Geophysical techniques in the study of hydrocarbon-contaminated soil

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Abstract— Geophysical surveys in particular ground penetrating radar (GPR), electrical resistivity tomography (ERT) and vertical resistivity probe (VRP) were used in mapping subsurface geological structures and groundwater contaminants at Sungai Kandis, Klang to identify the approximate boundaries of contaminant plumes and to provide stratigraphic information at this site. The study area was formerly an illegal dumping site of hydrocarbon and toxic waste. A good correlation exists between GPR signatures, ERT layers, vertical resistivity probe and the contaminated soil. The presence of contaminant plumes as well as the water table are also observed in the GPR and ERT sections at depths approximately of 0.5 to 1 m. In this study, a total of 16 GPR traverses and 10 ERT lines with lengths from 30 to 100 m were established. VRP measurements were conducted in 14 shallow boreholes with a maximum depth of about 1m. The VRP results show high apparent resistivity values ranging from 200 to 10000 Ωm associated with oil contaminated layer. The presence of this layer was also detected in the 2D resistivity sections as a thin band of high resistivity values ranging from 60 to 200 Ωm. In the GPR section, the oil contaminated layer exhibits discontinuous, subparallel and chaotic high amplitude reflection patterns.

Keywords: ground penetrating radar, electrical resistivity tomography, vertical resistivity probe, contaminated soil

INTRODUCTION

Ground penetrating radar (GPR) is a very useful geophysical method for use in hydrogeologic and nearsurface mapping studies (Kim *et al*., 2000). It can be used to study contaminants in groundwater, subsurface faulting, and underground cavities (natural or man-made), all of which pose potentially dangerous geological hazards. Geophysical exploration is a non-destructive, cost effective way to help locate and characterize these hazards and, at many sites, GPR is one of the better techniques for this search in the shallow subsurface. In addition to helping locate the water table, characterization of subsurface contamination produced by hazardous materials has become an important application of geophysical methods. The objectives of subsurface investigations at sites containing contamination caused by hazardous materials include: (1) the location of buffed materials; (2) the determination of the presence of contaminant plumes, their source(s), and geometry; and (3) the assessment of associated hydrogeologic conditions. The purpose for locating buffed hazardous materials is typically for site assessment and type of remedial action, usually involving excavation and safe disposal of the hazardous materials with minimal damage to the environment. Geophysical surveys can play an important role in defining the subsurface geology and the associated parameters which govern the movement of contaminant plumes (Daniels *et al*., 1995). Analysis of these data can help produce a more cost effective program in locating monitoring wells. Through early use of geophysical methods, such as seismic refraction, electrical resistivity, and/or GPR, many subsurface problems can be detected, and the sooner they are detected and evaluated, the quicker a strategic clean-up program can be implemented to minimize any further damage to the environment. GPR surveys can be very helpful and cost-effective in (1) locating strategic monitoring wells to sample subsurface soils and fluids; (2) determining hydrogeologic gradients; and (3) monitoring the clean-up process.

The GPR technique is similar in principle to seismic reflection and sonar techniques. Pulse-mode GPR systems radiate short pulses of high frequency (10-1000MHz) 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 with an amplitude A encounters an inhomogeneity in the dielectric constant (ε) of the subsurface, part of the incident energy with an amplitude A_R is reflected back to the radar antenna and part or the energy with amplitude A_T is transmitted into and possibly through the inhomogeneity. Figure 1 shows the basic components and functional operation of a pulse-mode GPR system. The electrical properties of geological materials are governed primarily by the water content, dissolved minerals, clay and heavy mineral content (Olhoeft, 1992).

