Reverse-Time Migration of Ultrasonic-Echo Data on a Foundation Slab

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ABSTRACT

The ultrasonic echo technique is a frequently used method in non destructive testing for geometry determination of concrete building elements. Important tasks are thickness measurements as well as the localization and characterization of built-in components and inhomogeneities. Currently mainly the Synthetic Aperture Focusing Technique (SAFT) is used for imaging. This algorithm is closely related to the Kirchhoff migration method and has difficulties in imaging steeply dipping interfaces and complicated structures such as steps and lower boundaries of voids. A reinforced concrete foundation slab with various reinforcement contents, different thicknesses and two pile heads was used for testing the prestack reverse-time migration (RTM) method. In a first step, the RTM was evaluated with synthetic 2D data. In the second step, ultrasonic measurement data recorded with shear wave transducers at two mutually perpendicular line profiles on the foundation slab were processed. The use of an automatic scanner simplified the measurements. Experiments such as the one detailed in this paper may be of interest to evaluate seismic migration methods on analogue models. A comparison of the RTM images with those of SAFT shows a significant improvement in the imaging of the geometry of the foundation slab. Vertical borders were reconstructed and the location and structure of the lower boundary of the foundation slab was reproduced better. Limitations still exist in imaging the pile geometry. The real data images show very noisy signals from the piles due to the reinforcement, edge effects and multiple reflections at the pile shaft.

Key words: Reverse-Time Migration, Synthetic Aperture Focusing Technique (SAFT), Non-Destructive Testing, Ultrasonic-Echo-Technique

1 INTRODUCTION

The ultrasonic echo technique is an important test method used in non destructive testing (NDT) to determine the interior of concrete building elements (Krause et al., 2008; Friese and Wiggenhauser, 2008). Important NDT tasks include thickness measurements, the localization of cracks and debondings as well as the localization and characterization of built-in components and inhomogeneities. The available Synthetic Aperture Focusing Technique algorithms (SAFT, e.g. Schickert et al. (2003)) for the reconstruction of ultrasonic echo data are closely related to Kirchhoff migration and have difficulties in imaging vertical dipping interfaces as shown in Figure 1. Reverse-time migration (RTM) has the poten-
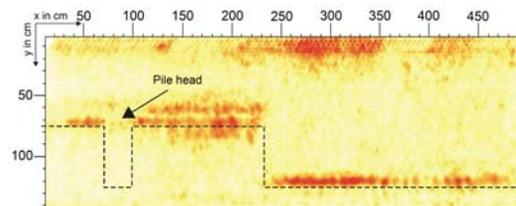

Figure 1. SAFT reconstruction of ultrasonic data collected on a foundation slab with a pile head (y = 70 cm - 100 cm) and a step (y = 235 cm)(cf. (Taffe, 2008))

tial to produce a more complete imaging of the features in the concrete specimens and was tested in this work at a foundation slab.

2   TEST SPECIMEN - FOUNDATION SLAB RUFUS

The test object was a reinforced concrete foundation (Figure 2) built at the BAM test site as part of the EU research project RuFUS (Re-use of Foundations on Urban Sites). The foundation slab is embedded in com-
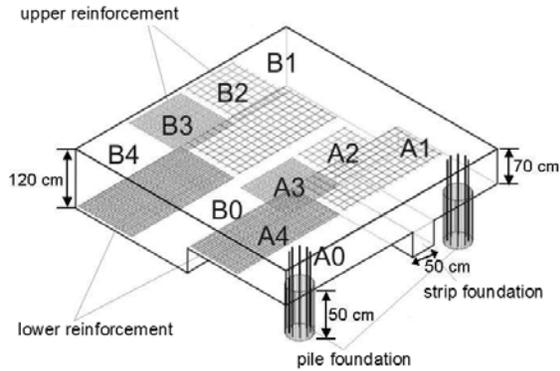
Figure 2. Geometry of the RuFUS foundation slab (Taffe, 2008)

pacted sand and consists of areas of different thickness, ten different reinforcement levels, a strip foundation and two piles. At the bottom of the foundation slab is a 5 cm thick layer of lean concrete. Figure 3 shows this layer and the different levels of reinforcement before concreting.

The tasks with respect to the foundation slab were thickness determination as well as imaging the vertical step, the two pile heads and the strip foundation. In addition, the dependency of the resolution on various factors (such as 3D effects and the reinforcement) had to be investigated.

