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Integration of seasonal frequency domain electromagnetic surveys and geological data for assessing the integrity of earthen levee systems. The case study of the Panaro River (Northern Italy)

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A R T I C L E I N F O

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A B S T R A C T

Floods rank among the most widespread and destructive natural hazards worldwide. The progressive degradation, impairment, and breach of earthen riverine levees can occur in both natural and anthropogenic environments, stemming from various scenarios or sequences of events. These may include hydraulic failure due to overtopping because of inadequate height, and structural failure occurring even prior to overtopping, due to insufficient geotechnical and hydraulic characteristics combined with external and internal erosion.

Following the catastrophic flood of December 2020, caused by the collapse of a section of the levee system of the Panaro River (a tributary of the Po River, Northern Italy), local Authorities initiated a comprehensive investigation into the causes of the breach. Numerous factors, including geological, geomorphological, and ecological features, were found to have contributed to the progressive decrease of the levee integrity prior to and during the flood. This prompted a broader multidisciplinary study of the Panaro River levee system.

The study expanded its focus to include the collapsed section (rebuilt in 2020), as well as an additional 30 km stretch of both the right and left levees north of Modena, totaling 60 km. Detailed geological and geophysical data were integrated into the analysis, with particular emphasis on evaluating the characteristics and integrity features of the levee system.

This analysis was carried out using Frequency Domain Electromagnetic Methods (FDEM) on the top of the levees, previously calibrated using Electrical Resistivity Tomography (ERT), geological mapping, core logs, and Cone Penetration Tests (CPTs). The FDEM surveys were repeated in different environmental conditions, specifically in the dry 2021 summer season and in the wet 2023 spring season, during heavy rainfalls that caused disastrous floods in several areas of the Emilia-Romagna Region. Out of the 60 km surveyed in the study area, the comparison of the two datasets highlights an interval of about 4 km where the internal portion of the levees is characterized by relatively coarse-grained materials and higher permeability making it more prone to internal erosion phenomena. This paper describes and integrates the results of these investigations, drawing attention to the strengths and limitations of the FDEM method when applied to extensive surveys on earthen riverine levee systems. The proposed methodology contributes as well to maintenance and retrofitting efforts to reduce flood risk in the context of the present climate change scenarios.

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1. Introduction

Floods rank among the most globally prevalent and devastating natural disasters (Jonkman, 2005). In both natural and built-up environments, various scenarios or chain of events can contribute to the progressive deterioration, damage, and breaching of earthen riverine levee systems during or after flooding events. These incidents may result from hydraulic failure due to insufficient height or structural failure attributed to inadequate strength (Morris et al., 2008), impacting both the waterside and landside slopes. However, prior and during the overtopping, numerous factors can contribute to the occurrence of failure and the onset of a potential failure mechanism does not necessarily result in a breach. For example, a substantial overflow can cause severe floods without leading to a breach in the levee. Additionally, the initiation of one failure mechanism may set off other processes, leading to a sequence of multiple failure mechanisms on the levee. Failures may commence with overtopping, preceded and/or followed by external erosion, ultimately resulting in a breach at a later stage. Conversely, internal erosion might initiate and progress without any external evidence until breaching occurs. Notably, almost half of all historical earth dam failures have been attributed to internal erosion mechanisms, second only to overtopping-related failures (Foster et al., 2000).

The potential chain of failure mechanisms becomes even more significant when considering existing structures and the history of the levee system, sometimes spanning several centuries. Although design regulations and maintenance guidelines, as well as national technical standards are well-established today (e.g., FEMA, 2005; CIRIA et al., 2013), historical levees have often been built in different phases, using potentially inadequate locally available materials, and without any building standard. Over time, the levees may have experienced damage, repair, rehabilitation, and modifications at various sites. In addition to the progressive weathering of the materials, biological activity could have also degraded the earthen structures. For instance, burrowing animals may have created discontinuities such as dens and setts, while vegetation may have modified the characteristics of the levee both at the surface and at depth leaving root holes (Bayoumi and Meguid, 2011). As a result, earthen structures with a long history may have their integrity significantly influenced by concealed and undetectable local variabilities or defects that may act as flaws for the initiation, continuation, and progression of internal erosion (Robbins and Griffiths, 2018) associated with hydrological load persistence and intensity (Vorogushyn et al., 2009).

The structural stability of a levee is closely related to its geometry, soil geomechanical properties, and compaction. The heterogeneity of grain sizes and hydraulic flow properties within earthen levees and foundation soils can encourage the development of preferential seepage pathways, internal instability, and contact erosion (Morris et al., 2008). Additionally, discontinuities generated by rigid structures potentially embedded in the levees, may turn out in weakness points during events that threaten its integrity. For existing levees, the predisposing, conditioning, and triggering factors mentioned above may not be readily detectable through visual inspection, suggesting that they could evolve without external evidence until the final failure occurs. Moreover, given the considerable length and potential heterogeneity of levee systems, comprising various supporting features and other components, their characterization cannot rely solely on direct investigations. Instead, it necessitates the use of efficient and economically feasible indirect extensive methods (Reynolds, 2011). Therefore, to characterize earthen structures, information gathered from direct investigations and monitoring campaigns must be complemented with indirect data from geophysical surveys. These surveys can aid in establishing the engineering geological model of the levee system, identifying local punctual, linear, or areal anomalies that can act as weak points and may influence its overall stability in the short- and long-term.

Two recent catastrophic flood events, which occurred in 2014 and 2020 along the Secchia and Panaro rivers, right tributaries of the Po River in the Emilia-Romagna Region (Northern Italy), underscored the vulnerability of the levee system to internal erosion (Taccari, 2015; Orlandini et al., 2015; Balistrocchi et al., 2021; Ceccato et al., 2022a; Ceccato and Simonini, 2023) and emphasized the urgent need for a comprehensive understanding of these aged and poorly known structures to facilitate the design of proper maintenance and retrofitting activities This has become even more relevant as the frequency and intensity of extreme weather events are on the rise, exemplified by the recent Romagna 2023 flood, marked by rainfalls exceeding a 200-year return period (Regione Emilia-Romagna, 2023; Barnes et al., 2023).

The aim of this study is to build an engineering geological reference model and assess the integrity of a 60 km stretch of the Panaro river levee system by integrating geological data with extensive, noninvasive geophysical surveys carried out in different environmental conditions, i.e., dry vs. wet season.

2. State of the art

In the critical context of levees integrity investigation and monitoring, geophysical techniques play a crucial role. Several methods have been developed and applied for various purposes. Specifically, electromagnetic surveys for acquiring electrical resistivity data proved to be a powerful tool in correlating soil resistivity with lithological, stratigraphical, and hydrogeological characteristics (Dezert et al., 2019; Cockx et al., 2007; Brevik et al., 2006; Kitchen et al., 1996).

The most used technique for determining the lithology and the stratigraphy of levees is Electrical Resistivity Tomography (ERT), often combined with other methods, primarily Frequency Domain Electromagnetic Methods (FDEM), and in some cases, Ground Penetrating Radar (GPR), calibrated with the aid of geological and geotechnical data (Araújo et al., 2023; Dezert et al., 2019; Perri et al., 2014; Tresoldi et al., 2018; Borgatti et al., 2017). These methods are extensively employed for monitoring subsurface moisture conditions, with diverse applications such as monitoring the integrity of railway embankments via ERT and FDEM (Chambers et al., 2014; Gunn et al., 2018), detecting potential water infiltration and instability in earth dams using ERT, FDEM, and GPR (Inazaki et al., 2016; Jodry et al., 2019), developing hydrogeological models for effective infiltration in arid environments and ephemeral rivers using ERT and FDEM (Shanafield et al., 2020; Cassiani et al., 2012; Villeneuve et al., 2015), and correlating vegetation with the degree of infiltration through ERT and FDEM (Zhu et al., 2013; Cassiani et al., 2012; Bréchet et al., 2012).

Other studies focus on enhancing the efficiency and effectiveness of these techniques and their combined utilization, including other geophysical techniques like different seismic methods (e.g. Busato et al., 2016) and thermal sensing (e.g. Borgatti et al., 2017; Radzicki et al., 2021).

The review by Dezert et al. (2019) emphasizes the importance of optimal technique combinations for this purpose. Additionally, innovative approaches like coupling ERT streamers with seismic measurements (Comina et al., 2020; Vagnon et al., 2022) and employing less invasive ERT acquisition methods using sponge electrodes (Umezawa et al., 2022) are highlighted.

