Abstract—Due to the huge computational cost, reverse time migration (RTM) of electromagnetic fields, and scattering of target shape is difficult. We implemented the stack RTM method to process the GPR data. Due to the limited borehole information, the 2D geological model is usually used in forward and backward extrapolation of electromagnetic fields. This paper adopts the normalized correlation to handle the back observation. It has been shown that the 3D RTM algorithm can reconstruct a target, and the interpretations of 3D RTM results and a round GPR data have been developed in recent years. RTM consists of three steps: the forward extrapolation of electromagnetic fields and moving the dip events to their true position. In contrast, the 2D RTM algorithm is usually implemented in its two dimensional (2D) form. The normalized correlation is the application of the imaging condition. Same numerical methods could be used in the first order FDTD method. This paper proposes a 3D RTM algorithm for GPR based on the high order FDTD method. The 3D high computational cost, reverse time migration (RTM) of target, and the interpretable underground target is generated during the correlation process. The effectiveness of stack RTM method to process the GPR data. We conclude that the 3D RTM algorithm can reconstruct a subsurface structure.

Keywords—Ground-penetrating radar (GPR), Reverse time migration (RTM), Stack RTM, Electromagnetic fields, Normalized correlation

$$\begin{align*}
E^{s+1} & = C_{EE} \cdot E^{s} \cdot C_{HH} \cdot \sum_{l=1-M} a[l] \cdot \partial H^{s+1} + J^{s+1} \\
H^{s+1} & = C_{HH} \cdot H^{s} \cdot C_{EE} \cdot \sum_{l=1-M} a[l] \cdot \partial E^{s}
\end{align*}$$
A. 3D RTM image result

The images show the reconstructed GPR profiles across the center of the cubic void. The profiles were generated by using the common source slice profiles at different frequencies. The void can be clearly identified in the images. Furthermore, the shape of the void agrees well with the true model. And the horizontal interfaces between concrete and soil are well defined.

The simulated common source used in this study was a Rick wavelet with a frequency of 1.0 MHz. The time window was 18 ns. Five source current lines were distributed on the offset 0.3 m, and the adjacent receiver interval was 0.3 m. The synthetic source position was 0.05 m, 0.35 m, 0.5 m, 0.6 m, and 0.7 m on the x-axis, respectively. Common source measurement was carried out on every source. The wavelet was applied to the calculated results in Fig. 1.

In order to obtain the RTM result, which can be seen in Fig. 4, we applied the commonly used matched layer. The computational region is divided into a subsurface cubic void model with relative dielectric constant of 5.0 and conductivity of 0.005 S/m. The upper media is concrete with a relative dielectric constant of 10 and conductivity of 0.001 S/m, while the lower media is soil with a relative dielectric constant of 5.0 and conductivity of 0.005 S/m. The simulation was performed with the cubic void size of 0.2 m. The depth of the void is 0.35 m.

Fig. 1. The whole computational region is divided into a cubic void model. The source current in Fig. 1 is set to obtain the RTM result. At present, we choose the imaging condition for GPR RTM is the anomaly interface between concrete and soil. Five different frequencies of the zero lag cross correlation were set to apply the imaging condition. Nevertheless, the imaging quality will be strong at the horizon and weak energy could be observed, which is related with the reconstructed slice profiles, cube (x, y, z) = (0.5, 0.5, 0.5), and (x, y, z) = (0.5, 0.5, 0.05). It is noticed that the focus event of the void can be clearly identified. Furthermore, the shape of the void agrees well with the true model. And the horizontal interfaces between concrete and soil are well defined.
B. Comparison between 3D and 2D RTM results

It is noticed that a majority of diffraction wave from the four edges of void has not been focused in the 2D RTM image. It is difficult to interpret the actual shape of void, which is denoted by dashed line. However, the four edges of the buried void have been well reconstructed in the 3D RTM image. And the scattering and diffraction energy from the four corners are well focused. Besides, the low-frequency noise is also weak in the RTM image reconstructed by the 3D algorithm in Fig. 6(b), compared with that by the 2D one in Fig. 6(a).

The dashed line denotes the actual shape of void in y-z plane. Figure 7 compares the GPR traces extracted from the reconstructed GPR images in Fig 6 at the position of y = 0.75 m. It is shown that the position of the horizontal reflection reconstructed by the 3D RTM algorithm coincide well with the actual interface depth of 0.35 m. In addition, the depths of top and bottom interfaces of the buried void in 3D RTM result is clear, and match well with the actual depth of 0.56 m and 0.66 m respectively. In contrast, the horizontal reflection from the concrete/soil interface by the 2D RTM algorithm has a small error and the top edge of the air cube is almost unrecognizable. It is concluded that, for a complicated 3D geoelectric structure, the 3D RTM algorithm can reconstruct a subsurface image with a higher precision and weaker low-frequency noise, compared with the 2D algorithm.
In this paper, a 3D RTM algorithm is proposed for improving the effectiveness of GPR imaging. The proposed 3D RTM algorithm is demonstrated to be effective in reconstructing GPR images by comparing with the 2D RTM algorithm. The normalized correlation imaging condition is used to provide a high order FDTD algorithm. The 3D FDTD algorithm is used in the 3D RTM algorithm to obtain a high frequency clutter level. The migrating algorithm for wavenumber modeling and heterogeneous dispersive environments is used in the 3D RTM algorithm. The proposed 3D RTM algorithm is demonstrated to work well in complex environments, which includes the migration of 2D GPR data extracted from the ground penetrating radar data. The proposed 3D RTM algorithm will be tested by the forward and backward extrapolation of the prestack RTM result and the stack RTM result. The effectiveness of the proposed 3D RTM algorithm is demonstrated to be high precision, which can help interpret the target shape. This work is supported by the National Natural Science Foundation of China (NO. 41604102).