River sedimentation modeling using ground-penetrating radar

M A Firdaus*, Widodo and Fatkhah

Geophysical Engineering, Faculty of Mining and Petroleum Engineering, Bandung Institute of Technology, Indonesia.

*Corresponding author: aldimfirdaus2@gmail.com

Abstract. In recent years, siltation has become quite a problem. It has been the main cause of flooding and a rapid decline in water quality. It is usually caused by a high river sedimentation rate and/or uncontrolled waste disposal. The increased rate of erosion also means that river sedimentation occurs faster than normal and could lead to environmental hazards, wildlife deaths, and the disruption of food and drinking water supply among other things. The question is how to monitor the sedimentation process of rivers without damaging the river itself. The suitable geophysical method is GPR. GPR is an active, non-intrusive geophysical method in which electromagnetic radiation and the reflected signals in the form of radar pulses are used for subsurface imaging. The objective is to investigate river sedimentation using GPR, we created the synthetic models based on geological models of rivers with different depths to create their 2-D radargrams to predict the actual model. We set up the first model RSM-I as control which consists of a layer of freshwater with $\rho = 16 \ \Omega m$, $k = 81$ and $\mu_r = 1$ of depth 5 m, two layers of sandstone with $\rho = 850 \ \Omega m$, $k = 2.5$ and $\mu_r = 1$ of total depth 4 m, and a layer of claystone with $\rho = 120 \ \Omega m$, $k = 11$ and $\mu_r = 1$ of depth 1 m. RSM-II and III are added with a buildup of saturated sediment with $\rho = 30 \ \Omega m$, $k = 15$, and $\mu_r = 1$ of depth 2.5 and 4 m, respectively. The radargrams’ reflector for each model shows a two-way travel time of 300-350, 150-200, and 60-90 ns in their respective order. GPR models can differentiate between the saturated sediment and freshwater, it shows good results regarding sediment investigation in rivers.

1. Introduction

Siltation is one of the reasons for flooding, wildlife deaths, and the downgrade of water quality. Siltation is caused by erosion and uncontrolled waste disposal that increases the river sedimentation rate. River sediment transport mechanism is divided into two types. Bedload where the sediment is transported along the surface of the bed and suspended load where the sediment is suspended in the fluid [1].

To prevent siltation, there needs to be a method that detects underwater sediment efficiently while providing high-quality results. To overcome this, we use the EM method, specifically ground-penetrating radar (GPR). GPR transmits EM radar waves and when the waves hits a boundary layer, some of the waves are reflected to the receiver and the rest of the waves are either refracted or scattered through the subsurface. The reflected waves are then plotted against its two-way travel time (TWTT) creating a radargram, a subsurface image with high resolution that is similar to a
seismogram in seismic reflection. GPR will detect the contrast between the water and sediment layer and can determine the depth of the river according to the thickness of the sediment. The advantage of GPR besides the high-resolution image is that the data acquisition requires no direct contact between the instrument and the freshwater layer, making it an effective method in preventing siltation in rivers. We used synthetic GPR data to model the river subsurface condition and to determine the river depth caused by sediment buildup at various sediment thicknesses.

2. Method

We used split-step algorithm\(^2\), a method for modeling and migrating GPR data in a heterogeneous media. The wavefield is extrapolated within the frequency-wavenumber (f-k) domain, from the 2-D Maxwell’s equations. Using the phase-shift technique, the extrapolation uses constant \( K \) (relative permittivity) and \( Q \) (quality factor). Then, the model parameters are characterized using the spatial distribution of the corrected \( K \) and \( Q \) factor values that are then integrated into the algorithm by a regular grid configuration. The radar wave attenuation and dispersion are calculated by a linear frequency-dependent \( Q \) model and shown in the propagation equation.

\[
J = (\sigma + i\omega\varepsilon)E = \varepsilon_T \frac{\partial E}{\partial t} \quad (1)
\]

\( \varepsilon_T \) is complex permittivity which can be written as

\[
\varepsilon_T = \varepsilon' - i[\varepsilon'' + \sigma(\omega)^{-1}] \quad (2)
\]

\( Q \) is the quality factor that shows how fast the EM wave dissipates, it is defined as the inverse of the loss tangent \( \delta \), the ratio of the imaginary to the real part of \( \varepsilon_T \).[3]

\[
Q = \tan \delta^{-1} = \varepsilon' [\varepsilon'' + \sigma(\omega)^{-1}]^{-1} \quad (3)
\]

Bano (4) using \( K \) dan \( Q \), determined the phase velocity \( V(\omega) \) and attenuation factor \( \alpha(\omega) \) are connected to a non-dispersive velocity \( V_0 \), and an exponential term \( n \), written as

\[
V_0 = \left\{ (\mu K \varepsilon_0)^{1/2} \cos \left[ \frac{\pi}{4} (1 - n) \right] \right\}^{-1} \quad (4)
\]

\[\]
\[
n = \frac{2}{\pi} \tan^{-1}(Q) \quad (5)
\]

\[
V(\omega) = V_0 \left[ \omega (\omega_c)^{-1} \right]^{1-n} \quad (6)
\]

\[
\alpha(\omega) = \omega [V(\omega)]^{-1} \tan \left[ \frac{\pi}{4} (1 - n) \right] \quad (7)
\]

The wavenumber \( k \) is then characterized using \( V(\omega) \) and \( \alpha(\omega) \) as

\[
k = \omega [V(\omega)]^{-1} + i\alpha(\omega) \quad (8)
\]

The radar wave propagation solution for a homogeneous and horizontally layered medium\(^2\) is given by

\[
E(k_x, z, \omega) = E(k_x, z = 0, \omega) \exp(-ik''_xx) \exp(-ik'_x z) \quad (9)
\]
\[ E(k_x, z, \omega) = E(k_x, z = \Delta z, \omega) \exp(-ik''z\Delta z) \exp(-ik'z\Delta z) \tag{10} \]

3. Results

These synthetic models are made considering the stratigraphy of a standard river (assuming the boundary layers are smooth because the sediment deposition is the size of fine sand or less). The resistivity and dielectric constant values are reference values \[^{[5,6]}\]. First, a homogeneous model of the sediment is created to check if the grid size and data response fit. The model can be seen in figure 1.

