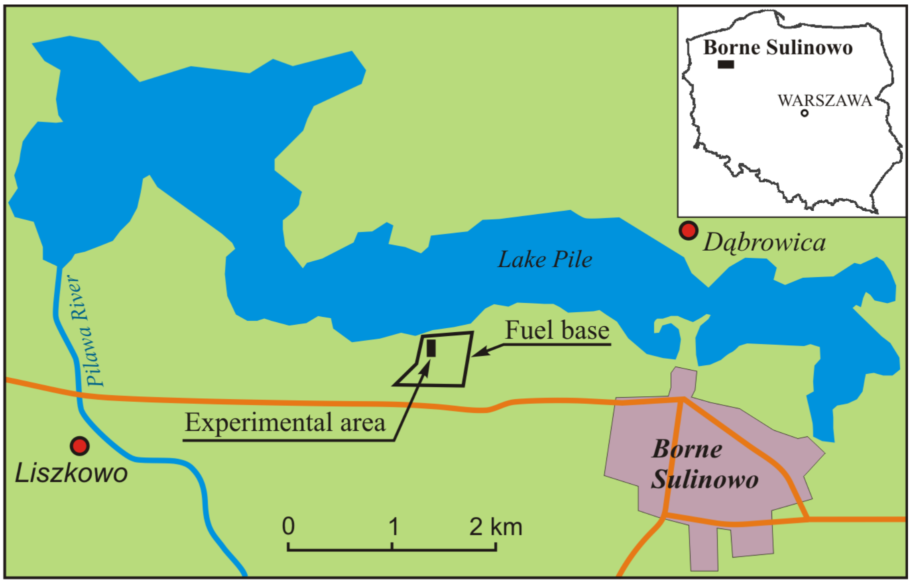


Fig. 1 Localization of study area.

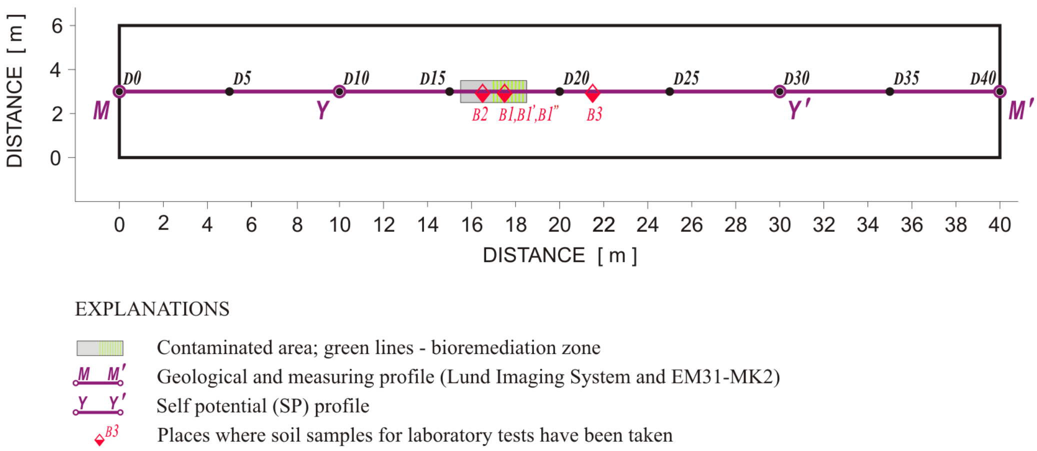


Fig. 2 Plan of survey area.

on the consolidated Mesozoic basement being a part of Middle Polish Anticlinorium. The Cenozoic cover consists of mudstones and Oligocene sandstones, clays, sands and Miocene mud approaching the thickness up to 160 m, the Pleistocene and Holocene sediments with changing thickness from 60 m to 200 m. Pleistocene sediments deposited in this area are of glacial (mainly boulder clays), fluvioglacial (sands and gravels) and limnoglacial origin (sands and mud). The youngest sediments were formed by rivers, lakes and biosphere activity (Żogała et al., 2008).

The experimental profile MM' of 40m length has been marked directky above the evidenced contaminated with oil derivatives plume (Fig. 2) (Żogała et al.. 2009a; Żogała et al.. 2009b).

Along this profile 9 shallow boreholes have been drilled to the depth 5.1 m each. On that basis the detailed geological section has been obtained (Fig. 3). To the recognized depth the sediments consist of sand with varied granulation and one gravel insert. The sands are very dry and that the first unconfined water level has been observed at the depth about 8 m. On the lithological profile (Fig. 3) with continuous red line the contaminated with hydrocarbon derivatives (NAPL) zone in 2007 has been marked and with red dashed lines the polluted plumes observed with resistivity imaging in spring 2008 and autumn 2008 respectively (after bioremediation) (Żogała et al., 2009a; Żogała et al., 2009b).