Figure 3. (a) and (b): Lean concrete layer and different levels of reinforcement before concreting (cf. (Taffe, 2008))

3   REVERSE-TIME MIGRATION

We chose the Reverse-time migration (RTM) for imaging of synthetic and experimental data. RTM was introduced by Mc Mechan (1983) and Baysal et al. (1983). RTM uses the full wave equation. The RTM implementation in this paper uses numerical solutions of the

acoustic wave equation. For the ultrasonic echo measurements at the foundation slab we used horizontally polarized shear waves which do not convert to other types of waves at interfaces. Thus using an acoustic RTM code is kinematically correct.

RTM is a wavefield-continuation method in time and is able to image waves even in areas with steep dipping reflectors and with strong velocity variations. A major disadvantage is the required extensive computing power and memory capacity.

The RTM algorithm we used is based on a two dimensional finite difference modeling code created by using the Madagascar software package (Fomel et al., 2013). RTM consists of the following main steps:

1.) The source wavefield is extrapolated forward in time assuming a known source location, source wavelet and a subsurface velocity model.

2.) The receiver wavefield is modeled backward in time, from known receiver locations, the recorded data and an assumed subsurface velocity model. For the reverse modeling the migration algorithm converts the receivers into sources and plays the recorded data back into the subsurface.

3.) 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 subsurface reflectors.

4   APPLICATION TO SYNTHETIC DATA

In a first step we tested RTM with synthetic 2D data to prove the concept of RTM and to obtain information about appropriate ultrasonic measurement parameters (e.g. number and positions of sources and receivers, recording time). As an example we chose the two-dimensional section marked red in Figure 4 through the foundation slab. This two-dimensional profile contains the vertical step, a pile and the reinforcement meshes A1 and B1.
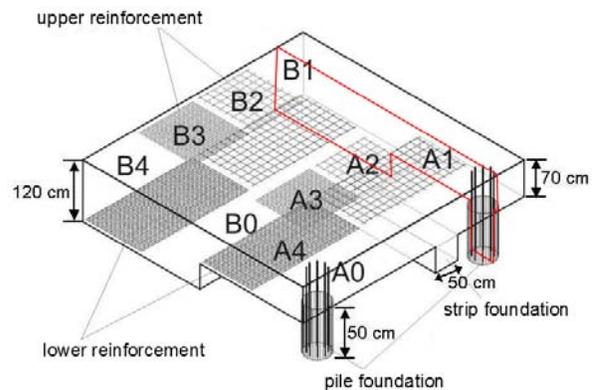

Figure 4. Two-dimensional section through the foundation slab (red) (cf. (Taffe, 2008))

The material parameters used in the velocity and density models for the simulation process are listed in Table 1. The structure of the velocity and density model is shown in Figure 5.

Table 1. Shear wave velocity v_s und density values ρ for the simulation process

Material	v_s $[\frac{m}{s}]$	ρ $[\frac{kg}{m^3}]$
Reinforced concrete	2750	2400
Compacted sand soil	300	1800
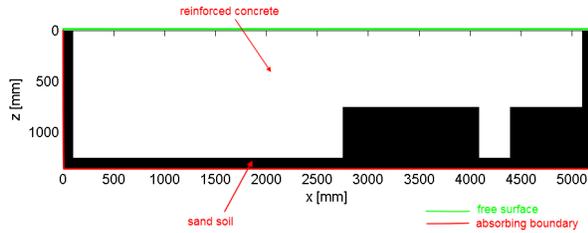
Figure 5. Structure of the velocity and density model for the simulation process including a vertical step and a pile head

To simplify the simulation and RTM of the synthetic data, both models are idealized. They do not contain any scattering aggregates inherent to concrete, since their precise distribution is not known. The 5 cm thick lean concrete layer is included in the concrete part of the model. The reinforcement was neglected.

Table 2 summarizes the simulation parameters used. The model consists of 5200 x 1350 grid points with a grid spacing of 1 mm. A ricker wavelet with a main frequency of 25 kHz was used as source signal.

**Table 2.** Parameters for the simulation process

Parameter	
Model size	5200 x 1350 grid points
Distance between grid points	0.001 m
Frequency of the Ricker wavelet	25 kHz
Sampling interval	$1 \cdot 10^{-7}$ s

Table 3 contains the parameters for the simulation and the RTM, which led to the most accurate image. We simulated 33 shots using 242 receiver positions (distance 0.02 m). Simulated recording time was 1.11 ms with a time step of $1 \cdot 10^{-7}$ s.