The literature underscores the significance of ERT and FDEM methods in monitoring soil saturation, groundwater infiltration and flow, and assessing earthen levee integrity. While GPR is useful for detecting features like cavities, burrows, dens, and fractures, it has limitations in penetration depth, particularly in the presence of conductive layers (Perri et al., 2014; Borgatti et al., 2017; Pennisi et al., 2023). Seismic methods including active (Multichannel Analysis of Surface Waves - MASW; Refraction Seismics) and passive surveys (Refraction Microtremor - ReMi; Microtremor Array Method - MAM; Horizontal-to-Vertical Spectral Ratio - HVSR) are also used for both stability analysis (Martelli et al., 2014) and levee characterization (Lorenzo et al., 2014; Busato et al., 2016; Craig et al., 2021).

ERT measurements, often combined with environmental monitoring

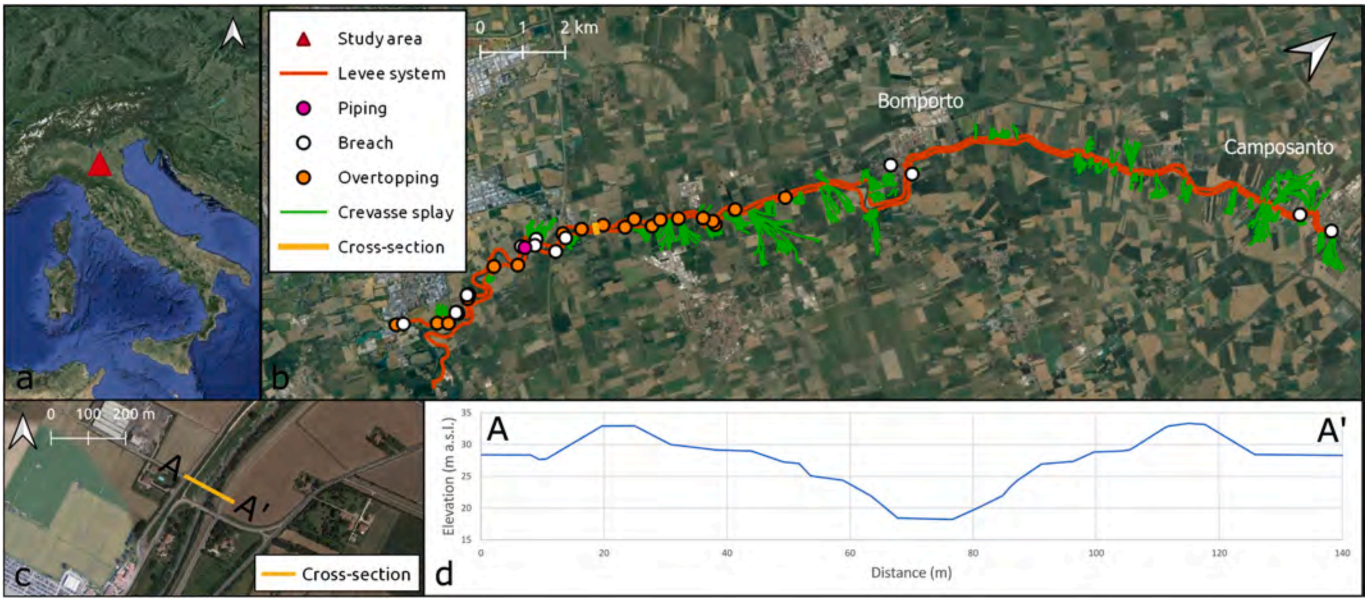

Fig. 1. Study area. a) geographical location; b) historical incidents and levee system failures along with mapped crevasse splay deposits; c) geographical location of the cross section in panel d near Navicello, north of Modena.

of variables such as temperature, precipitation, and river stage, prove effective in assessing soil conditions (Tresoldi et al., 2018; Zhu et al., 2013; Arosio et al., 2017). FDEM methods are valuable for determining soil moisture levels, either independently (Calamita et al., 2015) or alongside other techniques. However, these methods may encounter challenges due to sharp soil heterogeneity and external interferences.

A comprehensive characterization and monitoring of long stretches of levees involves combined ERT, FDEM, and direct geological and geotechnical data. While ERT may induce higher costs and time requirements, it can provide valuable calibration for FDEM on selected sections. Geotechnical investigations offer direct data about lithology and stratigraphy but are punctual, making it challenging to characterize large areas, especially in alluvial environments where heterogeneity is expected. It emerges that FDEM methods are favored for their potential calibration, reliability, cost-effectiveness, and efficiency. The apparent conductivity, as determined by electromagnetic induction, serves as a surrogate measurement for interpreting diverse soil properties, including lithology, clay content, degree of compaction and water content, etc. Numerous studies validated the efficacy of electromagnetic induction in assessing soil characteristics and their changes under varying boundary conditions (Doolittle and Brevik, 2014). Whether directly linked to a specific property or associated with changes in factors such as moisture and clay content, electromagnetic induction proves to be a versatile and effective methodology for detailed soil property analysis.

Most studies focus on limited sections of levees, typically spanning a few hundred meters, where prior seepage or damage has occurred (e.g., Lorenzo et al., 2014; Borgatti et al., 2017; Radzicki et al., 2021). In contrast, we propose a methodology, tested and validated over tens of kilometers, to develop a spatially continuous 2D engineering geological model and identify potentially vulnerable and/or restored sections of the levee system.

3. Study area

In this study, geological and geophysical data have been integrated to build an engineering-geological model of a 30 km stretch of the Panaro River levee system in the Province of Modena (Northern Italy), spanning from the outskirt of Modena downstream to the municipality of Camposanto (Fig. 1).

Table 1
Morphometry of the levee system in the study area.

Levee system metrics	Left bank	Right bank
Maximum elevation (m a.s.l.)	37	39
Minimum elevation (m a.s.l.)	17	26
Minimum levee height (m)	0	0
Maximum levee height (m)	8.6	10

The Panaro River flows through the Emilia-Romagna Region covering a total distance of approximately 150 km (Fig. 1). It has a catchment area of 1784 km^2, in the Northern Apennines, with an average annual precipitation of around 1000 mm. In its upstream section it crosses mountainous and hilly territories, with outcropping sandstones and clayey marls. As the river progresses downstream, it enters the Po Plain, at the foot of the Apennines, where recent alluvial deposits dominate the landscape (Castaldini and Ghinoi, 2008). Here, rivers and streams have built large and overlapping alluvial fans (Castiglioni et al., 1997). Fluvial scarps, traces of abandoned riverbeds and flood basins can be observed in the floodplain. The superficial alluvial deposits are Holocene in age and their particle-size distribution ranges from gravel to clay (Castiglioni et al., 1997). Anthropogenic activities have significantly altered the course of the Panaro River. For example, downstream a flood-control reservoir built in the 1980s to protect the city of Modena, extensive sections of the river have undergone progressive transformation since the XIX century, including meander cut-off and the construction of progressively higher and wider levees, resulting in an almost completely artificial and relatively narrow watercourse (Castiglioni et al., 1997; Castaldini and Ghinoi, 2008).

The present-day levee system represents repeated enlargements of the historical levees, which have been repeatedly repaired, rehabilitated, and modified over the years following overtopping and breaching events. The Panaro River has in fact experienced a significant number of flood events over the last centuries, evidenced also by numerous crevasse splay deposits along both sides of the main stream (Castaldini and Pellegrini, 1989; Panizza et al., 2004). In certain instances, flooding has been ascribed to overflow and internal erosion, yet for most events the causes remain unknown. In general, the scope of the levee system of the Panaro River is to confine a flood loading of a limited duration in response to rainfall events in fall or in spring, or to rapid snowmelt

Fig. 2. Study area showing the Panaro levee system between Modena and Camposanto municipalities surveyed with FDEM in dry and wet boundary conditions. The basemap is sourced from GeoPortale Regione Emilia-Romagna.

events in winter occurring in the Apenninic sector of the catchment.

In the study area, the height of the levees spans from 5 to 8 m, the width from 12 to 16 m, while the slope can locally exceed 35° (Fig. 1; Table 1). The levee system is constituted by homogeneous, compacted earthen structure, at places with armoured surfaces on the waterside, supporting features, and transitions to components such as bridges. The slopes are covered by spontaneous vegetation, sometimes as a result of seeding interventions. A gravel path or pavement on the crest allows the transit of service vehicles.

