

Application of Elastic Reverse Time Migration to Ultrasonic Echo Data in Civil Engineering

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Extended Abstract

Abstract

To improve ultrasonic imaging of concrete structures, we transferred a seismic migration technique, the Reverse Time Migration (RTM), to non-destructive testing. A 2D elastic RTM algorithm was tested on synthetic ultrasonic echo data. Compared to the typically used synthetic aperture focusing technique (SAFT) as well as our acoustic RTM algorithm, the presented elastic RTM results show an enhancement in imaging vertical reflectors and complex features inside the 2D numerical concrete model.

Keywords: Ultrasonic Echo Technique, Elastic Reverse Time Migration, Synthetic Aperture Focusing Technique

1 Introduction

The ultrasonic echo technique is an important test method used in non-destructive testing (NDT) to determine the interior structure of concrete building elements [1][2]. Important NDT tasks include thickness measurements, the detection of cracks and debonding as well as the localization and characterization of built-in components and inhomogeneities. The available Synthetic Aperture Focusing Techniques (SAFT) [3][4][5] for the reconstruction of ultrasonic echo data have difficulties in imaging vertically dipping interfaces as well as complex structures such as steps and lower boundaries of voids since only single reflections of the ultrasonic wavefield are considered.

Compared to SAFT, the geophysical imaging method Reverse Time Migration (RTM) has the potential to produce a more complete imaging of features inside concrete specimens. Therefore, in two preliminary studies [6-7], we tested a 2D acoustic RTM algorithm on measured ultrasonic echo SH-wave data (SH: horizontally polarized shear) of a concrete foundation slab and a polyamide specimen. Using an acoustic RTM routine, which is based on purely P-wave (P: compressional) propagation is kinematically correct and a valid assumption, since SH-waves do not convert to other types of waves at any contrast of impedance considering a two-dimensional case. Compared to SAFT our acoustic RTM results showed a significant improvement in imaging the interior structure of both test specimens. For example, vertical reflectors inside the concrete slab were reconstructed clearly, and more features could be found, which was not possible by traditional SAFT imaging.

However, an RTM algorithm, which operates with the full elastic wave equation instead of the full acoustic one has the potential to optimize the imaging results even further. This is due to the fact, that our ultrasonic measurement data are generated by exciting elastic waves and

amplitudes are not handled correctly by using an acoustic RTM algorithm. Therefore, in this study, an 2D elastic RTM algorithm capable to evaluate SH-waves only (elastic SH RTM), was applied to synthetic ultrasonic echo data.

2 Reverse Time Migration

Reverse Time Migration (RTM) is a standard imaging technique in the seismic industry and was introduced by McMechan [8] and Baysal et al. [9]. It is a wave-equation based imaging algorithm and uses the full wave equation. In contrast to SAFT, it is able to image reflectors even with steep dips and structures in areas with strong velocity contrasts. A major disadvantage is the required extensive computation and memory capacity. However, due to progress in parallel processing and other computational technologies, RTM has become attractive for the application in the field of NDT.

So far, there are two publications showing the application of an 2D elastic SH RTM algorithm to ultrasonic echo data. Asadollahi et. al [12] developed an analytical elastic SH RTM approach to make the RTM algorithm more efficient in terms of memory demand and computation time required and successfully validated their approach on synthetic ultrasonic echo data. Recently Büttner et al. [13] investigated an engineered barrier for nuclear waste storage by applying elastic SH RTM to synthetic and real ultrasonic echo data.

The 2D elastic SH RTM implementation in this study uses numerical solutions of the 2D elastic wave equation. We modified a two-dimensional finite difference modeling code from the Madagascar software package [14], which simulates SV- (SV: vertically polarized shear), P- and R-waves (R: Rayleigh) to a 2D SH elastic finite difference routine. Using this finite difference code and functions already implemented in Madagascar we created our own elastic SH RTM algorithm. The whole RTM routine can be divided into five steps. Steps two to four are carried out individually for each source-receiver configuration.