Table 3. Parameter for the simulation process and RTM (v_{sc} = shear wave velocity of the concrete layer, v_{ss} = shear wave velocity of the sand soil layer, ρ_c = density of the concrete layer, ρ_s = density of the sand soil layer)

Parameter	
Number of Sources	33
Number of Receivers	242
Distance between sources	0.15 m
Distance between receivers	0.02 m
Source position no. 1	0.02 m
Receiver position no. 1	0.02 m
Recording time	0.00111 s
Velocity - simulation	$v_{sc} = 2750 \frac{m}{s}$, $v_{ss} = 300 \frac{m}{s}$
Velocity - RTM	$v_{sc} = 2750 \frac{m}{s}$, $v_{ss} = 300 \frac{m}{s}$
Density - simulation	$\rho_c = 2400 \frac{kg}{m^3}$, $\rho_s = 1800 \frac{kg}{m^3}$
Density - RTM	$\rho_c = 2400 \frac{kg}{m^3}$, $\rho_s = 1800 \frac{kg}{m^3}$
Thickness of concrete layer	1.25 m

Figure 6 shows the structure of the velocity and density model used for the RTM. The outer limits of the foundation slab are assumed to be known. The model doesn't contain information on the step and the pile.
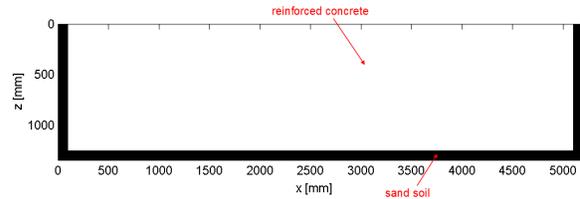
Figure 6. Velocity/density model used for RTM

The migrated image is shown in Figure 7. The receiver positions are marked in green and the source positions are marked in red. The vertical step is reconstructed perfectly in terms of width and height. The lower boundary of the foundation slab as well as the lower part of the pile shaft and the pile base are clearly imaged.

The semi-circular artifacts at the source positions (1) are caused by direct waves. The events parallel to the lower boundary of the foundation slab (2) are created by multiple reflections from the lower boundary in the synthetic data. Limitations exist in imaging the upper part of the pile shaft.

The use of the two-way wave equation produces artifacts in the reconstructed images. These events exist due to the correlation of waves which are not accounted for in the cross-correlation imaging condition (Díaz and Sava, 2012). In the left part of the migration result and in the area of the pile head stronger artifacts formed (dark shade). The reason is that in these areas the position of the lower boundary of the concrete layer in the models

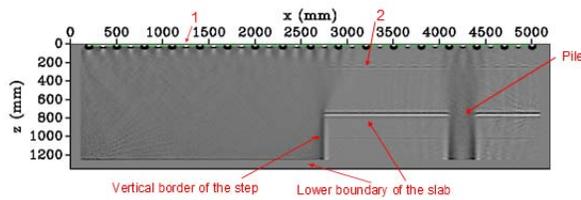for the RTM matches the real depth.

Figure 7. RTM image obtained with optimized migration parameters

5   APPLICATION TO REAL DATA

5.1   Ultrasonic Measurements

The main goal of this work was to test the RTM with ultrasonic measurement data, which were recorded at two profiles on the foundation slab (Figure 8). Profile 1 corresponds to the profile that we used for testing the RTM with synthetic data. The second profile crosses both piles and the strip foundation. Due to the page limits just data from profile 1 are presented here.
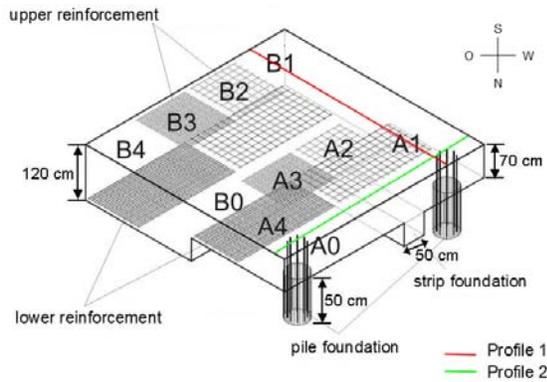

Figure 8. Two line profiles on the foundation slab (cf. (Taffe, 2008))

We used a multistatic arrangement to collect the ultrasonic-echo data. Two ultrasonic transducers were moved over the surface. Both were separated from each other and changed their positions and distances. Each transducer array (Figure 9) consists of 32 dry point piezoelectric contact transducers, which excite shear waves. The measurement frequency was 25 kHz. The shear waves were polarized in the plane perpendicular to the measuring direction.

