Geophysical Methods Applied in Ultrasonic Inspection and Monitoring of Concrete Constructions

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Introduction

Geophysical methods have been applied in civil engineering for decades. Starting point – and this is no surprise – were geotechnical projects where geophysical tools are essential for site characterization, evaluating the geological structure, and estimating geotechnical parameters. Using geophysics is extremely valuable because the subsurface is known to be inhomogeneous, and drilling and sampling alone will never reveal the full picture. First methods related to civil engineering and their applications are compiled in Ward (1990). Tremendous progress has been made ever since. Nowadays, geophysical methods are included in handbooks and standards for site characterization or earthen constructions, documented, e.g., for river embankment investigations in CIRIA (2013). The use of geostatistical methods allows, if applied properly, the quantitative use of geophysical data in geotechnical calculations, as shown for example by Rumpf & Tronicke (2014). The latest summary of engineering geophysics is given in Medhus & Klinkby (2023).

Figure 1: *GPR depth slice projected onto a reinforced concrete bridge, next to BAM automated NDT scanners (Source: BAM)*

This article focuses on the application of geophysical methods on varying scale, going from meters to centimeters or millimeters, and an anthropogenic material, namely concrete. There are good reasons for this as concrete is by far the most produced material by mankind, and its production is responsible for about 8 % of the global carbon footprint (Nature, 2021). Inspection and monitoring of concrete constructions, namely the ageing infrastructure, contributes to the safety of our daily life but also keeps structures in service, avoiding the necessity of reconstruction.

Geophysics and non-destructive testing

In the past 25 years, several geophysical methods have successfully paved their way to non-destructive testing in civil engineering (NDT-CE), the most prominent being (ground penetrating) radar with an example shown in Figure 1. By raising the antenna frequencies into the GHz-range and reducing the size and weight of equipment to something less than your hiking shoes, several manufacturers are now providing tools for rebar or tendon duct localization and other applications with a performance superior to the traditionally used electromagnetic induction instruments. Other methods have been invented and used in both domains in parallel, such as the self-potential method in geophysics and the very similar half-cell potential method in NDT-CE, the latter used for detection of active corrosion of rebar in concrete.

Not only geophysical methods have found their way to NDT-CE but geophysicists as well. The only full professorship for non-destructive testing in Germany is held by a geophysicist, Christian Grosse. The first author of this paper is head of the division “NDT methods for civil engineering” at the *Bundesanstalt für Materialforschung und -prüfung* (BAM), one of the largest research groups in this field. BAM is also currently financing a related junior professorship at TU Berlin, again held by a geophysicist, Sabine Kruschwitz. In addition, there is an increasing number of scientists, postdocs and PhD students venturing into this field, including four of the co-authors of this paper. Together, we cover a wide area of topics, methods and applications, and contribute to guidelines, standards and training. However, this paper will focus on seismic and seismological methods applied to (ultra-)sonic methods in civil engineering based on decades of research in this field (Niederleithinger, 2017). This paper does not claim to be a formal review of geophysics in NDT-CE. It rather shows diverse applications of geophysical methods in NDT-CE that are currently explored in the authors' research group.

Seismic migration for ultrasonic imaging

Elastic waves reflected and scattered at boundaries, inhomogeneities, voids, and objects are both used in geophysics and NDT-CE to probe and image the structures under investigation. In the former, frequencies between 1 Hz and 1 kHz are common for exploring the Earth, resulting in wavelengths of a meter and above, reaching depths of up to several kilometers. The latter prefers frequencies between 25 and 100 kHz for concrete, wavelengths being in the cm-range, and thus a depth of penetration seldom more than 1 m (Fig. 2). While in geophysics P-wave data acquisition is dominant, in NDT-CE mostly SH-wave transducers are used, among others because of their better coupling to the concrete surface and avoidance of surface waves and wave conversions. For any type of wave, a single measurement (a signal caused by an artificial source, recorded by a receiver, both at the surface of the medium) does not help much. The underground structure can only be reconstructed by using lots of source-receiver configurations and the appropriate application of sophisticated imaging algorithms.

