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Monitoring of Concrete Infrastructure with Active Ultrasound Coda Wave Interferometry

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ABSTRACT: Coda Wave Interferometry has been used in Geophysics to detect weak changes in scattering media. Past research in Structural Health Monitoring has shown that this methodology can be applied to concrete structures to detect material changes by calculation of relative velocity changes. Successive measurements with embedded ultrasonic transducers provide a repeatable signal for reliable long-term monitoring of concrete. To research the application in real-world structures, we have embedded ultrasonic transducers in a bridge in Ulm and a Metro station in Munich, Germany. This study gives an overview of the monitoring of these two structures. The results show the potential and challenges of the method. Data evaluation can be largely automated to gain insights into material changes and other influences on the structure, such as traffic-induced load and temperature variations. The experiments demonstrate the ease of installation, longevity of the sensor installation, and sensitivity of the measurement technique, but highlight problems with the application, especially if electromagnetic noise affects data quality. As no confirmed substantial damage was recorded during the monitoring period on both structures, we evaluate load tests to investigate the effect of static load on the structures and the coda monitoring results. The experiments show that the influence of load can be detected, even if the temperature influence is not removed from the data. This indicates that online damage detection with coda monitoring is possible, but further research on damage detection in real-world structures has to be conducted to confirm laboratory findings.

KEY WORDS: Active Ultrasound Measurements, Coda Wave Monitoring, Embedded Transducers

1 INTRODUCTION

Coda Waves – multiply scattered late-arriving seismic waves - have been studied in seismology for decades. Beginning with Keiiti Aki's work in 1969 [1], where he developed a method to determine the seismic moment of earthquakes from coda waves the analysis of these waves has since evolved as a valuable tool for understanding subsurface properties. In *Coda Wave Interferometry* (CWI), the medium acts as an interferometer, combining the scattered waves originating at a source at the receiver [2]. This enables the detection of small velocity variations in a material volume with a limited number of sources and receivers. These changes are often not detected by analyzing the direct wave. Applications of CWI include the detection of stress, temperature, and damage-related material alterations across multiple scales.

The heterogeneous composition of concrete allows the application of CWI in infrastructure as most structures are composed of concrete. Planès and Larose [3] have summarized the applications of CWI in concrete, including sensitivity to thermal fluctuations and stress-induced changes via the acoustic-elastic effect. Their following work has also shown the potential of localizing change with a sensor network [4], highlighting the potential of CWI for monitoring changes in large concrete structures. Their sensitivity-kernel-based approach leverages the spatial sensitivity of coda wave measurements, which allows analysis of different volumes of material with a limited number of measurements and sensors.

These advancements and the necessity of constant coupling for long-term monitoring have initiated the design of special embedded piezoelectric transducers [5]. To further investigate the potential of concrete damage assessment by coda waves on the micro and macro scale, a DFG funded research group (FOR 2825) has combined modelling, simulations, laboratory experiments, and applications of CWI in large structures [6] using these transducers.

This publication intends to give an overview of two monitored structures, the applied technology, and key findings with their implications for future wider application of CWI-Monitoring to ensure early damage detection in infrastructure and support authorities and infrastructure owners in the process of long-term maintenance and infrastructure planning. The monitoring of large structures poses unique challenges as influences of temperature, traffic-induced load, and other external factors are detected with CWI. These factors must be taken into account to isolate indicators of material degradation. In this context, we will present results from monitoring a road bridge in the city of Ulm and a subway station in Munich. At both structures, retrofitted transducers have been used to monitor material degradation and environmental influences for several years. Therefore, they are representative specimens for analyzing the potential of CWI monitoring.

2 METHODOLOGY

2.1 *Active Ultrasonic Measurements and Coda Wave Interferometry*

. For active CWI measurements in concrete, ultrasonic waveforms are consecutively recorded as time series $u_1(t)$ and $u_2(t)$. When a pulse is emitted at the source, elastic waves travel through the medium and are scattered at inhomogeneities (e.g.