Figure 9. Ultrasonic transducer array consisting of 32 dry point contact transducers

For the measurements an automatic scanner was used (Figure 10 and 11) with which the receiving transducer could be automatically moved from measuring point to measuring point for the respective source position. The length of the scanner is 1.2 m. On both profiles we used 32 source positions and a receiver spacing of 2 cm. Source-receiver offsets were limited to a maximum of 2.3 m due to time restrictions.


Figure 10. Scanner on the foundation slab moving the receiving transducer array (E)

Figure 11. Scanner on the foundation slab with transmitting (S) and receiving (E) ultrasonic transducer arrays

Figure 12 shows the recorded raw data at source position no. 8 of profile 1. The direct wave (1) and the reflection of the wavefield at the lower boundary (2) of the foundation slab as well as a multiple reflection (3) at this boundary are visible. Furthermore the reflection of the direct wave at the eastern (4) and western (6) upper edge of the foundation slab are shown. An apex of a reflection hyperbola is visible at 92 cm caused by a metal bracket inside the slab (5).

Prior to the RTM we performed the following processing steps of the data: muting crosstalk, time interpolation and bandpass filtering (cut-off frequencies: 8 kHz/100 kHz).
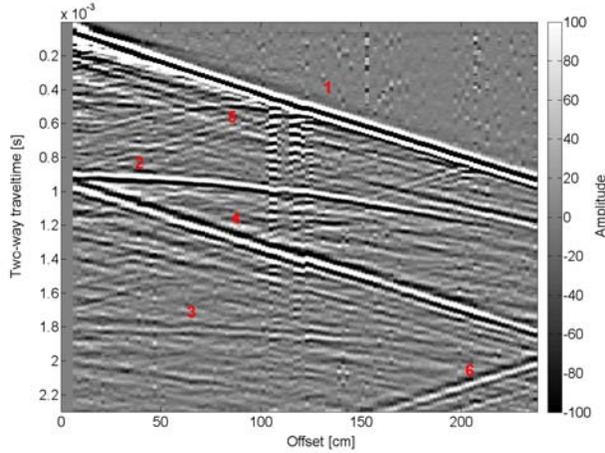
**Figure 12.** Received ultrasonic-echo data for source position no. 8 at 1.15 m

5.2   RTM Images - Profile 1

The structure of the velocity and density model which we used for the RTM images presented in this section, is shown in Figure 6. For the reinforced concrete we chose a shear wave velocity of 2740 m/s, based on a preliminary velocity analysis. The other migration parameters are summarized in Table 4. The recording time was 1.7 ms. The source and receiver positions correspond to the measurement parameters.

Table 4. Parameters for RTM for profile 1 (v_{sc} = shear wave velocity of the concrete layer, v_{ss} = shear wave velocity of the sand soil layer, ρ_c = density of the concrete layer, ρ_s = density of the sand soil layer)

Parameter	
Model size	5200 x 1350 grid points
Distance between grid points	0.001 m
Frequency Ricker wavelet	25 kHz
Sampling interval	$1 \cdot 10^{-7}$ s
Recording time	0.0017 s
Number of sources	32
Number of receivers	varies
Distance between sources	0.15 m
Distance between receivers	0.02 m
Source position no. 1	0.02 m
Receiver position no. 1	0.031 m
Velocity - RTM	$v_{sc} = 2740\ \frac{m}{s}$, $v_{ss} = 300\ \frac{m}{s}$
Density - RTM	$\rho_c = 2400\ \frac{kg}{m^3}$, $\rho_s = 1800\ \frac{kg}{m^3}$
Thickness of concrete layer	1.25 m

For the image shown in Figure 13 we applied a bandpass filter process to the data (cut-off frequencies: 8 kHz/100 kHz).
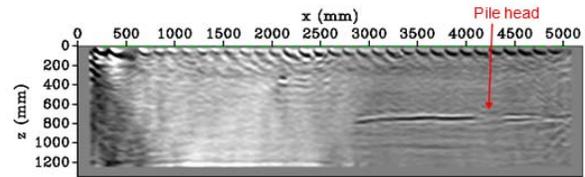

Figure 13. RTM image of profile 1

The lower boundary of the foundation slab is reproduced at the correct depth, showing a low amplitude at the model boundaries. The structure of the lower boundary shows some ripples and some dip in the area of the vertical step.

The pile head (gap in the lower boundary reflection) is shown in the correct position. The position of the step is shifted by about 10 cm to the right. The pile shaft

and pile base are missing.