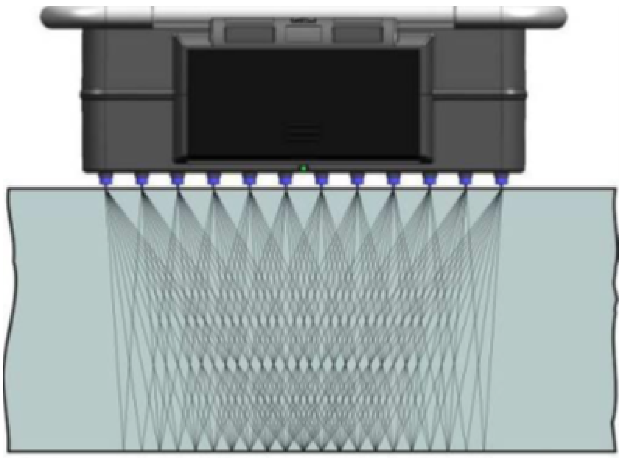

Figure 2: *Sketch of a multi-offset ultrasonic echo device with 12 banks of point contact transducers, both working as transmitters and receivers. This type of instrument was co-invented and patented by BAM in 2013 (Source: BAM).*

An invention made twice: SAFT and Kirchhoff migration. Research on imaging procedures for ultrasonic echo concrete testing goes back about three decades. Simple algorithms using a constant-velocity assumption have been used to correct the time of arrival of echoes (and thus the depth of reflectors) before 1995. More sophisticated algorithms have been developed since, most of them summarized under the name "Synthetic aperture focusing technique" (SAFT). Many developments have come from (or at least were heavily influenced by) the group of the late Karl Langenberg at the University of Kassel, Germany (Langenberg et al., 2009). The most used variants resemble well established geophysical migration techniques in the time domain (e.g. Kirchhoff migration) or the frequency domain (e.g. Stolt migration). A comparison was made by, e.g., Büttner et al. (2021). Most of the time the developments in NDT and geophysics have been made totally independent. However, there have been a few successful attempts to transfer geophysical imaging methods to concrete NDT in the past. For example, Ballier et al. (2012) applied the one-way wave equation method to ultrasonic data to detect voids in tendon ducts. The state of the art of ultrasonic imaging of concrete is summarized by Krause et al. (2011). Modern commercial instruments have a simplified version of SAFT implemented to provide almost real-time imaging (Fig. 3). However, as is well known for Kirchhoff imaging, SAFT has certain limitations when it comes to imaging of complex structures.

Figure 3: *Commercial ultrasonic instrument on a concrete test block. Image on screen is a SAFT result for a single measurement set-up, showing the top of the tendon duct and the backwall (Source: BAM).*

Reverse-time migration improves images. Reverse-time migration (RTM) has become a standard tool in reflection seismics. As it involves wavefield simulations forward (with the actual source function) and backwards (with the recorded data as sources) in time, the computational cost is much higher compared to most other methods. First applications to ultrasonic echo data from concrete objects go back just a few years (Beniwal & Ganguli, 2015; Grohmann et al., 2016). It has been shown that structures such as tendon ducts, steps in the backwall or damages at reinforcement bars can be resolved much better with RTM compared to SAFT.

Currently, research focuses on the use of full elastic simulations instead of acoustic codes in the RTM work flow. Recently, Grohmann et al. (2022a) have shown that full elastic RTM is able to provide highly resolving images of the internal structure of concrete elements, providing for instance a way of determining the diameter of tendon ducts. Figure 4 shows a 2D model for a concrete reference specimen used at BAM. The model consists of a three-step homogeneous concrete layer surrounded by a 0.02 m-thick layer of air at the sides and lower edge. Simulations were performed for 99 source and 199 receiver positions (SH-waves, Ricker source wavelet: 50 kHz). The RTM imaging result (Fig. 5) shows a highly resolving picture of the geometry. Note that the velocity and density model used here incorporated information on the shape and location of the backwall and the side edges, but not on the existence of the circular air voids.

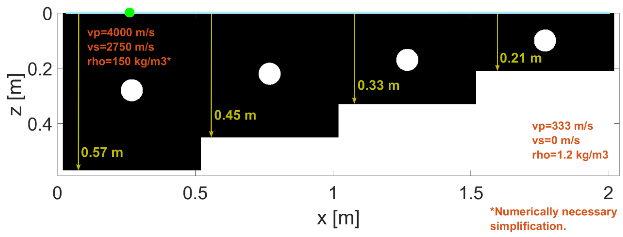

Figure 4: Model structure used for elastic simulations in the RTM studies (Grohmann et al., 2022a).