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grains) or reflected at boundaries (e.g. concrete-air boundary). Therefore, when recording several milliseconds of signal after emission of the pulse, a waveform consisting of the direct wave travelling between source and receiver and later arriving scattered and reflected coda waves is recorded (for a sample waveform, see section 2.4, Figure 3). Changes in the medium (e.g. cracks) change the wave propagation and therefore the recorded waveforms. To detect such waveform changes, the basic measure for signal comparison is the *correlation coefficient* ($-1 \leq CC \leq 1$), calculating a measure of signal similarity on a time window [$t1, t2$]. A decrease of CC indicates a change in wave propagation but is not linked to a specific physical property of the material.

Changes in the material affecting the bulk or shear modulus, directly influence the propagation velocity of P- and S-waves respectively. Therefore, CWI evaluates velocity changes, by analyzing phase shifts in the signals. The standard method for this analysis is the stretching technique [7], where the first signal is time-stretched to align with the second. The following equation describes the calculation of a velocity change using the stretching technique [3]:

$$argmax(CC(\varepsilon)) = \frac{\int_{t1}^{t2} u_1[t(1+\varepsilon)]u_2[t]dt}{\sqrt{\int_{t1}^{t2} u_1^2[t(1+\varepsilon)]dt \int_{t1}^{t2} u_2^2[t]dt}} \quad (1a)$$

$$\varepsilon = -\frac{dv}{v} \quad (1b)$$

By varying the stretching factor ε, the correlation coefficient in equation (1a) is maximized. The maximizing stretching factor corresponds to the relative velocity change (equation 1b) between the recording of u_1 and u_2. To analyze spatially localized changes, CC and ε can be evaluated on different time windows [$t1$, $t2$], which corresponds to different sensitivities described by sensitivity kernels (see [8]).

For CWI in monitoring a reference needs to be chosen to determine the baseline. After choosing the baseline, all material changes altering wave propagation in a structure can be tracked by repeated ultrasonic recordings given source and receiver position and coupling do not change. In practice, several different approaches for choosing the reference exist, depending on the magnitude of change and the minimum threshold of CC that allows a reliable analysis of velocity change. If the medium is influenced by non-permanent environmental changes, the reference can be kept fixed, (fixed-reference technique), making a comparison to the baseline timestamp straightforward. Other methods change the reference constantly, e.g. the stepwise reference method [9] or a rolling reference method [10]. The velocity change can be referenced to the baseline as well, but the correlation coefficient is not referenced to the baseline anymore. The rolling reference method is especially advantageous in practical monitoring scenarios, as the reference lag can be adjusted based on external influences such as temperature or known stress variations, thereby improving the robustness of the velocity change estimation over time.

2.2 Sensors and Sensor Installation

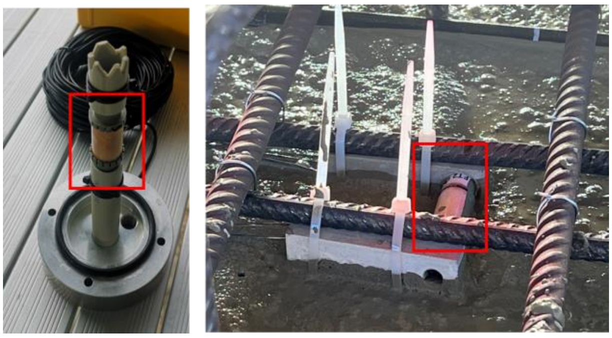

Figure 1. ACS S0807 (red square) prepared for retrofit with a grouting cap, prepared for the desired installation depth (left) and attached to the rebar before concreting (right).

For long-term monitoring of real structures, it is essential to ensure constant coupling. Therefore, cylindrical piezoelectric P-wave transducers (type: S0807, dimensions: length 72mm, diameter 20mm) described in [5] and developed in cooperation with Acoustic Control Systems (ACS) are designed to be embedded in concrete, either attached to the reinforcement before concreting or retrofitted in an existing structure (Figure 1). In retrofit applications, the structure is evaluated with Ground Penetrating Radar (GPR) before drilling to avoid damage to rebars and tendons. The sensors are then placed within the borehole and regrouted using reusable grouting caps.

