Multi frequency Ground-Penetrating Radar method for mapping underground pipes and man-made objects

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Abstract. Mapping of subsurface infrastructure such as pipelines, pipe ducts as well as man-made objects located below the earth surface is a difficult task in geotechnical engineering due to the need to direct contact to the object. Ground-Penetrating Radar (GPR) method as one of geophysical methods is an appropriate technique to solve such problems due to its capability to effectively provide the existence, the location and the depth of buried shallow objects. Despite many advantages, the application of GPR method is limited by achieved depth and resolution range that is frequency dependent. To overcome such problems, the so-called multi-frequency compositing method with Optimal Spectral Whitening (OSW) technique is studied and applied on real data acquired in the Muarakarang Combined Cycle Power Plant area located in the Northern part of Jakarta, the Capitol of Indonesia. Datasets from GPR measurement with 100 MHz and 250 MHz was used. Each radargram from the same path was processed individually and then joined to become multiple composite radargram. The resulted composite radargram from a GPR line we studied has shown clearer image for interpretation rather than individual interpretation. The applicability of this multi-frequency compositing recommend further study to solve some facing problems in geotechnical engineering.

1. Introduction

Mapping of near surface infrastructures such as pipelines, pipe ducts and other man-made objects located below the ground is difficult task for geotechnical work since its technique needs direct contact to the object to recognize its existence. Ground-penetrating radar (GPR) as a geophysical method is commonly used to overcome such problems due to its non-destructive nature and its implementation in the field can coexist with other activities that do not interfere with each other. This method is able to identify and find subsurface objects effectively.

Despite many advantages, this method is limited by achieved depth and resolution range that is frequency dependent [1, 2]. Resolving power of GPR system to find anomalous objects underground is determined by the frequency content of GPR waves emitted by transmitter. Its dominant frequencies deliver information about optimum depth of investigation whilst its bandwidth determine the spatial resolution. Anomalous objects having a variety of size and depths require various GPR antenna frequencies to be deployed in order to image their general condition in the measurement area. Higher antenna frequencies can reach shallower depth with higher spatial resolution and vice versa. To obtain a more detailed subsurface image from surface to desired depth of investigation, a technique to combine radargrams obtained from
measurement with various antenna frequencies on the same path has been developed. This so-called multi frequency radargram compositing technique [3, 4, 5] was applied on real data, which are acquired in the Muararakang Combined Cycle Power Plant area in Jakarta, Indonesia to mapping pipeline network and other made-made objects in subsurface. This study demonstrates the applicability of multi-frequency compositing technique to solve a problem in geotechnical engineering.

2. Data and methods

2.1. Multi-frequency compositing

Development of Multiple-frequency compositing technique is aimed at increasing radargram resolution at deeper depth at working frequency reference by conducting a fusion of radargrams acquired with two or more different working frequency antennas from the same path into one radargram. Some different approaches are now exist in the multiple frequency compositing technique. Priska et al. (2019) studied three different approaches, i.e. simple summation; dominant frequency amplitude equalization (DFAE) which comparing average radargram amplitude spectrum of each radargram; and optimal spectral whitening (OSW), an approach including the amplitude ratio but based on the Berlage wavelet analysis as the weighting factor in the radargram compositing technique [5]. From that study, it is concluded that the OSW technique produces the best resolution results among other multiple-frequency techniques used in the study [6].

Based on the above mentioned results, we apply OSW technique. In this method, the weighting value is stated by the equation below as [5, 6]:

\[
Aw = \begin{bmatrix}
A_{f1}^{m1} & A_{f2}^{m1} & \cdots & A_{fN}^{m1} \\
A_{f1}^{m2} & A_{f2}^{m2} & \cdots & A_{fN}^{m2} \\
\vdots & \vdots & \ddots & \vdots \\
A_{f1}^{mM} & A_{f2}^{mM} & \cdots & A_{fN}^{mM}
\end{bmatrix}
\begin{bmatrix}
w_{m1} \\
w_{m2} \\
\vdots \\
w_{mM}
\end{bmatrix} =
\begin{bmatrix}
s_{f1} \\
s_{f2} \\
\vdots \\
s_{fN}
\end{bmatrix}
\]  

(1)

where

- \( Aw \) : radargram spectral amplitude value
- \( A_{fN}^{m} \) : the spectral amplitude on m-th data and N-th frequencies
- \( w_{m} \) : weighting of m-th data
- \( s_{f} \) : spectral amplitude value on N-th frequencies, which is usually a constant

Weighting factor based on the OSW method was applied at some time interval, with the time interval was calculated from the dominant period length of Berlage wavelet from the lowest frequency. After the weighting factor was calculated, then it was scaled based on the RMS amplitude value on that interval before being distributed to all data on the radargram, using linear interpolation by multiplying it with radargram amplitude that being previously normalized. This so-called multi frequency radargram compositing technique was applied on real data, which were acquired in the Muara Karang Combined Cycle Power Plant area in Jakarta, Indonesia to detect pipeline network and man-made objects in subsurface.