At x = 2100 mm and z = 300 mm a circular reflector is reconstructed, which can be assigned to a metal bracket (Figure 14).
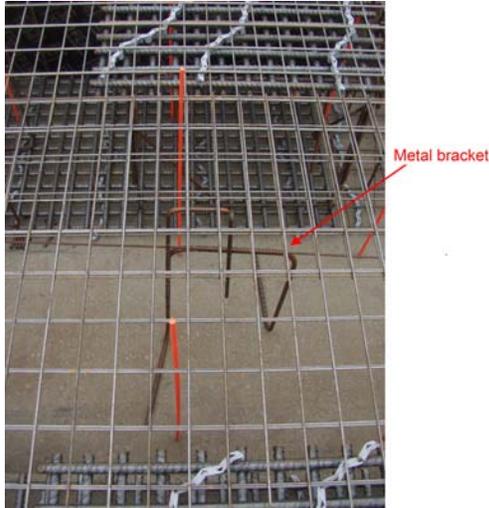

Figure 14. Metal bracket inside the foundation slab

Figure 15 shows the RTM image after stacking the images obtained from just shot points no. 27 to 32. The lower boundary of the slab is now imaged clearly with a higher amplitude and a small depth offset. Furthermore a phase jump can be recognized, which is possibly caused by debonding in this area. The stacking of the images of just shot points no. 7 to 15 illustrates clearly that the vertical edge of the step is reproduced (Figure 16). For this image we additionally applied an AGC and trace normalization to the data.
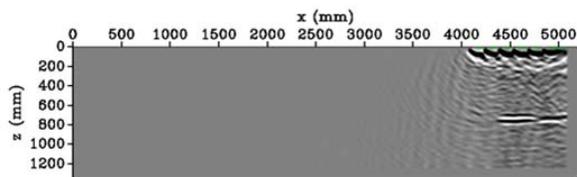

Figure 15. RTM image after stacking the images obtained from shot points no. 27 to 32
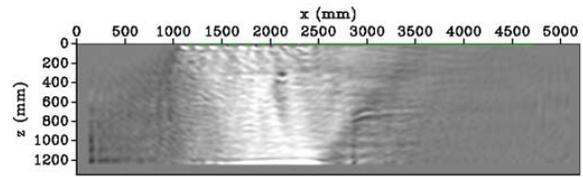
Figure 16. RTM image after stacking the images of the shot points no. 7 bis 15 and applying an AGC and trace normalization to the data

In a next step, we carried out a 3D/2D-correction of amplitude and phase in addition to bandpass filtering, AGC and trace normalization. The lower boundary of the slab is now clearly visible at the foot of the vertical step (Figure 17).
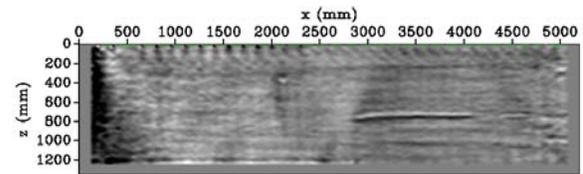
Figure 17. RTM image after applying a 3D/2D-correction

Using the $x^2 - t^2$-method we determined an average shear wave velocity of the reinforced concrete of 2811 m/s and an approximate depth of the lower boundary of the slab of 1213.2 mm and 726.9 mm. This led to the conclusion that most of the energy of the wavefield was reflected at the lower boundary of the reinforced concrete layer rather than at the lower boundary of the lean concrete layer.

The RTM image calculated with the average shear wave velocity of 2811 m/s shows stronger artifacts on the left side of the image, due to the use of a more accurate migration velocity (Figure 18).
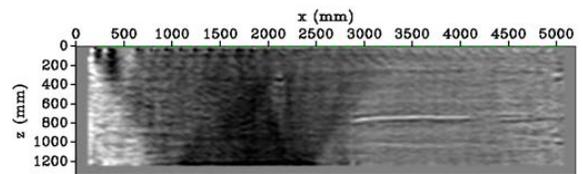
Figure 18. RTM image using the calculated average shear wave velocity of 2811 m/s

5.3   SAFT Image - Profile 1

Figure 20 shows the image obtained from the 3D - SAFT reconstruction of profile 1. The ultrasonic measurements were made in July 2004 with the array A1220 (Figure 19). This array consists of 12 transmitting and 12 receiving dry point contact transducers which excite shear waves (bistatic method). The measurements were carried on automatically using a scanning system. The step width was 5 cm across the surface and the measurement frequency was 33 kHz.

