Seismic and electrical monitoring of an earthen dam: first results from Fourcare test site (NW Italy)

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Introduction

Earthen dams, embankments and levees are often constructed in alpine regions for water storage, flood management and power generation. The dams could be subjected to incidents and failures due to overtopping, seepage, internal erosion, showing their vulnerability to aging and degradation processes (Chongxun et al., 2008; Talukdar & Dey, 2019). Earthen embankments located in alpine regions, are also exposed to freezing-thawing cycles and environmentally-linked natural hazards which can further affect their mechanical properties, emphasizing the need of continuous monitoring and assessments of long-term stability (Jabbarzadeh & Mousavi, 2025; Papathoma-Köhle et al., 2011).

Traditional monitoring techniques (e.g. monitoring of the piezometric level within the dam) are often invasive and offer only spatially limited information. For this purpose, integrating geophysical monitoring can provide a comprehensive image of subsurface conditions and allow the early detection of internal erosion processes. Electrical Resistivity Tomography (ERT) is a well-established technique to estimate preferential seepage pathways in earthen embankments (e.g., Camarero et al., 2017; Moreira et al., 2022; Oh, 2012; Panthulu et al., 2001), while ERT time-lapse can be used to monitor temporal variations in saturation under changing environmental conditions and to track the evolution of preferential flow pathways.

Previous studies have proven passive seismic monitoring effective in estimating shear-wave velocity and stiffness modifications of earthen dams caused by internal erosion, showing its potential to identify critical geotechnical conditions that may require intervention (e.g., Aguiar & Maciel, 2022; Planes et al., 2015).

In this study, we integrate both ERT and passive seismic monitoring to estimate temporal hydraulic and mechanical modifications in an earthen dam in northern Italy. Particularly, we have installed a network of seismic 3-component stations and an array of electrodes for the monitoring of geophysical parameters of the dams; the monitoring activity lasted for 8 months, in order to investigate the dam response to different environmental conditions.

Test site

The selected test site is the Fourcare dam located in Aosta Valley (Northwestern Italy, Fig. 1) at an elevation of 2325 m. Commissioned by Monterosa S.p.A, it was constructed as a water basin for the production of artificial snow for the nearby ski facilities. The reservoir is fed by the nearby Fourcare stream and, with a maximum depth of approximately 12.5 m, it can store around 127,000 m^3 of water. The embankment slopes are composed of mechanically compacted coarse-grained material and, to prevent water infiltration, an impermeable layer was installed between the dam body and the reservoir.

Seven inclinometers and four piezometers are installed along the embankment perimeter. Piezometer reveal a heterogeneous water table suggesting non uniform seepage conditions, whereas inclinometer measurements indicate localized deformations of the embankment. Furthermore, from local inspections, water seepage has been observed along the southern side of the embankment, while a naturally formed pond on the northwestern side could indicate a potential connection to the reservoir, although this has not been confirmed.

