Investigation of Underground Hydrocarbon Leakage using Ground Penetrating Radar

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Abstract. Ground Penetrating Radar (GPR) survey was carried out in several petroleum plants to investigate hydrocarbon contamination beneath the surface. The hydrocarbon spills are generally recognized as Light Non-Aqueous Phase Liquids (LNAPL) if the plume of leakage is distributed in the capillary fringe above the water table and as Dense Non-Aqueous Phase Liquids (DNAPL) if it is below the water table. GPR antennas of 200 MHz and 400 MHz were deployed to obtain clear radargrams until 4 m deep. In general, the interpreted radargram sections indicate the presence of surface concrete layer, the compacted silty soil followed by sand layer and the original clayey soil as well as the water table. The presence of hydrocarbon plumes are identified as shadow zones (radar velocity and intensity contrasts) in the radargram that blur the layering pattern with different intensity of reflected signal. Based on our results, the characteristic of the shadow zones in the radargram is controlled by several factors: types of hydrocarbon (fresh or bio-degraded), water moisture in the soil, and clay content which contribute variation in electrical conductivity and dielectric constants of the soil.

1. Introduction

Ground Penetrating Radar (GPR) is a geophysical technique that is used to investigate shallow and high resolution subsurface condition based on the principles of electromagnetic (EM) wave propagation within materials. It is widely applicable for near surface geophysical, environmental, agricultural, forensic as well as geotechnical purposes [1][2]. In this paper we discuss the application of GPR survey as a non-destructive test (NDT) technique to investigate traces of possible hydrocarbon or other liquids leakage beneath petroleum plant. The hydrocarbon spills that may be caused by crack in pipes are generally grouped into two categories: as Light Non-Aqueous Phase Liquids (LNAPL) if the plume of leakage is distributed in the capillary fringe above the water table and as Dense Non-Aqueous Phase Liquids (DNAPL) if it is below the water table [2].

An increase in petroleum hydrocarbon concentration in soil is directly proportional to the increase in resistivity and a decrease in dielectric permittivity [3]. GPR responses shown by radargrams can be site specific, however, in general the presence of hydrocarbon in the ground will increase the radar
reflectivity [4][5]. In some cases, the reflectivity tends to decrease due to high loss scattering of GPR signal when hydrocarbon fluids infiltrate the capillary fringe in soil as well as combination effects of contaminant vapor and water-gasoline-soil roughness [3]. GPR signal attenuation also can be associated with the increase in electrical conductivity due to biodregadation of hydrocarbons in soil [2][3].

In this study, radargrams from GPR measurements at several petroleum plants are examined to investigate hydrocarbon contamination beneath the surface due to possible cracks in pipes or leakage on underground sewers.

2. Method

GPR is operated by transmitting low energy EM wave at frequencies between 25 MHz and 1 GHz to the ground through transmitter antenna and receiving the reflected wave through receiver antenna. The proportion of reflected wave is influenced by contrast in radiowave velocities in materials which is a function of magnetic permeability, dielectric permittivity, electric conductivity and frequency [1]. For low-loss materials, the velocity of radiowave can be regarded as a function of dielectric constant only,

\[ v \approx \frac{c}{\sqrt{\varepsilon_r}} \]  

where \( c \) is the speed of light in free space and \( \varepsilon_r \) is the dielectric constant of a particular material. The amplitude reflection coefficient is

\[ R = \frac{v_1 - v_2}{v_1 + v_2} \]  

or

\[ R \approx \frac{\sqrt{\varepsilon_2} - \sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2} + \sqrt{\varepsilon_1}} \]

which expresses the portion of the reflected EM signal recorded at receiver antenna (Fig. 1).