Reflected signals are amplified, transformed to the audio-frequency range, recorded, processed, and displayed. From the recorded display, subsurface features such as soil/
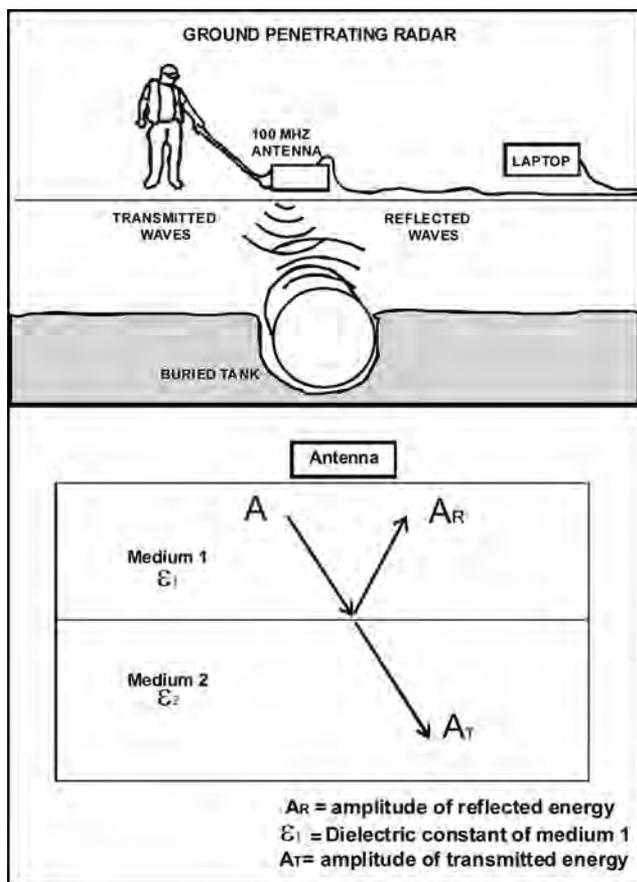
Figure 1: Basic components and functional operation of a pulse-mode GPR system.

Figure 2: Location of the study area.

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 traveltime measured in nanoseconds.

The penetration capabilities of GPR are site specific and depend upon the frequency spectrum of the source excitation signal, the antenna radiation efficiency, and the electrical properties of the subsurface materials. Attenuation losses are caused by: (1) conversion of the radiated energy to heat through electrical conduction losses; (2) dielectric relaxation losses in water; and / or (3) chemical diffusion in clay minerals. The effect of signal scattering by small scale heterogeneities can also increase attenuation with increasing frequency (Olhoeft, 1992). Materials with high conductivity, such as clayey soils, will rapidly reduce the depth of penetration. 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

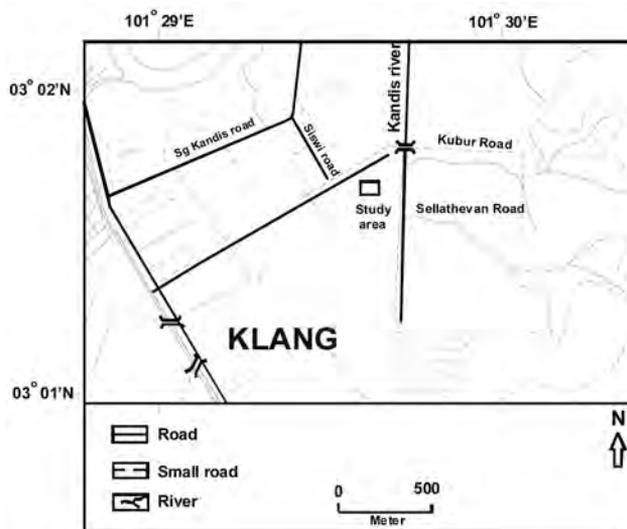Investigations of the subsurface layering, contaminant distribution and hydrogeology were accomplished by hand-augered borings whereby resistivity of the contaminated zones were detected by a probe lowered vertically in the shallow hand-augered hole (Atekwana *et al.*, 2000). Results show higher apparent resistivity associated with the vadose zone and the most interesting feature in the data was a sudden decrease in apparent resistivity (15-30 Ωm) coincide with sand and gravel layer contaminated with gasoline. Resistivity of the underlying layer corresponding to gravel saturated with hydrocarbon free product show slightly higher apparent resistivities perhaps related to unaltered hydrocarbon free product (Atekwana *et al.*, 2000).

Surface resistivity measurements have long been used in the study of contaminated soil especially of hydrocarbon contaminant (Mazac *et al.*, 1990). This technique is very popular in detecting oil-contaminated soil due to its decrease in soil conductivity when contaminated with oil. The resistivity technique in this case is used especially for locating the hydrocarbon plume in the soil if it is originated from a particular spill area. Layer of low conductivity can be detected if the contaminated site is a long period dumping site. For this technique, basically the current is injected into the ground through a pair of electrodes and another pair of electrode will be used to measure the potential existing due to the passage of the current (Koeffoed, 1979). The potential is then converted into apparent resistivity and by inversion (Loke & Barker, 1996) to true resistivity. Electrical imaging is a survey technique for an area of complex geology where the use of resistivity sounding and other techniques are unsuitable for providing detailed subsurface information in a limited area which cannot be easily provided by other techniques (Barker, 1999).