These transducers can function both as sources and receivers, converting electrical signals into mechanical vibrations (elastic waves) and vice versa. In a sensor network, a typical configuration involves a source transducer emitting waves with one or several transducers acting as receivers (pitch-catch configuration). These roles can be interchanged, so source transducers can become receivers. With a bandwidth between 50 and 100 kHz, the transducers combine the possibility of analyzing direct waves for a large transducer distance with the high-frequency scattering properties required for CWI. Therefore, they are well suited for long-term structural health monitoring of concrete structures.

2.3 Measurement Devices

For monitoring with CWI, a custom measurement device was developed, as described in [11]. The device (Figure 2) is based on a Raspberry Pi and is capable of measuring one sensor combination every 5-10 seconds. The core component, the Raspberry Pi serves as the control unit, addressing the measurement PCBs, data storage, and transmission.

The system includes a power and pulse board that can send a 300Vpp double rectangular pulse to up to 75 multiplexed channels. The signal is then digitized and saved on the Raspberry Pi. The modular design of the measurement board allows the addition of temperature and humidity sensors to track environmental parameters.

The measurement device has shown that it can produce good data quality compared to a commercial system based on a NI-DAQ Mx and Keithley Multiplexer as described in [12]. The major advantage of the commercial system is the measurement

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repetition rate. Therefore, it is used in experiments where fast dynamic changes in the medium require quick data collection.

Figure 2. W-Box, custom made CWI Measurement device based on a Raspberry Pi.

2.4 Ultrasonic Measurements – Direct Wave and Coda

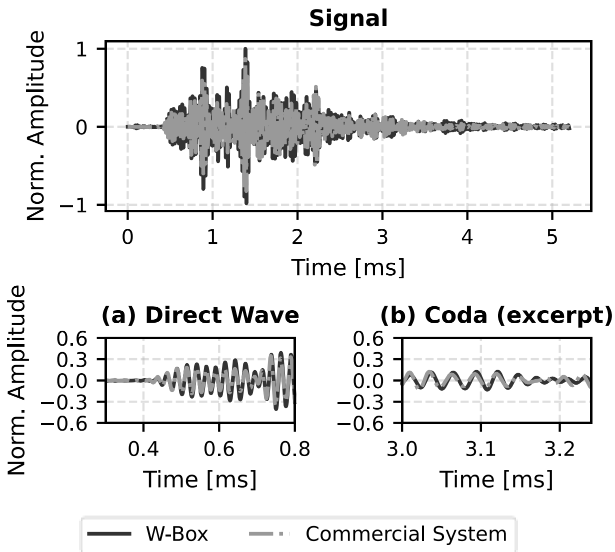

Figure 3. Two ultrasonic signals were recorded at a bridge in Ulm, Germany comparing the commercial US data acquisition device and the self-made W-Box. (a) The direct wave and (b) an excerpt of the coda.

Figure 3 shows two signals recorded with the W-box and the commercial data acquisition system in November 2021 and December 2021. In the direct wave (a), small amplitude differences are visible, primarily due to the different resolutions of the systems (14-bit vs. 16-bit). Despite this, the waveforms align closely. This supports the use of the slower W-box for long-term monitoring, supplemented by the faster commercial system when higher temporal resolution is required.

Figure 3 (b) shows an excerpt of the coda. A small shift can be detect, caused by temperature variations. During the time between the two displayed measurements, the temperature at the bridge decreased by approximately 3.5 degrees. This shows the sensitivity of the coda. The influence of temperature on the ultrasonic velocity measured by CWI has been researched, e.g. in [13] and quantified at around 0.03-0.06 percent per Kelvin, which varies depending on the investigated structure. The onset of coda waves is a gradual transition. Even after the first arrival in figure 3, high energy reflections are recorded until 1.5 ms. Nevertheless, at this time the recordings do already include scattered coda waves. Therefore, the evaluation window for CWI has to be chosen individually for every source receiver pair after analysis of the wave recording.

