GPR attribute analysis for the detection of LNAPL contaminated soils

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Abstract. Light non-aqueous phase liquids (LNAPL) are hydrocarbons, immiscible in water and less dense than water. This paper uses GPR attribute analysis to evaluate the LNAPL contaminated soils. A GPR experiment for LNAPL leakage in a sand box is set up in the laboratory. After GPR data processing, three types of attributes are calculated. The instantaneous amplitude attribute describes the LNAPL pollution range even though the difference of electromagnetic properties is small between the target and the surrounding media. The similarity attribute delineates the boundary of LNAPL contaminated area based on the variations of the media through calculating the similarity of the adjacent traces’ waveforms and amplitude. The energy attribute helps to determine the source point of LNAPL leakage in recent LNAPL leakages. We believe that the GPR attribute analysis has a great potential to improve the interpretation of the GPR detection at actual LNAPL contaminated sites.

1. Introduction

Ground penetrating radar (GPR) uses high frequency (10MHz ~ 3GHz) electromagnetic waves to detect the size, location, and attribute of underground targets depending on the difference of electromagnetic properties between targets and surrounding rock [5]. As a non-destructive detection technology, GPR has been widely used in the near-surface investigations [4]. GPR attributes can find out the hidden details in radar data, and quantitatively describe the characteristics of radar data in terms of geometry, kinematics, dynamics or statistics. Attribute analysis comes from seismic exploration, and more than 50 different seismic attributes are calculated based on seismic data [3]. Some of them are more sensitive to special reservoirs, some are better at finding underground targets that are not easy to detect, and some have been used as indicators of oil and gas [2]. Because GPR and seismic exploration have the same wave theory, similar data processing and data interpretation technology, GPR attributes can be calculated by learning from the seismic attributes. In recent years, the attribute analysis has been used to improve the quality and efficiency of GPR data interpretation [6,7,9].
Light non-aqueous phase liquids (LNAPL) are hydrocarbons, immiscible in water and less dense than water [8]. The most common LNAPLs are petroleum and petroleum products. The leakage of LNAPLs during production, storage, refining, and transportation cause soil and groundwater pollution. In many cases, GPR is the more adequate geophysical tool for detecting contaminated areas. However, it is still not routinely used because complex soil environment and weak signal response make interpretation difficult. In this paper, we try to use GPR attributes to find out the hidden information in GPR data and improve interpretation of the contaminated area.

2. Attribute analysis

2.1. Instantaneous attributes

Instantaneous attributes, commonly used GPR attributes, refer to instantaneous amplitude, instantaneous frequency, and instantaneous phase. The three attributes are obtained by constructing complex signal through acquired real signals by Hilbert transform. The instantaneous amplitude reflects the signal energy and energy attenuation at a given time. Instantaneous phase is a measure of the continuity of the events on a radar profile, which is not affected by the amplitude intensity, so it is helpful to the interpret deep weak signals. Although the instantaneous frequency attribute is easy to be disturbed by noise, it can describe the absorption and attenuation of electromagnetic waves by underground media.

2.2. Similarity attribute

Similarity is a distance measure quantifying the semblance between two trace segments. It is calculated as one minus the distance between the trace segments' vectors, normalized to the sum of the vector length. The average similarity \( S_{\bar{m}(m,n)}(t) \) between all neighbors is calculated by Equation (1) and (2) [1].

\[
S_{\bar{m}(m,n)}(t) = \frac{1}{4} \left( S_{T_{m,n-1}T_{m,n+1}}(t) + S_{T_{m+1,n-1}T_{m+1,n+1}}(t) + S_{T_{m+1,n-1}T_{m-1,n+1}}(t) + S_{T_{m-1,n-1}T_{m+1,n+1}}(t) \right),
\]

where

\[
S_{T_{m,n-1}T_{m,n+1}}(t) = \frac{\sum_{i=N}^{x} [T_{m,n-1}(t+i) - T_{m,n+1}(t+i)]^2}{\sqrt{\sum_{i=N}^{x} T_{m,n-1}(t+i)^2 + \sum_{i=N}^{x} T_{m,n+1}(t+i)^2}},
\]

\( T_{m,n+1} \) and \( T_{m+1,n} \) are neighboring traces. The similarity gives the value 1 if the trace segments are identical and 0 if they have a phase-shift of 180 degrees. Compared to a cross correlation of the trace vectors, similarity also responds to amplitudes.

2.3. Energy attribute

The energy attribute is usually used to highlight areas characterized by strong amplitude changes. Signal energy is mathematically defined as

\[
E_{T_{m,n}}(t) = \frac{1}{2N+1} \sum_{i=N}^{x} T_{m,n}(t+i)^2,
\]

where \( E_{T_{m,n}}(t) \) denotes the energy value for a trace \( T \) with crossline position \( m \), inline position \( n \) calculated at time sample \( t \) using a window length of \( 2N+1 \) samples. Evaluation of this equation over all inline, crossline, and time samples of a 3D data set results in a 3D energy volume.
3. Experimental data

3.1. Data acquisition and processing

We set up a sand box experiment of LNAPL leakage in the laboratory. The size of the sand box is 48.2cm × 46.8cm × 50cm. In the sand box, diesel oil, quartz sand and water are mixed to simulate LNAPL polluted soil. First, the sand box is filled with dry quartz sand with a relative dielectric constant of 3.5. Then, the water is mixed into the sand, and a total of 18.9L water is injected. Then the sandbox stands for 48 hours to make the mixture stable. Next, 100ml of diesel oil mixed with Sudan dye is injected into the sand through a syringe, and the injection point is just in the center of the sand surface.