![Figure 1. Illustration of GPR basics (left) and real measurement in the field (right)](image)

Reflection profiling mode using bistatic antenna of 200 and 600 Hz was deployed during the data acquisition in the field (Fig. 2) to obtain radargrams or GPR reflections profiles. For each designated buried pipe elongated in a certain direction, three GPR lines were made at the surface: one was made right along the axis (center) of the pipe, two were on the left and right sides of the center line at about 30 – 50 cm from the center. This is to ensure coverage of radargrams in anticipating the geometry of leakage or plume of contaminant in the subsurface. Several crossing lines were also made to verify the presence and depth of pipes. To obtain visually clearer and interpretable GPR sections, raw
radargrams were processed through several steps such as dewow, DC shift correction, band pass filtering and background removal and sometimes migration [1][2].

3. Results and Discussion

Figure 2 depicts three parallel GPR sections above an elongated pipe directed to the same direction of the sections (Line 24 at the longitudinal axis of the pipe). These lines were measured to investigate the possibility of leakage from pipe containing flowing water from a large water tank in a petroleum plant in Java. At the surface, hydrocarbon spills were spotted around the lines. From these sections, a first layer of about 0.3 m thick is identified as undisturbed layering pattern. From the artificial outcrops dug near the lines (Fig. 3), it was confirmed that the first layer is concrete pavement having almost the same thickness. Below this layer, silty soil was found overlying a compacted sandy soil. The reflections of these layers are clearly identified from the sections with relatively high signal amplitude from depths of about 0.3 to 2m. Below the sandy soil, a layer of silt or clay was found. Water table is identified from the sections at about 2 m deep and this was verified by inspecting several water wells at hundreds of meters from the lines.

Between horizontal distances 0 – 60 m and 90 – 100 and depths 0.3 – 1.5 m, blurred zones or shadow zones of low signal amplitude are identified. These zones may be attributed to the presence of LANPL in the vadose zone above water table where vapor phase of hydrocarbon displaced the water and hence reducing the reflectivity of the signal [6]. Other possible explanations for this signal attenuation feature are occurrence of hydrocarbon biodegradation [2][3] and a plume of water dominated mixture of oil and water in a silty or clayey environment. The sharp boundary of water table in non-shadow zone (right part of the radargrams) may be associated to contrast of dielectric permittivity between the...
sandy-clay layer and the water saturated layer whereas below shadow zone (left part of the radargrams) is caused by water displacement from the transition zone above the capillary fringe [6]. A typical of liquid plume or leakage is also identified below water table between horizontal distances 60 – 70 m. This feature may be attributed to the presence of DNAPL which displace water from the pore space and deposited through the water saturated layer. NDAPL is insoluble in water and it can be migrated along groundwater flow which is important to notice from the environment point of view.

**Figure 3.** Some artificial outcrops were dug to validate the interpretation of GPR sections.

**Figure 4.** Examples of radargrams recorded at a petroleum plant in Sumatera.

Figure 4 shows another examples of radargram taken at a petroleum plant in Sumetera. Hyperbolic features are related to the positions of pipes intersected by the GPR lines. The layering pattern at depths of 0.2 -0.3 m indicates the concrete layer covering the measurement area. At several spots, pattern of shadow zones are identified from the surface (at 10 m, 20 – 30 m, 37 m, and 60 – 65 m). These features are related to the presence of mixtures of hydrocarbon spill and meteoric water on the surface (Fig. 5). The water table beneath the surface is identified at about 2 m deep. Low amplitude shadow zones are also identified vertically traversing the water table up from the vadose zone (LNAPL) down to the water saturated layer (DNAPL).

**Figure 5.** Mixture of hydrocarbon spill and meteoric water on the surface.

4. **Summary**
Investigation of underground hydrocarbon leakage using ground penetrating radar has been carried out. The interpreted GPR sections indicate the presence of surface concrete layer, the compacted silty soil, sand layer and the original clayey soil as well as the water table. The presence of hydrocarbon plumes are identified as low amplitude shadow zones which can be interpreted as due to existence of LANPL in the vadose zone above water table reducing the reflectivity of the signal, or due occurrence of hydrocarbon biodegradation, or due to water dominated mixture of oil and water in a silty or clayey environment.

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