3 MONITORED STRUCTURES

In the past years, we have instrumented two structures with the embedded ultrasonic transducers and recorded data with the W-Box. The recorded signals are directly uploaded to a database, where the signals can be analyzed (e.g. CC analysis) or requested for further evaluation through a MySQL API in Python.

3.1 Gänstorbrücke Ulm

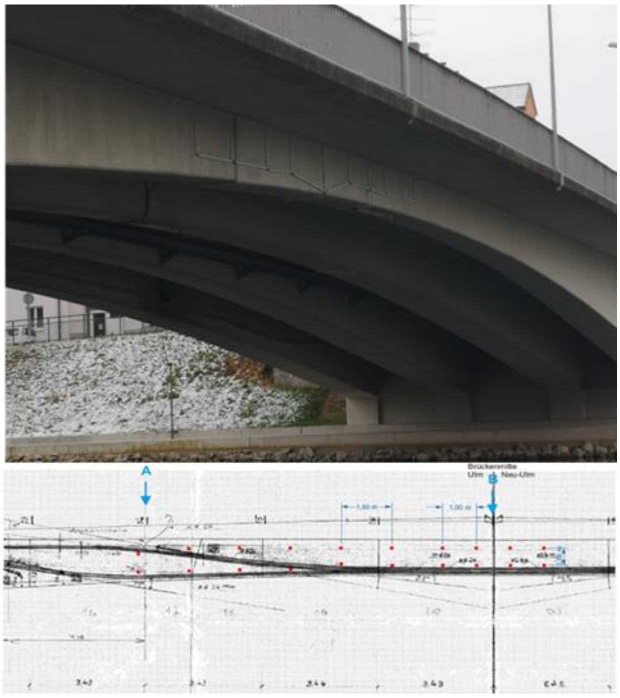

Figure 4. Sensor installation at 'Gänstorbrücke', Ulm. 20 sensors are installed in an array in the centre of the bridge (marked with red dots).

In 2020, 24 Ultrasonic transducers were embedded in the 'Gänstorbrücke' bridge in Ulm to monitor damage to the structure under constant traffic between the cities of Ulm and Neu-Ulm, Germany. The sensors were installed in the abutment and the center of the bridge (Figure 4). The bridge, designed by Ulrich Finsterwalder, is a 96m prestressed concrete structure, composed of two parallel partial structures with two slabs per partial structure. Of the 24 sensors, 20 were installed in the centre of the bridge in a single slab. Prior to the installation of the CWI monitoring system, the bridge was instrumented with a commercial monitoring system including acoustic emission, strain sensors, and temperature sensors in 2018 [14], after significant damage was detected to ensure safe operation until demolition and reconstruction in 2025.

To further evaluate CWI monitoring capabilities, in 2021, a static load experiment was conducted using a 15t and a 32t

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truck to evaluate the behaviour of the bridge under a substantial load and the influence on coda waves. The monitoring system remained operational from 2020 until February of 2025 to test the longevity of the sensors as well as the signal quality. Over the five years of monitoring, no additional permanent damage was recorded on the bridge by the commercial monitoring system, confirming the stability of the bridge and the reliability of the monitoring systems.