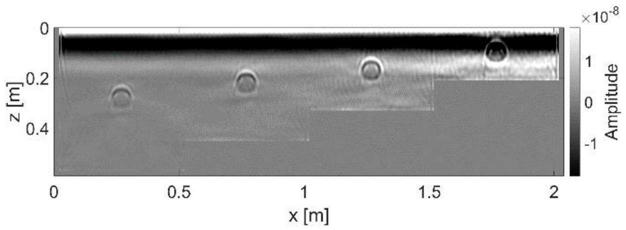

Figure 5: Elastic RTM result for a simulated measurement (99 source positions, 199 receiver positions) on the structure shown in Figure 4 (Grohmann et al., 2022a).

RTM results for actual measured data are published by, e.g., Grohmann et al. (2016), Grohmann et al. (2017), and Büttner et al. (2021). Furthermore, Grohmann et al. (2022b) recently submitted an article on the application of elastic P-SV RTM to synthetic ultrasonic echo data.

Full-waveform inversion will provide better velocity models. Until now most ultrasonic imaging methods used for concrete are based on a constant-velocity model. For many structures this is no valid approximation though, due to, e.g., fluctuations in concrete quality and embedded steel or air-filled objects. In seismics, full-waveform inversion (FWI) has recently got much attention to provide, among others, information on the velocity distribution. Due to increasing computing power even in desktop computers and the availability of commercial and open-access code libraries, FWI has started to appear in scientific papers on concrete imaging as well. Köhn et al. (2016) showed an application on weathered building stones. Reichert et al. (2022) presented a study on anomaly detection and a concrete model. Krischer et al. (2022) studied the possibility to detect voids in tendon ducts based on simulated data. In the opinion of the authors of this paper, FWI is one of the most promising techniques in ultrasonic imaging. Additionally, the combination of FWI and sophisticated imaging techniques such as RTM will lead to much better images of concrete constructions, as shown by Nguyen & Modrak (2018) for numerical experiments.

Seismological tools for construction monitoring

Structural health monitoring (SHM) of concrete structures, bridges in particular, has been a topic for quite some time in order to predict the performance, to increase the structural safety, and to allow the continued operation close to the end of their lifetime. Among other methods and sensors, recording vibrations by geophones to determine eigenfrequencies and eigenmodes and to derive damage forecasts from their changes is an established method in civil engineering, but lacks sensitivity and specificity to detect damages in the early phase. Recently, the acoustic emission method (AE, a high-frequency equivalent to microseismology) got much attention. AE piezo-receivers have been installed at several ageing prestressed bridges to detect wire breaks, which may lead to structural failure. SHM sensor installations are meanwhile sometimes connected to automated warning and closure systems. At the same time, data can be stored in building information modeling (BIM) systems and can also be used to feed digital twins (Niederleithinger, 2022, see also Fig. 6). Unfortunately, there are still gaps in the SHM sensor portfolio. Sensing and data processing technologies adapted from or inspired by geophysics can be of help.

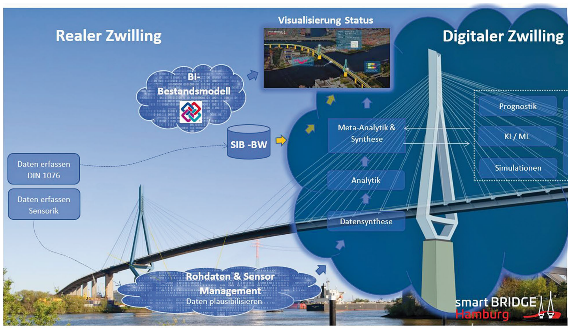

Figure 6: Simplified sketch for a bridge monitoring system including a digital twin to predict performance based on simulations fed by sensor data (Project SmartBridge, Grabe et al., 2020).

