Imaging of temporal changes in large scale critical objects – Earthfill dam in Rybnik

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Summary

In this work we focus on large earthfil dam of Rybnik reservoir as an example of critical infrastructure that is influenced by changing precipitation patterns. The most significant is the level of water in the reservoir, which is changing more often and have larger amplitude to mitigate potential floods resulted from changing climate. The multi method geophysical survey were executed in October 2023 and the second time-lapse part in June 2024. The seismic methods that use multiple types of seismic waves: refractions, reflection and surface waves were planned. Additionally, a fiber optic cables were deployed in a shallow trench along the whole seismic line of 800 m. They were used with two types of interrogators to verify the usefulness of Distributed Acoustic Sensing (DAS) technique with comparison to standard seismic. The survey was supported with ERT and spectral GPR with pseudo 3D measurements. Additional use of DAS measurements and innovative capabilities of spectral GPR gives additional verification of geophysical parameters allowing precise estimation of errors. The use of DAS technology allows both shallow and deep imaging and shows a great potential in any environmental seismology applications. It is however emerging technology. Those data should be treated with caution.

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Introduction

Change of current weather patterns related to climate change affects the whole surface of the Earth. Changes in weather in global scale are well monitored in real-time and can be precisely estimated. We see changes in the sea ice, degradation of glaciers and changes in annual temperatures. However, changes in the subsurface are much harder to be observed. Using geophysical methods it is possible to observe subsurface characteristics and in regions of high impact of climate warming such as Arctic and Antarctic regions, where such changes are strong and rapid, it can be done with high precision (Majdański et al., 2022).

Similar effects can also be noticed in Europe, and in underestimated can cause serious threats to the critical infrastructure and ecosystem. The effect of climate changes in general are manifested by gradual change of weather variability and frequency of extreme events including increase of precipitation and increasing amount of flash floods and long droughts periods. All direct, and indirect effects cause changes in water, which is the key element for environmental stability. One of the key problems related to climate changes is estimation, how those factors and changing hydrological regimes in Poland impact critical infrastructure, and are potentially hazardous to society. Examples here are artificial objects like large dams and flood embankments, but also natural objects like landslides.

In this work we focus on large earthfil dam of Rybnik reservoir (Fig.1) as an example of critical infrastructure that is influenced by changing precipitation patterns. The most significant is the level of water in the reservoir, which is changing more often and have larger amplitude to mitigate potential floods resulted from changing climate.

Fig.1 *The front dam of the reservoir in Rybnik, the southern Poland. This reservoir supports large coal plant and helps to mitigate floods. The survey were 800 m long along the crust of the dam for seismic, end extended to 3D survey for ERT and GPR measurements.*

Fieldwork

The multi method geophysical survey were executed in October 2023 and the second time-lapse part in June 2024. Fieldworks were designed to recognize both structure of the earthfill dam and its natural base that was not recognized before (similar to Majdański et al., 2018). The seismic methods that use multiple types of seismic waves: refractions, reflection and surface waves were planned. Such combined use allows to image shallow subsurface with traveltime tomography and MASW, but also show clear geological structures with reflection imaging. Seismic acquisition was performed with standalone DATA-CUBE stations with 4.5 Hz 3C geophones. Stations were deployed every 5 m. Additionally, a fiber optic cables were deployed in a shallow trench along the whole seismic line of 800 m. They were used with 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. EpsilonSensor – 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 EpsilonSensor only.

As seismic source we used weight drop with both vertical and shear component, but also standard sledgehammer (Fig.2). Timing of shots were recorded with GPS based device. All measurement, including two seismic sources with 5 m spacing and two different recording systems took one day.

The seismic survey were supported with innovative Ground Penetrating Radar (GPR) with multi spectral characteristics (FIG.2). This new device allows to measure a wide spectrum of magnetic field that can be processed with techniques similar to seismic. GPR covers the near-surface depths with high resolution, much needed for correct reflection seismic processing. As GPR measurements are much faster than seismic, a pseudo 3D survey were executed along the seismic line and several crossline profiles. The whole work was performed in a few hours just after the seismic measurements, to avoid possible negative interaction between the equipment.

As the water effects and hydrogeological processes are the most important in this study the Electro Resistivity Tomography (ERT) survey with standard ABEM Terrameter LS equipment were executed. This pseudo 3D measurements were co-located with GPR. ERT survey were executed the next day to avoid interference with other devices.

