Multi survey investigation of active seismic techniques for environmental seismology

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Summary

Effects of climate change observed in the northern hemisphere are visible in changing precipitation patterns, more extreme weather events, and larger variation in hydrological processes in catchments, thus higher risk of floods. Embankment damage can be caused by aging, failing foundations, seepage, internal erosion, void formation, and the growth of cracks in the embankments. Our work involves utilizing a range of seismic techniques, including active seismic method and distributed acoustic sensing (DAS) on the same profile at the Orzepowice embankment, Poland. In order to evaluate these values, we employed seismic travel time tomography to identify spatial variations, MASW technique to gauge water infiltration, and employed reflection seismic imaging to identify geological structures beneath the embankment. We used seismic travel time tomography for recognition of spatial differences, MASW technique to assess water infiltration and reflection seismic imaging to recognize the geological structures. Three component active seismic show that compression wave (P-wave) is really clear in vertical component (P) and shear wave (S-wave) is very obvious in other horizontal components (S1 & S2). Combining P and S wave images allows for attribute inversions of rock properties, such as fluid content, pore pressure, stress direction and fracture patterns.

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Introduction

Effects of climate change observed in the northern hemisphere are visible in changing precipitation patterns, more extreme weather events, and larger variation in hydrological processes in catchments, thus higher risk of floods. Those effects are influencing all critical objects like dams and embarkments increasing the risk of damaging and making them more vulnerable to extreme events (Tamarin-Brodsky et al., 2020). Because of that we propose to use environmental seismology techniques to monitor such objects.

Embankment damage can be caused by aging, failing foundations, seepage, internal erosion, void formation, and the growth of cracks in the embankments. Therefore, it is imperative for all embankment locations to undergo comprehensive stability evaluations and seismic integrity assessments amidst significant ground vibrations (Yordkayhun et al., 2021).

Our proposal involves utilizing a range of seismic techniques, including active seismic method and distributed acoustic sensing (DAS) on the same profile at the Orzepowice embankment, Poland (Figure 1A). Combining compression and shear wave velocities allowed us to characterize the elastic properties of the materials comprising the embankment and assess its seismic stability in relation to local soil stiffness and site response. In order to evaluate these values, we employed seismic travel time tomography to identify spatial variations, utilized the MASW technique to gauge water infiltration, and employed reflection seismic imaging to identify geological structures beneath the embankment (Harba et al., 2019).

Three component active seismic data was acquired by using 3C geophones (P, S1, S2) to determine the type of wave (primary wave or vertical and horizontal shear waves) and its direction of propagation (Figure 1B). DAS is a method of recording seismic data by measuring dynamic strain with two reference light pulses traveling down an optical fibre as a seismic sensor. The natural flaws of the fiber are impacted by those pulses, and the strain may be deduced from the phase lag between the backscattered signal at the front and end of the gauge length (Figure 1C). Two essential DAS acquisition parameters are pulse width and gauge length (Bakulin et al., 2018).

