# Fast geophysical imaging of earthen levees to prevent failure

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ABSTRACT

Recent floods in Northern and Central Italy resulted in severe damages bringing public attention to river embankments stability.

Most of the embankments are very old and have been repeatedly repaired with heterogeneous materials and few data are available about their internal properties.

In addition, the recent changes in the precipitation regime with short and often repeated rainfalls increase the hydraulic stress on the levees, especially on the top portion that is weaker and that was rarely stressed in the past.

Fast mapping of the critical segments was achieved using a dual imaging system based on multichannel radar (GPR) and multi-spacing frequency-domain electromagnetic induction (FDEM).

This high-resolution geophysical imaging procedure, has been developed, tested and validated in various sites in North-eastern Italy.

The fast imaging approach was designed to be practical and cost-effective allowing for a daily investigation of 10-15 km of embankment.

KEY WORDS: Levees, fast imaging, FDEM, GPR

## INTRODUCTION

The dramatic floods that occurred in Northern Italy, in particular in the Veneto Region and in the Emilia Romagna Region in the years 2010 and 2013, highlighted the extreme vulnerability of several river embankments, which represent the sole defense from floods.

Failures are in large part caused by the textural properties of the levees and of the underlying deposits that control the seepage throughout or under the embankment.

Water filtration often causes piping and progressive erosion of the fine fraction resulting in subsequent collapse.

Internal erosion occurs when water flows through pervious sand bodies, cavities and cracks.

These openings may be the result of inadequate compaction during construction, differential settlement, desiccation, earthquake shaking and animal burrows. Internal erosion affects stability and durability of the structures.

Embankment monitoring is currently based, on visual inspection and localized geotechnical tests. However, this approach is generally inadequate to ensure safety and prevent collapses during floods.

Geophysics, among the various monitoring methods, could provide a continuous image of the levee interior.

In the literature are reported several studies focusing on a strict comparison between the various geophysical techniques (Fauchad and Meriaux, 2007 Asch et al., 2008; Niederleithinger et al., 2012) while other authors considered also the integration between methods (Chen et al., 2006; Mydlikowski et al., 2007; Inazaki, 2011).

Fast scanning was attempted using electromagnetic induction (EMI) sensors (Dunbar et al., 2007; Doll et al, 2014), while GPR (Xu et al. 2010; Di Prinzio et al., 2010) was the selected method to high resolution local imaging and discover voids and animal burrows. Resistivity profiling (ERT) is probably the most effective but it is slow and too expensive to become a practical tool for extensive monitoring of thousands of kilometres of levees.

Tech-Levee-Watch project, funded by Fondazione Cariplo (grant N. 2016-0785), focuses on the development of a cost-effective method to prevent levee failure.

Fast and cost-effective scanning using a dual imaging system comprised of multichannel GPR and multi-array FDEM is also within the objectives of the project (Francese and Monteiro-Santos, 2014). The anomalies mapped by dynamic scanning could be further analyzed by aid of 2D or 3D standard resistivity profiling.

In the failure-prone segments or in the segments that are already critical is planned the installation of long-term monitoring system based on ERT, to provide daily updates of the subsurface 2D tomography images of the embankments.

## THEORY AND METHODS

Experimental data were acquired using multi-array FDEM associated with a multi-channel GPR (Francese and Monteiro-Santos, 2014; Morelli et al., 2015).

GPR measurements mostly targeted the top portion of the levee (to detect burrows) while the body and the base of the levee is imaged with a medium degree of resolution using the FDEM data.

Multi-array FDEM data could be also inverted using a quasi-2D algorithm. Results from quasi-2D inversion are fully-comparable with standard resistivity profiling (Francese and Monteiro-Santos, 2014).

The devised approach has still some drawbacks (for example the real geometry of the anomaly is not resolved, the GPR penetration is low, the varying water content should be properly taken into account, etc) but experimenting different arrays and splitting data acquisition in different seasons will lead to the development of a fully-functional and reliable system.

### FDEM (Dualem 642S)

The FDEM cart (Dualem 642S) is equipped with an electro-magnetic transmitter, operating at 9 KHz, and 3 couples of electromagnetic receivers (horizontal co-planar and perpendicular) spaced of 2 m, 4 m and 6 m respectively.

The transmitter coil energized with an alternating current at an audio frequency, generates a time-varying magnetic field called primary field. This magnetic field induces very small currents in the earth that generate a secondary field which is sensed, together with the primary field, by the receiver coils. The ratio of secondary to the primary magnetic field is linearly proportional to the terrain conductivity (McNeill, 1980).

Using this configuration the FDEM instrument takes six simultaneous readings every second.

The distance between the head of instrument and the back of the towing vehicle was large enough to be negligible in the response of the 6 m-spaced sensors.

### GPR (IDS streamX)

The GPR system is based on the propagation of electromagnetic waves in the subsoil (Davis e Annan, 1989; Annan e Cosway, 1992). Part of the signals emitted will be reflected at the interface between two materials with different electric properties.