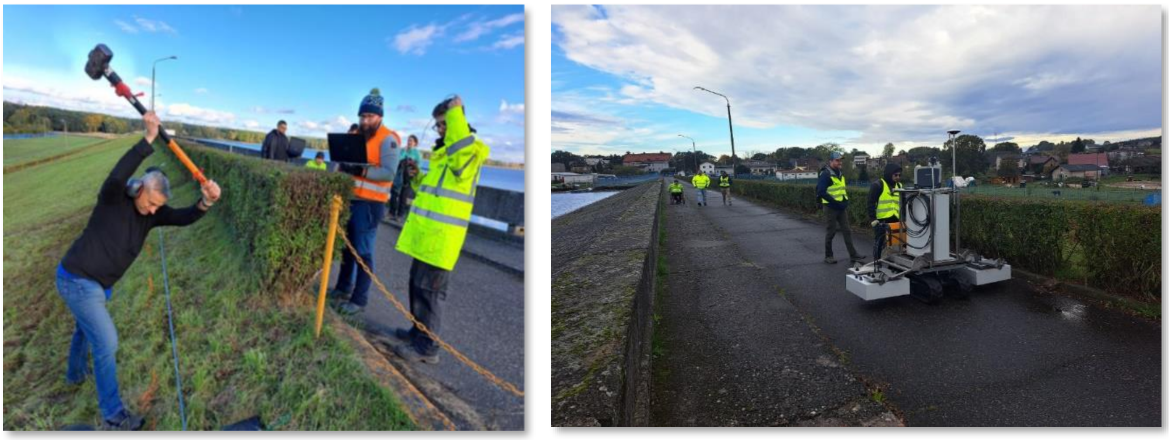

Fig.2 *A combination of near-surface geophysical methods (seismic tomography and imaging, GPR, ERT) were used to image the structure of the dam. Seismic survey based on standard geophones supported with additional fiber optic sensor (DAS). All measurements were planned as time-lapse survey to catch temporal changes. Seismic measurement with sledgehammer source (left), spectral georadar (right).*

All measurements were precisely located with geodetic measurements. This is critical, as the second stage of measurement were planned for June 2024 as time-lapse image. All surveys, seismic, GPR and ERT were repeated with exactly the same locations, the same devices and parameters. In June, after the snow melting, the hydrological conditions in the reservoir were significantly different comparing to

October previous year. We expected to observe different hydrological state in the dam and its surroundings. This forcing should impact each part of the dam with different strength as a result of imperfections in the structure resulting from ageing and 40 years of constant usage. Also the different water level in the structure should be spatially variant due to varying porosity, local imperfections and inhomogeneities in material used in for construction.

Data and processing

Active seismic data were processed with standard imaging algorithms including advanced noise attenuation techniques (Roshdy et al. 2022). An example of 3C seismic data are presented in Fig.3, showing stacks of three shots in one location sorted to receiver domain. The left panel shows vertical component typically used in the near-surface applications with visible P wave arrivals in the first 200 ms. All components show rich S wave field and strong surface waves visible down to 900 ms and useful energy clearly recorded along the whole line and all offsets. This allows to use variable seismic techniques like MASW, travel time tomography and reflection imaging, and allows use of multi method approach (Marciniak et.al. 2019) to estimate uncertainty for the final reflection image. Another set of seismic data were recorded with DAS devices. The continuous recording were cut according to GPS times of shots and stacked vertically. The comparison of both devices shows significant differences in recorded frequencies, but both acquisitions shows clear S waves recorded along the whole seismic line. The first few meters, that are crucial for reflection imaging and cannot be extracted with used survey geometry, are clearly imaged with GPR technique. This shallow information is crucial for static corrections, especially in changing water saturation in the first few meters expected in time-lapse surveys. Because we used spectral GPR it was possible to also deeper structures and compare the results with seismic images. Analysis of ERT data, which is especially sensitive to water saturation, shows clear state of water infiltration. After the time-lapse observations resulting change will give additional insight to the state of the structure of the dam. Finally, DAS infrastructure was used to record 5 days of continuous ambient noise. This data gives good estimation to surface waves that is used in MASW technique. We have clear recordings of surface waves from active seismic, still use of DAS gives us much lower frequencies thus deeper recognition of the S waves velocity field.