3.2 Metro Station Scheidplatz Munich

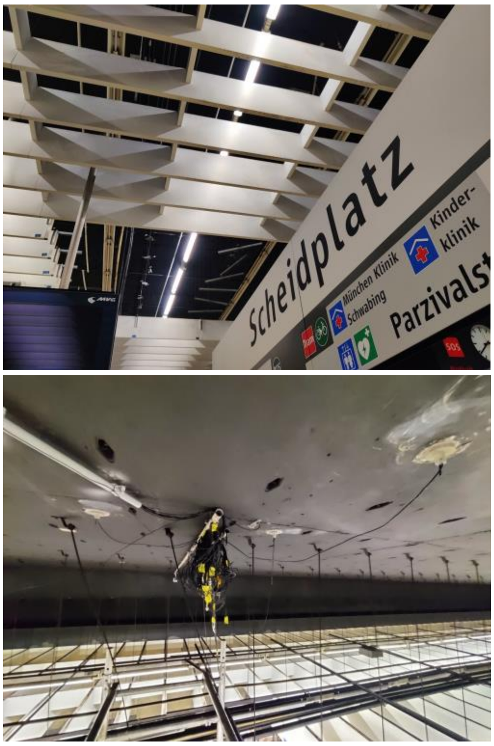

Figure 5. Sensor installation at 'Scheidplatz', Munich.

The '*Scheidplatz'* metro station in Munich, Germany opened in 1972, just before the Munich 1974 Summer Olympics. On the surface of the metro construction, several tramways and bus stops are located. As a result, the ceiling structure is subject to constantly varying loads due to public transport activity. To monitor the crack behaviour and load variations caused by passing and stopping tramways, 15 sensors were embedded in the ceiling in 2022 (Figure 5).

The brittle outer layer of the ceiling made overhead regrouting difficult. As a result, two sensors have bad coupling to the structure, leading to reduced signal quality. Nevertheless, they are still operational. Therefore, surface inspection is advised before retrofitting sensors, to devise the suitable regrouting technique. Besides the monitoring aspect, the installation was a pilot run for the W-Box and the installation procedure in an environment with significant electromagnetic noise.

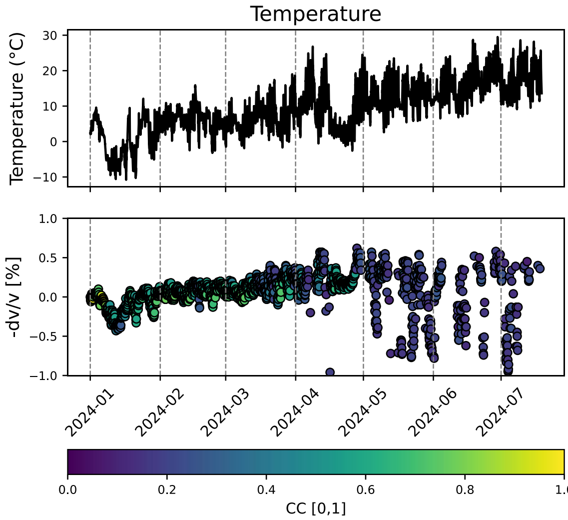

Figure 6. Temperature (top) and CWI velocity change at Gänstorbrücke for the first half of 2024. The color of the scatters represents the correlation coefficient.

4 MONITORING RESULTS

4.1 Gänstorbrücke Ulm

Since its installation in 2020, the monitoring system has remained operational with only a few periods of downtime caused by instrument failures and network problems. Neither the coda monitoring system nor the commercial acoustic emission monitoring system recorded significant new damage during this period. This shows that the measures taken to preserve the bridge until reconstruction were sufficient.

The data quality throughout the entire monitoring period is consistently good. A minimal number of measurements were influenced by electromagnetic noise, which can be eliminated by frequency analysis. Without any new damage in the monitored area, we cannot make conclusions about the ability to distinguish damage from environmental influences in a real-world monitoring setup, however.
Nevertheless, the dataset provides valuable insights to assess the requirements for a real-world monitoring setup. Especially temperature changes cause strong signal decorrelation. Figure 6 shows the temperature and the relative velocity change of a representative transducer pair for the first half of 2024. During this time the temperature ranges from -10°C to nearly 30°C. The velocity change was calculated on the first three milliseconds of the signal, thus investigating both, the direct wave and the coda, using the fixed reference method. Figure 6 shows a clear correlation of temperature and velocity change, particularly visible in the trough in January 2024. The relation between temperature and velocity change is linear, as shown in [15]. For 'Gänstorbrücke' we estimate a change of -0.025 percent per Kelvin.