THE COURSE OF RESEARCH

It was assumed that during research the method of detailed evidence of the polluted hydrocarbon derivatives has been developed with the aim of geoelectrical methods connected with geochemical tests. For this purpose, in autumn 2007 in controlled way the small selected area (3 m x 1 m) along the MM' profile has been polluted (Fig. 2) The

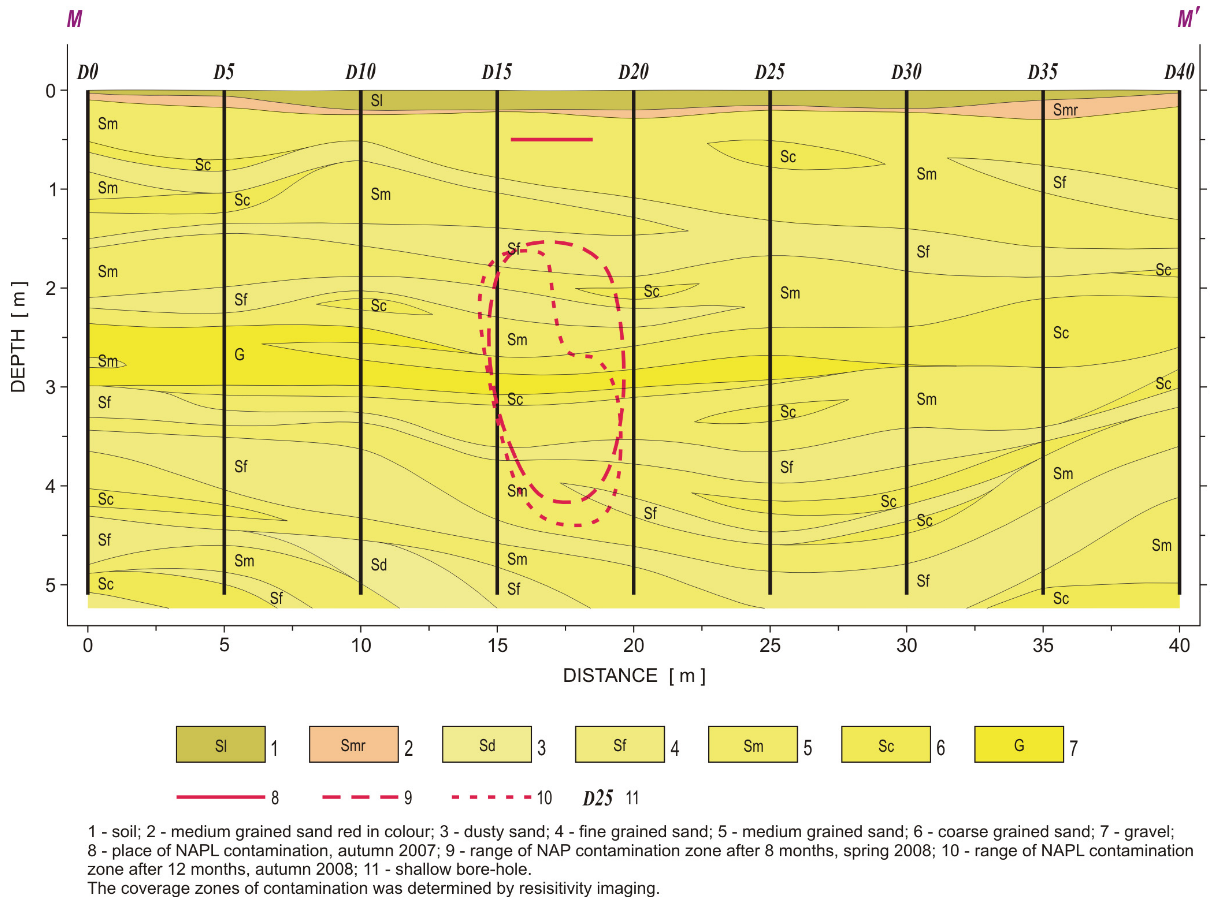


Fig. 3 Lithological profile (Żogała et al., 2009c).

electromagnetic (EM) and resistivity imaging measurements together with laboratory geochemical measurements of the hydrocarbon content in soil samples before and after the application of hydrocarbons into the soil have been carried out. The results of significant anomaly of measured electric soil parameters – connected with pollution – increase of resistivity and decrease of apparent conductivity of soil. The same has been also confirmed by laboratory test.

Half year later at spring 2008 the next EM and resistivity imaging measurements has been carried out to observe the pollution migration. Afterward, above the half of the polluted area between 17.0 m and 18.5 m of the MM' profile has been exposed to the biological mat containing *Yarrowia lipolityca* yeasts submerged in sodium alginate and the process of bioremediation has been started.