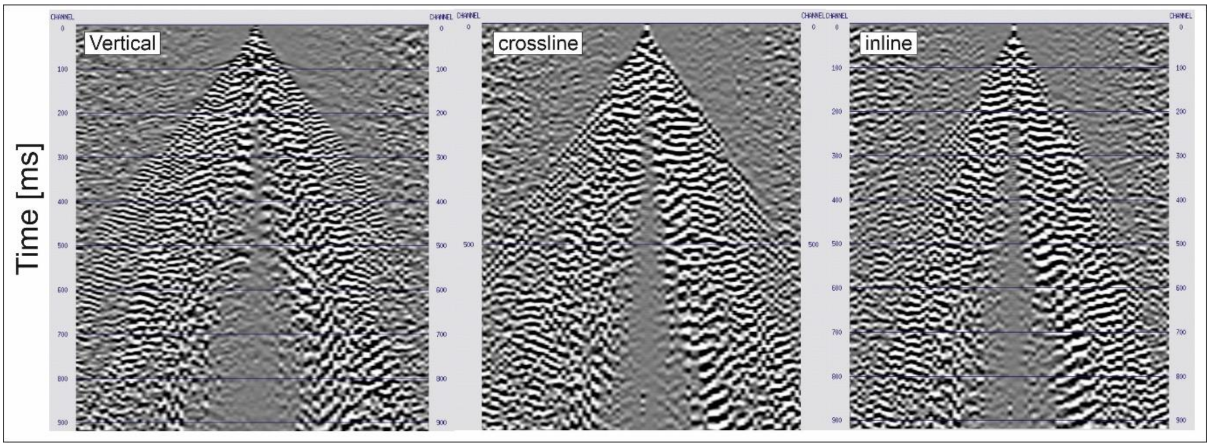

***Fig. 3** An example of 3C seismic data gathered in Rybnik. P wave arrivals are only visible in the vertical component. Rich S waves and surface waves field is visible at all offsets.*

Conclusions

A combination of standard seismic, GPR and ERT methods gives a clear image of the geological structure beneath the dam and verification of water saturation in its structure. Additional use of DAS measurements and innovative capabilities of spectral GPR gives additional verification of geophysical parameters allowing precise estimation of errors. With time-lapse data we will be able to visualise hydrogeological processes in the structure of the dam. The multi method approach (Ebong et al. 2024; Marciniak et al., 2022) that uses combination of seismic, GPR and ERT methods will be particularly useful in this case, as we expect to see significant changes in hydrogeological state.

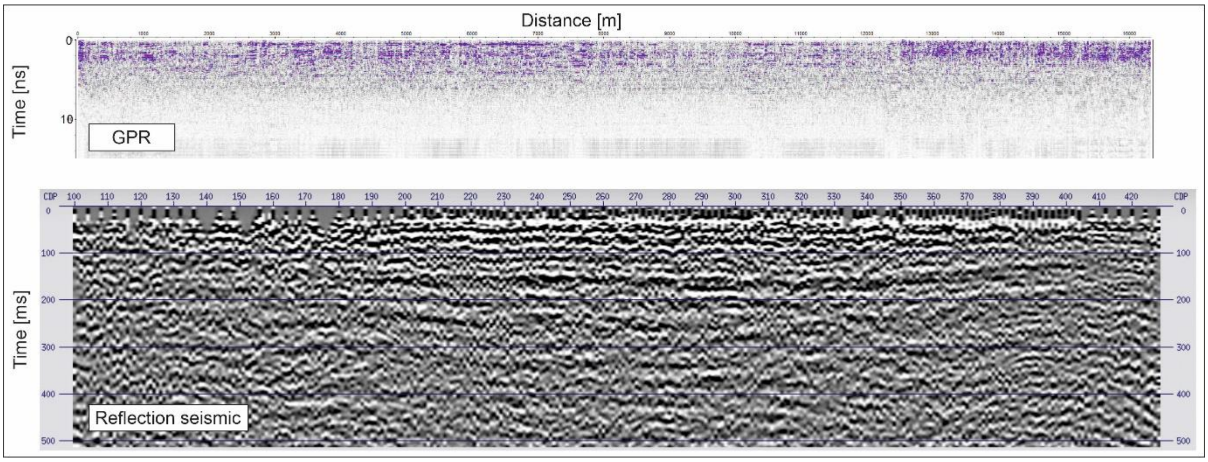

Fig. 4 Resulting GPR image of the Rybnik Dam (top). The reflectivity in the structure is changing horizontally showing differences in compaction of the material and influence of hydrogeological processes. Useful signal reaches depth of 10 m. Reflection seismic image (bottom) show geological structures below the dam, but also show diversification in the structure of the dam.

The use of DAS technology allows both shallow and deep imaging (Bakulin et al., 2018) and shows a great potential in any environmental seismology applications. It is however emerging technology that use several different measurement principles, and measure different parameters. Those data should be treated with caution, but possibly could improve our understanding of the subsurface. At the moment any active seismic DAS surveys should be accompanied with standard geophone based measurements. Together those seismic techniques supported with standard GPR and ERT measurements are capable of imaging all hydrogeological processes with great precision.

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