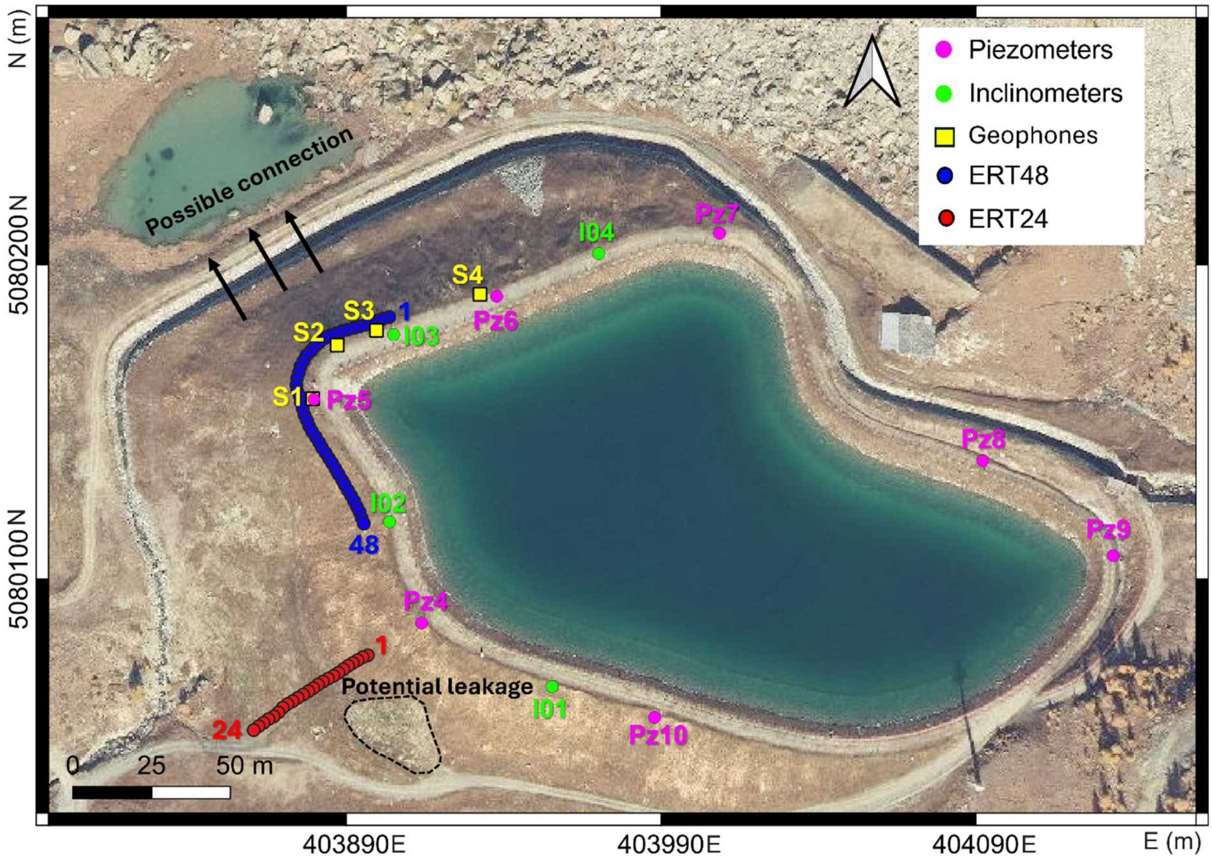

Fig. 1 - Test site showing the location of seismic geophones and electrical lines, together with the installed piezometers and inclinometers. Potential leakage zones are reported in black.

The array for the ERT monitoring were located along two main profiles (ERT48, ERT24 in figure 1), disposed on the north-western and southern sides of the embankment; the main target of the ERT time lapse measurements were to relate the temporal changes of electrical resistivity with the variations of the water content, close to two critical areas of the dams. Four 3C geophones (S1-4) were located along the Northen side of the dam, partially overlapped to ERT48, with S4 deployed in an area not covered by it.

Methods

Two ERT lines (ERT48 and ERT24), installed in October 2023, have been acquiring daily subsurface resistivity measurements until April 2024 through a Syscal Pro (IRIS Instruments) resistivity meter. ERT48, consisting of 48 electrodes at 2-m spacing, was positioned at the corner of the northern and western sides of the dam crest, to monitor a possible connection with the naturally formed pond highlighted in Fig. 1. ERT24, with 24 electrodes and the same spacing, was installed along the southern slope, close to the identified potential leakage area (black dashed line in Fig.1). To achieve both adequate lateral and vertical resolution of resistivity variations, data were acquired along both profiles using Wenner-Schlumberger and Dipole-Dipole array configuration, with automatic sequences. The time lapse inversion of the 2D pseudo-sections was performed using ResiPy (Blanchy et al., 2020). To better visualize saturation modifications over time, daily resistivity changes were computed as in percentage differences relative to the first reference acquisition.

Four geophones (S1 to S4) were installed at the north-western side of the reservoir and have been acquiring continuous passive seismic data until the first months of 2025. Each station includes a 2 Hz triaxial high-sensitivity geophone (200 V/(m/s)) and an on-purpose designed digitizer/recorder (GEA–GPS, developed by PASI s.r.l. and Iridium Italia s.a.s.) ensuring continuous seismic noise recording at 250 Hz sampling rate and daily remote information about the system state of health by a GSM–GPRS module. Synchronization between the different stations is provided by GPS timing. Data are stored in 1 h files in an internal 32 GB memory card. Spectral analysis of the continuous recordings was carried out to identify the embankment’s natural frequency. For this purpose, we computed single-station spectral ratios applying standardized filtering, windowing and smoothing procedure reported in literature (Colombero et al., 2018).