The soils constituting the main body of the levees alongside the Panaro River can be described as a mixture of sand and silt, occasionally mixed or interbedded with sand and, in some sections, with clayey silt, in highly variable percentages both longitudinally and at different depths (Ceccato et al., 2022a). The clay component is relatively small, implying low plasticity. The levees experience partial saturation conditions, with variable water contents at depth and longitudinally, depending on the river stage and the groundwater level of the phreatic aquifer. Shear strength is variable, and typical of a compact but very fragile soil. While the frictional component does not exhibit significant variability, the effective cohesion component does (Ceccato et al., 2022a).

The foundation soils generally share similar characteristics with those of the levees described above. The construction materials were in fact often excavated directly from the riverbed and the nearby floodplain. Consequently, the internal structure of the levees is likely to exhibit heterogeneity in both lateral and longitudinal directions, remaining largely undocumented (Ceccato et al., 2022b). Moreover, in recent years, burrowing mammals contributed to increase the vulnerability of the levee system to concentrated leak erosion and/or backward erosion piping (Orlandini et al., 2015; Ceccato and Simonini, 2023), in combination with the spreading of invasive alien plants like *Arundo donax*, whose extremely superficial root system can locally enhance levee instability.

4. Materials and methods

In recent years, extensive geological surveys and geotechnical tests have been carried out along the Panaro River levee system to monitor stability, optimize periodic controls, enhance engineering design, and program maintenance operations. Geomorphological mapping has been carried out to identify paleo riverbeds and crevasse deposits along the present river path and locate the position of breaches and overtopping events during historical floods. This was achieved with the aid of historical maps and aerial images, along with DEM from LiDAR surveys. In situ tests included Cone Penetration Tests (CPTs) and Seismic Cone Penetration Tests (SCPTs) at a depth of 30 m from the levee crest (about 100 logs), as well as cored boreholes reaching depths of 20 m (about 25 core logs). Finally, two extensive FDEM campaigns were carried out on the levee crest of both right and left side, in August 2021 (dry condition, about 60 km) and May 2023 (wet condition, about 14 km), along with ERT surveys. A length of 188 m of ERT data was used for the calibration out of 2346 m in total, designed to calibrate the geophysical data on selected sections.

In the following sections, the initial calibration procedure with ERT, geological data and the FDEM surveys in different boundary conditions performed in the study area (Fig. 2) will be described.

4.1. Resistivity calibration: FDEM - ERT and FDEM - CPT/CPTU/cores

Ensuring the correct calibration of geophysical measurements obtained with different instruments is essential in any monitoring or comparative activity. Therefore, to characterize the electromagnetic response of each material, we performed a comparative analysis between ERT and FDEM by analyzing the surveys carried out along some selected locations at the same moment and following the same survey path. This comparative analysis is crucial, given that the ERT technique has demonstrated its robustness in lithological and stratigraphical analysis, as well as in water content estimates (e.g. Dezert et al., 2019). However, as mentioned above, it is noteworthy that ERT surveys involve considerable cost and time, whereas FDEM surveys are faster and can collect larger datasets at the same time.

Fig. 3a illustrates a comparison between FDEM and ERT profiles. One can see that the overall resistivity trend is very similar and there are quite small local differences in the values, which are always slightly higher for the ERT data. The two datasets contain 300 and 1965 measurements for the ERT and FDEM surveys, respectively, and so a quantitative one-to-one comparison is problematic. However, given the electromagnetometer efficiency and cost-effectiveness in achieving results comparable to those obtained through ERT surveys (see also Araújo et al., 2023) the CMD-Explorer electromagnetometer by GF Instruments has then been used to survey 60 km of the Panaro River levees (Fig. 1, Fig. 2).

The subsequent phase involved correlating resistivity values with the lithologies, utilizing Cone Penetration Test and borehole core data collected along the Panaro River levee system. The integration of CPT data ensures a robust correlation between the electromagnetic measurements, soil properties and stratigraphy. Fig. 3-b and Fig. 3-c illustrate an example of correlation between FDEM data and direct measurements, namely CPT and borehole data. Besides establishing a direct link to specific properties or capturing changes of parameters like moisture and clay content, the calibration through geological and geotechnical data enhances the precision and reliability of the FDEM for a better understanding of soil properties.

From this correlation, we derived a relationship between resistivity

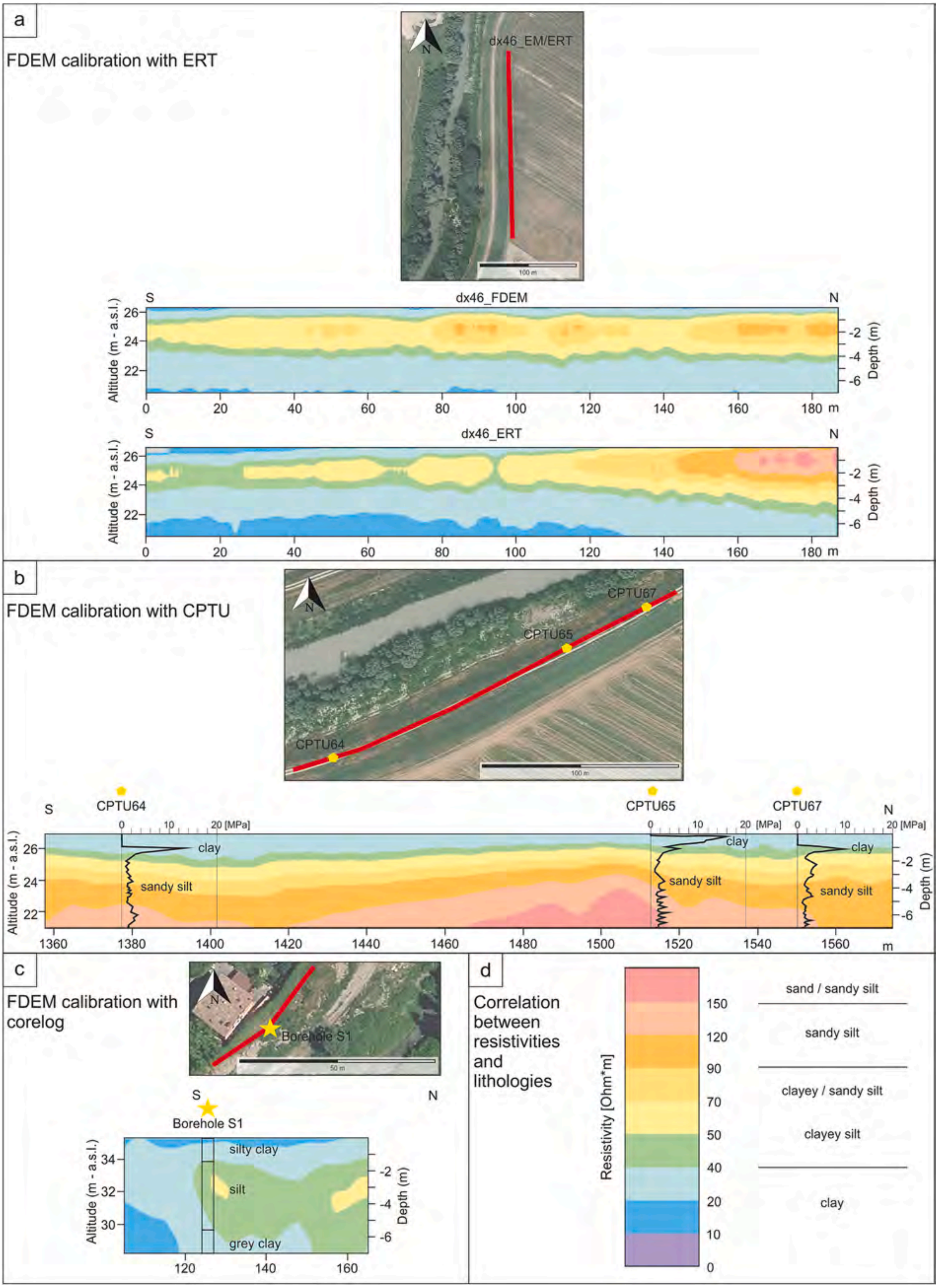

Fig. 3. a) FDEM data calibration by using ERT along a 188 m-long section surveyed with both methodologies. b) an example of FDEM data calibration by using CPTUs. c) an example of FDEM data calibration by using core-log data to correlate resistivity values (in dry conditions) and the corresponding lithology. d) Resistivity color scale along with the associated inferred lithology.

