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Geophysical investigation using resistivity and GPR: A case study of an oil spill site at Seberang Prai, Penang

ZAW WIN[1]*, UMAR HAMZAH[1], MOHD AZMI ISMAIL[2] & ABDUL RAHIM SAMSUDIN[1]

[1]Pusat Pengajian Sains Sekitaran dan Sumber Alam, Universiti Kebangsaan Malaysia
43600 Bangi, Selangor, Malaysia
[2]Agensi Nuklear Malaysia, MOSTI
*Email address: rofiquezw@gmail.com

Abstract: Subsurface contamination by light non-aqueous phase liquids (LNAPLs) is one of the most pressing environmental issues in the industrialized and developing world. Non-invasive geophysical techniques have proven to be effective in identifying contaminated areas. In this study, a 2D electrical resistivity imaging and ground penetrating radar (GPR) survey has been carried out at a site to investigate the nature and extent of an oil spill into sandy soil and groundwater from old transformersat an abandoned power station. Hand-augered boreholes revealed that the water level was at 1.5 m and shallower towards the coastline, which is about 100 m from the site. The presence of several oil plumes were detected at the top of the water table in 2D resistivity sections as a zone of high resistivity with values ranging from 450 to 1000 Ωm. The low resistivity zones below the water table are interpreted as saline water. In the GPR section, the oil contaminated layer exhibits discontinuous, shadow and chaotic high amplitude patterns.

Keywords: electrical resistivity imaging, ground penetrating radar, oil spill

INTRODUCTION

The purpose of locating contaminants is typically for site assessment to determine the type of remedial action, which usually involves excavation and safe disposal of the hazardous contaminants with minimal damage to the environment (Halihan *et al*., 2005). The most common soil and groundwater contamination problems result from the release of petroleum products (Newell *et al*., 1995). Petroleum products such as nonaqueous phase liquids (NAPLs) are hydrocarbons that exist as a separate, immiscible phase when in contact with water and/or air. NAPLs are typically classified as either light nonaqueous phase liquids (LNAPLs), which have densities less than water or dense nonaqueous phase liquids (DNAPLs) with densities more than that of water. The LNAPLs on the water table do not necessarily stay in one place; they can migrate, exist as a partially dissolved phase and even be temporarily submerged below the water table during times of high rainfall. Migration of LNAPL's in the subsurface appears to be associated with rainfall, seasonal variations and the hydrologic gradient in an area. LNAPL's above the water table can be concentrated by changes in the permeability of the subsurface materials in the unsaturated zone. All of these factors make it very difficult to adequately estimate the quantity or continuity of subsurface hydrocarbon contaminated products.

Clearly, to overcome these difficulties, data gathering techniques must be developed so that areas or volumes of the contaminated subsurface can be examined. These methods should be economical when compared to alternative techniques. Geophysical subsurface investigations such as ground penetrating radar (GPR), electrical resistivity imaging (ERI), electromagnetic induction, spontaneous potential and vertical resistivity profiling (VRP) are techniques that are routinely used to investigate the subsurface for engineering and environmental purposes. The GPR and ERI techniques has been the subject of considerable interest among geophysicists for mapping subsurface contaminants in recent years. These methods are applicable as the NAPL contaminated zone is electrically different from the surrounding material, thus presenting anomalies suggestive of their location (Mazac *et al*., 1990; De Ryck *et al*., 1993; Redman *et al*., 1994). High resistivity anomalies obtained by surface resistivity methods can indicate the location of LNAPL. LNAPL was identified from a high resistivity anomaly in Arizona (Benson & Mustoe, 1998). Controlled experiments have also been conducted for evaluating ERI during gasoline spills (Daily *et al*., 1995). In cases where a plume has aged approximately 50 years, an LNAPL can show an elevated conductivity relative to the surrounding geologic material (Atekwana *et al*., 2000).The initial free product accumulation may show up as a resistive area only until biodegradation becomes established. After time, the mixed zone and underlying aquifer may show anomalously low resistivity. This suggests that LNAPL sites should be treated as individual cases, with changes dependent on site composition, time, and many other variables specific to the location (Atekwana *et al*., 2000).