The immobilization of yeast cells involved adding of 2000 ml of 2.5 % sodium alginate to 500 ml of concentrated biomass (15 x 10^{11} cells) and dropping the resulting solution by a multi-needle jet into 0.2 M solution of calcium chloride. Finally, 2.5 l of beat where received and the number of cells in 1 ml of beads was 1.7 x 10^{9} (Kowalczyk et al., 2009; Robak et al., 2011).

The following measurements – for the monitoring of polluted plume and the bioremediation process – have been carried on at autumn of 2008. The EM, Resistivity Imaging and Gradient Self Potential methods have been applied. The EM and Resistivity Imaging measurements have been realized along the 40 m MM' profile. The experimental SP measurements were realized on shorter 20 m long YY' profile (Fig. 2) using non–polarizable electrodes $Cu/CuSO_4$ recommended for such measurements. They are reducing electrical coupling occurring on the electrode – soil contact.

THE BRIEF DESCRIPTION OF THE SELF POTENTIAL MECHANISM

The electrical Self Potential (SP) method can be applied in those areas where the premises of the polarized geological bodies exist and the geology of subsurface strata and depth of their occurrence is appropriate for the SP survey. The penetration depth of the method is determined by the size of the polarized body and the size of the potential drop on its surface. Polarized geological bodies are the result of natural ability of same rocks either geological, geochemical or biological processes to create electrical sources in geological medium. The

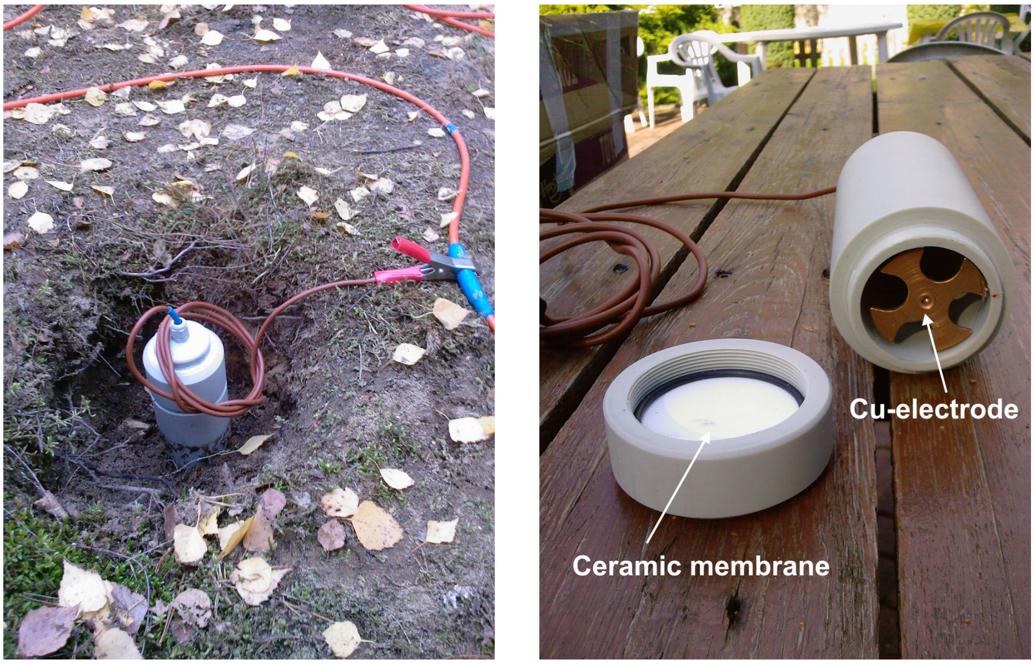


Fig. 4 Non-polarizable electrodes.