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The color scale in Figure 6 indicates the correlation coefficient. When CC remains high, the results of the fixed reference CWI can be interpreted reliably. This is only valid for small temperature variations (± 10°C). In summer, the correlation coefficient decreases significantly, causing outliers and jumps in the results, which cannot be physically interpreted due to the strong decorrelation.

To improve the robustness for a long-term analysis, one could shift to the stepwise or rolling reference CWI. However, preliminary analyses of the 'Gänstorbrücke' dataset have shown that this does not significantly improve the interpretation of the long-term trends. Furthermore, these methods require more computational power and time. Given the focus on detecting short-term permanent change (i.e. damage) we propose to analyse the data in short rolling time windows while tracking the temperature to define a corridor of expected velocity change induced by temperature. To this purpose, a linear regression model is trained using temperature measurements and corresponding calculated velocity changes. This model allows the prediction of temperature induced 'normal' velocity changes. Based on the root mean square error (RMSE) of this model, a corridor can be defined indicating the velocity change attributed to temperature change with a certainty of 95%. This corridor can serve as a threshold for outlier detection and enable the automatic detection of no temperature induced changes.

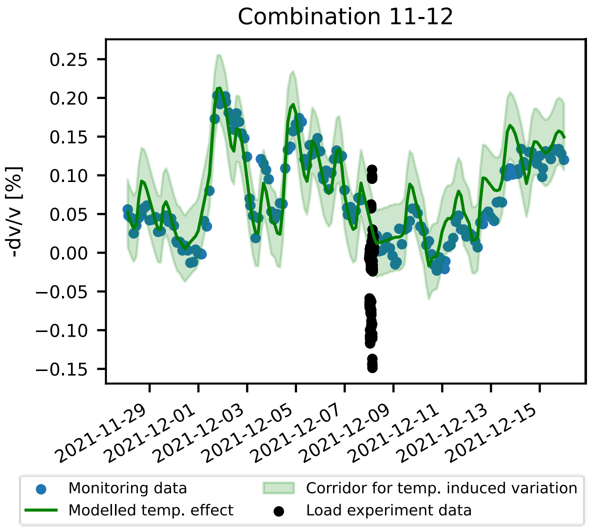

Figure 7. CWI velocity change in December of 2021. The temperature effect on the velocity change is modeled and a corridor of expected temperature induced velocity change is calculated. The data from the load experiment is highlighted in black.

Figure 7 shows this method for a three-week period in December of 2021, the time of the static load test. As the load test represents the largest known mechanical disturbance to the structure during the monitoring period, it serves as the best representation of damage-induced changes. A detailed analysis of the load test can be found in [15]. One can see that the linear model of temperature-induced velocity change fits well for the analyzed period. Using the fixed reference approach, CC remains above 0.65 throughout the analysed subset. The temperature changes in these weeks were below ± 10°C. The permanent monitoring data is represented with blue scatters and the load test data is highlighted using black scatters.

One can see in Figure 7, that the velocity change induced by load is of the same magnitude as the change induced by temperature. Nevertheless, as the temperature model gives a corridor of expected change, the outliers can be detected. Combination 11-12 is a sensor combination with a minimum distance to the nearest loading point of 10 meters. Importantly, as during the load test, the bridge was not loaded all the time, the datapoints at unloaded measurements are within the temperature corridor. For sensor combinations located closer to the load application points, stronger deviations were observed (see [15]).

With the results of the load experiments, we show that for permanent monitoring a windowed approach can be beneficial for damage detection. Although no new damage was detected, the results show the capabilities of monitoring using CWI and embedded sensors. Key conclusions of this long-term experiment are:

- Data quality remains consistent with embedded transducers, although temperature variations have a big influence on the signals.
- The fixed reference method cannot be applied over long periods, even if no damage has been recorded.
- The load-induced perturbations can be detected within the temperature trend, even if they are of similar magnitude.
- A short window, fixed reference approach enables fast automated data analysis, and potentially allows for edge computing on site, while allowing for the detection of perturbations in the temperature trend.