A geophysical investigation was conducted in an abandoned power plant station situated in Seberang Prai, Penang (Figure 1).The survey was carried out over an area of 50 m x 30 m. Four transformers had been based in the study sites, which were recently removed. There are also pipelines and reinforced remains in the surveyed area. Some concrete foundations are noticed on the surface. The objective of the

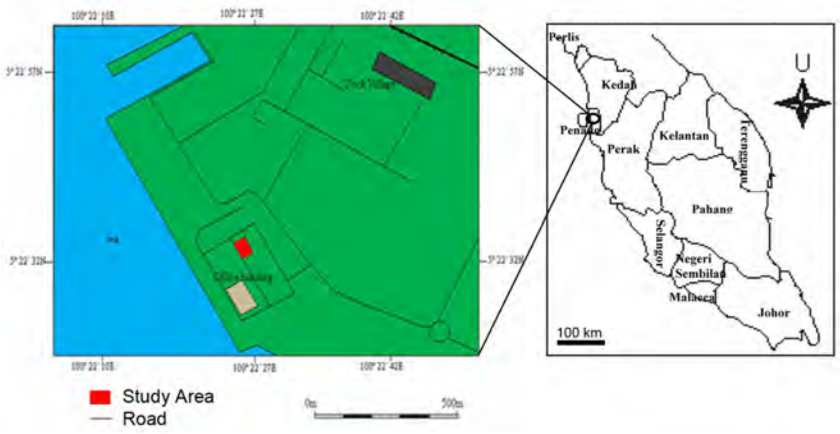


Figure 1: Location of the study area.

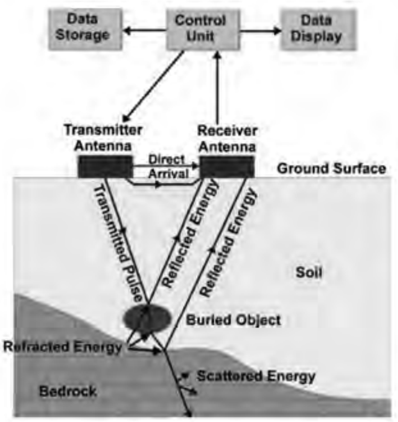
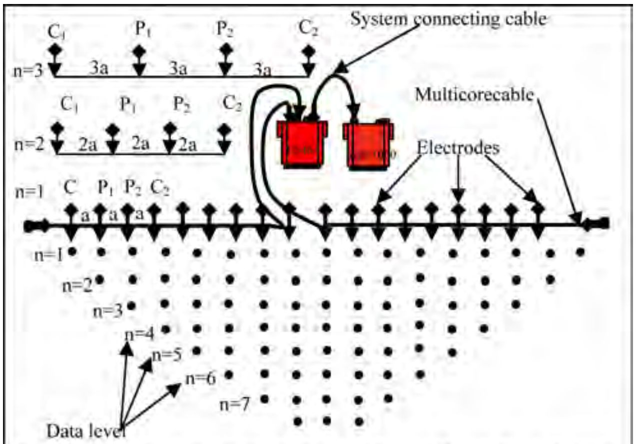


Figure 3: GPR schematic, from Environmental Protection Agency (EPA).



C_1 and C_2 are the current electrodes and P_1 and P_2 are the potential electrodes. a, 2a and 3a are the electrode separation for n=1,n=2 and n=3 respectively. The dots represent locations of the potential points measured below surface of the survey line

Figure 2: The arrangement of electrodes for a 2-D electrical survey and the sequence of measurements used to build up a pseudosection.

subsurface investigation was to determine the location and extent of contaminants; ascertain the presence of contaminant geometry, plumes and their sources; and asses associated hydrogeological conditions. Many shallow boreholes were drilled and soil samples were collected for this purpose.