2.2. Site conditions

Study area is B-zone in Muararakang Combined Cycle Power Plant area located in the northern part of Jakarta, the capitol of Indonesia (figure 1). Typical soil profile of the area is shown in figure 2. This soil profile is extracted from boring and SPT data of BH-3 located in the study area. Lithologically the soil profile consists of mixed soft, brown colored gravelly - silty clay with middle plasticity from surface to 2 m depth. Beneath this layer, brown colored, water saturated, degradable fine sand exists. This layer has a very low bearing capacity with only 3-4 N-SPT value from 2m to 12 m depth as seen in figure 2.
2.3. GPR data acquisition and processing
Ramac GPR system with 100 MHz and 250 MHz antenna was deployed. Two datasets from GPR measurement at 10 lines are available for this study, but only resulted data from line 19 is used in this paper. Figure 3 (a) and (c) show GPR measurement in lines adjacent to line 19 by using 100 MHz antenna. That measurement line crosses the location of buried pipe. The appearance of pipes on the surface can be seen in figure 3(b) and (d) and will be used for validation.

Individual GPR data was processed using Reflexw software from Sandmeier [7] with conventional processing steps including dewow, bandpass filtering, DC component subtraction, f-k filtering and background removal. Multiple composite radargram compositing step was then performed to join individual radargram.

![Figure 1. Study area located at Muara Karang Combined Cycle Power Plant in the northern part of Jakarta, the capitol of Indonesia. Some of GPR lines are shown.](image-url)
Figure 2. Typical soil profile extracted from boring and SPT data of BH-3 located in the study area. Note very low SPT value of fine sand from the depth of 2 m to 10 m exhibits very low bearing capacity.

Figure 3. GPR acquisition in the study area: GPR campaign on the road crossing location of buried pipes (a; c). Six pipes of 10cm in diameter at 2 levels that go into the duct (c) and one 50cm diameter pipe that go into the ground (d)
3. Results and discussion

Soil profile as seen in figure 2 shows soil condition that is relative homogeneous soil from surface until depth of 2m. That soil profile is extracted from Boring at point BH-3 that was carried out until the depth of 30m. SPT within this 2 m thick soft clay was not carried out. SPT value or N-SPT of about 4 from 2 m to 12 m depth for fine sand are relatively very low. That value indicates a very low and homogeneous soil bearing capacity. Such soil conditions make it easier to interpret the data.

We collected GPR data from measurement using 100 MHz and 250 MHz antenna, but only resulted data from line 19 is discussed. Figure 4.(a) and (b) show processed radargrams of line 19 which were acquired with 100 MHz antenna and 250 MHz antenna, respectively. From 100 MHz radargram, only object located at depth of about 1 m is recognized. Produced blurred radargram is most probably caused by a relative water saturated ground.

![Figure 4](image)

**Figure 4.** Processed 100 MHz radargram (a), processed 250 MHz radargram (b) of line 19 and their composite radargram using multi-frequency compositing technique. Combined radargram shows clearer images for interpretation rather than individual radargram.
Similar result is also shown in 250 MHz radargram, exhibiting clearer image of subsurface. This result shows that GPR system with 250 MHz antenna is adaptable for measurement on water saturated ground until 2.5 m depth. Combined radargram produced using multiple frequency compositing with OSW technique is shown in figure 4(c). It shows a clearer image of subsurface compared to individual radargram.

Three anomalous objects are recognized in the combined radargram, i.e. object at 6 m distance from origin at depth of about 0.75 m and object at 6.5 m distance from the first pipe at 0.9 m and last object at 1.5 m depth. We interpret the first anomalous object as pipe with 50 cm diameter located at about 75 cm depth, as revealed in the figure 3(d). The second anomalous object is most likely to be a group of 6 pipes with 10 cm in diameter arranged in 2 level at about 90 cm depth. Those type and size of the pipes are validated by pipeline continuity the appearance of the pipe on the surface, as seen in figure 3(b) and (d). The last object located at 6 m depth beneath the first object is probably bottom part of the pipe conduit. Bottom part of conduit under second object is hard to recognize in the combined radargram.

Three anomalous objects were identified, i.e. 50 cm diameter steel pipe at 6 m distance from the origin at 0.75 m depth, a group of 6 10cm diameter pipe at 0.9 m and bottom part of duct at 6.5 m distance from the origin at 1.5 m depth. The applicability of this multi-frequency compositing recommend further study to solve some facing problems in geotechnical engineering.

4. Conclusion
We applied multi-frequency compositing method with the aim at increasing the radargram resolution at deeper depth at a working frequency reference. This technique was done by combining radargram acquired with two or more different working frequency antennas from the same path. Optimal spectral whitening (OSW) technique, that is superior in comparison to other techniques in multiple-frequency compositing we studied previously, is used. The applicability of this method is tested on data acquired in Muarakarang Combined Cycle Power Plant area by using 100 MHz and 250 MHz GPR antenna, the resulted composite radargram joining 100 MHz radargram and 250 MHz radargram show clearer image for interpretation rather than individual interpretation.

The success of this research prompts us to further develop this method in detail for common cases in geotechnics such as detecting underground sewers, the boundaries of the hard layer and the overlying soft ground, and complex pipelines.

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