GEOLOGY OF THE STUDY AREA

The study area is about 20 km southwest of Kuala Lumpur (Figure 2) and is basically consists of Quaternary alluvium overlying the Kenny Hill Formation of weathered metasedimentary rock type. The alluvial deposits generally

consist of very soft to firm silty clay up to a depth of 25-30 m with some intermediate sandy layers (Tan *et al.*, 2003). Beneath the silty clay layer generally consist of silty sand. Residual soils (Grade VI) and completely weathered materials (Grade V) derived from the weathering of quartzite were only encountered at about 40 m deep. The behaviour of soft alluvial soils is influenced by the source of parent material, depositional processes, erosion and fluctuations in groundwater levels. Alluvial soils in Klang area usually show good stratification and sometimes organic matter, seashell and organic wood are also present in this deposits.

From the hand-augered soil boring, red brownish silty to very fine sand is found at depth of 0 cm to about 20 cm. Underlying this layer is a light grey silty clay of about 20 cm in thickness. The red brownish silty clay again appeared from depth of 40 cm to 70 cm. Very soft greenish clay is found below 70 cm until about 100 cm. During the boring, the water table was at about 70 to 80 cm from the surface. A geological profile was also derived by investigating the river bank near the study area. Vertically, the height of the river bank from top to bottom is about 2 m and it consists of dry sandy soil at the top with a thickness of about 30 cm. Underlying the sandy soil is light colour silty clay of about 100 cm thick. This layer is underlain by very soft grey clay of about 100 cm thick to the river base.

METHODOLOGY

The survey discussed in this paper was carried out using a RAMAC SYSTEM consisting of a Model PR-8304 profiling recorder with automatic gain ranging, graphic, magnetic tape data recording, and a copper-foil dipole antenna having a center operating frequency of 100 MHz. Data collected were processed using software to produce 2D radargram in time scale. Prior to producing the time section, all data were filtered to remove the DC current effect and multiplied by gain functions to overcome the attenuation effect of the earth materials. This was carried by using 'Ground vision' software. Measurements were made along 16 lines where 9 lines were established in the Northeast-southwest direction and the remaining 7 lines were shot along northwest- southeast bearing (Figure 3). The length of the survey lines was from 25 to 100 m. Half of the survey line 16 was carried out in the uncontaminated zone which is out side of the main study area for data comparison purposes.

In the resistivity survey, measurements were made along 9 traverse lines in NE-SW and NW-SE directions as shown in Figure 4. The length of each survey lines were between 50 to 100 metres. Expected maximum depth of current penetration into the soil is approximately about 10 to 20 metres. ABEM Terrameter model SAS 1000 instrument was used for the data collection. Sclumberger array electrode confuguration was used to provide a good vertical resolution for a clear image for groundwater and sand-clay boundaries. The data collected in the field is interpreted using the computer software RES2DINV (Loke & Barker, 1996) which will
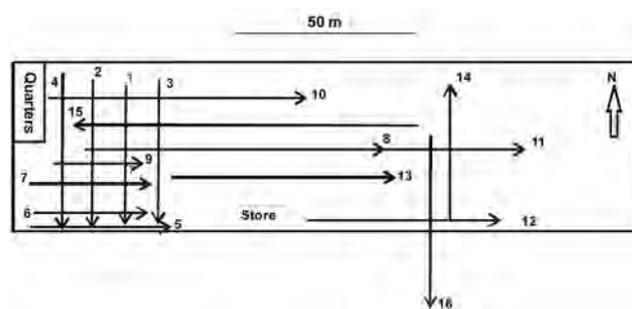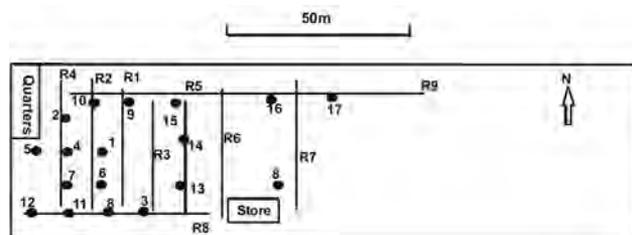

Figure 3: Location of GPR traverse lines.