METHODOLOGY

Electrical resistivity imaging (ERI)

A solution to contaminant detection and monitoring problems in the vadose zone is the utilization of electrical imaging to provide more complete site data coverage. Electrical resistivity surveys involve injecting current into the ground between two electrodes, and measuring the voltage difference between two other potential electrodes. For nearly a century, these surveys have been used to perform one-dimensional profiling (detection of lateral changes in underground electrical properties by moving a fixed electrode array along a survey transect) or sounding (detection of vertical changes by expanding an electrode array about a fixed location). Within the last decade, development of multi-conductor electrode cables and computer driven, automated switching, as well as innovative processing of large resistivity data sets enable simultaneous performance of profiling and sounding to produce two-dimensional “electrical images” depicting detailed variations in subsurface electrical properties.

ERI is an inverted model of hundreds to thousands of four electrode resistivity measurements (Figure 2). Hundreds of measurements of a site are required to produce a 2-D or 3-D ERI model of the subsurface. An ERI image is taken using an acquisition algorithm that collects data from a series of electrodes placed either on the surface or located in boreholes. Two-dimensional data are collected using a linear array of electrodes and 3-D data can be collected using electrodes placed as a series of 2-D arrays or a 3-D electrode grid. The image is developed using an inversion algorithm. The inversion algorithm uses the collected apparent resistivity data to create a model space of resistivity values that would replicate the collected data.

The ABEM Terrameter model SAS 1000 was used for data collection in this survey. The measurements were carried out using Sclumberger protocol electrode configuration. The Sclumberger protocol provides detailed data related to limited depth with good vertical resolution for a clear image of groundwater and sand-clay boundaries. The applied current intensity was in the10–50 mA range. The data collected in the field are interpreted RES2DINV software (Loke & Barker, 1996), which automatically subdivide the subsurface into a number of blocks and then use a least-squares inversion scheme to determine the appropriate resistivity values for each block in 2-D. In the resistivity survey, measurements were made along NE-SW and NW-SE directions. Geoelectrical imaging surveys are normally carried out with multielectrode resistivity system. In this survey, 41 electrodes were deployed in a straight line with constant spacing and connected to a multicore cable (Figure 2). A computer-controlled system (Griffith *et al.*, 1990) was then used to select the active electrodes for each measurement.

Ground penetrating radar (GPR)

GPR uses the reflection and scattering response of a propagating radio-frequency electromagnetic wave (MHz) to non-invasively 'image' variations in the dielectric properties of the subsurface (i.e., the permittivity, conductivity and magnetic permeability of the subsurface materials). As a near-surface investigation method, it is particularly successful at detecting changes in pore fluid content related to the appearance of water and/or contaminant plumes and can be used to map relatively expansive areas to a depth of 10 m or more (Cassidy, 2007). The GPR technique is similar in principle to seismic reflection. Pulse-mode GPR systems radiate short pulses of high frequency (10-1000 MHz) electromagnetic energy into the ground from a transmitting antenna. The propagation of the radar signal depends on the frequency-dependent electrical properties of the ground. Electrical conductivity of the soil or rock materials along the propagation paths introduces significant absorptive losses which limit the depth of penetration into earth formations and is primarily dependent upon the moisture content and mineralization present. When the radiated energy encounters an inhomogeneity in the electrical properties of the subsurface, part of the incident energy is reflected back to the radar antenna and part is transmitted into and possibly through the inhomogeneity. The basic components and functional operation of a pulse-mode GPR system are shown in Figure 3.The electrical properties of geological materials are governed primarily by the water content, dissolved minerals, clay and heavy mineral content (Olhoeft, 1992) and functional operation of a pulse-mode GPR system.