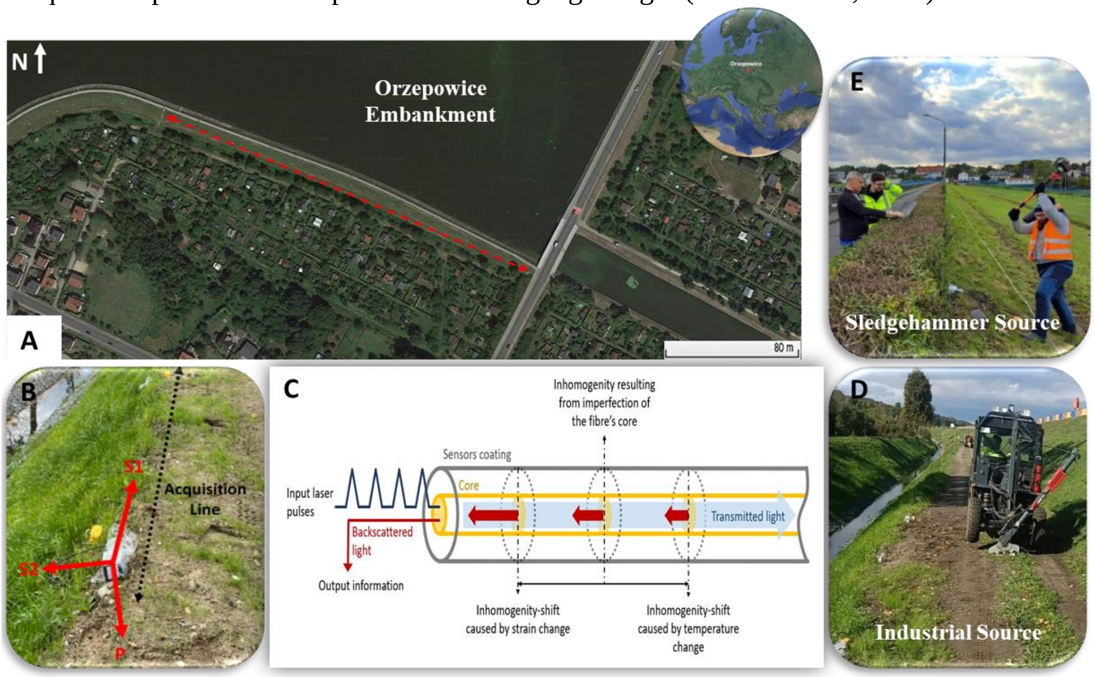

***Figure 1A** The location map for the study area at Orzepowice embankment, **B** Three components active seismic survey, **C** Distributed Acoustic Sensing (DAS) theory, **D** Industrial source, a weight drop with both vertical and horizontal component and **E** 5 kg Sledgehammer source in use.*

Fieldwork

In October 2023, both the active and passive seismic surveys were completed, and in June 2024, the second time-lapse segment will be executed. Here we present our survey geometry, initial results and gathered data. We used standard standalone data cube seismic stations with 3C 4.5Hz geophones combined with two separate DAS installations. As sources both sledgehammer and industrial s-wave source were used (Figure 1D & 1E). Stations were deployed every 4 m. Hammer shooting was every 2m and shooting by industrial source was every 4m.

Additionally, a four loops of fibre optic cables were deployed in a shallow trench around the whole seismic line of 270 m. We were used two types of interrogators to verify the usefulness of Distributed Acoustic Sensing (DAS) technique with comparison to standard seismic, but also to compare both DAS technologies between them. The first one consisted of a Febus A1 interrogator with a dual switch module. Epsilon sensor is a monolithic fibre optic sensor from the Nerve-Sensors family and standard telecom cable were simultaneously connected to the unit. The second system consisted of a Neubrex S4110 interrogator with an Epsilon sensor only.

Data Analysis

When measuring with both vertical and horizontal component geophones, multicomponent seismic recording captures the seismic wavefield more thoroughly than traditional single element methods (Figure 2). Compressional waves are the fastest of all the elastic waves to appear, often have high signal-to-noise ratios, exhibit almost rectilinear particle motion, be readily created by a wide range of sources, and spread through fluid environments (Farfour et al., 2016).

S-wave velocity is substantially lower than P-wave velocity and S-waves can only propagate in an elastic media; the fluid or gas has no effect on the wave's velocity of propagation. The phenomenon of shear wave splitting, which permits anisotropy analysis using the P-SV and P-SH wavefields. These characteristics of the S-wave allow the converted wave data to yield useful information on correlations, lithofacies changes, lithology, and the confirmation of amplitude anomalies on P sections. Converted wave recordings also improve the accuracy of joint inversion and the interpretation of AVO/AVA data (Szymańska-Małysa et al., 2019).

P-waves represent as an indication for clear images of the structure and S-waves sensible for voids, cracks and water content. Moreover, S-waves are characterised by shorter wavelengths thus giving significantly better resolution in the near-surface applications where P-waves imaging is lacking (Caudron et al., 2024).