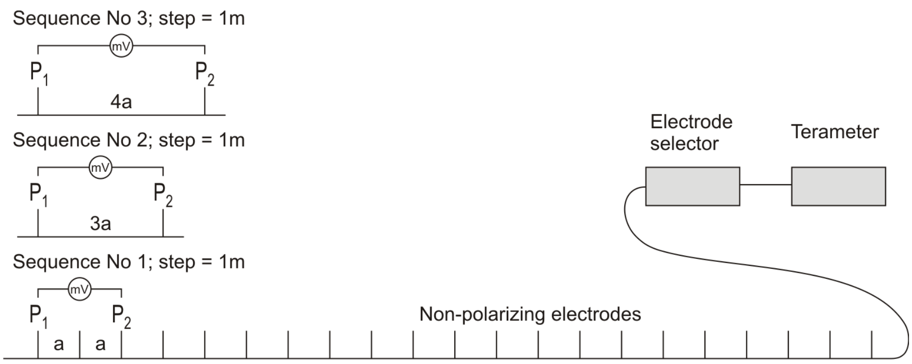
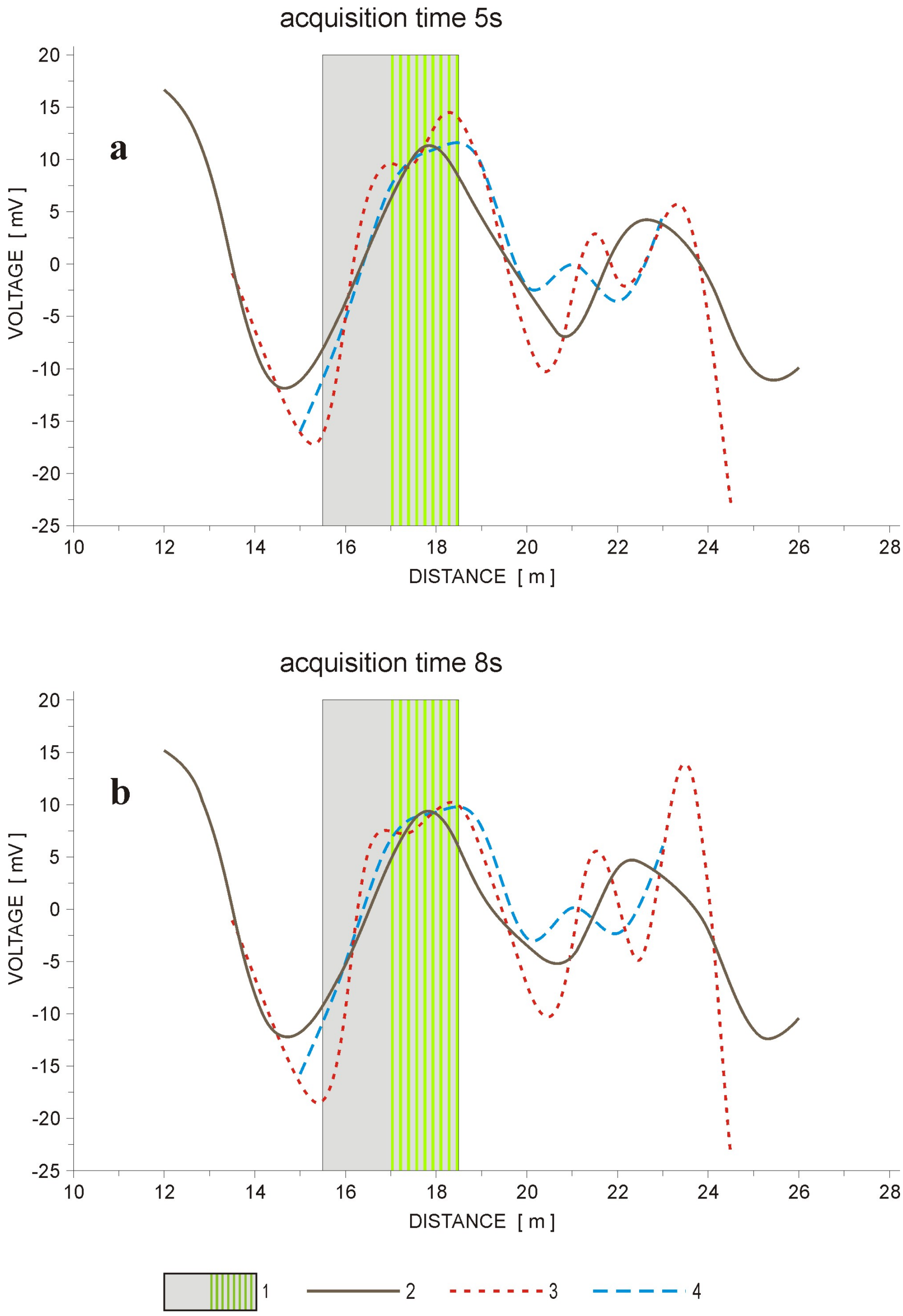


Fig. 5 The measurements the SP gradient method.

geological bodies are polarized when certain minerals are occurring or fluids are saturating the pore space generating good electrical conductivity. Ore-bearing minerals existing on the boundary between saturated and vadose zone are suspect to corresponding red-ox processes. As a result two in opposition polarized zones are emerging in the ore-body and the electrical current is generated in the geological medium (Dzwinel, 1972).

In case of electrolyte occurring in the pore space the mechanism of SP generation is related with flow, diffusion and concentration of ions. As a result the measured self potential is a sum of streaming potential occurring on the boundary mineral – fluid, diffusion potential and connected gradient of ion concentration and mineralization potential (arising from ion content), thermoelectric potential (resulting from thermal gradient) and bioelectric potential (presence of plant roots). In addition, the activity of microorganisms generates significant variations in soil and groundwater chemistry changing the level of red-ox reactions. However, the microorganism activity and its influence on the SP value is not fully recognized. The yeasts introduced into the polluted soil have changed the value of streaming potential influencing on electrical properties of the interface boundary fluid – mineral. In described case the fluid was NAPL which due the yeasts activity has been decomposed into the organic acids and water. The microorganism cells attached to the mineral grain are behaving as a colloid particles causing the increase of effective surface (the surface charge density is increasing) in this way increasing the polarization effect (Atekwana and Atekwana, 2010).