Reflected signals are amplified, transformed to the audio-frequency range, recorded, processed, and displayed. From the recorded display, subsurface features such as soil/soil, soil/rock, and unsaturated/saturated interfaces can be identified. In addition, the presence of floating hydrocarbons on the water table, the geometry of contaminant plumes, and the location of buried cables, pipes, drums, and tanks can be detected (Benson & Mustoe, 1996). The GPR data are presented as a two-dimensional depth profile along a scanned traverse line in which the vertical axis is two-way travel time measured in nanoseconds. The radar frequency selected for a particular study is chosen to provide an acceptable compromise between deeper penetration and higher resolution. High-frequency radar signals produce greater resolution, but are more limited in depth of penetration. Further information on the GPR technique can be obtained from Daniels (1996) and Reynolds (1997), while Daniels (2004) gave a detailed description of GPR systems, data processing and interpretation.

The RAMAC system ground penetrating radar was used in this study. The RAMAC system consists of a Model PR-8304 profiling recorder GPR with automatic gain ranging and graphic and/or magnetic tape analog data recording, and a copper-foil dipole antenna having a center operating frequency of 250 MHz. Data collected were processed using 'Ground vision' software to produce 2D radargram in time scale. Prior to producing the time section, the data were filtered to remove the DC current effect and multiplied by gain functions to overcome the attenuation effect of the earth materials. Measurements were made along five lines where three lines were established in the NE-SW direction and the remaining two lines were shot along NW-SE (Figure 4).

Vertical resistivity probe

Vertical resistivity probe(VRP) measurement was carried out in hand-auger drilled boreholes using a sensor consisting of a close-spaced permanent vertical array of mini-electrodes made up of 2.5 mm diameter steel rod fixed at 25 mm spacing and mounted inside a 60 mm diameter PVC pipe. The electrodes were joined to the ABEM SAS 300C Terrameter by a cable inside a 20 mm diameter PVC pipe. The probe was lowered into the shallow borehole and good coupling of the probe with the borehole wall or the soil formation was ensured by pressing it into the wall. Apparent resistivity measurements were made using a 25 m Wenner array at every 50 mm interval.

RESULTS AND DISCUSSION

A total of 22 shallow holes were augured for the VRP survey and some of their positions are as shown in Figure 4.The VRP results show resistivity variation from top to the bottom of the hole ranging from 50Ωm to almost 1000Ωm. Resistivities higher than 200 Ωm coincide with the oil-mixed sand. The thickness of the top sand overlying the contaminated layer is with resistivity ranging from 30 to 200Ωm. The contaminated zone was mapped by plotting the neighbouring VRP positions as shown in Figure 5. During the VRP survey the water level was at a depth of 0.7 m due to high sea level. The site is about100 m from the shoreline.

The inversed resistivity imaging of all 2D models show high resistivity that extends from near the surface to a depth of 1.5 m with the resistivity values ranging from 500 to 2500 Ωm (Figures 6-9).Very high resistivity of this first layer is closely connected to both very dry sands covering

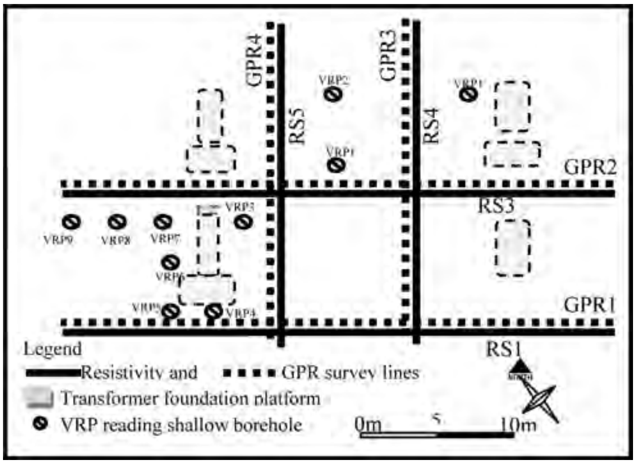


Figure 4: Location of resistivity survey, GPR survey lines and boreholes for the VRP survey.

