

Using Full-Waveform Inversion for imaging of Impact Echo data of concrete structures

Introduction

Non-destructive testing (NDT) methods are essential for the maintenance of reinforced concrete structures like bridges, tunnels, or power plants. They provide the basis for evaluating the structural condition and planning appropriate maintenance measures while preserving the structural integrity. To ensure that such structures can be operated safely, inspections are carried out in regular intervals. Impact Echo (IE) is an NDT method commonly applied for the inspections of thick and highly reinforced concrete structures (Sansalone and Carino 1988). Due to its low-frequency nature it is less affected by the heterogeneity of reinforced concrete, which results from the composition of aggregates, pores, and cement matrix along with steel rebars.

Many other NDT methods like Ground Penetrating Radar or Ultrasonic Testing produce a direct image of the subsurface, making the interpretation of inspection results straightforward. In contrast to this, IE aims to measure a specific resonance frequency of the structure, which is correlated to its thickness (Gibson and Popovics 2005). Possible defects inside the structure can be detected through a frequency shift. Therefore, results are often displayed in frequency spectra measured along a line (B-scans) or frequency maps acquired over a surface (C-scans) (Wiggenhauser 2003). The current inspection procedure for IE has two main disadvantages: it disregards most parts of the signal since it only focuses on one single frequency. Furthermore, the interpretation of results in frequency domain is challenging, especially when multiple frequency peaks are present (Dethof and Keßler 2024). For example, defects can cause frequency shifts towards lower frequencies since the defect presents a structurally weak area. However, if a defect is great enough, it causes an additional higher frequency peak, which is correlated to its depth (Carino 2015).

This work aims to provide a proof-of-concept that the Full-Waveform Inversion (FWI) can be successfully applied to IE data to directly image the subsurface structure. For the numerical simulations, a staggered-grid finite differences code called EFIT (elastodynamic finite integration technique) (Fellinger et al. 1995) is used, while a 2D elastic FWI utilizing the adjoint gradient method is applied for the inversion. Inversions are performed on noisy, synthetic data generated using numerical simulations with a heterogeneous concrete model.

Theory

Impact Echo

During IE tests, a small mechanical impact is generated (manually) on a plate-like structure, and the resulting displacement is recorded a couple of centimetres away from the impact location. The method aims to measure the frequency of the zero-group-velocity S1 Lamb wave mode f_{S1} . This frequency is directly correlated to the thickness of the structure d :

$$f_{S1} = \frac{\beta(v)c_P}{2d}$$

Here c_P is the P-wave phase velocity and β is a Lamb wave correction factor, which depends on the Poisson's ratio ν of the material and for concrete has values between 0.945 and 0.957 (Gibson and Popovics 2005). As this Lamb wave mode has a group velocity of zero, its energy remains at the impact location. Simultaneously, it offers sub-wavelength resolution, which allows the detection of defects in thick and highly reinforced concrete structures through changes in the resonance frequency. In most cases, the recorded waveforms are analysed in frequency domain using the Fast Fourier Transform. However, analysing the frequency spectra is not always easy due to the presence of other frequency peaks like Eigenmodes (Dethof and Keßler 2024). As a result, IE is applied less frequently than other NDT methods, which offer a direct imaging of the subsurface structure.

Full-Waveform Inversion

Since IE utilizes Lamb waves, which can only be created by multiple P- and SV-waves reflections between opposing free surfaces, elastic wave simulations need to be performed during the FWI process. For the proof-of-concept 2D inversions are performed first. For this, the adjoint gradient method was implemented according to the documentation in (Köhn et al. 2021). The inversion was performed simultaneously for the P- and S-wave velocities c_P , c_S , as well as for the mass density ρ . For the setup, a single source with five receivers to each side was chosen. The receivers and the source are all spaced 6 cm apart from each other resulting in a total aperture of 30 cm. To mitigate the problem of strong artifacts near the source and receiver locations, a gradient normalization based on a diagonal pseudo-Hessian obtained from the total forward wavefield energy at each grid cell was used (Plessix and Mulder 2004) in combination with a taper based on a 10% Tukey window.

