Three dimensional reverse time migration on common offset GPR data for void imaging

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Abstract. Three dimensional (3D) Reverse time migration (RTM), as an indispensable imaging technique, has been widely applied to the observed seismic data imaging. However, the RTM of Ground Penetrating radar (GPR) is usually implemented in its two-dimensional (2D) form. This paper proposes a 3D RTM algorithm on common offset GPR data for void imaging. In this algorithm, the 3D finite difference time domain (FDTD) method is applied to calculate the backward extrapolation of electromagnetic fields. And the time zero imaging condition is applied to obtain the final RTM results. Comparisons of the imaging results of 3D and 2D RTM demonstrated that the 3D RTM imaging results were superior to those of 2D RTM. And 3D spatial distribution of Void can be imaged by the proposed 3D RTM algorithm with high accuracy, which can help the subsequent interpretation of GPR profile.

1. Introduction

Over the past years, Ground Penetrating Radar (GPR) have been widely applied to shallow subsurface void imaging with the advantages of non-intrusiveness, high accuracy and high resolution. Generally, it is difficult to accurately estimate the positions of void from the GPR image with low signal-to-noise directly, due to the complex strong diffracted waves are generated. Various GPR imaging algorithms, such as full waveform inversion, back-projection, reverse time migration (RTM) has been proposed to handle this problem. Among of them, RTM has been widely used in GPR imaging due to its simple theory, easy implementation and high accuracy [1]. At present, two dimensional (2D) RTM has been widely used to image of observed and synthetic GPR data [1][3]. Nevertheless, the observed GPR signal is propagated in actual three dimensional (3D) space. The high precision image of underground 3D target distribution is difficult to obtained by implementing 2D RTM algorithm of GPR, even illusions would be produced. 3D RTM is an effective technique to reconstruct a clear 3D target image by applying to the vertical profiles and horizontal slices simultaneously [4].

The most widely used data acquisition mode of commercial GPR system is Common offset acquisition due to the fixed offset and its high efficiency. The common offset GPR data, which similar to post-stack or zero offset seismic data, can be imaged by zero time imaging condition due to its offset is smaller than the length of survey line and the wave length.

Therefore, we present a 3D RTM algorithm of common offset GPR data based on finite difference time domain method (FDTD) and the zero time imaging condition in this paper. And the proposed 3D RTM algorithm is applied to image the observed 3D GPR data which observed on subsurface 3D void physical model. 3D void spatial distribution can clearly depicted with high accuracy. Further, the incomparable superiority of 3D RTM has been proven by the compared 3D RTM and 2D RTM imaging result.
1.1. 3D RTM algorithm of GPR
The implement of RTM for common offset GPR data is to extrapolate the GPR signals received by the surface receiving antennas along the time axis from maximum time. When the time is backward to zero, all the energy of the reflected waves and diffracted waves would be converged to its true space position. And the final RTM result can be obtained by applying the imaging conditions. In the proposed 3D RTM of GPR algorithm, the extrapolated electromagnetic wave of GPR was calculated by 3D FDTD and the zero time imaging condition, which based on exploding reflector principle is applied to yield the final RTM result.

1.2. Electromagnetic field extrapolation by 3D FDTD
According to the electromagnetic field theory, the 3D electromagnetic wave equations of GPR is given by
\[ \begin{align*} \nabla \times H &= \varepsilon \frac{\partial E}{\partial t} + \sigma E, \\
\nabla \times E &= -\mu \frac{\partial H}{\partial t}. \end{align*} \tag{1} \]

Where \( E \) and \( H \) are the electric and magnetic field, respectively. \( \varepsilon \), \( \sigma \) and \( \mu \) represent the permittivity, conductivity and permeability of media, respectively. And \( t \) is the time.

In order to solve the equation (1), the central difference is applied to approximate the spatial and temporal derivatives in FDTD. The detailed formulas can be obtained in the literature [5]. Furthermore, the UPML boundary condition is used to absorb the strong reflected waves at the truncated boundaries of the computation domain [2]. Thus, the 3D extrapolated electromagnetic fields at each time step can be obtained.

1.3. Zero time imaging condition
The zero time imaging condition can be developed by the exploding reflector method. The common offset GPR data can be simulated with the exploding reflector method as follows [6]: All reflectors at time \( t = 0 \) are treated as sources in the subsurface, and the reflector is matched well with the true subsurface before the explosion occurred \( (t = 0) \). The wave equation upward propagates the energy using the half wave velocity and each receiver records the signal as the common offset GPR data which shown in Figure 1(a). On the other hand, the reverse time extrapolation (exploding-reflector imaging) shown in Figure 1(b) is performed by propagating the recorded GPR data at the receivers back in time to the sources using the half wave velocity. The reverse time extrapolation is implemented by solving the equation 1 using the 3D FDTD. The half wave velocity can be obtained by multiplying by four to permittivity \( \varepsilon \) in equation 1. And the recorded data at the receivers on surface are enforced as a boundary condition, acting as sources. This extrapolation is continued backward in time \( t = 0 \), then all depths are imaged simultaneously. The final image is formulated as follows:
\[ I(x, y, z) = E(x, y, z, t = 0) \tag{2} \]
2. Experimental GPR data test