The GPR cart (IDS streamX) is an array of 16 transmitting-receiving dipoles, 0.1 m spaced and oriented parallel to the towing direction, arranged in 15 bistatic channels. The frequency of the antennas is fixed and it is 200 MHz.

Using this configuration the sampling grid of the radar swath resulted very dense with an in-line trace spacing of 0.05m and a cross-line trace spacing of 0.10m.

## DATA ACQUISITION

Radar has a limited signal penetration in a conductive environment and the changes in the varying water content of the levee itself could affect the response of the electro-magnetic sensors.

For these reasons the GPR should be collected in mid-summer after a very dry period while the FDEM are to be collected during the winter, immediately after the rain season.

In these conditions it could be assumed that the levee body is an homogeneous medium (dry or water saturated) and the changes in the geophysical response are only related to its internal structure.

The sytem was tested at various surveys in different levee conditions. Dual data were collected along the Secchia River in Ponte Alto (Modena), along the Po River in Mazzorno Sinistro (Rovigo), along the Piave River near Ponte di Piave (Treviso) and along the Bacchiglione River in Vo di Mulini (Vicenza).

## RESULTS

### Bacchiglione River

Multi-array FDEM data collected in dynamic mode proved to be reliable to generate resistivity profiles along the levee crown line.

The initial analysis of the multi-spacing FDEM data led to an almost instantaneous mapping of the sand layers in the body of the levee. Four low-conductivity segments were detected (Figure 1) just plotting the horizontal co-planar response of the 2m-spacing sensor (HCP2). These anomalies are probably located within the levee body.


Figure 1: FDEM data showed four clear anomalies along Bacchiglione embankments (Francese and Monteiro Santos, 2014).

ERT profile, using a 48-electrode system, was collected at each of the four sites to validate the FDEM response.

The resistivity inversion confirm the presence of anomalous body range from 150 ohm*m to 200 ohm*m.

These resistivity values are typical for sands and confirmed the presence of a resistive/sandy layer in the levee body.

The FDEM data were then inverted with a smooth algorithm using an homogeneous initial model of 30 mS/m and allowing for a maximum of 10 iterations.

Comparison of the FDEM and of resistivity inversions exhibit a good similarity although the values in the FDEM inversion are slightly larger (Figure 2).

At site w, in a fairly conductive environment, the FDEM and the resistivity inversions are almost identical.

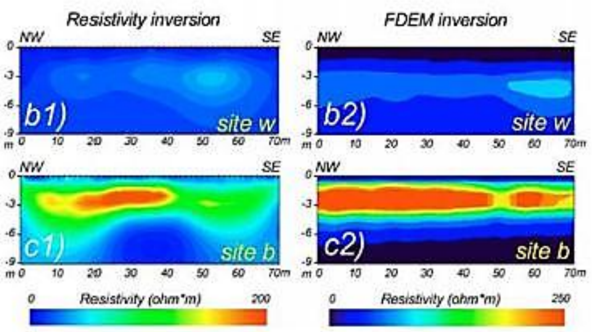


Figure 2: Comparison between standard 2D resistivity profiling inversion and dynamic FDEM profiling inversion at site w and b of Figure 1 (Francese and Monteiro Santos, 2014).

## Po River

Multi-array FDEM data have been collected in dynamic mode along Po embankment segment in Mazzorno Sinistro, in particular along the levee crown line and on the top of the lower berm (Figure 3).

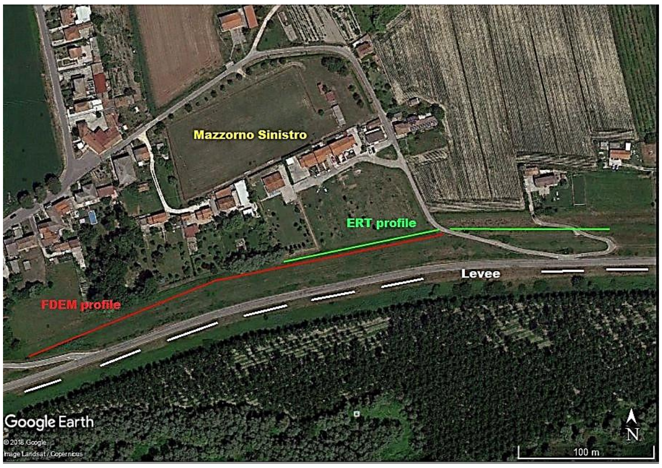


Figure 3: FDEM and ERT profiles along the Po River in Mazzorno Sinistro (Rovigo).

In this area water filtration and piping often cause progressive erosion and sands mounds.

The FDEM data were inverted with a smooth algorithm using an homogeneous initial model of 30 mS/m to obtain resistivity profiles.

The FDEM profile shows high resistivity values below the levee basement.

To validate the FDEM response an ERT profile, using a 48-electrode system, was collected at this site.

The resistivity inversion confirm the presence of anomalous body with resistivity values about 150 ohm*m (Figure 4).

This anomaly is probably due to the presence of a sandy layer underneath the levee body.