Simulations and inspection scenario

Since concrete is a strongly heterogeneous material, assuming a homogeneous material for low-frequency inspections such as IE is not justified. In fact, it was found that especially the pores inside the concrete cause a non-negligible amount of noise (Schubert and Köhler 2008). Because of that, a robust algorithm is required when simulating elastic wave propagation in such media. In this study, EFIT (Fellinger et al. 2008) is used for the simulations. It is a staggered-grid finite differences code that iteratively solves the integral form of Cauchy's equation of motion and the deformation rate equation. Since all components of the stress tensor and velocity vector are located at different points inside a grid cell, an averaging scheme is created, improving the robustness of the code for such strongly heterogeneous media.

In this study, a simulation domain with dimensions of 3 m $\times$ 0.6 m with a grid cell size of 3 mm is used. The domain is made of reinforced concrete. The rebars have a diameter of 12 mm and are located 51 mm away from the nearest surface in increments of 30 cm. For the ground truth (observed) data, aggregates and pores inside the concrete are explicitly discretized like the concrete model described in Schubert and Köhler (2004). The P- and S-wave velocities inside the aggregates are 4400 m/s and 2700 m/s, respectively. The densities have a value of 2700 kg/m³ for all aggregates. For the cement matrix which also includes aggregates smaller than the grid cell size of 3 mm, a P-wave velocity of 3600 m/s, an S-wave velocity of 2100 m/s as well as a density of 1900 kg/m³ are chosen, which are realistic values for mortar. The concrete has a porosity of 2 vol.-% and all pores are modelled as a vacuum to avoid numerical dispersion in the inside.

The defect is modelled as a generic, circular low velocity zone with a P-wave velocity of 2400 m/s, a S-wave velocity of 1500 m/s and a density of 800 kg/m³. It resembles a structurally weak area, which could be the result of a void, a crack system, or a honeycomb. The centre of the defect is located at $x=1.16$ m at a depth of 0.26 m. It has a diameter of 72 mm, which means that the size-to-depth-ratio is too small for a location of the defect with standard IE data evaluation (Carino 2015). Adjacent to the defect ($x=1.46$ m, $z=0.35$ m) is a steel inclusion of the same size. Based on current detection limits, detecting this defect should not be possible (Carino 2015). The centre of the array (e.g., the source position) described in the previous subsection is located at $x=1.35$ m.

With this configuration, the expected (defect-free) resonance frequency f_{S1} is about 3.2 kHz. The mechanical impact used in real inspections can be described by a half-cycle sine curve (Goldsmith 1960). However, artifacts are generated in the simulations due to the non-differentiability at the start and end of the pulse (Dethof 2025). Therefore, a Gaussian pulse is used to avoid this problem. Both source functions have their maximum at a frequency of 0 Hz independent of the centre frequency. Therefore, a centre frequency higher than the expected f_{S1} is required to excite this resonance. Here, a centre frequency of 8 kHz is chosen.

Starting model

For the initial model, it is assumed that no prior information regarding the concrete structure or the location of steel reinforcements is available. Consequently, a homogeneous initial model is adopted. However, determining the most suitable material parameters for such a model is not straightforward. Due to the strong heterogeneity of the concrete, the energy transport becomes diffusive (Schubert and Köhler 2004). As a result, the effective wave speeds are generally lower than the average wave speeds set by the material parameters (Dethof 2025). To find the most suitable starting model, a grid search using four different values for P- and S-wave speeds was conducted. Here, the P-wave velocities varied from 3561-4011 m/s and S-wave velocities varied between 1958-2408 m/s in increments of 150 m/s, respectively. The maximum values for this grid search were determined by the average wave speeds inside the medium (disregarding diffusivity). Ultimately, it was found that a P-wave velocity of 3711 m/s and a S-wave velocity of 2108 m/s showed the smallest residual to the observed data. A cubic interpolation of the results was also conducted but was unable to improve the residual.

The true subsurface model used for the inversion is shown in Figure 1. The corresponding source–receiver configuration is also illustrated in this figure.

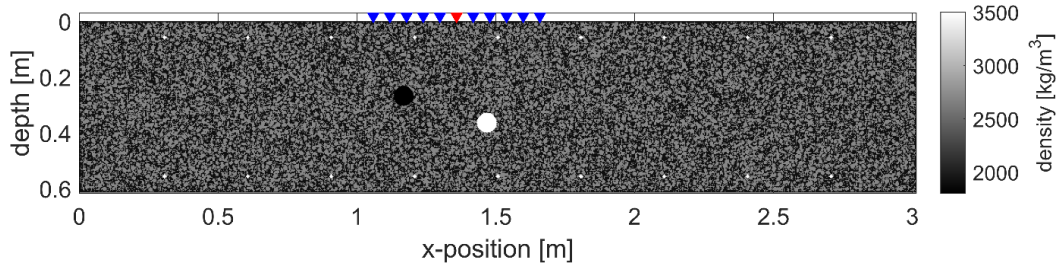


Figure 1 Density of the concrete model used to simulate the observed data. The red triangle marks the source location, while blue triangles indicate receiver positions.