Fig. 4. Acquisition phase during the dry survey. The CMD-Explorer by GF Instruments has been mounted on a PVC and Teflon sledge and towed by a quad to cover 60 km of levees (performed two times, one for each coil's configuration – HIGH and LOW, for a total of 120 km).

values and lithology referred to the first survey, acquired during a long dry period in August 2021 (Fig. 3d) to facilitate the interpretation and characterization of the lithological and stratigraphical features of the levees.

4.2. First FDEM survey in dry conditions

In August 2021, a FDEM survey was carried out by utilizing the CMD-Explorer electromagnetometer. This instrument employs a single transmitting coil to generate a primary magnetic field, inducing a secondary current into the ground. Three receiver coils, positioned at fixed offsets from the transmitting coil, capture the induced signals. There are two coil configurations for acquiring resistivity data, namely: co-planar (HCP) and perpendicular (PRP). The HCP configuration is designed to detect variations in electrical conductivity closer to the surface (*LOW mode*), while the PRP configuration is optimized at detecting deeper structures (*HIGH mode*). The Depth of Investigation (DOI) is determined by coil offset and the distribution of soil electrical resistivity. In this study, the maximum depth achieved with an adequate signal-to-noise ratio is approximately 6 to 7 m below the surface, which may reduce in areas with highly conductive materials at or near the topographic surface. The instrument simultaneously records six resistivity values (two sets for each of the three available offsets), along with the in-phase and out-of-phase components. Specifically, in *LOW mode* the instrument collects data up to depths of about 1.1, 2.1, and 3.3 m below ground level, while in *HIGH mode*, it samples depths up to about 2.2, 4.2, and 6.7 m, for each of the three coils offsets.

The in-phase component represents the relative amount of the primary magnetic field (measured in parts per thousand, ppt) and is indicative of the magnetic susceptibility of the materials being measured. This parameter is particularly useful for identifying artificial metallic elements such as cables, reinforced concrete, pipes, and rebars. Consequently, the in-phase map aids in discriminating artificial structures from geological features observed in apparent resistivity maps.

The manufacturer specifies a measurement accuracy of ±4 % at 50 mS/m, with temperature stability exceeding 0.1 mS/m/°C for gradual temperature changes, as typically encountered during field operations.

The CMD-Explorer operates through electromagnetic induction, eliminating the necessity for ground contact. To efficiently cover 120 km (30 km along each levee in both *HIGH* and *LOW* modes), a quad vehicle was used to tow the instrument. The instrument was mounted on a cart made of PVC and Teflon to minimize possible interference with the electromagnetic field (Fig. 4). This setup ensured the instrument maintained at an almost constant elevation above the ground equal to 0.3 m. The entire 120 km FDEM survey (Fig. S1) was completed in four days with an acquisition speed between 10 to maximum 20 km/h.

Data acquisition, with a fixed time triggering interval of 0.5 s, was synchronized with a Differential Global Positioning System (DGPS) to ensure accurate spatial coordinates. A GPS RTK Stonex S990, accompanied by a tablet for remote tracking, facilitated the data collection process. Relevant topographic features, including power grids, were mapped along the survey routes to serve as ground control points.

Subsequently, the FDEM profiles were processed (Fig. 5) using EM4Soil software (EMTOMO Ltd) in the following sequence:

- ➢ GPS FDEM data link and geometry assessment;
- ➢ Data quality control, establishment of affordability thresholds, and filtering;
- ➢ Merging of HIGH and LOW mode measurements;
- ➢ Initial model setup and 2D data inversion;
- ➢ Creation of resistivity maps.

4.3. Second FDEM in wet conditions and seasonal comparison

In May 2023, immediately after a period of heavy rainfall and flooding that devastated large areas of the Emilia-Romagna Region (Regione Emilia-Romagna, 2023; Barnes et al., 2023), a second FDEM survey (Fig. S2) was carried out to evaluate resistivity variations under different environmental conditions. The aim was to measure resistivity in specific areas characterized by higher resistivity values, therefore correlated to coarse-grained lithologies, identified during the first investigation campaign.

While the "dry-conditions survey" encompassed a length of 60 km along the levees and employed the CMD-Explorer towed by a quad vehicle (August 2021 survey), the "wet-conditions survey" covered a shorter distance, equal to 14 km, achieved by carrying the instrument manually, on foot. This reduced distance was chosen based on the results of the "dry-conditions survey", which revealed higher resistivity values indicative of more permeable sandy material in selected sectors of the levee system.

The instrument's sampling rate was set at 0.5 s, as in the "dry-conditions survey". As a result, a higher spatial data density was achieved during the "wet-conditions survey" due to the slower acquisition velocity. This enhanced resolution allowed for a more detailed assessment of resistivity values, enabling a comprehensive analysis of possible groundwater flowpaths along and across the levee structure. In general, taking measurement every 0.5 s yields a relatively large dataset compared to the length of the structures. Assuming a quad vehicle traveling at 20 km/h, approximately one measurement every 2.7 m would be collected. Since one of the goals of this study is to compare the data between dry and wet conditions, it was essential to homogenize the datasets to enable a proper analysis of the differences between the two acquisitions.

Specific levee sections obtained during both dry and wet conditions

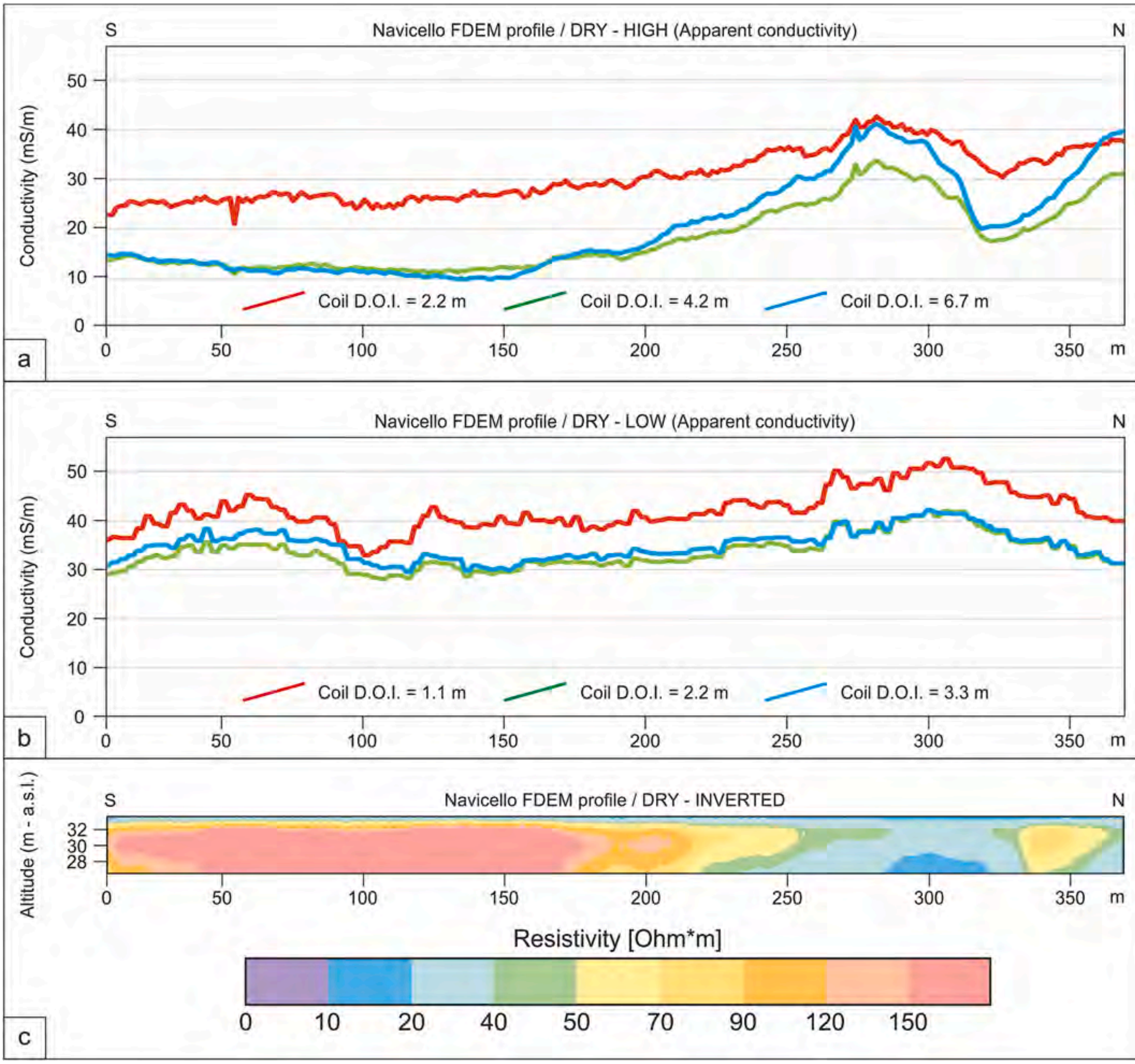

Fig. 5. Processing of FDEM data. a) HIGH coil's configuration apparent conductivity data (the reciprocal of apparent resistivity). b): LOW coil's configuration apparent conductivity data (the reciprocal of apparent resistivity). c) the resulting inverted resistivity section by combining HIGH and LOW data and its corresponding resistivity color scale.

were selected and clipped. During the common section clipping phase, sections with excessive noise, signal corruption and saturation from nearby power lines or large pipes were excluded to maintain data integrity. This process considered the behavior of the in-phase data, focusing on retaining only the lithologic and stratigraphic relevance of the dataset.