Figure 4: Location of Resistivity survey lines and boreholes for VRP survey.

automatically subdivide the subsurface into a number of blocks and then it uses a least-squares inversion scheme to determine the appropriate resistivity values for each block in 2-D. Geoelectrical imaging surveys are normally carried out with multielectrode resistivity system. In this survey, 41 electrodes are deployed in a straight line with constant spacing and connected to a multicore cable. A computer-controlled system (Griffith *et al.*, 1990) is then used to select the active electrodes for each measurement. The data gathered in this survey is interpreted using an inexpensive microcomputer to provide an inverse resistivity section.

VRP measurement was carried out in the hand-augered boreholes using a sensor consisting of a close-spaced permanent vertical array of mini-electrodes made up of 3 mm diameter copper rod fixed at 25 mm spacing and mounted inside a 60 mm diameter PVC pipe. The electrodes were joined to 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 mm Wenner array at every 50 mm interval. A total of 17 shallow holes were augered for the VRP survey and their positions are as shown in Figure 4.

RESULTS AND DISCUSSION

VRP results show resistivity variation from top to bottom of the hole with values ranging from 50 Ωm to almost 10,000 Ωm. Resistivities higher than 200 Ωm coincide with the oil-mixed grey clay. The thickness of top soil consisting of silt to fine sand overlying the contaminated layer varies from 50 to 200 mm with resistivities ranging from 10 to 100 Ωm. The contaminated zone was mapped by plotting
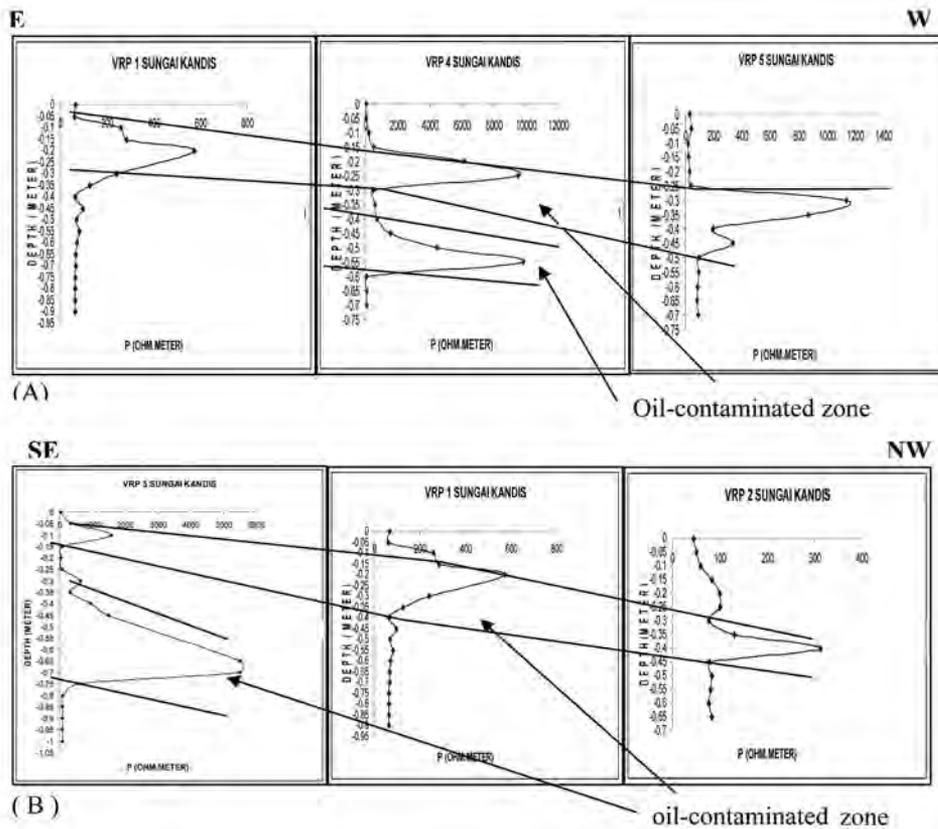
Figure 5: Cross section of VRP resistivity across few boreholes.

the neighbouring VRP stations as shown in Figure 5. Figure 5(a) shows the E-W section across VRP stations 1 to 4 with zone of high resistivities corresponding to variable thicknesses of contaminated zone from 15 to 30 cm. Figure 5(b) shows the N-S VRP section with different thickness and depths of contaminated zone. In this section, the thickness of contaminated zone varies from 10 to 40 cm and it was detected from depth as shallow as 5 cm to 75 cm.