![Figure 1.](image)

*Figure 1.* (a) Homogeneous model of saturated sediment with \(\rho = 30 \Omega m\), \(\varepsilon_r = 15\) and \(\mu_r = 1\). (b) Homogeneous model radargram response.

Three models were made to simulate rivers with varying depths. The models are named RSM-I, RSM-II, and RSM-III and respectively have an ascending sediment thickness. The models’ antenna frequency is 100 MHz. The sediment layer is saturated to simulate the river sediment deposit. The models and their radargrams are shown in figures 2-4.

![Figure 2.](image)

*Figure 2.* (a) RSM-I models the initial river condition. The stratigraphy consists of a layer of freshwater with \(\rho = 16 \Omega m\), \(\varepsilon_r = 81\) and \(\mu_r = 1\) of depth 5 m, two layers of sandstone with \(\rho = 850 \Omega m\), \(\varepsilon_r = 2.5\) and \(\mu_r = 1\) of total depth 4 m, and a layer of claystone with \(\rho = 120 \Omega m\), \(\varepsilon_r = 11\) and \(\mu_r = 1\) of depth 1 m. (b) RSM-I radargram response with reflector two-way travel time of 300-350 ns.
Figure 3. (a) RSM-II. The stratigraphy consists of a layer of freshwater with $\rho = 16 \ \Omega m$, $\varepsilon_r = 81$ and $\mu_r = 1$ of depth 2.5 m, a layer of saturated sediment with $\rho = 30 \ \Omega m$, $\varepsilon_r = 15$ and $\mu_r = 1$ of depth 2.5 m, two layers of sandstone with $\rho = 850 \ \Omega m$, $\varepsilon_r = 2.5$ and $\mu_r = 1$ of total depth 4 m, and a layer of claystone with $\rho = 120 \ \Omega m$, $\varepsilon_r = 11$ and $\mu_r = 1$ of depth 1 m. (b) RSM-II radargram response with reflector two-way travel time of 150-200 ns.

Figure 4. (a) RSM-III. The stratigraphy consists of a layer of freshwater with $\rho = 16 \ \Omega m$, $\varepsilon_r = 81$ and $\mu_r = 1$ of depth 1 m, a layer of saturated sediment with $\rho = 30 \ \Omega m$, $\varepsilon_r = 15$ and $\mu_r = 1$ of depth 4 m, two layers of sandstone with $\rho = 850 \ \Omega m$, $\varepsilon_r = 2.5$ and $\mu_r = 1$ of total depth 4 m, and a layer of claystone with $\rho = 120 \ \Omega m$, $\varepsilon_r = 11$ and $\mu_r = 1$ of depth 1 m. (b) RSM-III radargram response with reflector two-way travel time of 60-90 ns.

The radargrams show a clear image of the river’s subsurface. The strong reflector indicates a contrast dielectric constant difference between the layers. RSM-I’s reflector has the highest travel time range at 300-350 ns, while RSM-III’s reflector has the lowest travel time range at 60-90 ns.

To calculate the depth of the river, we use the relationship between the propagating velocity of the electromagnetic wave in a medium and the travel time ($TWTT$) \cite{7}. Using the velocity structure \cite{4}, the propagating velocity in the freshwater model is calculated to be 0.033231 m/ns. The thickness of a layer is defined using equation (11).

$$\text{Thickness} = V_{med} \times \frac{(TWTT_T - TWTT_B)}{2} \quad (11)$$

Where $V_{med}$ is the propagating velocity of the electromagnetic wave in a medium, $TWTT_T$ and $TWTT_B$ are the two-way travel time of the top and bottom layers, respectively. Based on equation (11), the thickness of freshwater in RSM-I, II, and III are estimated to be 4.98465-5.815425 m, 2.492325-3.3231 m, and 0.99693-1.495395 m, respectively. The actual and calculated water depths are presented in table 1.
4. Conclusion
GPR synthetic modeling using split-step algorithm successfully simulated the radargram of rivers, the contrast between the freshwater and sediment layer in the radargram is the key in determining the river depth. Each model’s river depth can be calculated and sediment buildup can be determined. This shows that GPR can be used as a mitigation for river siltation and further research is required regarding the use of field data in conjunction with synthetic data to produce a higher quality subsurface image of the riverbed.

5. References
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| River Sedimentation Model | Actual Water Depth | Calculated Water Depth |
|--------------------------|--------------------|------------------------|
| RSM-I                    | 5 m                | 4.98465 - 5.815425 m    |
| RSM-II                   | 2.5 m              | 2.492325 - 3.3231 m     |
| RSM-III                  | 1 m                | 0.99693 - 1.495395 m    |

Table 1. River sedimentation model water depths comparison.