Results

Figure 2 (a to c) shows the electrical resistivity section measured along ERT24, using Wenner-Schlumberger configuration, on October 30, 2023, January 30, and March 30, 2024, respectively. A progressive enlargement of a high-resistivity zone at the beginning of the profile, can be observed over time, extending over the first 15 m of the profile on March 30, 2024. This trend may be also observed from Figure 2d and e, indicating the freezing of saturated soil during winter period. Between January and March, at approximately 20 m along the profile, a sudden decrease in resistivity is observed, possibly indicating presence of melting water.

A strong and continuous amplification of the signal can be observed at 10 Hz, indicating this value as the resonance frequency of the dam body. This can be observed in Figure 3a, dealing with the single station spectral ratios computed for station S4. This hypothesis was further confirmed by 3D numerical modelling of the dam eigenfrequencies performed in COMSOL Multiphysics. Despite temperature and precipitation fluctuations (Fig. 2b), the peak frequency remains quite constant, suggesting that the overall structural stiffness is stable and not significantly influenced by seasonal freezing–thawing cycles. A delayed and weak response to air temperature modifications is depicted at the daily and seasonal scales. However, during transitional seasons (mid-September, late October 2023 and late Aprile, 2024) some local fluctuations can be observed, possibly indicating local instabilities related to water seepage.

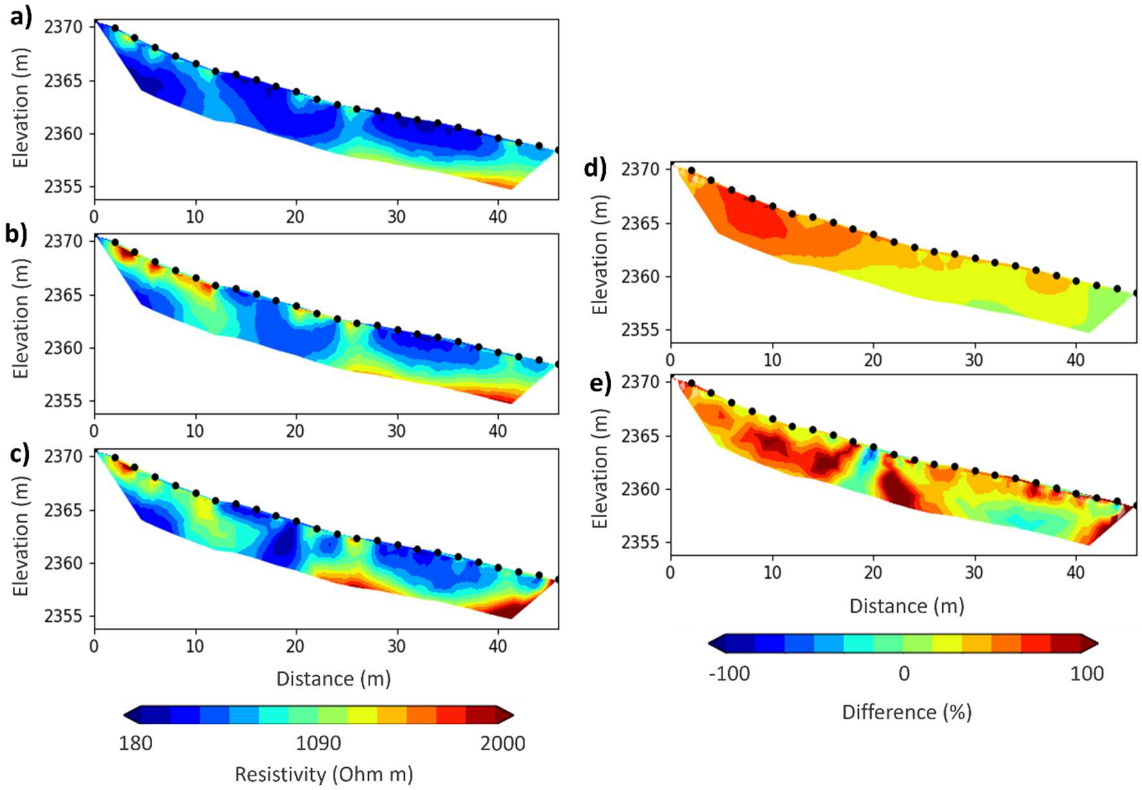

Fig. 2 - Time-lapse ERT24, obtained using Wenner-Schlumberger arrays, for three acquisition dates spanning approximately five months: (a) October 30, 2023; (b) January 30, 2024; (c) March 30, 2024. Panels (d) and (e) show the percentage resistivity differences relative to October 30, 2023, for January 30, and March 30, 2024, respectively.