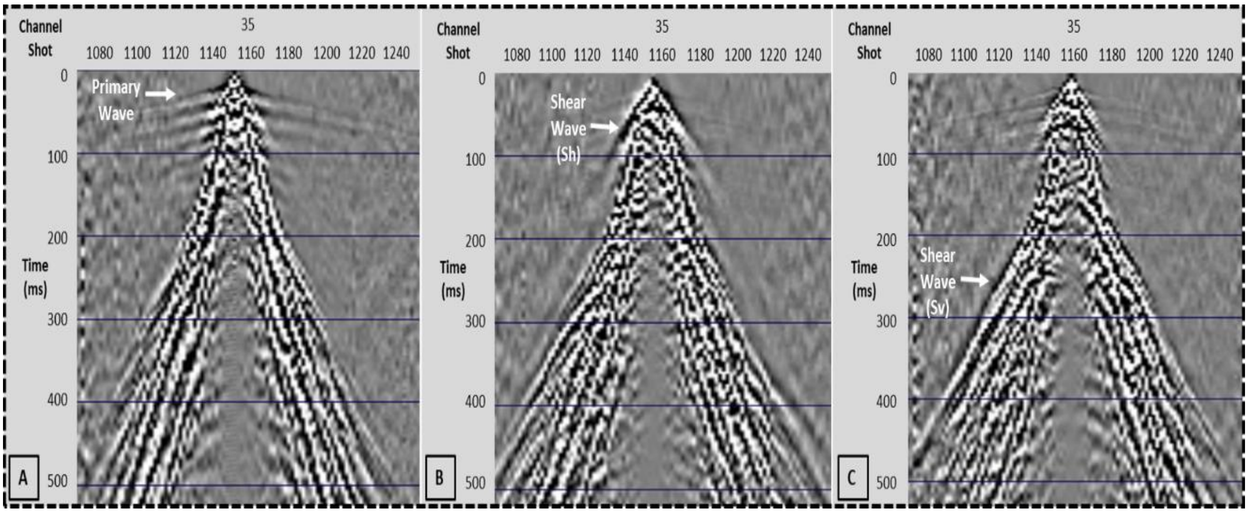

***Figure 2A** Vertical component (P) for receiver domain using hammer source to show p-waves, **B&C** Two horizontal component (S1,S2) for receiver domain using hammer source to show s-wave(Sh & Sv).*

DAS devices can be divided into two groups. The first group consists of devices that are sensitive to backscattered light intensity, and are primarily useful for intrusion detection purposes. The second group, quantitative phase-sensitive DAS systems, are the preferred choice for engineering and seismic applications due to their ability to provide reliable and high-quality data with a low noise floor. The specific acquisition method can be used to further divide both groups into smaller sub-groups, but the basic principles and objectives remain unchanged.

Quantitative DAS interrogators use the Raleigh backscattering phenomenon to measure changes in phase angle between successive measurements. The phase angle changes in direct proportion to the strain-rate in the fibre. The sensor's strain rate provides two significant pieces of information about the state of the fibre: the magnitude of its strain and the rate at which the changes occur. The "acoustic" in the name of the system originates form the accuracy of the systems, which allow to measure the strain as small as ones caused by acoustic vibrations. High-performance DAS interrogators combined with a suitable sensor can provide measurements with a spatial resolution of down to one metre and a sampling frequency of thousands of samples per second over a range of tens or even hundreds of kilometres.

The DAS system consists mainly of the opto-electrical device called the interrogator and the distributed optical sensor. In theory, any piece of optical fibre can be a distributed sensor. However, practice shows that in most cases, due to the brittleness of the raw fibres, special distributed sensors are required. In the group of special sensing fibres we can distinguish between layered cables and fibre optic monolithic sensors. Sensing cables consist of coating and reinforcing layers that effectively protect the fibre from damage. The strain is transferred through the layers in a successive manner, which may lead to considerable strain losses. In the monolithic sensor, such as the Epsilon Sensor, the fibre is permanently and completely bonded to the composite core of the sensor, so the strain losses do not occur.

Figure 3 show the comparison of industrial source between DAS and two component of 3C active seismic for shear waves (S1&S2), showing very clear S waves arrivals visible also at zero offsets, that are not recognisable at standard geophones. The kinematics of both data sets are the same, still DAS showing strain instead of displacement velocity is significantly different in form. Signal to noise ratios are very good in both data sets and clear arrivals are visible for the whole offsets.