Elevation pairing was a crucial aspect of the processing, where average elevations along the investigated sections were utilized to ensure an accurate comparison between the two surveys (dry and wet, 2021 and 2023, respectively). Following elevation correction, a Full-Solution inversion was performed, starting from an average conductivity model of the surveyed soil portion. This inversion process played a pivotal role in deriving comprehensive insights into the subsurface characteristics. FDEM data inversion is essential for translating measured EM responses into subsurface resistivity information.

EM4Soil software employs a Full-Solution algorithm by directly solving Maxwell's equations, providing an accurate representation of subsurface resistivity. The process begins with an initial resistivity model of the subsurface. Using forward modeling, the algorithm predicts the FDEM responses that would be measured at the surface based on this model. The difference between these predicted responses and the actual measured data (misfit) is used to iteratively update the resistivity model. This iterative inversion process minimizes the misfit by adjusting the model parameters. The subsurface is discretized into cells, each with its resistivity value, which is updated during inversion. The Full-Solution algorithm integrates geological constraints and regularization techniques to ensure that the solution is geologically plausible and smooth, preventing overfitting. The iterative process continues until the misfit is minimized to an acceptable level.

Upon completion of inversion, the processed data were exported and

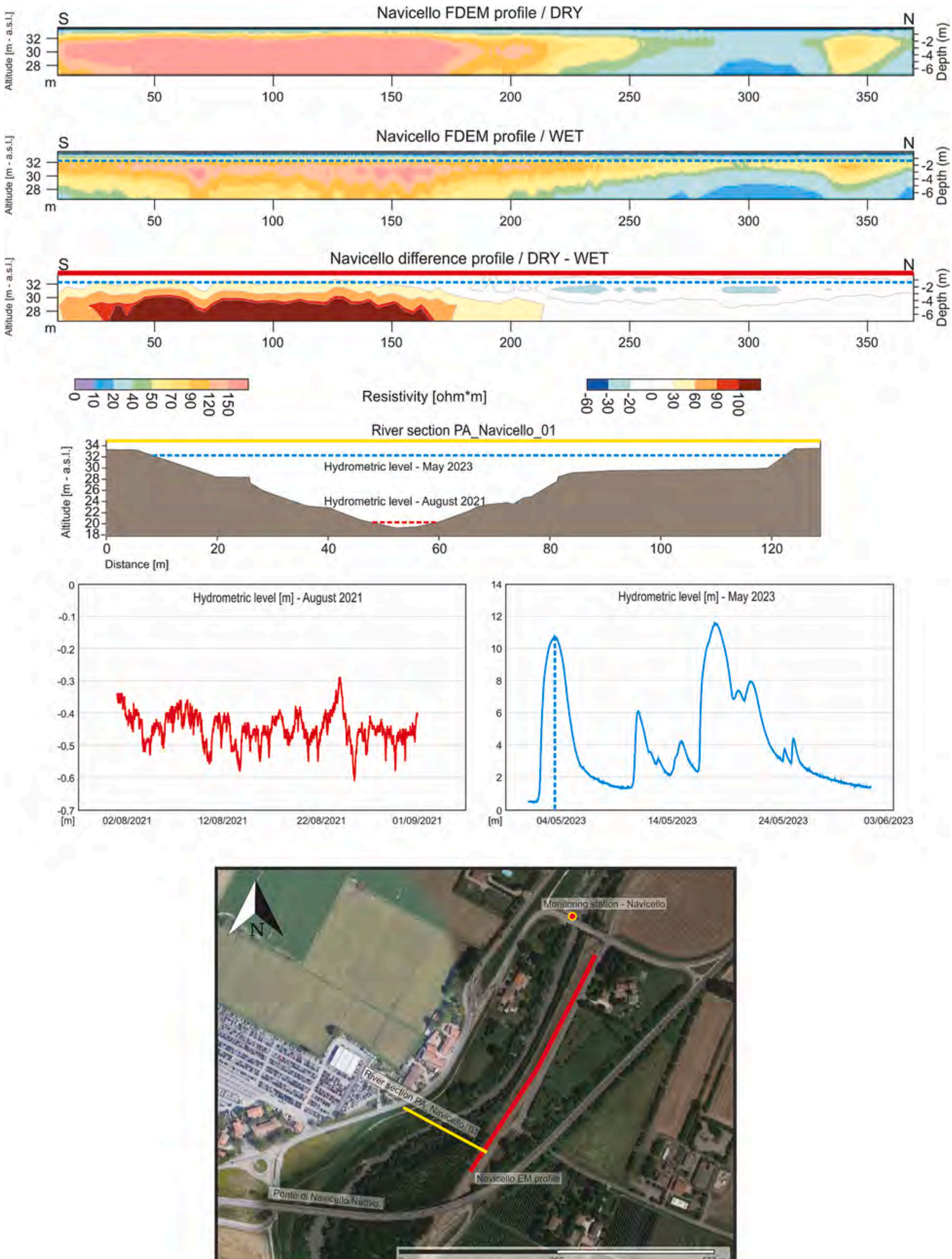

Fig. 6. Comparison between geophysical results and the flood monitoring data coming from the Navicello monitoring station. River section taken from the Geo-Portale AIPo website. Hydrometric level from the Dext3r ARPAE, Navicello gauge station.

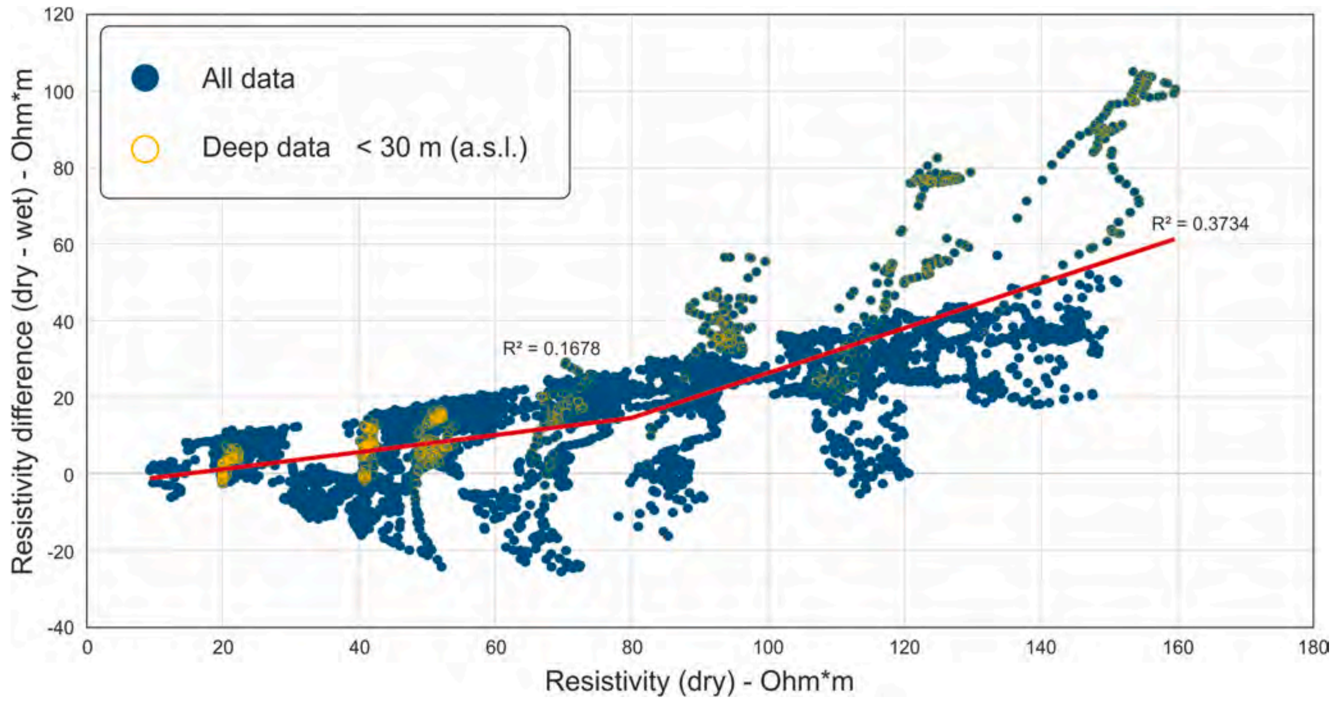

Fig. 7. Crossplot of resistivity values measured in dry conditions and the difference of resistivity between dry and wet conditions along the Navicello FDEM profile shown in Fig. 6.

visualized on resistivity graphs and maps. Subsequently, the selected sections underwent re-gridding and alignment to homogenize the number of cells across the grids, facilitating meaningful comparison and subtraction between the two datasets. The final step involved calculating their differences, providing insights into variations between the datasets under dry and wet conditions and allowing examination of changes in resistivity values along the levees.