Coda-wave interferometry detects subtle changes in concrete. When using higher ultrasonic frequencies in concrete, the waves are scattered at small cracks, pores and gravel aggregates. This allows the transfer and application of geophysical coda-wave-based techniques to test and monitor concrete. By comparative analysis of the scattered waves using coda-wave interferometry (CWI), small changes in the waveform can be linked to velocity changes in the medium (Snieder et al., 2002). With CWI, the nonlinear behavior of seismic velocity can be quantified, which is not possible with analysis of the direct wave; therefore, it can detect, e.g., strain changes that might act as early damage indicators. CWI can be used in single sensor-pair analysis to detect changes (Planès & Larose, 2013) but is most useful in an array setup allowing for localization of change by inversion (see, e.g., Xue et al., 2022). If CWI is set up for permanent structural monitoring of engineering structures, constant coupling of the measurement equipment has to be ensured. Niederleithinger et al. (2015) have proposed to use piezoelectric transducers embedded into structures, which have been tested in the lab and on in-service structures such as the “Gänstorbrücke” bridge in Ulm (Epple et al., 2023). These experiments have shown that the influence of temperature change is significant and has to be accounted for in the evaluation of possible damage. Nevertheless, when temperature effects are eliminated, small changes in the structure, induced by load-bending of the bridge, can be detected, as summarized in Figure 7 (Epple et al., 2022).

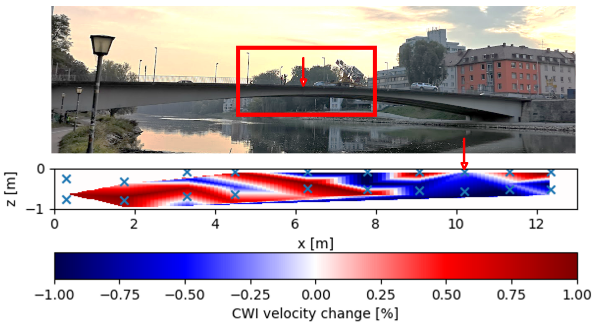

Figure 7: *Map of velocity change induced by a 35-ton truck in the center of the bridge (red arrows) measured with an array of embedded ultrasonic transducers located in the area indicated by the red rectangle. The load causes tensional stress (negative velocity change, blue) at the bottom of the bridge and diagonal stress patterns at the left according to the layout of internal tendon ducts. Modified from Epple et al. (2022).*

Rotational seismology helps to monitor buildings. Conventionally, vibration monitoring is performed by geophones (measuring velocity) or piezo-accelerometers in three spatial components (3C). To calculate movements and rotations, integration is necessary which involves limitations and errors, especially when determining the so-called inter-story drift. In the frame of the project *Giotto*, seismologists from TU Munich and U Hamburg together with engineers from BAM are evaluating the potential of 6C-sensors (including three components of rotation, measured by fiber-optic devices, Fig. 8). Currently, seismic interferometry (cross-correlation of ambient-noise signals at several receivers) is used for velocity estimation and coda-wave interferometry for delineation of changes. This has

Figure 8: *Conventional seismometer (left) and rotational sensor Blueseis-3A (right) at the BAM test site (Liao et al., 2022).*

been tested on a bridge model structure at BAM’s test site (Fig. 9) and compared to results achieved by conventional seismometers and ultrasonic measurements (Liao & Hille, 2022; Liao et al., 2022). It has been shown that the results from the rotational sensors are comparable to those of conventional instrumentation (Fig. 10 and Liao et al., 2022). Changes in the structure’s condition, e.g., variation of prestress and load, can be detected. Next steps are measurements on a large-scale shake table to prove that the rotational sensors can give added value.

Material characterization

Ultrasound estimates concrete strength. To characterize concrete, often strength estimates are needed. Beside destructive tests, non-destructive alternatives using ultrasound are also applied. Ultrasonic P-wave velocity measured by time of flight data in transmission mode is used since decades as an indicator for concrete strength, but requires local calibration due to the large amount of influence factors on both parameters (Deutsches Institut für Normung, 2021). In a study using X-ray computed tomography (CT) and diffuse ultrasound on a set of concrete samples with different strengths, it has been shown that diffusivity derived from ultrasonic traces shows a slightly better correlation to strength than velocity (Fig. 11 and Landis et al., 2020). Thus, advanced analysis of ultrasonic signals may provide reliable non-destructive alternatives for future routine concrete strength estimates.