- 1.) Estimation of suitable velocity and density models.
- 2.) The source wavefield is extrapolated forward in time using the source location, the source signal and the estimated migrations models (from 1.). The scattered wavefield is recorded at the receiver positions.
- 3.) The receiver wavefield is propagated backward in time, from all receiver locations using the estimated migrations models (from 1.). The receivers are converted into sources and the data recorded by the receivers (from 2.) are reversed in time and injected into the sources.
- 4.) The imaging condition used here computes the zero lag of the local cross-correlation between the two simulation results at all model grid points to find positions of existing reflectors in the examined medium.
- 5.) For the final result, the correlation images of all configurations are stacked.

3 2D Numerical Concrete Model

For simulation of elastic ultrasonic SH data, we used a 2D numerical concrete model (width: 2.04 m and depth: 0.59 m) which corresponds in its geometry to one of our laboratory specimens. Figure 1 shows the geometry of the model as well as material parameters. It includes a three-step homogeneous concrete layer with four integrated circular air voids (diameter: 0.08 m). A 0.02 m thick layer of air surrounds the concrete layer at the sides and lower edge.

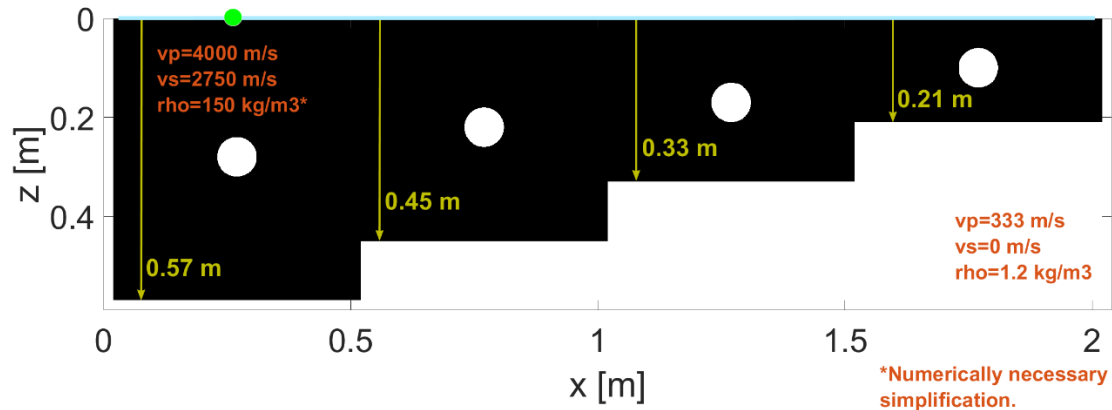


Figure 1: 2D three-step concrete model.

We defined absorbing boundaries at the sides and lower boundary of our model domain and assumed a free surface for the top edge. As source signal a Ricker wavelet was injected at the source positions as acceleration signal into y -direction perpendicular to the x - z -modeling domain. At the surface of the model, we defined 99 source positions with 199 receiver positions each. Thus, 99 shot records were generated, containing 199 traces respectively. Source no. 1 was located at $x = 0.04$ m and receiver no. 1 at $x = 0.03$ m. In Figure 1, source position no. 11 is marked green, as an example, and the corresponding receiver positions are highlighted blue. Table 1 summarizes the simulation parameters used.

Table 1: Simulation parameters

Simulation parameter		Simulation parameter	
Model size [grid points]	4080 (x) x 1180 (z)	Frequency Wavelet [kHz]	50
Spatial sampling interval [m]	0.0005	Wavelet delay [s]	0.00004
Simulation time [s]	0.00087	Distance of Sources [m]	0.02
Temporal sampling interval [s]	$1 \cdot 10^{-8}$	Distance of Receivers [m]	0.01