In comparing the dry- and wet-condition datasets, the top interval of 2 m below the topographic surface have not been interpreted due to the influence of local variability in compaction and moisture fluctuations driven by rainfall and evapotranspiration processes.

5. Results and discussion

A comprehensive characterization of earthen structures, their foundation soils, and the geological and geomorphological context is crucial for preventing flood risk. To improve the initial assessment and characterization based on geological and geotechnical data, a large geophysical dataset has been collected under varying conditions, including factors such as season, climate, and different river stages and groundwater levels with the aim of conducting a seasonal comparison. In particular, geological data, geotechnical in situ tests, and ERT-calibrated FDEM surveys have been combined and cross-validated to develop a comprehensive 2D engineering geological model of the investigated levee system in the frame of flood risk mitigation actions.

The first FDEM survey, acquired in a dry period (August 2021) and conducted along 60 km of right and left levees allowed the methodology to be progressively refined and adapted to the aims of the study. Following a thorough analysis and considerations in alignment with the stakeholders, areas with prevalent sand and silt mixtures, characterized by higher permeability and erodibility, thus deemed critical in the context of internal erosion onset and levee stability, have been interpreted. Out of the "dry-conditions survey" engineering geological model, approximately 14 km have been selected for an additional survey, the "wet-conditions survey" for which a wet period with a prolonged high stage of the river have been waited for until May 2023.

Analyzing the profiles illustrating resistivity differences between dry and wet-conditions, a consistent correspondence between high river stages and identified resistivity variations has been found. Specifically, the largest resistivity change, from higher to lower resistive values, was observed at the base of some sections of the levees, aligning well with the river stage records during the May 2023 flood phase (Fig. 6). This suggests enhanced seepage processes occurring through the base of a total of about 4 km of levees sections, where predominantly sandy materials were already been identified during the dry-conditions survey.

This lateral and basal seepage aligns well with the hydrogeological principles outlined by Shanafield et al. (2020), reinforcing the reliability of the dataset acquired in both hydroclimatic phases and the calibration between measured resistivity values and lithologies. This approach therefore further demonstrates the value of combining seasonal geophysical surveys with geological data to pinpoint areas subjected to infiltration and seepage processes, supporting the findings of various previous studies (Araújo et al., 2023; Perri et al., 2014; Utili et al., 2015; Tresoldi et al., 2018 among others). Additionally, these findings could be integrated into studies aimed at the estimation of vulnerability indexes related to the probability of occurrence of internal erosion, for which field data are often limited (Camici et al., 2017; Michelazzo et al., 2018).

Some limitations of the FDEM dataset differences must also be acknowledged, particularly those concerning the aforementioned 2 m-thick layer lying below the ground surface, which exhibit high local variability that can hamper the interpretation of seasonal resistivity changes. Only through continuous monitoring is it possible to carefully interpret the surveys, even considering the obvious variations that could be related to environmental conditions such as temperature, air humidity and minor precipitation events.

However, while continuous monitoring is essential to assess soil moisture and resistivity variations with time (Calamita et al., 2015; Tresoldi et al., 2018), the assessment of levee vulnerability to internal erosion is more related to its lithology and stratigraphy. Therefore, the seasonal comparison allows the focus to be drawn on water content variation in the subsoil, assuming that 2 m below the ground surface, lithology, stratigraphy and compaction degree would remain unchanged between August 2021 and May 2023, thereby emphasizing the change in

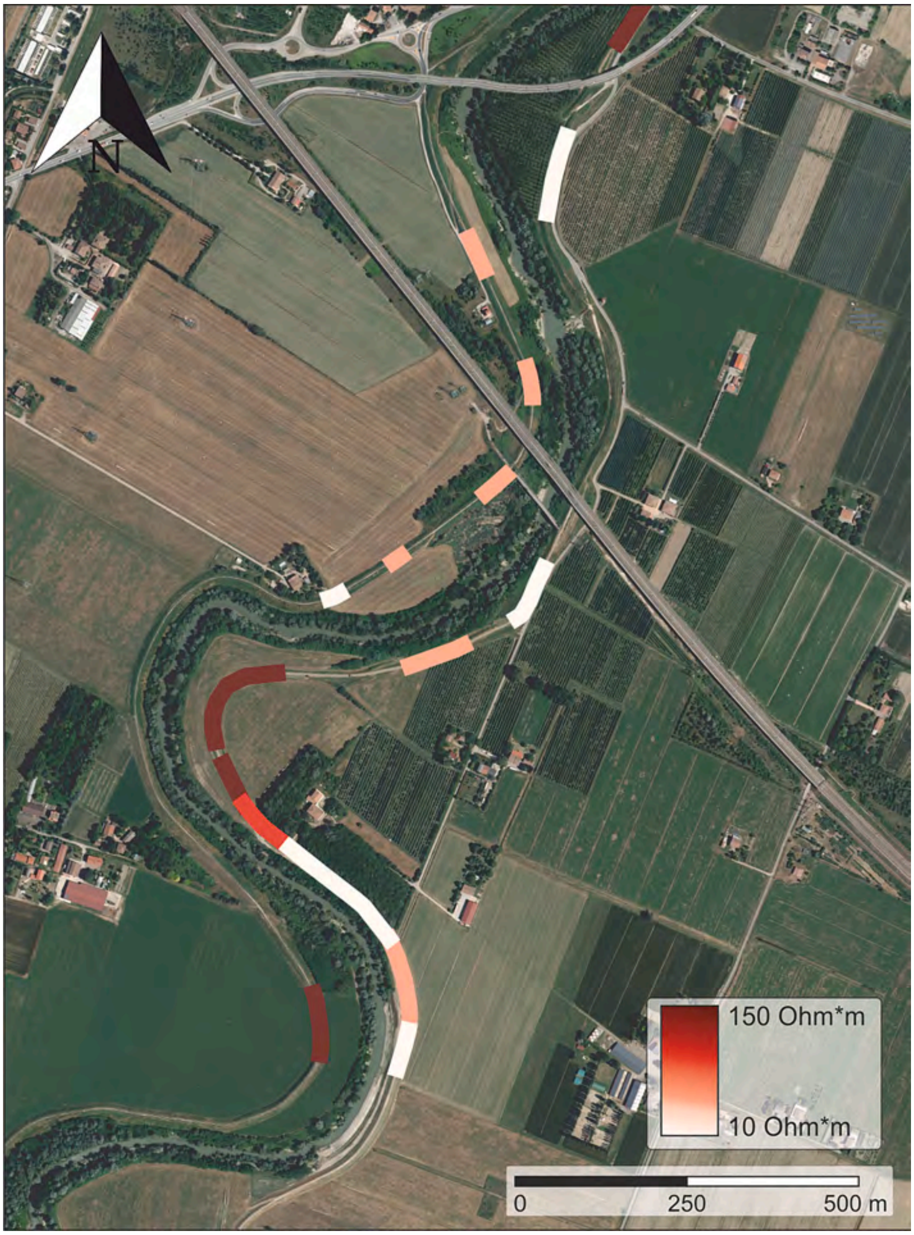

Fig. 8. An example of the results obtained from the difference between dry and wet FDEM surveys shows resistivity differences plotted along the levees, providing a zonation of areas prone to higher vulnerability.

fluid content between these two surveys.