Ultrasound helps to check concrete barriers in nuclear waste disposal sites. Engineered barriers are a key element to enable safe nuclear waste disposal. Different production methods are discussed to construct the concrete sealing structures. To allow for non-destructive quality assurance, ultrasonic investigations are researched (Effner et al., 2021; Lay et al., 2021). One method currently under research for the construction of sealing structures is magnesia concrete applied in a shotcrete procedure. The ultrasonic echo method was evaluated as a means of quality assurance by Lay et al. (2022) in cooperation with TU Bergakademie Freiberg in several tests in a previous underground salt mine (Fig. 12). Imaging of internal structures and defects, such as delamination, has successfully been achieved in the shotcrete. In several test blocks of var-

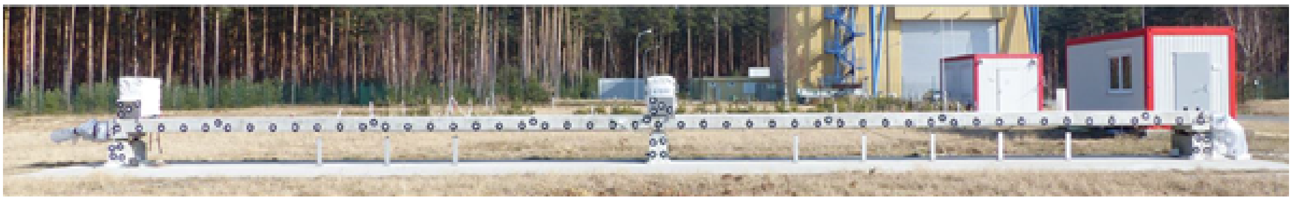

Figure 9: *BAM's bridge model BLEIB for sensor evaluation at the test site at Horstwalde, Germany. Longitudinal prestress and load is variable (Liao & Hille, 2022).*

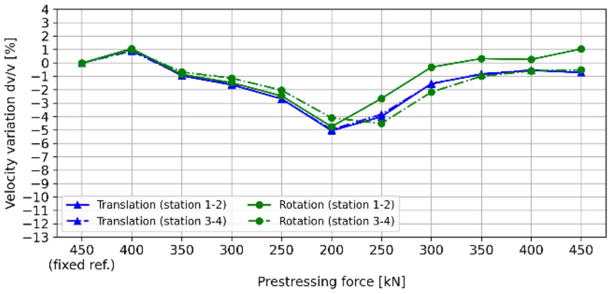

Figure 10: *Velocity changes derived from trace correlation and CWI from conventional and rotational sensors on both halves of the BLEIB structure during changes of longitudinal prestress (Liao et al., 2022).*

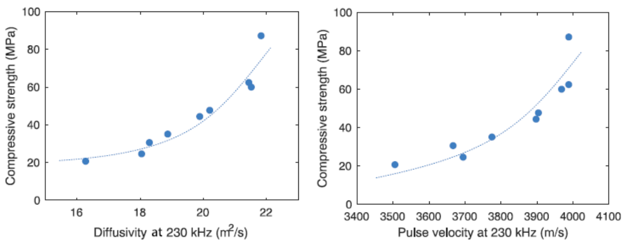

Figure 11: *Correlation of diffusivity and velocity derived from ultrasonic transmission measurements to compressive strength of concrete samples (Landis et al., 2020).*

Figure 12: *Ultrasonic measurements at a shotcrete block in an underground salt mine (Lay et al., 2022).*

ious sizes, no consistent concrete section boundaries have been found by ultrasonic imaging, which was verified by subsequent drilling and complementary tests. In contrast, an experiment with artificial defects imitating cracks, air-filled voids, and material with lower density has challenged the current methods and shows their limitations (Lay et al., 2022). Significant defects, such as an unintended large delamination, are identified and confirmed by drilling (Fig. 13). However, several smaller defects have not been identified. Generally, ultrasonic imaging provides a suitable base as a means of quality assurance during and after the construction of concrete sealing structures. However, further developments are required to enhance the reliability of the method, particularly in shotcrete, and a full validation is still pending. Nevertheless, the method has potential to increase the safety of nuclear waste repositories.