1 - NAPL contaminated area; green lines - bioremediation zone; 2 - sequence No 1, P_1P_2 = 2m (2a);
3 - sequence No 2, P_1P_2 = 3m (3a); 4 - sequence No 3, P_1P_2 = 4m (4a)

Fig. 6 Selected parts of SP curves in different acquisition time windows.

SELF POTENTIAL SURVEY

The SP measurements are realized determining the potential drop between two electrodes (P_1 and P_2) installed in the soil. In this case the non-polarizable electrodes are recommended. In described work the $Cu/CuSO_4$ electrodes have been used – it means that the Cu rod was submerged in $CuSO_4$ solution which was in contact with the soil through semi-permeable membrane (Fig. 4). Such system is reducing the undesirable polarization of electrodes observed in case of steel electrodes pushed in the soil.

In the measurements the SP gradient method has been applied. The scheme of the measurement set is presented in Figure 5.

Surveys were carried out along the YY' profile (Fig. 2) in two series with acquisition time 5 s and 8 s. The signal was always sampled with 0.1 s step and the

Table 1 Interpretation results of SP curves for contact polluted zone – bioremediation zone.

Electrode spacimg	P_1P_2 = 2m		P_1P_2 = 3m		P_1P_2 = 4m		Median	Quartile deviation
Acquisition time	5 s	8 s	5 s	8 s	5 s	8 s		
V_{min}/V_{max}	0.90	1.06	1.16	1.85	1.51	1.35	1.26	0.19
α	0	0	5	10	8	6.5	5.8	3.2
z [m]	2.12	2.12	2.11	2.09	2.10	2.81	2.12	0.01

Table 2 Interpretation results of SP curves for contact bioremediation zone – clean zone.

Electrode spacing	P_1P_2 = 2m		P_1P_2 = 3m		P_1P_2 = 4m		Median	Quartile deviation
Acquisition time	5 s	8 s	5 s	8 s	5 s	8 s		
V_{min}/V_{max}	0.79	0.62	0.74	1.04	0.55	0.68	0.71	0.07
α	-2	-3	-2	0	-5	-3	-2.5	0.5
z [m]	2.12	2.08	1.41	1.41	0.70	0.71	1.41	0.52

mean value was recorded. In each measurement series 3 measurement cycles has been realized automatically with electrode spacing 2 m, 3 m and 4 m shifting the electrodes with 1 m step.

INTERPRETATION AND RESULTS

Introductory interpretation was based on the visual inspection of the course of SP values along the profile. One is looking for extreme value which may be related with the existence of disturbing structures (bodies) in geological medium. Steep slopes of SP gradient curves may indicate on the high resistivity contrast in the medium. Assuming the disturbing body as a spherical, one may estimate the polarization angle value of this sphere and the depth of its center which is localized in the middle of the distance between the potential extreme values (V_{min} and V_{max}). For the potential curve passing above the epicenter of the disturbing body there exist the relation between the potential ratio V_{min}/V_{max} and the polarization angle α (Zaborovskij, 1963; Dzwinel, 1972):

$$\frac{|V_{\min}|}{V_{\max}} = f(\alpha)\,,$$

Polarization angle is the angle between the horizontal axis and polarization axis of the spherical anomaly. Knowing the polarization angel one may estimate the depth of center of the spherical body from the relation (Dzwinel, 1972):

$$z = \frac{d}{\frac{3}{2}\sqrt{\tan^2\alpha + 8/9}}\,,$$

where d is distance in [m] between the extreme potential values (min. and max.) observed in the self potential curve.

The obtained results are presented as curves of SP potential versus the profile length (Fig. 6)

Next the ratio V_{min}/V_{max} for each electrode spacing and each acquisition time has been calculated for contacts:

- polluted zone – bioremediation zone
- bioremediation zone – clean zone.

For first contact the calculated ratio values are in the range from 0.9 to 1.85 what correspond to the polarization angle from 0^o to 10^o (Table 1) and for the second contact in the range 0.62 to 1.04 what correspond to the polarization angle from – 5^o to 0^o (Table 2). For both contacts the depth of the centers of disturbing spheres were also estimated (Table 1 and Table 2).

The results of SP measurements allow to locate the anomaly source along the survey line, to determine its probable nature (distribution of potential signs and polarization angle of the sphere) and to estimate the occurrence depth of the anomaly center. Each of separated anomalies is related to the contact zone which appears in the area of theoretical sphere. For separated zone diameter of theoretical sphere has been calculated which informs on the size of contact zone.