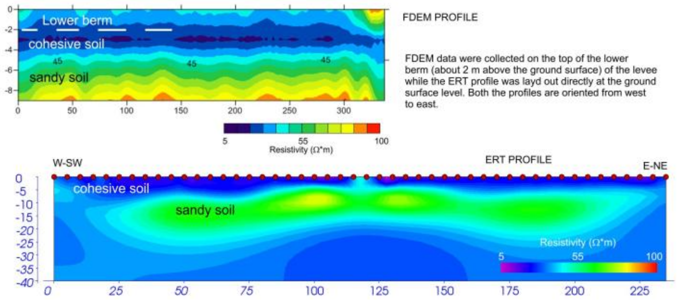


Figure 4: FDEM and ERT 2D resistivity profiling inversion. FDEM data was collected on the top of the lower berm of Po River levee, while ERT profile was layd out at the ground surface level.

## Piave River

Ground penetrating radar (GPR) surveys were conducted at two sites in which there is a good knowledge about levee stratigraphy and the soil under the embankment foundation.

In the first site animal burrows are visible on the side of the embankment.

The reflectivity map calculated at an approximate depth of 1m below the levee crest shows a series on linear reflectors caused by cavities.

FDEM data, in particular the sensor with the most superficial response (HCP2) shows the same results as negative anomalies of conductivity (Figure 5).

The electrical tomography on the side of the embankment validates the results of the investigations clearly highlighting the presence of a series of high resistivity cores that correspond to the cavities inside the body of the embankment.

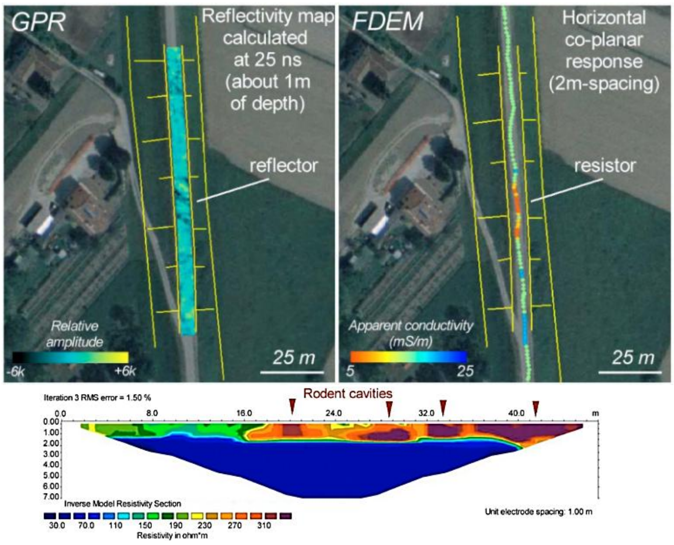


Figure 5: Burrows showed a signature both in the GPR (left) and in the FDEM datasets (right) along the Piave River. ERT data collected on the side of the embankment validates the results (bottom).

In the second site, a series of sand mounds were located at the foot of an earthen levee.

Reflectivity maps showed some clear anomalies caused by the sand “pipes” developed underneath the levee at at a depth of about 1.5 m (Figure 6).

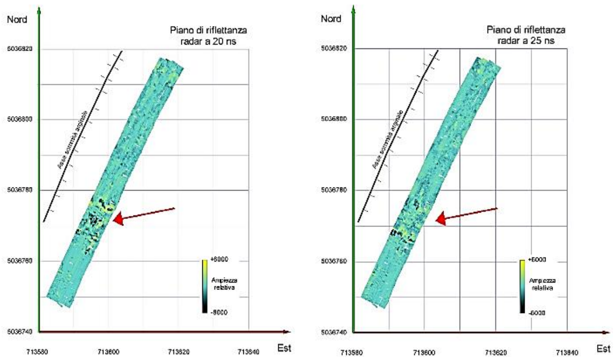


Figure 6: Reflectivity maps calculated at 20 ns (about 1.0 m of depth) and 25 ns (about 1.2 m of depth) at the bottom of the levees of the Piave River.

## CONCLUSIONS

A fast and efficient method to scan the earthen levees has been experimented and tested along several rivers in Northern Italy.

The method is based on a dual survey: multi-channel radar GPR and multi-spacing fixed frequency FDEM, combining high resolution and rapid coverage.

The system delivers extreme resolution in the top and thinner portion of the levee (GPR data), while the body and the base of the levee (FDEM data) is imaged with a medium degree of resolution.

Some theoretical limitations related to the reduced penetration of the radar signal and to the varying water content in the levee have been overcome carrying out the survey in specific climatic conditions.

The major conductivity anomalies identified by fast scanning method were validated collecting resistivity profiles at specific locations.

The inversion of the FDEM data led to resistivity images fully comparable to the ERT data. This procedure still requires some tuning of the processing parameters but it is already in the range of the achievements and in the near future there will probably be no need of validating the FDEM results with static measurements.

The dual geophysical imaging system is cost-effective, the scanning is dynamic and can detect conductivity anomalies (resistive layers) in the levee body and in the underlying sediments. The dual geophysical imaging system is capable of daily production larger of more than one order of magnitude as compared to DC resistivity profiling.

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