4 2D Elastic SH- and Acoustic RTM Results

For elastic SH RTM evaluation of the 99 synthetic shot records different velocity models were used. For the first RTM reconstruction the outer boundaries of the concrete layer were assumed to be known (Figure 2a). The corresponding RTM result (Figure 3a) shows the imaging of the first air void as well as the step edges running parallel to the top edge. Moreover, the top edges of the second and third air void as well as the vertical edge of the first step are clearly visible. The strong near surface artifact, which masks the fourth air inclusion, is caused by the direct wave. For a second migration, we integrated the first step, which was successfully reconstructed, into a new migration model (Figure 2b). The RTM result (Figure 3b) now shows the imaging of the vertical edge of the second step as well as the lower edge of the second air void. We continued this process by iteratively integrating reconstructed reflectors into new migration models (Figure 2c and 2d) to perform further RTM calculations. With this approach, all reflectors could be reproduced correctly (Figure 3c and 3d). Compared to the corresponding acoustic RTM results (Figure 4) of the elastic SH data (exemplary performed using the migration models presented in Figure 2a and 2d), a significant improvement of the imaging quality could be achieved. By applying elastic SH RTM, we were able to improve imaging of the cross-sections of the air voids (marked exemplary with red arrows). Furthermore, the

vertical edge of the first step was more sharply reproduced by using elastic SH RTM (marked with green arrows).

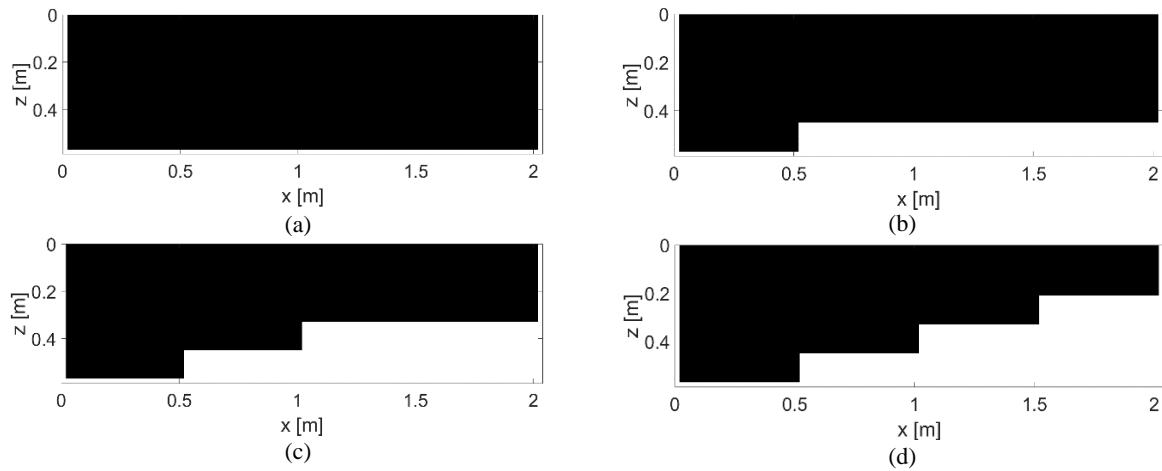


Figure 2: Structures of velocity and density models used for acoustic and elastic SH RTM migrations: (a) homogeneous migration model, (b) one-step migration model, (c) two-step migration model and (d) three-step migration model.