The MALA proEX GPR system used in the experiment is employed the antenna with the central frequency of 1600MHz. The layout of survey lines is shown in Figure 2. There are 50 parallel survey lines with a line interval of 1cm. The trace increment is 0.5cm.

A data processing flow sequence which is applied on GPR data consisted of: DC filtering, Automatic gain control (AGC) for amplitude recovery, band pass filtering to remove the low and high frequency noise, and background removal to remove the direct wave. Figure 3 shows the GPR profile from the line L25. In the Figure 3(a), the processed data show a relatively strong reflected signal area located between 0.15-0.35m in horizontal position and 1-7ns in two-way travel time.

![Figure 1](image1.png) **Figure 1.** Description of adjacent traces in a 3D GPR data set.

![Figure 2](image2.png) **Figure 2.** Layout of the GPR survey lines.

![Figure 3](image3.png) **Figure 3.** GPR profiles from the survey line L25. (a) processed data, (b) instantaneous amplitude.

3.2. Attribute analysis

The attribute analysis of instantaneous amplitude is applied to the processed data, the result of L25 is shown in Figure 3(b). An area with relatively strong instantaneous amplitude is located at the
horizontal position of 0.15-0.35m and the two-way travel time of 1-5ns, and the intensity gradually weakens from shallow to deep. It is estimated that this area is polluted by LNAPL. At both ends of the survey line, it shows strong amplitude values at the time of 1ns, which are supposed to be the reflection from the boundary of the sandbox.

The attribute analysis of similarity and energy are calculated based on 3D GPR data. Using equations (1) and (2), we calculate the similarity attribute, as shown in Figure 4. The black ring anomaly seen in the figure indicates that the small similarity value. The small value emphasizes the large variability of neighboring data and enhance edges of anomalies. The black ring shown in Figure 4 is indicated the boundary of the LNAPL contaminated area. Although the difference of the relative permittivity between the LNAPL polluted medium and surrounding soils is small, the discontinuity of data is highlighted through similarity analysis, i.e., the edges of pollution range is delineated.

Energy is commonly used attribute in GPR data. It highlights the area where the reflected signal energy change. The energy attribute slice of 3D GPR data is shown in Figure 5. The energy attribute generates the values from 0 to 1 through normalization. By adjusting the energy threshold, the range of strong energy change in a certain depth can be displayed. Figure 5(a) and (b) represent energy attribute slices with energy thresholds of 0.1 and 0.05, respectively. According to the pattern of LNAPL seepage and dispersion, the high energy area in Figure 5(b) should be related to the source of LNAPL pollution. This inference can be applied to recent LNAPL leakages. In the mature LNAPL contaminated area, the hydrocarbons undergo significant change. This complicates the electrophysical properties of the subsurface and makes GPR data interpretation more difficult.

![Figure 4. A similarity attribute slice of 3D GPR data at depth of 0.05 m.](image)

![Figure 5. An energy attribute slice of 3D GPR data at depth of 0.05m with the energy threshold of 0.1 (a) and 0.05 (b).](image)

After the experiment, the sandbox is excavated layer by layer to verify the data interpretation. Time domain reflectometer (TDR) is used to measure the water content of the sand at various depths. Figure 6 shows the water content distribution. It includes three zones: the residual zone, the transition zone,
and the saturation zone. The transition zone is located between 30cm and 42cm, the residual zone is above 30cm, and the saturated zone is below 42cm. The water table is located at 42cm.

Figure 7 shows the photos after excavation, and Figures 7(a), 7(b) and 7(C) are located at the depth of 5cm, 10cm and 15cm, respectively. It can be seen that LNAPL exist in the residual zone and does not enter into the transition zone. The location and range of the pollution area is consistent with the data interpretation given by the attribute analysis. LNAPL diffuses downward and outward from the injection point, and the content of LNAPL decreases with the depth deepening and range increasing.

**Figure 6.** Water content measured by TDR in the sandbox.

**Figure 7.** Photos at the depth of 5cm (a), 10cm (b) and 15cm (c) after the sandbox is excavated layer by layer.

### 4. Conclusions

GPR data are acquired in a sand box experiment of LNAPL leakage in the laboratory. Through the use of GPR attribute analysis, it has been possible to evaluate the LNAPL contaminated soils. The instantaneous amplitude attribute is good at highlighting the horizontal change of subsurface media. Therefore, it describes the LNAPL pollution range, even though the electromagnetic property difference is small between the target and the surrounding media. The similarity attribute delineates the boundary of LNAPL contaminated area based on the variations of the media through calculating the similarity of the adjacent traces’ waveforms and amplitude. The energy attribute helps to determine the source point of LNAPL leakage in the recent LNAPL leakages. We believe that the GPR attribute analysis has a great potential to improve the interpretation of the GPR detection at actual LNAPL contaminated sites.

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