In order to test the proposed 3D RTM algorithm of GPR, a physical model with the size of 4.0 m × 2.0 m × 1.2 m has been built to obtain the observed 3D GPR data. The physical model is divided into two parts by a horizontal interface between the quartz sand and concrete with depth of 0.8 m. There are three typical voids are buried in the quartz sand shown as Figure 2(a). From left to right are the empty metallic ball with the diameter of 0.16 m, empty paper box with the size of 0.12 m × 0.21 m × 0.12 m, and basketball with the diameter of 0.24 m, respectively. And the central positions of them are (1.0, 3.25, 0.44) m, (1.0, 2.0, 0.3) m, (1.0, 0.75, 0.35) m, respectively. There are 26 survey lines arranged on the surface of the quartz sand. Among of them, 17 lines along x-axis and 9 lines along y-axis with both line interval of 0.25 m, which is shown as dotted line in Figure 2(b). The GSSI-4000 GPR system and the shielding antenna with the central frequency of 400 MHz are used to measure the GPR data. The acquisition model is point measurement with point distance of 0.025 m. The sampling number is 1024 and the time window is 14 ns.

The observed GPR profiles of line X9 and X10 are shown in Figure 3. The line X9 is arranged on the above of the empty paper box and there are no voids below the line X9. From Figure 3, we can see that the strong diffracted wave has been produced by the empty paper box. And horizontal reflected wave produced by interface between the quartz sand and concrete also displayed at about 11 ns. It is difficult to locate position of the empty paper box from the GPR profiles directly. Nevertheless, there are not empty paper box below the survey line X10, the diffracted wave also generated, which would be disturb the subsequently imaging result.
Figure 3. The observed GPR profiles of line X9 (a) and line X10 (b)

Figure 4 shows the reconstructed results of empty paper box by RTM algorithm. The Figure 4(a) and (b) are the 2D and 3D RTM result of observed GPR profiles of line X9, respectively. And The Figure 4(c) and (d) are the 2D and 3D RTM result of observed GPR profiles of line X10, respectively. It is note that the almost diffracted wave energy converged to the position of empty paper box. And the imaging results are matched well with the true position. However, the 2D RTM result shown in Figure 4(a) has been higher resolution with lower clutter compared with Figure 4(b). The false images displayed in Figure 4(c) and (d) will be disturb the subsequently interpretation.

Figure 4. the RTM imaging results of the observed GPR Profiles of line X9 and X10. (a), (b) are the 3D and 2D RTM results of line X9, respectively. (c), (d) are the 3D and 2D RTM results of line X10, respectively.

The 3D RTM results of the observed GPR data of 26 survey lines is shown in Figure 5. We can see that it can clearly distinguish the position and range of empty metallic ball, empty paper box and basketball. The reflected waves correctly return to the actual position and the diffracted wave are converged completely and the 3D spatial distribution of voids can be accurately delineated with no other false results. So it is conclude that the proposed 3D RTM of common offset GPR data can effectively imaging the subsurface voids with high resolution.
3. Conclusions

A 3D RTM algorithm of common offset GPR data is developed based on 3D FDTD and zero time imaging condition. 3D RTM imaging results of three voids demonstrated that the proposed 3D RTM algorithm can make the reflected waves correctly and the diffracted wave converged to their actual position and the location and shape of the void are clear depicted. Compared with 2D RTM result, 3D RTM result showed better imaging effect, which can improve the interpretation accuracy of radar data processing and effectively guide radar field measurement.

References
[1] Bradford J H 2015 Reverse-time prestack depth migration of GPR data from topography for amplitude reconstruction in complex environments Journal of Earth Science 26 791-798
[2] Li J, Zeng Z, Huang L and Liu F 2012 GPR simulation based on complex frequency shifted recursive integration PML boundary of 3D high order FDTD Computers & geosciences 49 121-130
[3] Liu, S., Lei, L., Fu, L., Wu, J., 2014. Application of pre-stack reverse time migration based on FWI velocity estimation to ground penetrating radar data Journal of Applied Geophysics 107 1-7
[4] Liu H, Long Z, Tian B, Han F, Fang G and Liu Q H 2017 Two-dimensional reverse-time migration applied to GPR with a 3-D-to-2-D data conversion IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 10 4313-4320
[5] Millington T M, Cassidy N J 2010 Optimising GPR modelling: A practical, multi-threaded approach to 3D FDTD numerical modelling Computers & Geosciences 36 1135-1144
[6] Zhu T, Carcione J M, Botelho M A B 2016 Reverse time imaging of ground-penetrating radar and SH-seismic data including the effects of wave lossQ-compensated GPR imaging Geophysics 81 H21-H32.