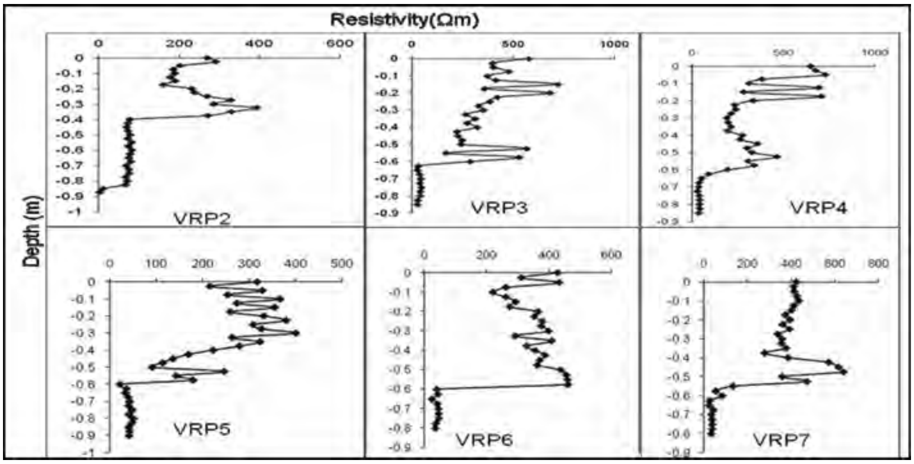


Figure 5: VRP resistivity across a few boreholes.

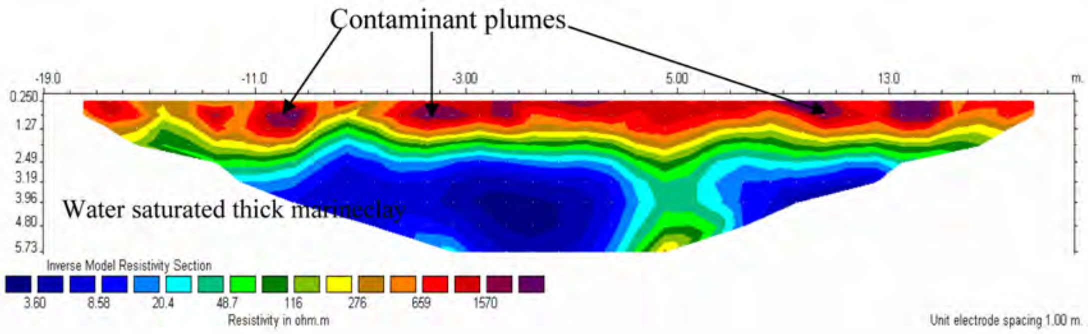


Figure 6: 2D resistivity inversed section of survey line 1 of the study area.

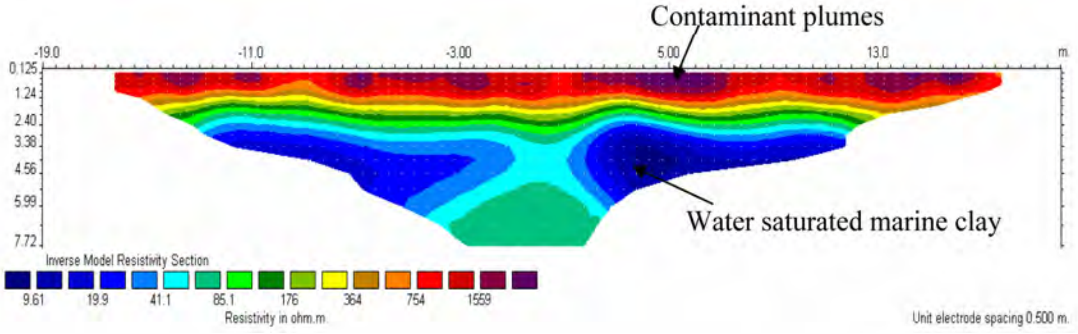


Figure 7: 2D resistivity inversed section of survey line 3 of the study area.