4.2 Metro Station Scheidplatz Munich

Since the sensor installation in 2022, signals have been continuously recorded at 10-minute intervals at 'Scheidplatz'. This cycle reveals results indicating general increasing and decreasing trends in relative velocity change, which are attributed to temperature variations inside the concrete ceiling.

From February 24th to March 13th, 2023, the measurement frequency was increased to one measurement per minute to determine whether it was possible to study the structural behaviour following a transient load. In this case, the transient load was induced by tramways stopping directly above the sensor array. The total load of these tramways varies depending on the vehicle type, ranging from 560 kN to 722 kN, distributed over three or four axles. The results of March 18th are displayed in Figure 8.

During this period, the overall change in dv/v was approximately 0.20%, primarily attributed to temperature variations. Additionally, multiple frequent relative velocity drops of approximately 0.02% were observed, which generally recovered to their original values within 10 to 15 minutes.

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These relative velocity drops were caused by the transient loads exerted by the passing tramways. Tramway operations conclude at approximately 1:15 AM; however, some relative velocity drops were detected even after this time. This is likely due to tramways passing through the station without stopping as they transit to the depot.

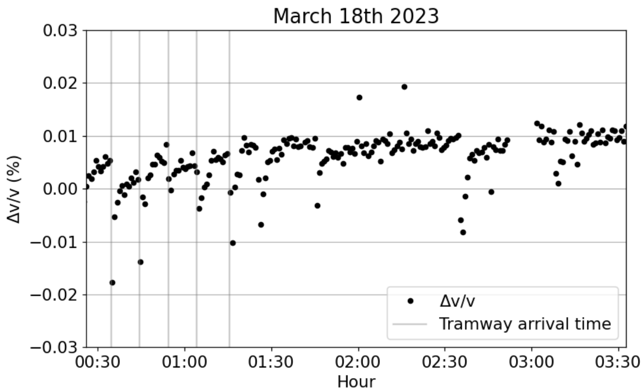

Figure 8. Relative velocity change. Velocity drops visible after the tramway stops above the sensor array.

This confirms that both stopping and passing tramways induce velocity drops in the structure. Previous experiments with CWI in 4-point bending tests [16, 17] have shown that velocity changes are predominantly negative. While we expect an increase in velocity in the pressure zone due to an increase in bulk modulus, the tension zone is dominant, especially in cracked specimens, causing a velocity drop with increasing load. As the installed structure is already cracked, the opening of cracks with load contributes to the velocity decrease. The observed velocity drops are reminiscent of the time-dependent nature of rock healing [18], and similar applications to assessing damage in concrete materials through slow dynamics [19]. To examine potential long-term variations in the relaxation processes of the structure, high-temporal-resolution measurements were repeated a year and a half later. This test was conducted from October 18th to November 7th, 2024, this time, the signal quality was significantly degraded. Additionally, we conducted controlled experiments by positioning a tramway stationary above the sensor array and regulating the passage of tramways to analyse their impact on the recorded signals.

Upon reviewing the data, it was evident that, starting in September 2024, electromagnetic noise levels had abruptly increased. This increase did not coincide with maintenance work on the electrical network, making the source of the noise not identifiable. Since then, data quality has deteriorated considerably, as illustrated in Figure 9, to the point where the recovery curves can no longer be extracted as in previous periods.

Various low-quality data rejection strategies were implemented based on waveform characteristics such as amplitude, duration, and signal-to-noise ratio (SNR). However, while these strategies were successful in filtering out the low-quality data, the remaining usable waveforms were insufficient for a detailed slow dynamics analysis. Alternative approaches involving frequency filtering were explored, but in this case, the frequency bandwidths of the ultrasonic signals and the electromagnetic noise overlapped, rendering this method ineffective. The measurement device was inspected, confirming that it was not the source of the recorded noise. While poor sensor coupling or cable damage has not yet been ruled out, further investigation is necessary to determine the exact cause of the signal degradation. To prevent similar interference in future implementations of this method, it is recommended to monitor and mitigate potential sources of electromagnetic noise, such as maintenance work on nearby electrical networks, and to establish shielding or filtering techniques that preserve signal integrity.