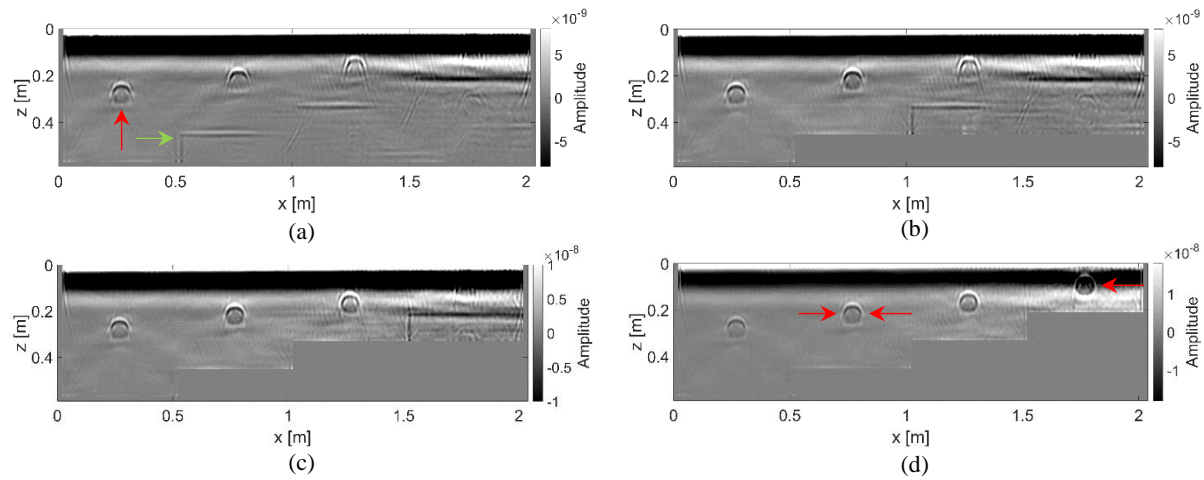


Figure 3: 2D elastic SH RTM results using: (a) the homogeneous migration model, (b) the one-step migration model, (c) the two-step migration model and (d) the three-step migration model.

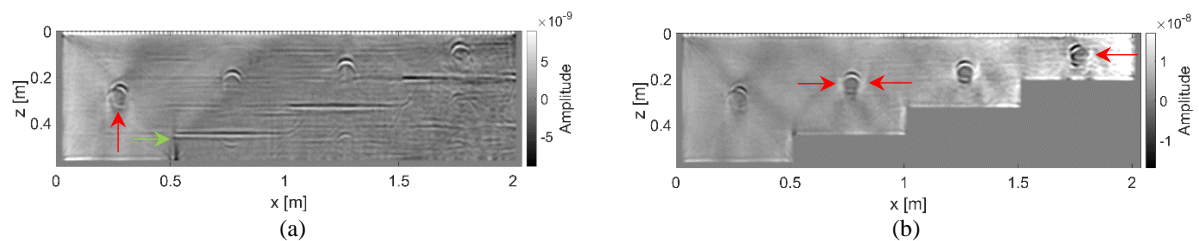


Figure 4: 2D acoustic RTM results using: (a) the homogeneous migration model and (b) the three-step migration model.

5 Comparison with 2D SAFT Reconstruction

Figure 5 shows the 2D homogeneous SAFT reconstruction result of the 99 synthetic shot records. We used the Intersaft software [15] to perform the SAFT reconstructions as well as a homogeneous velocity model ($v_s = 2750$ m/s). This result clearly illustrates the limitations of SAFT, since no vertical reflectors and lower boundaries of the four air voids were imaged. In addition, the top edge of the first air inclusion was only partially reproduced (marked with a red arrow in Figure 5).

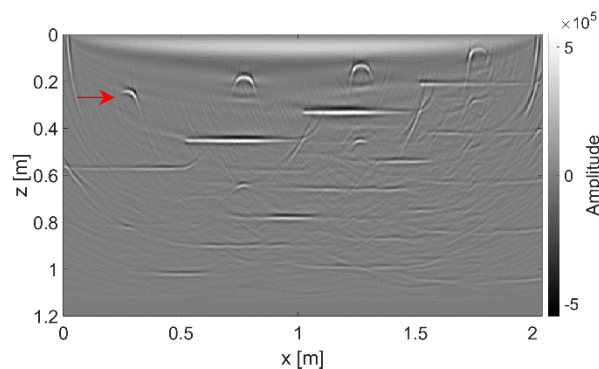


Figure 5: 2D homogeneous SAFT result of elastic SH data.

6 Conclusions and Future Work

In this study, the potential of a 2D elastic SH RTM algorithm to image ultrasonic echo data generated by SH-wave transducers was evaluated based on 99 synthetic shot records, which were simulated with a complex numerical concrete model containing three steps and four circular air voids. Our results show that elastic SH RTM is a step forward for ultrasonic NDT in comparison to acoustic RTM and SAFT imaging.

In contrast to 2D SAFT imaging, the vertical step edges as well as lower edges of the circular air voids could be imaged clearly. Compared to acoustic RTM, reconstruction of the cross sections of the air inclusions could be improved as well as imaging of the vertical step edges.

In future work, the applicability of our 2D elastic SH RTM algorithm to image real ultrasonic echo SH-wave data has to be evaluated. Corresponding ultrasonic measurements are currently conducted at one of our laboratory concrete specimens.

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