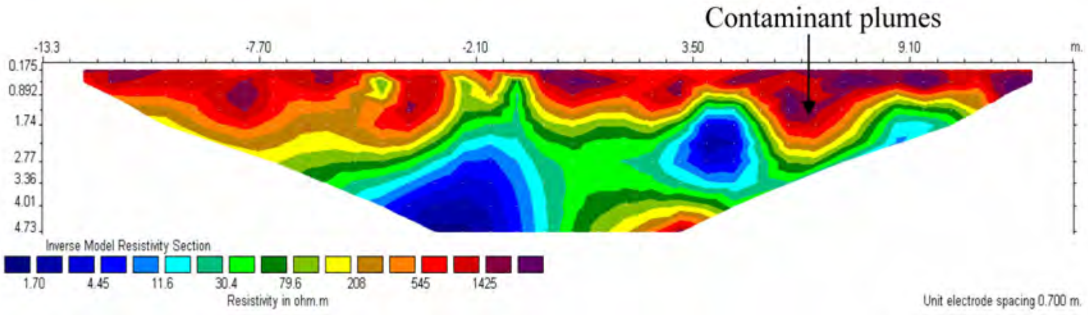


Figure 8: 2D resistivity inversed section of survey line 4 of the study area.

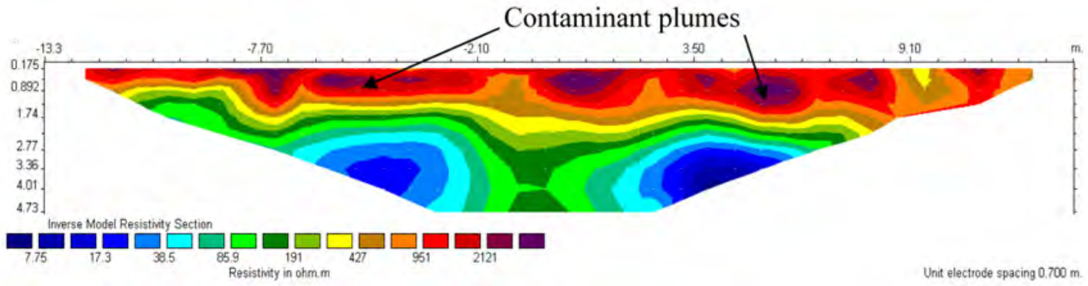


Figure 9: 2D resistivity inversed section of survey line 5 of the study area.

the site and oil contamination evidenced to depths of 0.7 to 1.5 m. The high resistivity “plume” observed in the greater part of the profile is relevant to oil contamination that was observed in the shallow boreholes. The zones correlate very well with places where transformers had been situated. These high resistivity zones are the result of leaking of hydrocarbons contaminants from the transformer. The second layer is composed of poorly water saturated sands with resistivity ranging from 20 to 420 Ωm. The third low electrical conductivity layer is composed of seawater saturated sand and clay with resistivity values ranging from 1.5 to 20 Ωm. Its lower part represents an aquifer whereas the upper one a capillary rise zone. The study also observed that the hydrocarbons are partly absorbed by soil grains and pore spaces.

Average water saturated sands are able to absorb up to 25–45 g/l of hydrocarbons (Malina, 1999). The oil derivative substances migrate in accordance with ground water flow direction to the SW in the upper part of this zone. The contaminants have spread to a considerable part of the study area through this way.

The total of 9 GPR lines was conducted. The best fit of the four profile 2D radargram are presented and interpreted in this paper. All of the GPR sections show the same reflection pattern. Each model can be basically divided into three particular reflection patterns representing different soil types (Figures 10-13). At depths of 0 to 0.9 m, there is an increase in wavelength and amplitude in first the 40 ns where the reflections are flat and show high amplitudes. This is caused by the increase in velocity of the EM wave propagation associated with sand and silt layers. Below this layer, from 40 ns to 85 ns at depths of 1 to 1.5 m, a discontinuous and shadow pattern representing contaminated zone is observed. Underlying this layer, the reflection is weak and is sometimes called the free-reflection zone.