Fig. 7 illustrates the relationship between the electrical resistivity measured in dry conditions and the resistivity difference between dry and wet conditions, highlighting the impact of water on the resistivity values. From the cross plot in Fig. 7, it can be observed that for resistivity values lower than 80 Ohm*m in dry conditions the difference between dry and wet resistivities is always less than 30 Ohm*m. However, for higher resistivity values, the difference increases, reaching up to nearly 100 Ohm*m. This confirms that the dry resistivity values are primarily related to the grain size of the embankment materials, with higher resistivities corresponding to coarser materials, mainly sandy sediments, and lower values associated with silty and clayey sediments. Additionally, high-resistivity values coupled with low resistivity differences correspond to the shallowest layers, which were largely unaffected by the rise in the Panaro River's water level during the flood stage. These layers experienced minimal water infiltration or groundwater flow, except for direct rainfall infiltration. As a result, their resistivity values show little variation between dry and wet conditions, reflecting the limited impact of floodwaters—apart from a few negative values visible in the Navicello difference profile (Fig. 6). The vertical alignment of outliers in the graph may result from the grid levels used in the analysis, potentially affecting the distribution of data points.

One of the key outcomes of this three-year study is the development of a map highlighting areas that require further investigation, close monitoring, or structural interventions. Beginning with a broad coverage of 60 km, the mapping process has progressively refined its focus to 4 km, prioritizing areas based on their vulnerability to seepage and internal erosion. An example is shown in Fig. 8, where the difference between dry and wet resistivity is plotted. Zones with higher resistivity differences are more prone to seepage and internal erosion following the rise in river water levels, as previously described. This approach serves as a robust tool for decision-makers and authorities involved in infrastructure management, enabling targeted interventions.

The assessment of seepage processes through a comparison between dry and wet-conditions FDEM surveys is grounded, as previously mentioned, on evaluating the decrease in resistivity following the

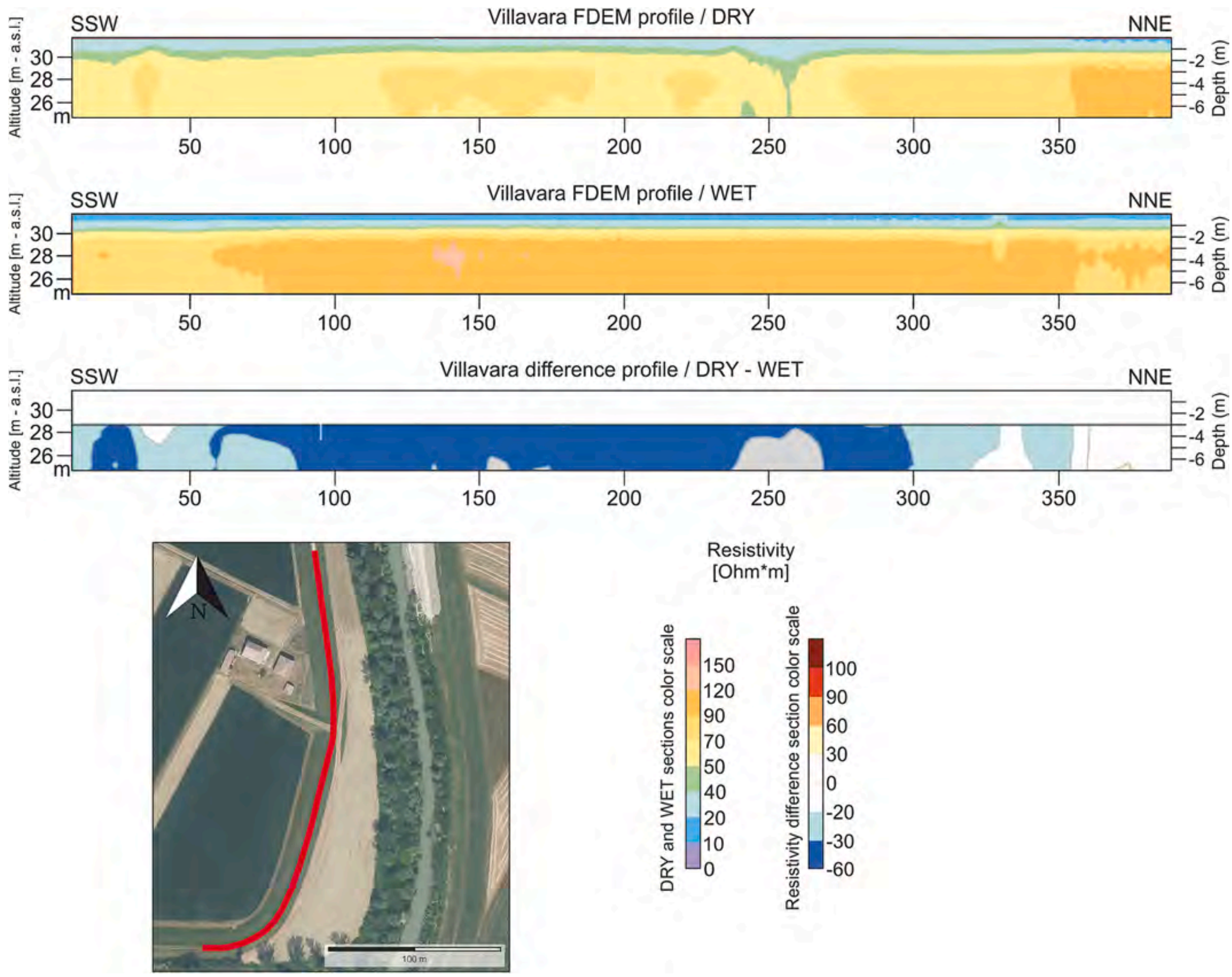

Fig. 9. Example of negative difference in resistivity, meaning that the resistivity has increased after the heavy rainfall and flood of May 2023.

relatively more rapid infiltration and groundwater flow through coarse-grained, more permeable materials during prolonged high river stages. Although the comparison highlighted localized differences due to preferential groundwater flow in sand-rich sections, an exception of approximately 1 km out of the 14 km surveyed was found. In Fig. 9, this unexpected outcome is depicted, where resistivity increased after heavy rainfalls and seepages, thus resulting in a negative difference between dry and wet-conditions measurements.

A possible interpretation could be the dilution of the Panaro River water by meteoric, more resistive water permeating the soil during the flood event. Alternatively, it could be ascribed to wrong/poor instrumental calibration, although this latter hypothesis does not seem realistic, as the electromagnetometer performs an automatic calibration before each measurement. The self-calibration has been performed far away from metal or any man-made object, and all the calibrations done with the ERT preliminary surveys were in quite good agreement, as already discussed beforehand. In any case, this issue is going to be analyzed in further surveys on selected areas.

The repeated seasonal FDEM surveys have also proven effective in mapping and characterizing renovation/reconstruction works carried out on the Panaro river levee system. In particular, the sectors that have undergone rehabilitation, clearly emerge in the 2D engineering geological model of the investigated levee system. For instance, the 2020 levee breach section received meticulous attention, leading to the acquisition of a 3D FDEM dataset to better understand the spatial variability of resistivity and, hence, the associated materials. In Fig. 10 the portion of levee that has undergone reconstruction is evident, as it is characterized by lower total resistivity compared to the neighboring stretches, due to the materials used in the recent rehabilitation work, described as follows. The preliminary operations for the closure of the breach entailed several phases. Firstly, the laying of boulders up to approximately 1.5 m in height from the ground level was conducted to stabilize the area. Subsequently, the restoration of the original levee both in terms of elevation and shape was achieved using soil sourced from a quarry. To reinforce the levee and mitigate infiltration and seepage phenomena, piles of up to 8 m in length were driven along the waterside slope. To ensure the impermeability of the levee slope, a bentonite mix was laid from the top of the reconstructed levee, anchored to the protected lowland. This material was then covered with a geosynthetic material preventing intrusion by burrowing animals and slope instability. The river-facing portion of the levee was then coated with approximately 50 cm of soil, followed by the application of a biostraw to facilitate grass growth and prevent surface erosion. Along the landside slope, a double-twist metal mesh was installed for the same purpose of deterring burrowing animals. To complete the process, the entire levee surface was treated with hydroseed, followed by the restoration of the service track along the levee crest.