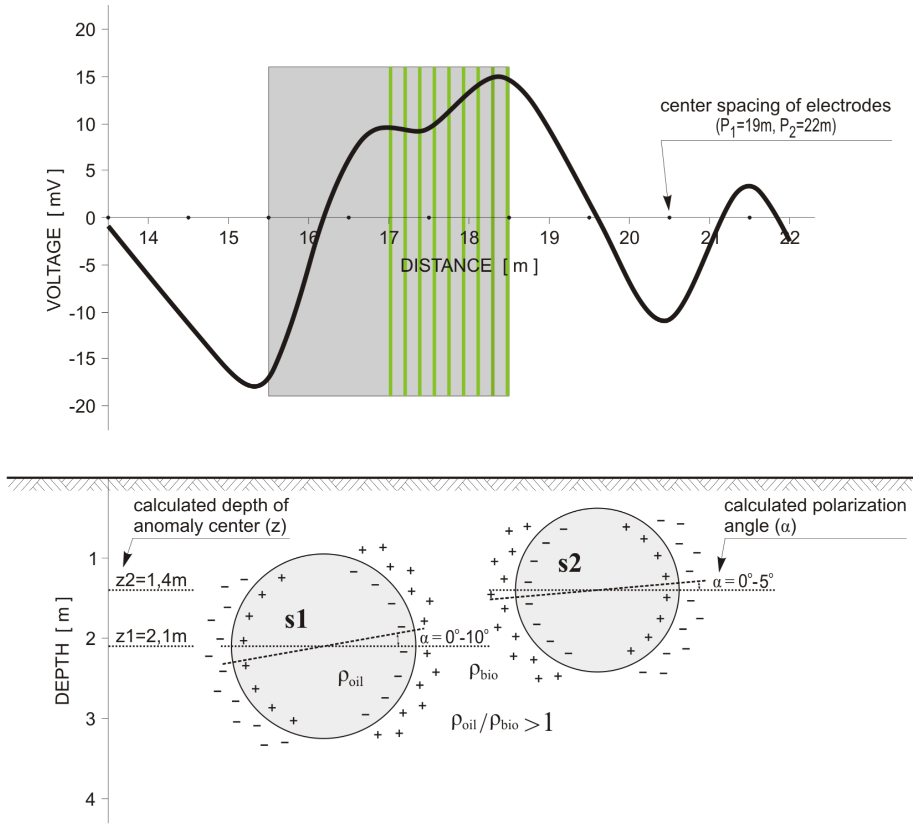


Fig. 7 Results of modeling of contact spheres for electrode spacing P_1P_2 = 3 m and acquisition time 5 s.

The diameter of the sphere was estimated from (Zaborovskij, 1963):

$$2r^2V_0\frac{\rho_{oil}}{2\rho_{bio}+\rho_{oil}}=\frac{|V_{\min}|\left[1+\frac{9}{16}\left(\tan\alpha-\frac{2}{3}\frac{d}{z}\right)^2\right]^{\frac{3}{2}}4z^2}{\sin\alpha+2\frac{d}{z}\cos\alpha}$$

where V_0 – potential drop between contacting zones, ρ_{oil} – resistivity of the polluted zone read off from resistivity imaging inversion model, ρ_{bio} – resistivity of bioremediation zone read off from resistivity imaging, V_{min} – SP potential minimum value, α – polarization angle, z – depth of the anomaly center and d – distance between SP extreme values in contact. For the first zone the contact sphere radius is estimated as 1.15 m and for the second is 1.02 m respectively. An example of calculations for acquisitions time 5 s and electrode spacing P_1P_2 = 3 m is presented in Figure 7.

DISCUSSION

The interpretation of SP curves allowed for quantitative description of the area polluted by oil derivatives. Results of the interpretation have indicated of the depth of the center of the contacts polluted – bioremediated and bioremediated – clean areas and their diameter. Depth to the center of the first zone was approximately 2.1 m below surface (16.2 m of MM' profile) and the second zone 1.4 (19.5 m of MM' profile). The diameter was 2.3 m and 2.04 m respectively.

Figure 8a presents the results of resistivity imaging of the soil from the autumn 2007 (before the controlled pollution). Figure 8b shows result from spring 2008 (8 month after pollution) and in Figure 8c the results are presented from autumn 2008 (4 month after the initiation of the bioremediation process). The analysis of resistivity cross-section from the last period of measurements (Fig. 8c) confirm the results obtained by SP measurements. The modeled sphere (s1 and s2) can also be observed on the resistivity inversion model. One can notice the contact zones of the bioremediated, polluted and clean soil.