Geologically, the discontinuous and shadow reflection zone represents oil contaminated sand. The presence of oil is detected in this zone especially above the water table at depths ranging from 1 to 1.5 m. Clay and water saturated layers reduce the apparent resistivities or increase the electrical conductivity of the environment to produce weaker GPR reflection pattern as compared to the overlying layer. The discontinuous reflection pattern is also known as the fuzzy or shadow zone and coincides well with the oil contaminated layer. The same pattern has also been reported in a previous study (Atekwana *et al*., 2000). The layer below depths of 1.5m consists of recent marine clay. This high conductivity soft clay will absorb the GPR reflection to produce much weaker reflection zones compared to the layer above. The strong reflector at about 2 m depth in the GPR section is interpreted as top of clay layers

The geoelectrical resistivity results of both VRP and surface resistivity imaging in this study show high resistivity representing oil-contaminated zone as previously reported (Olhoelf, 1992). The results of comparing the VRP result of shallow boreholes and electrical resistivity images indicate that ERI is a good technique for detecting oil contaminants in the shallow subsurface. It should be noted that the ERI images do not provide a signal such that the presence of the type of contaminants is the only explanation for any given anomaly. Some confirmatory drilling almost always is required. Locating anomalies and thus potential hydrocarbon contamination more precisely using ERI techniques allows the subsurface to be drilled and sampled much more effectively and comprehensively than any other currently available technique. This site was reasonably simple in that there was only one contaminant of interest and the resistivity signature for hydrocarbon contrasted clearly with any geologic signatures. If the hydrocarbon was further aged resulting in conductive features as reported along with resistive features (Atekwana *et al.,* 2000), or if the geology had strongly resistive features, the work may not have been as successful.

CONCLUSION

The presence of several oil plumes were detected at the top of the water table in 2D resistivity sections as a zone of high resistivity with values ranging from 450 to 1000 Ωm. The low resistivity zones below the water table are interpreted as saline water. In the GPR section, the oil contaminated layer exhibits discontinuous, shadow and chaotic high amplitude patterns.

The results of comparing the VRP result of shallow boreholes and electrical resistivity images indicate that ERIis a good technique for detecting oil contaminants in the shallow subsurface. Notwithstanding this, confirmatory drilling almost always is required. The ERI techniques would facilitate more effective drilling and sampling compared to other currently available techniques.

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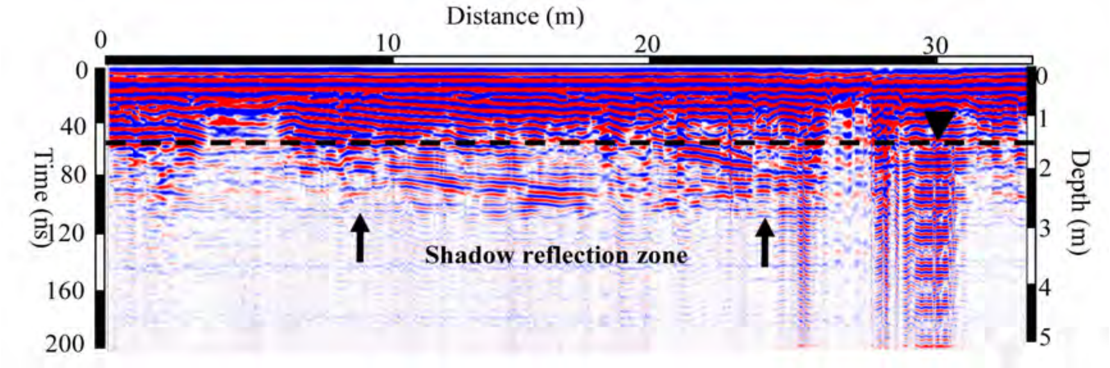

Figure 10: A 2D radargram section of GPR line 1.