transmitting transducers   receiving transducers
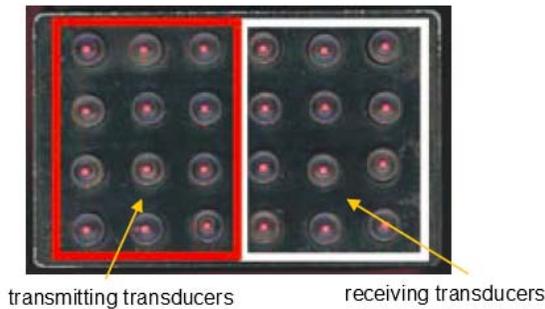
Figure 19. Ultrasonic transducer array A1220

For the SAFT-reconstruction we chose a migration velocity of v = 2700 m/s. According to the state of the art in NDT, the envelope of the receiving signals is calculated. Blue/red corresponds to high and white to low values of the envelope.
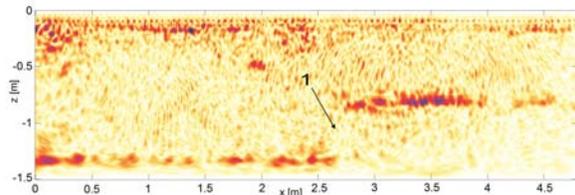
Figure 20. SAFT-reconstruction of profile 1

Except for the vertical faces, all reflectors are imaged in the SAFT reconstruction (Figure 20). However, the lower boundary of the slab is imaged with gaps. Compared to the RTM image (section 5.2) the lower boundary of the slab shows different x-positions in the area of the vertical edge of the step (1), probably due to the bistatic measurement setup and the large distance between the measuring points of 5 cm.

6   DISCUSSION

The comparison between RTM and SAFT imaging shows a significant improvement in imaging the geometry of the foundation slab by RTM. However, it must be noted that a quantitative comparison between the two

algorithms is not possible in the current stage. For the SAFT algorithms a bistatic measurement setup and a distance between shot points of 5 cm was used. All the examples for RTM were calculated with a multi-offset geometry and a distance between receiver positions of 2 cm.

The images show a horizontal displacement of the vertical step of about 10 cm. Since the pile head was reproduced at the correct position, the displacement of the step is rather an error in construction drawings then an imaging artefact.

The imaging of the pile geometry wasn't fully successful, since the measured data show noisy signals from the piles due to the reinforcement, edge effects, multiple reflections at the pile shaft, 3D effects, and the attenuation of the waves in concrete.

The light ripples in the structure of the lower boundary of the slab could have been caused by the migration algorithm or have been formed during the construction of the slab. The latter might as well be the cause for the dip of the lower boundary of the slab in the area of the vertical border of the step. Furthermore, material inhomogeneities might cause the ripples and the dip.

The use of transducer arrays is a general problem because the RTM code currently assumes point sources. Therefore, the migration algorithm doesn't correctly calculate shot and receiver wavefields.

The quality of the resolution of the lower boundary of the slab does not appear to be dependent on the extent of the lower reinforcement. Furthermore, the application of the 3D/2D-correction did not significantly improve the image quality.

7   CONCLUSIONS

We used synthetic and measured data sets to check the applicability of RTM to image ultrasonic echo data collected on a reinforced concrete foundation slab. The tests yielded promising results and showed that RTM is a step forward for the ultrasonic echo technique used in nondestructive testing.

The imaging of the location and structure of the lower boundary of the slab could be improved with RTM compared to conventional imaging techniques (SAFT). By using RTM vertical borders could be imaged clearly and more flaws could be found. To gain a more precise comparison between the images produced by SAFT and RTM, ultrasonic echo measurements using a distance of 2 cm between shot points will soon be performed and evaluated.

By optimizing the measurement equipment, a higher amplitude resolution should be achieved to improve the reconstruction of the pile geometry. A different scanner allowing larger aperture should be utilized for realizing a better resolution of the features inside the slab as well as reduction of artefacts and measurement uncertainties.

Furthermore, a core sample should be taken for an anal-

ysis of the depth offset and phase jump of the lower boundary of the slab at the specimen boundaries.

RTM artefacts have to be analyzed and eliminated. For this task alternatives to the cross correlation imaging condition may be used. In addition, the algorithm should be expanded to three dimensions and the full elastic wave equation. Another topic to be addressed is to how to account for the size of the ultrasonic arrays. Experiments such as the one detailed in this paper may be of interest to evaluate seismic migration methods on analogue models.

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