Similar correlation exists with the changes of soil apparent conductivity presented in Figure 9. Horizontal extents of contact zones are well correlate with observed soil apparent conductivity (sphere diameters are marked by horizontal lines s1 and s2). The contact zone between polluted and remediated areas exist in the center of the low apparent conductivity anomaly (Fig. 9) while the contact zone between bioremediated – clean soil is observed in that part of apparent conductivity profile where the specific increase of soil conductivity occurs. At the same time the soil conductivity value for the second

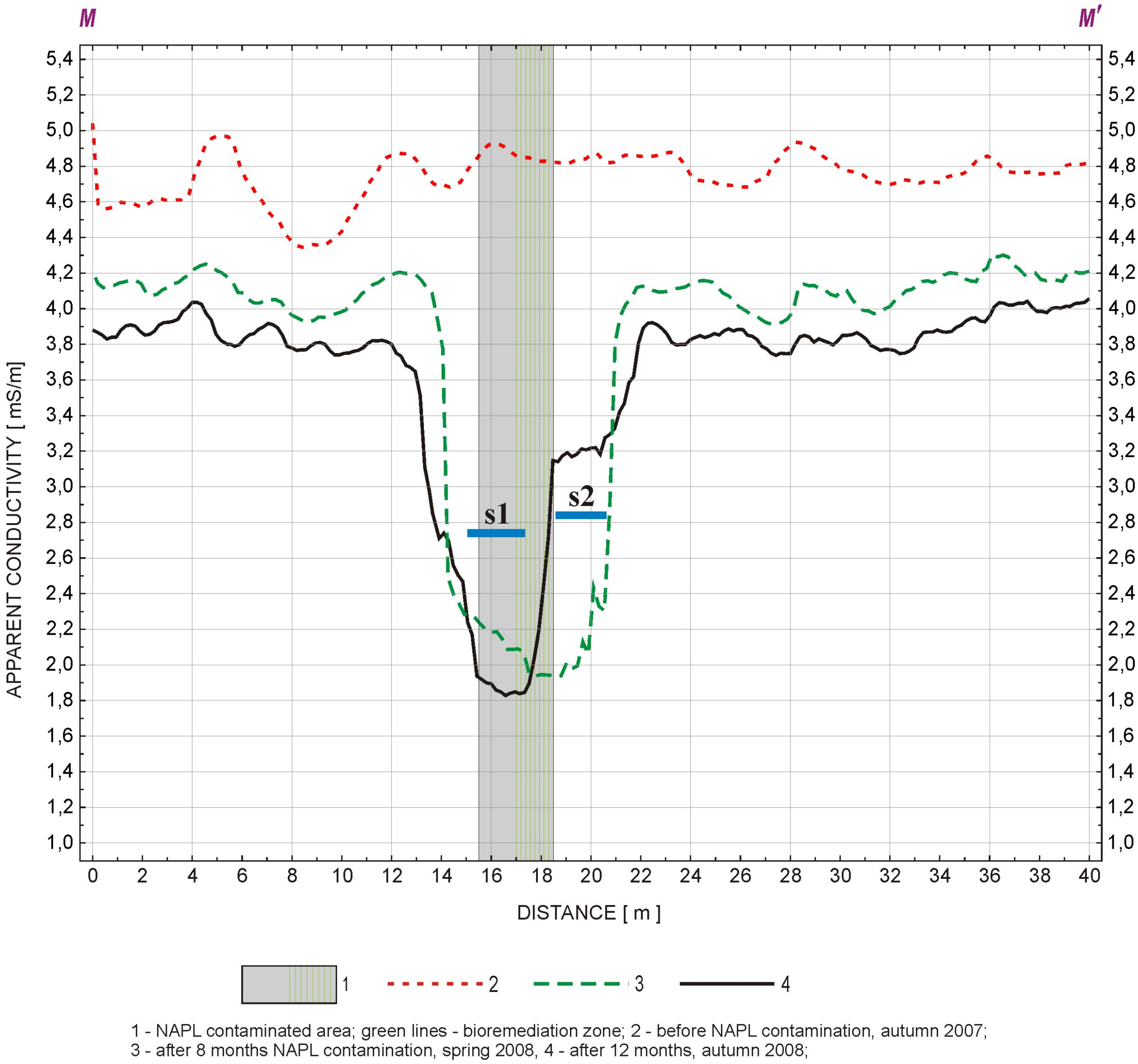


Fig. 9 Variations of apparent conductivity along the MM' survey line.

contact zone is still relatively lower than in the surrounding area.

Results of SP measurements indicate that the anomaly size depends on concentration changes of hydrocarbons in the soil. In polluted zone their concentration is larger than in other edges and due to this the bioremediation intensity is larger in the central part of the polluted zone – first zone. The modeled first zone is bigger and its center is related with bioremediation occurring at the depth above 2 m below surface. Probably to that depth at the time of measurements (autumn 2008) the activity of microorganisms has been occurred.

The second zone is located in the outer edge of the pollution, the concentration of hydrocarbons was lower there, therefore, the activity of yeasts also. This results are in lower SP anomaly. The comparison of SP curves (Fig. 6) with results of resistivity imaging (Fig. 8c) and changes of apparent conductivity (Fig. 9) for the autumn 2008 indicate that SP profiling can be effectively applied to mapping the polluted areas and to monitor their bioremediation with location of their contact zones.