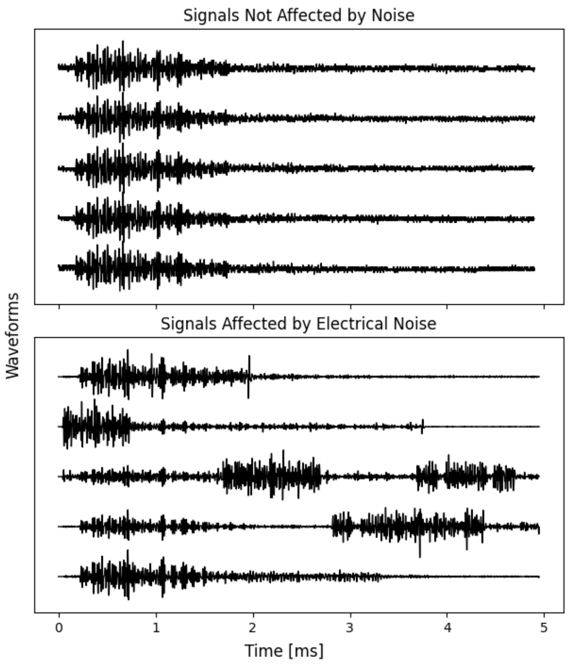

Figure 9. Representative pre-processed waveforms with good quality (Top) and low quality likely due to electrical noise (Bottom).

5 CONCLUSION AND OUTLOOK

The presented CWI monitoring experiments show the potential and challenges of application in real world structures.

Installation: Embedding sensors either in existing structures or previously to casting the concrete is an easy way to ensure coupling and longevity.

Data quality: The measurement devices and cables must be tailored to the monitoring situation. In high electromagnetic noise locations like metro stations, data quality can suffer. An increased measurement repetition rate, or on-site rejection of ‘bad’ measurements can improve the data quality, but better shielding of cables and the measurement device can avoid data quality problems and ensure a seamless dataset.

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Data evaluation: Temperature influences the data evaluation strategy. The influence depends on the individual structure and the location of the monitoring system. If long-term monitoring is the goal of the installation, temperature must be monitored. To display long-term trends, advanced methods like the stepwise method must be applied, but its benefits have to be evaluated individually. If the data is only evaluated on shorter time windows, the fixed reference method suffices, and corridors can be defined allowing automated outlier detection. This accelerates the calculation of results, enabling data analysis on-site, with online and automated monitoring results.

Detection of changes not induced by temperature: The target of CWI monitoring is the detection of irreversible change. Previous research has shown that CWI analysis can detect e.g. cracking [16] or akali silica reaction [20], and can potentially monitor all material altering damage processes in concrete. In this study, we have shown the influence of traffic and load, which must be accounted for to distinguish between reversible changes and material degradation. Combining traffic/load monitoring with CWI could improve damage detection reliability. Furthermore, the analysis of recovery curves after repeated loading, as explored in the 'Scheidplatz' experiment, suggests the potential for damage state assessment. This aspect requires further controlled laboratory research.

The presented experiments and the datasets offer a strong foundation for further research. In February of 2025, shortly before the decommissioning of the 'Gänstorbrücke', a tendon was deliberately cut, and the effects of its destruction were monitored closely with CWI. This dataset provides the opportunity to further determine the detection and localization capabilities of CWI in real-world structures. Additionally, monitoring continues at 'Scheidplatz', where further experiments targeting damage assessment under repeated controlled loading can be conducted once electromagnetic noise issues are resolved. The continuous monitoring gives the opportunity to confirm laboratory experiments showing the potential of damage detection using CWI [4, 16, 20].

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