The integration of ERT and FDEM methods with geotechnical data

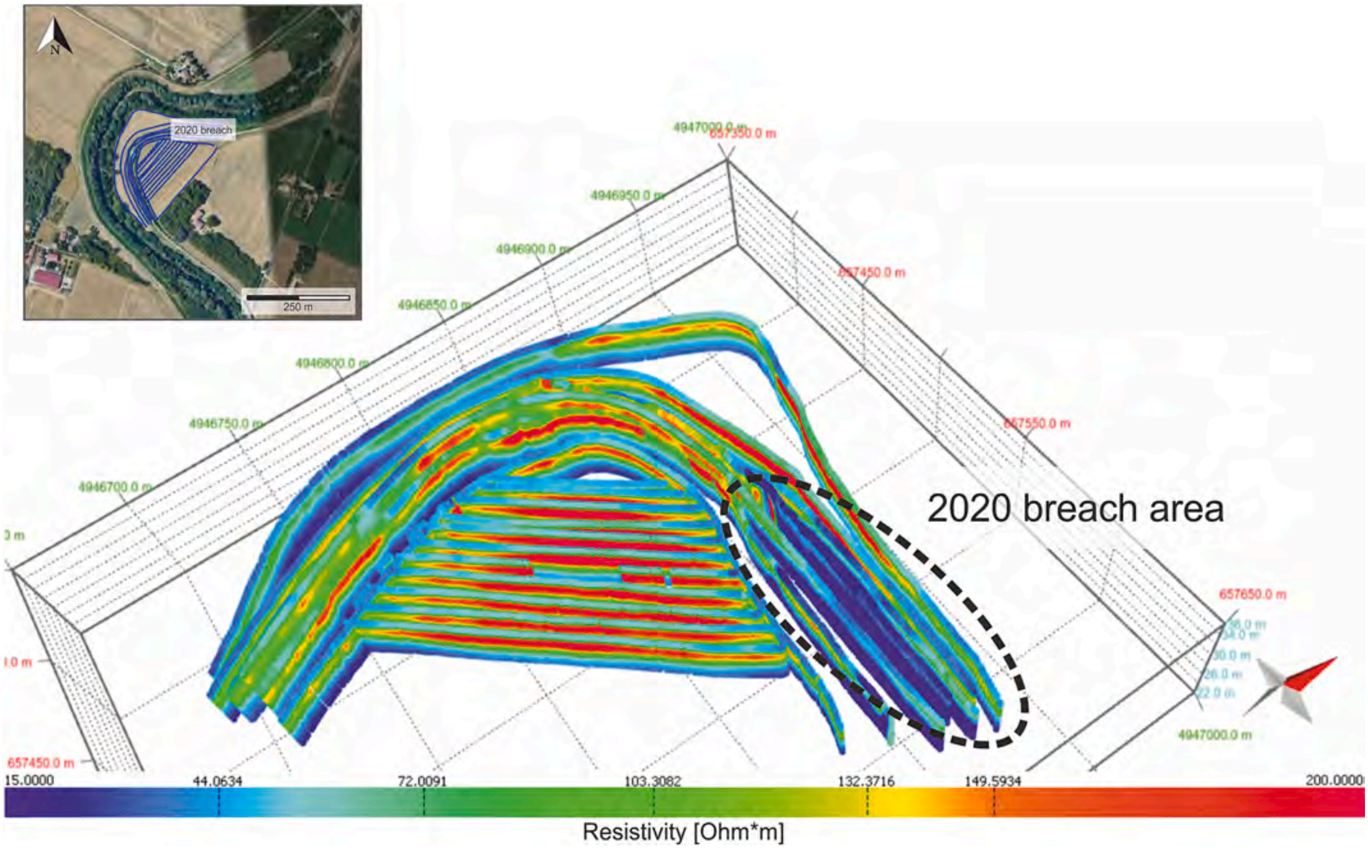

Fig. 10. 3D view of the 2020 breach area. The low resistivity sector in correspondence with the 2020 breach area is due to the interventions carried out to rehabilitate the levee. In this figure the dataset is shown as a set of FDEM section for a clearer display, but a 3D volume has been created too.

has proven effective in developing a spatially continuous 2D engineering geological model and identifying vulnerable and restored portions of the levee system. However, the study highlights several critical aspects that warrant further discussion.

Firstly, the reliability of resistivity measurements is influenced by environmental conditions, emphasizing the need for continuous monitoring to accurately capture temporal variations. This aligns with findings by Zhu et al. (2013) and Arosio et al. (2017), who noted the importance of considering environmental variables in geophysical surveys.

Secondly, the classification of resistivity differences into internal erosion vulnerability classes provides a valuable framework for infrastructure management. However, the local unexpected resistivity increase following rainy periods suggests that soil moisture dynamics are more complex than initially anticipated, requiring further research to refine the interpretation models, which are strictly site-dependent.

Finally, the study underscores the potential of combining geophysical methods with direct geotechnical data for a comprehensive assessment of the levee system integrity. The use of spatially dense geophysical data enables the correlation of precise yet localized direct investigations, providing near-continuous spatial information and characterization. This is crucial for identifying the most vulnerable zones and facilitating effective planning and management of remediation or restoration activities. Although continuous monitoring techniques (e.g., Zhu et al., 2013; Arosio et al., 2017) can provide valuable insights, they are typically limited to relatively small sections of the levee system due to logistical constraints. In contrast, the proposed integrated approach allows for the mapping of extensive stretches of the levee system, covering several kilometers in a relatively short period, to identify areas where internal erosion may initiate.

6. Conclusions

Floods are recognized as one of the most widespread and dangerous natural disasters globally. The gradual deterioration, impairment, and failure of river levees can occur in both natural landscapes and anthropogenic environments, resulting from a variety of scenarios or sequences of events. These may encompass hydraulic failure due to insufficient height and structural failure resulting from inadequate strength. In particular, internal erosion mechanisms have been recognized as the cause of almost half of all historical levee dam failures. Ageing earthen structures may be affected by concealed and undetectable local variabilities or defects that may act as flaws for the initiation, continuation, and progression of internal erosion.

To assess the integrity of the Panaro River levee system after the 2020 breach and to identify potentially vulnerable sections, geological and geophysical data have been integrated on a 30 km stretch of both the right and left levees North of Modena, totaling 60 km. The initial step involved conducting a FDEM survey on the levee crest in dry environmental conditions (August 2021). The results have been calibrated with ERT and lithological and stratigraphical evidence from in situ cores and geotechnical tests and a first engineering geological model of the levees has been put forward. Based on the results, the second step involved conducting a second FDEM survey, carried out in wet environmental conditions (May 2023) on a 14-km-long subset of the levees. This subset was selected based on geological features, previous levees failures, and the presence of exposed elements such as urban and industrial areas.

The first 2D engineering geological model of the entire investigated area is available for further applications. The second, more detailed 2D model is available for a 14-km subset, where the difference between FDEM datasets (dry-wet) has been calculated. Out of the 60 km, about 4 km are currently considered potentially prone to internal erosion. In particular, the surveys on saturated levees under wet and/or flood conditions allowed to identify areas where seepage is occurring during high stages of the river, as a consequence of the presence of silt and sand mixtures in the body of the levee and in the foundation soils. In these areas, under critical hydraulic conditions and if other internal flaws, such as cracks, burrows or artificial elements would also be present, internal erosion processes might initiate, continue, progress, and lead to breaching.

Given the challenges associated with visually inspecting factors affecting levee integrity, the substantial length of the study area, and the potential heterogeneity of levee systems, a comprehensive characterization relies on efficient and economically viable noninvasive, extensive methods. These surveys significantly contribute to advancing our understanding of the integrity of the levee system, enabling the identification of sections potentially vulnerable to internal erosion and the assessment of restoration works. In this context, the engineering geological model proves beneficial for end-users and decision-makers. It provides a ranking of the critical sections of the levee system, serving as a crucial preliminary step in any risk management procedure aimed at evaluating the best operational strategies.

CRediT authorship contribution statement

N. Bertone: Writing – review & editing, Writing – original draft, Investigation, Data curation. **E. Forte:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **G. Titti:** Writing – review & editing, Writing – original draft, Data curation, Conceptualization. **R. Zambrini:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization. **P. Macini:** Writing – review & editing. **A. Mocnik**: Investigation, Data curation. **S. Parodi:** Writing – review & editing. **F. Pellegrini:** Writing – review & editing. **M. Possamai:** Writing – review & editing, Investigation. **C. Staboli:** Writing – review & editing, Investigation. **M. Valente:** Writing – review & editing. **L. Borgatti:** Writing – review & editing, Writing – original draft, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Lisa Borgatti reports financial support was provided by Italian Ministry of University and Research. Lisa Borgatti reports financial support was provided by Agenzia Interregionale per il fiume Po. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enggeo.2024.107749.

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