It should be pointed that measurements have been carried out in relatively unique environmental conditions. They are specified by large resistivity and conductivity contrast in dry geological sediments with large concentration gradients of the hydrocarbon components in the pore space.

CONCLUSIONS

The SP method has proved to be a good method to identify the size and depth of occurrence of contamination and the bioremediation zone.

Resistivity Imaging, EM and SP methods documented similar ranges of size of contaminated and bioremediation zones. Good approximation of size of contaminated area and degree of bioremediation obtained from SP survey probably is caused by uniquely environmental conditions: relative deep ground water level (10-12 m), dry post-glacial sandy soils in the vadose zone.

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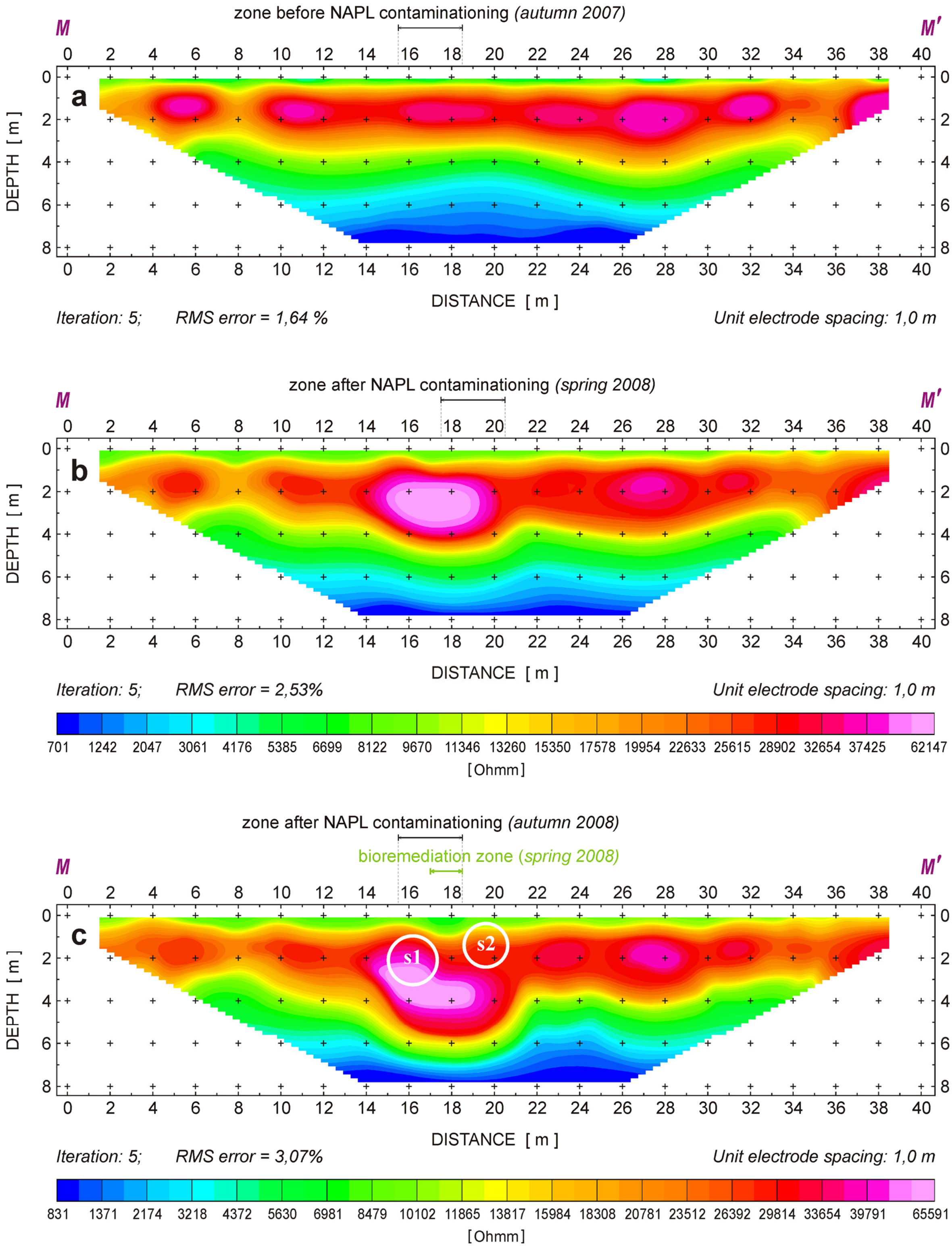

Fig. 8 Resistivity cross-sections:
a) before NAPL contamination (autumn 2007),
b) after NAPL contamination (spring 2008),
c) after 1 year NAPL contamination (autumn 2008) (Żogała, in press)