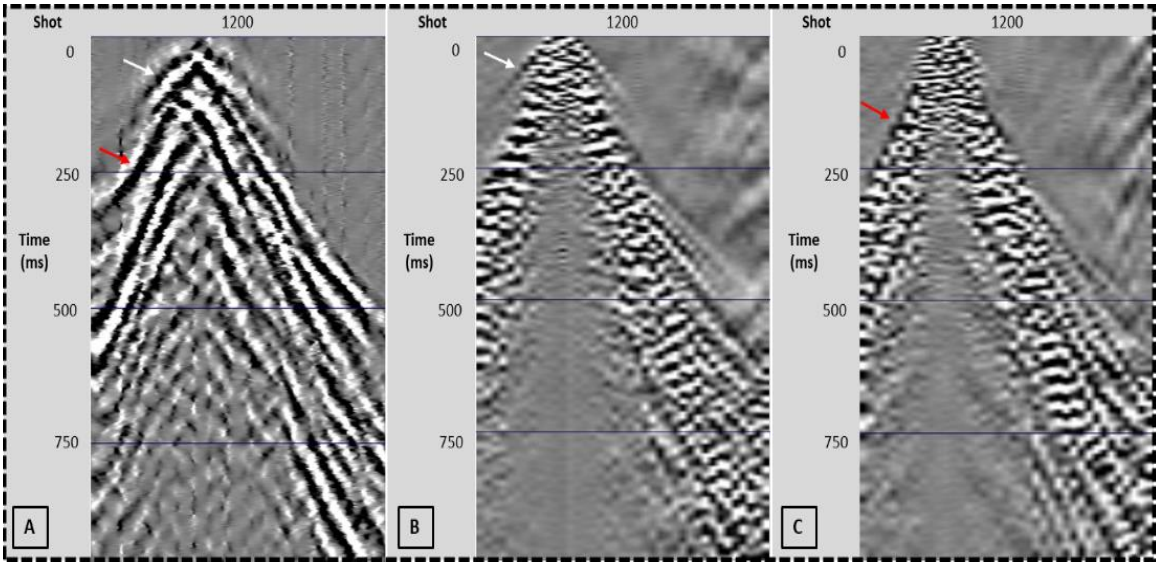

Figure 3A *DAS shot using industrial source,* ***B&C*** *Two horizontal component of 3C active seismic (S1,S2) for shot domain using industrial source.*

After gathering and reformatting the seismic data, we made vertical stack for three stick at every shot location. After that we build geometry and applying F-K filter to remove linear noise and low cut filter to remove low frequency noise (Roshdy et al., 2022). Figure 4 show brute stack for 3C active seismic by using hammer source.

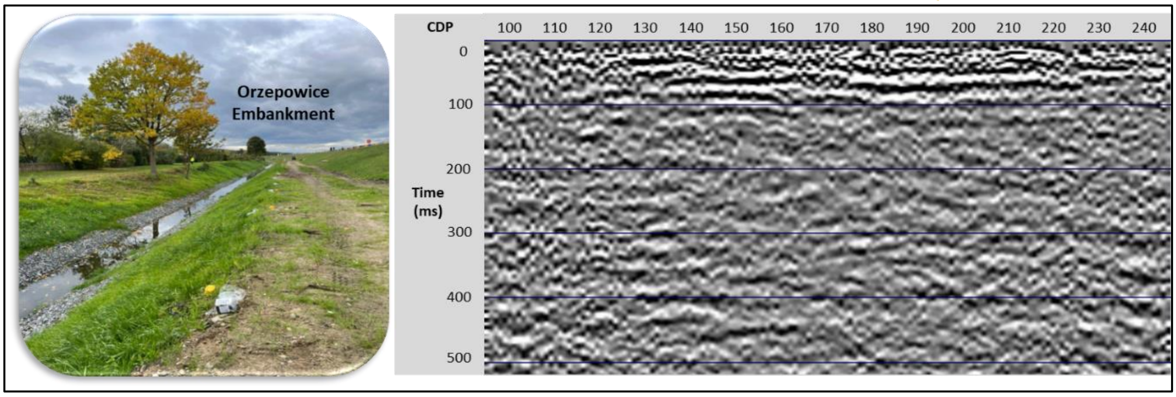

Figure 4 *Brute stack for 3C active seismic by using hammer source.*

Conclusion

We used seismic travel time tomography for general recognition of spatial differences, MASW technique to assess water infiltration and reflection seismic imaging to recognize the geological structures under the embankment. Three component active seismic show that compression wave (P-wave) is really clear in vertical component (P) and shear wave (S-wave) is very obvious in other horizontal components (S1 & S2). Combining P and S wave images allows for attribute inversions of rock properties, such as fluid content, pore pressure, stress direction and fracture patterns. Industrial source is better than hammer source as signal amplitude and resolution in active seismic and DAS. Distributed Acoustic Sensing (DAS) use a single fibre optic sensor replaces thousands of traditional point sensors, providing knowledge of the distribution of the measured quantity over the entire measurement length. DAS data show shear waves much better, in sense of resolution and frequency band, than 3C active seismic. We plan to record seismic data on exactly the same line in June 2024 to obtain time laps observation and recognize the different in the medium. The combination between 3C active seismic and DAS will help us to detect local damage (e.g. cracks) and comprehensively assess the state of deformation of the Orzepowice embankment.

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