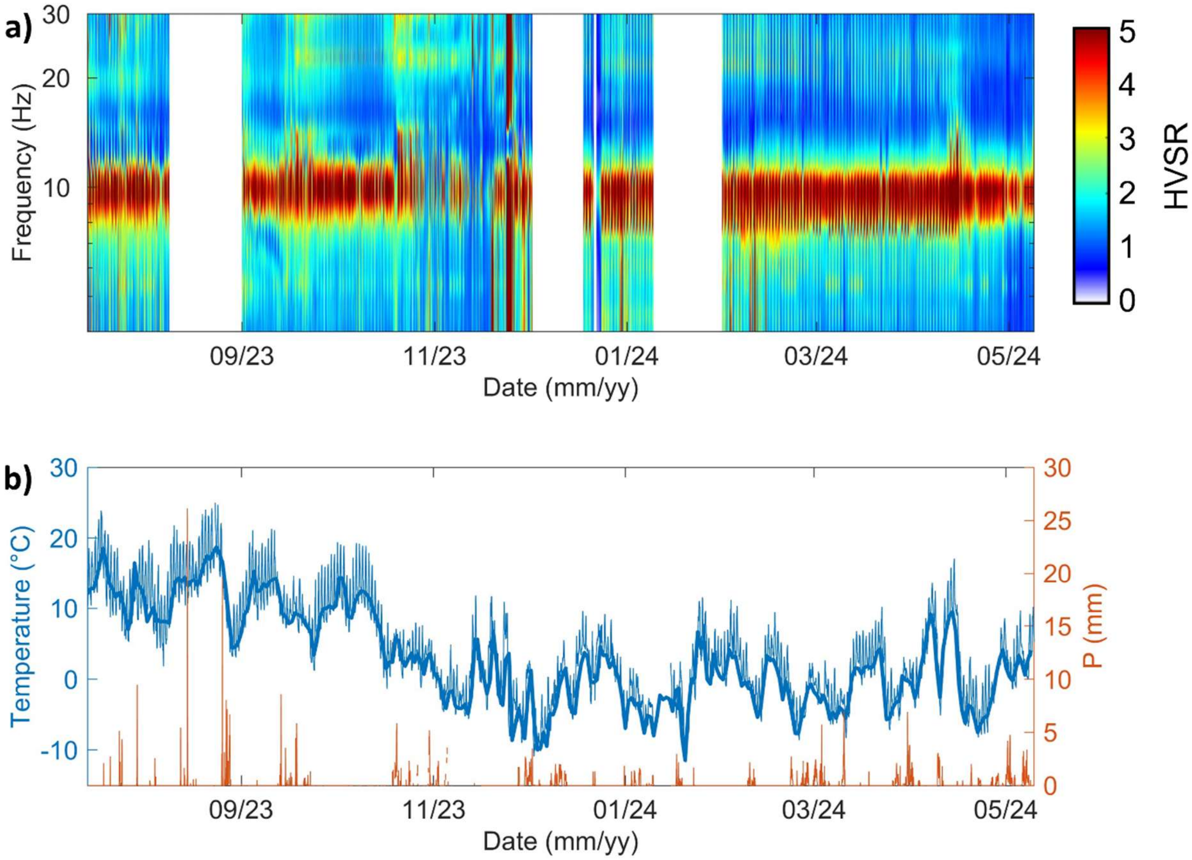

Fig. 3 - (a) Horizontal to Vertical Spectral Ratio (HVSR) measured at S4 from August 2023 to May 2023. White bands refer to periods with no data. (b) Temperature and precipitation acquired at the nearest weather station.

Conclusions

We monitored the hydraulic and mechanical behaviour of the Fourcare earthen dam in the Aosta Valley using an integrated geophysical approach combining ERT time-lapse and passive seismic monitoring. ERT time-lapse revealed temporal variations in soil saturation, with high resistivity zones forming during winter, indicating soil freezing and sudden resistivity drops in late winter/early spring, likely associated with melting water. Passive seismic monitoring allowed for the estimation of the resonance frequency of the dam, measured at 10-Hz. The peak frequency showed no strong dependency on environmental fluctuations, suggesting that the overall structural stiffness of the embankment is not significantly affected by freezing–thawing cycles. Local fluctuations in resonance frequency, were detected during transitional seasons, potentially indicating areas of localized instability related to water seepage.

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