Figure 6 shows an example of 2D radargram section of Line 16. Basically, the section can be divided into three particular reflection pattern representing different soil types. At depth 0 to 0.5 m, the reflections are flat and showing high amplitudes where as at depth of 0.5 until 1.5 m it shows discontinuous and chaotic pattern. Underlying this layer, the reflection is weak and unclear or sometimes called free-reflection zone. A geological section from a nearby riverbank plus soil stratigraphy from a few shallow boreholes augered during soil sampling were used to interpret the GPR section. In general, based on the geological logs, the top layer (0-0.4 m) consists of silt to fine reddish sand. In some places, it also contains some coarse sand particles. The high amplitude-continuous reflections are associated with sand and silt layers.

Geologically, the discontinuous and chaotic reflection zone at depth of 0.6 to 1.4 m represents dark grey to reddish silty clay. In some places, this layer also contains thin reddish fine sand. The presence of oil is detected in this zone especially above the water table at depth ranging

from 0.8 to 1.0 m. Clay and water saturated layers reduce the apparent resistivities or increase the conductivity of the region to produce weaker GPR reflection pattern as compared to the overlying dry layer. The discontinuous reflection pattern layers which coincide with the oil contaminated layer are also known as fuzzy or shadow zone as reported by Atekwana *et al*. (2000). Figure 6 shows an example of GPR results from the northern part of line 16 which was located in the contaminated zone.

Layer below than 1.2 m consists of soft grey clay. This high conductivity soft clay absorbs the GPR reflection to produce much weaker reflection zone as compared with the above layer. The strong reflector at about 1.3 m depth in the GPR section is interpreted as top of clay layer