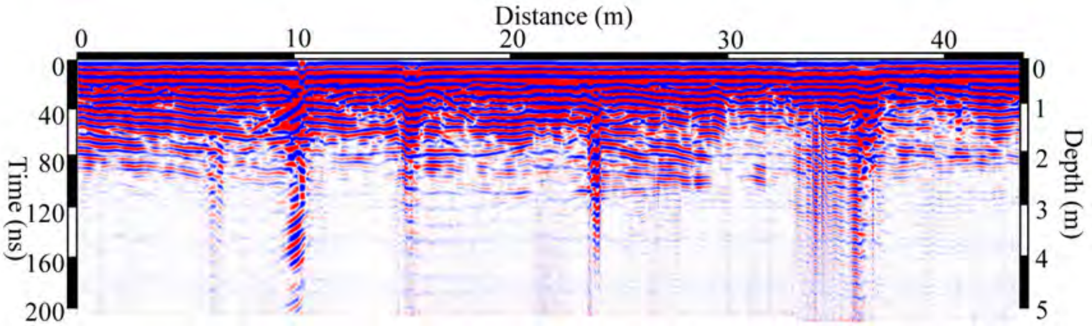

Figure 11: A 2D radargram section of GPR line 2.

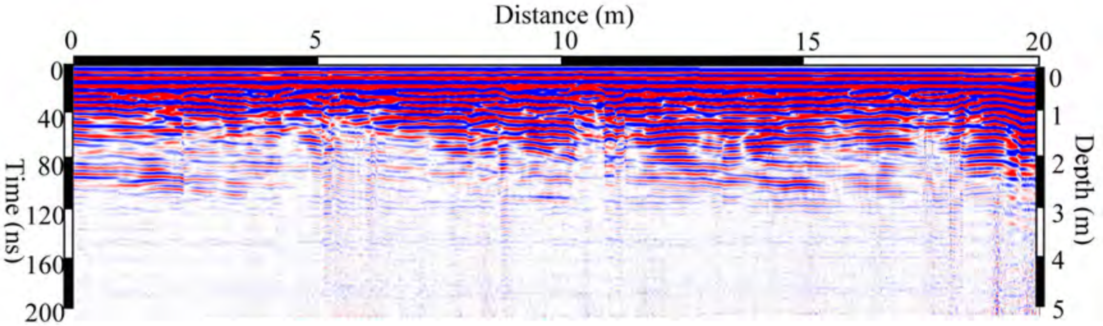

Figure 12: A 2D radargram section of GPR line 3.

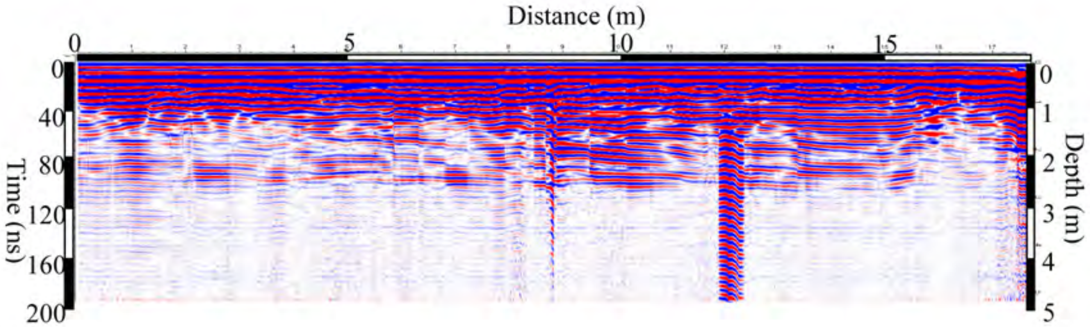

Figure 13: A 2D radargram section of GPR line 4.

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