Inversion results

In total two different inversions are performed: one using both x- and z-components and one using only the vertical (z-)component. The latter scenario is chosen as current IE inspections only measure and utilize the vertical component. The length of the signals used for the inversion is 0.75 ms, which is considerably shorter than regular IE signals. However, it is known that most defect information is contained at the start of such signals (Dethof 2025), which is why this window is chosen here.

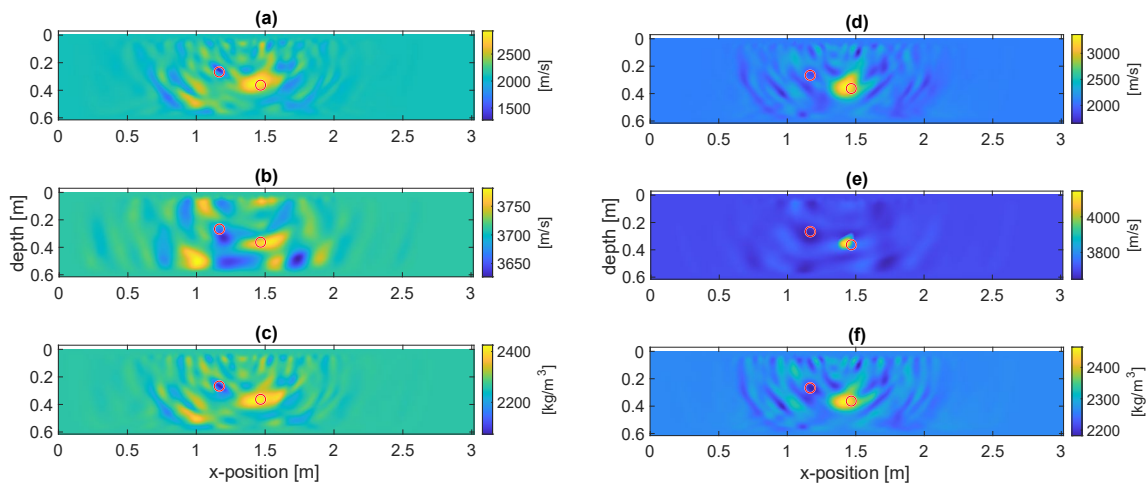


Figure 2 Inverted S-wave velocity (a, d), P-wave velocity (b, e), and density (c, f) using both-components (a-c) in contrast to a single (vertical) component (d-f).

Figure 2 a-c shows the inverted material parameters when using both components. It can be observed that both c_s and ρ capture the defect and the steel object well. They are clearly indicated and precisely localized even though, they seem larger in the inversion compared to their actual size. The P-wave velocity also shows some indications for these objects, but the inversion result is strongly influenced by artifacts. The residuals were reduced by 33% (x) and 35% (z), respectively.

When evaluating the inversion result for a single component (Figure 2 d-f), a clear indication for the steel object can be identified for each parameter. However, only c_p shows a minor indication for the defect. In this case the residual of the vertical component was reduced by 34%. Indications of the rebars are not visible for either of the two scenarios. It must be mentioned that, for both scenarios, the inversion was only performed for 5 iterations. Beyond that point the models started to adjust to the random noise caused by the rebars and the concrete. This further reduces the residuals, allowing reductions of more than 70% to be achieved, however, it also produces artifacts and weakens the actual defect indications.

Conclusions

Overall, the results demonstrate that FWI is capable of transforming IE into a true imaging-based method. A localization of objects beyond current detection limits is possible. However, inversions should (currently) be stopped after a few iterations since the model tends to adjust to the random noise generated by the background medium beyond that point. The inverted models presented in this study therefore only reduced the residual by about 35% compared to the initial model. The advantages of using two components for IE measurements were demonstrated as an improved defect detectability was observable. In the future, the methodology developed in this synthetic study will be transferred to real measurement data.

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