2D electrical resistivity measurements using Schlumberger array were conducted along 9 lines in the study area. An example of inversed resistivity model representing line 3 (Figure 7A) shows a top thin layer with low apparent resistivities ranging from 8 Ωm to 40 Ωm associated with water saturated layer from top to about 0.5 m depth. For this line, the survey was conducted during wet season where the water saturated top layer shows low resistivity. Lying immediately below this layer is a zone of higher resistivity (59-200 Ωm) at depth between 0.5 to 1.5 m which coincides with the oil-contaminated zone determined by VRP survey. The underlying low resistivity zone (5-17 Ωm) corresponds to the thick grey soft clay layer. Similar pattern of resistivity distribution is also shown in line 5
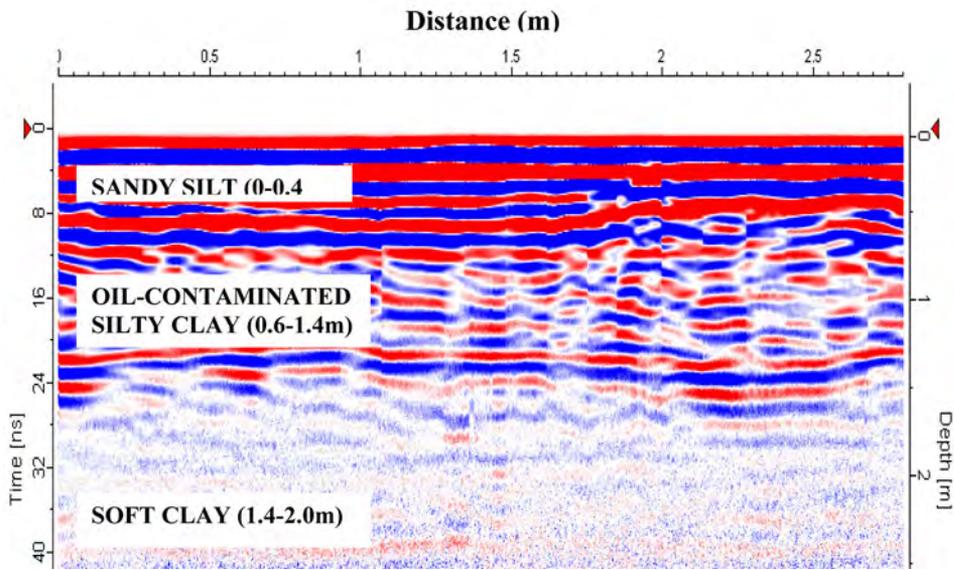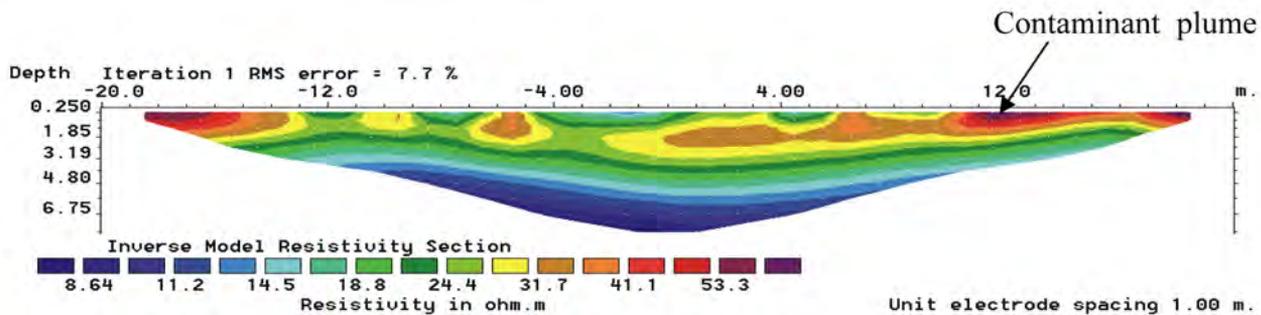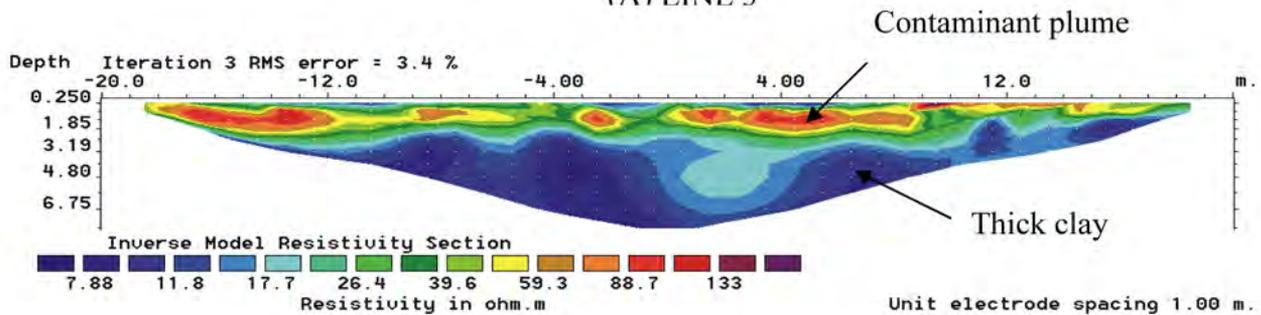
Figure 6: A 2D radargram section of GPR line 16.

Figure 7: Inversed resistivity model for line 5.

(Figure 7B) where the contaminant plumes are located on top of low resistivity thick clay layer.

The resistivity survey results of both VRP and surface resistivity imaging in this study show high resistivity representing oil-contaminated zones as previously reported (Olhoeft, 1992). However, Atekwana *et al.* (2000) reported resistivity decreases in their studies at a former petroleum refinery in Michigan, USA. At this site, continuous hydrocarbon releases from storage facilities and pipelines resulted in seepage of the hydrocarbons into the subsurface and contaminated the sediments and groundwater for more than 50 years. The difference may be related to a few contribution factors such as the site condition, climate and biodegradation activity (Sauck, 2000). The subsurface volume including the upper water table and lower unsaturated zone may produce high resistivity, but with time will change to conductive conditions as biodegradation and chemical reactions produce the iron-rich leachate (Sauck, 2000).

CONCLUSION

From this study, oil-contaminated layer has higher resistivity values compared with the top sand-silt layers and the underlying thick soft clay. Based on VRP survey,

the resistivity values of this layer is from 200 to 10,000 Ωm. The zone of this oil-contaminated layer is shown in all inversed models of the 2D electrical survey. Resistivity values calculated from the 2D electrical surveys representing the oil-contaminated layers are ranging from 60 to 200 Ωm sandwiched between the top sand-silt and the thick soft clay. Promising results were also obtained in the GPR survey where 3 obvious reflection patterns representing top sand-silt layer, oil-contaminated zone and the underlying thick soft clay were detected in all 2D radargrams of the GPR traverse lines.

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