Summary and Outlook

The examples presented above and the work of other researchers show that geophysics can actually lead to an improved inspection and monitoring of concrete structures. The contributions cover a wide range, from new sensors, data processing and imaging methods, new ways to determine material parameters to ideas how to detect changes in the material in an early phase. The authors believe that this is just the beginning of a journey and an exciting field for geophysicists to work in. For instance, the application of microseismic tools ("acoustic emission" in NDT-CE) and distributed sensing for bridge monitoring are currently explored. However, a slight change of the mindset compared to traditional geophysical projects is required. Results are demanded more or less in real time or at least next day. The person with the drilling machine might wait just behind you to check your results. Validation is key.

Acknowledgments

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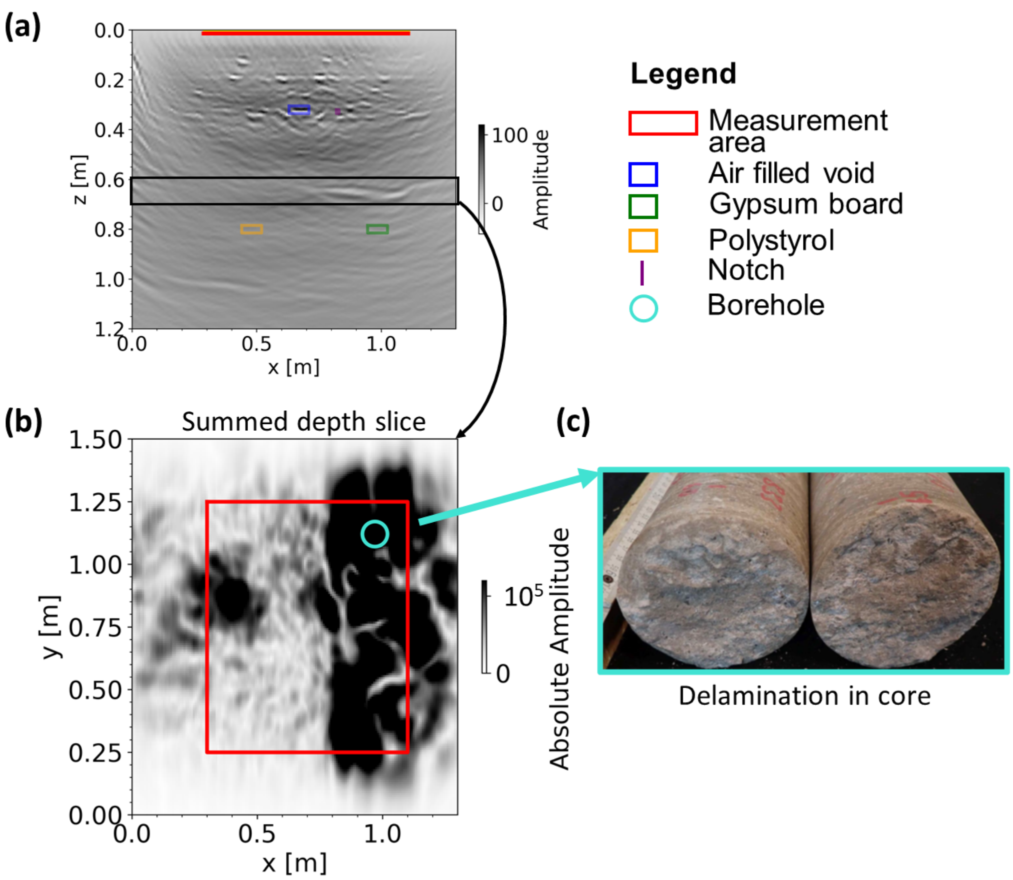

Figure 13: *Ultrasonic imaging (Kirchhoff migration) of a shotcrete test block containing artificial and real (unintended) flaws (Lay et al., 2022).*

burg, Ruhr-Universität Bochum, Colorado School of Mines and the funding by BMWK, BMBF, BASt and DFG. We also appreciate the patience and curiosity of the (civil) engineers at BAM, specifically within division 8.2 "NDT methods for civil engineering" when working with us geophysicists. A special thanks to the geophysical community for inspiring discussions in various fields and particularly: Happy 100th birthday, DGG!

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