Environmental and Engineering Geophysical Society
Symposium on the Application of Geophysics to Engineering & Environmental Problems
22-26 March 2015 - Austin, TX, USA

Levee imaging using multi-array electromagnetic (EM) induction and multi-channel radar (GPR)

G. Morelli[1], R.G. Francese[2,3], F.A. Monteiro Santos[4] and R. Taylor[5]

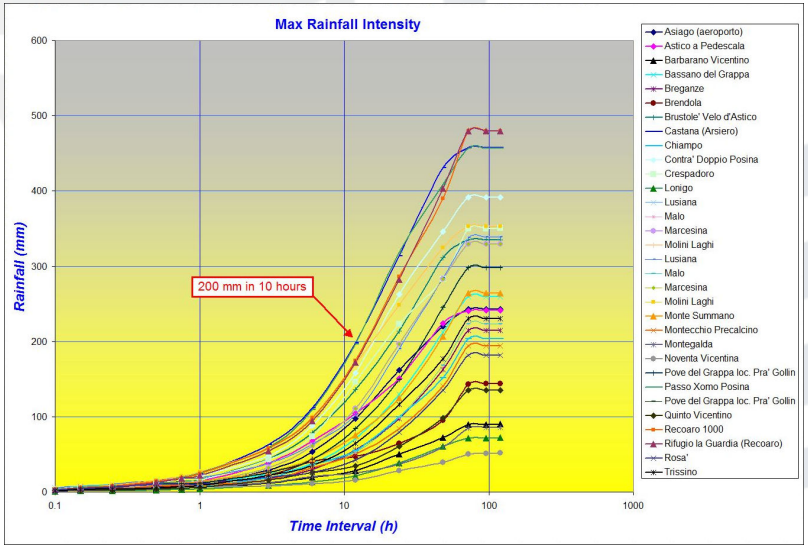
1. Geostudi Astier S.r.l., Italy
2. OGS - National Institute of Oceanography and of Experimental Geophysics, Italy
3. University of Parma, Department of Physics and Earth Sciences, Italy
4. Universidade de Lisboa, Instituto Don Luís-Laboratório Associado, Portugal
5. Dualem Inc., Canada

Introduction and motivations

OGS

Recent events of heavy rainfall in Europe and elsewhere seem to be generating run-off with more momentum, causing greater stress on levees and more frequent failures.

At the same time, catastrophic losses from levee failure to agriculture, infrastructure and the general economy are all too familiar.



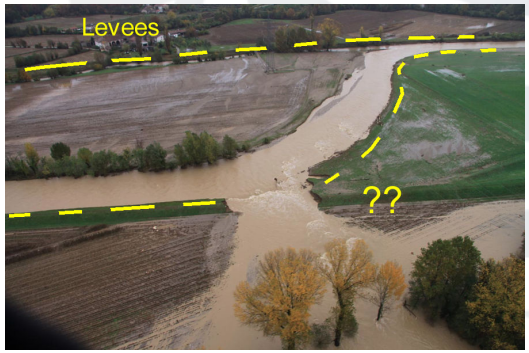
Introduction and motivations

OGS

A period of heavy rainfall in northern Italy in the autumn of 2010 provides an example. Here are some consequences by early November of that year:

-Levee collapses : 15

- Involved Area: 14,000 square km;
- Involved Municipalities: 131;
- Involved Population : 500,000;
- Human Deaths: 2;
- Farm animal losses: 230,000;
- Landslides : 51
- Closures of major roads: 55;
- Flooded locations: 29
- Flooded area: 140 square km;



Usually no evident reason for levee collapse

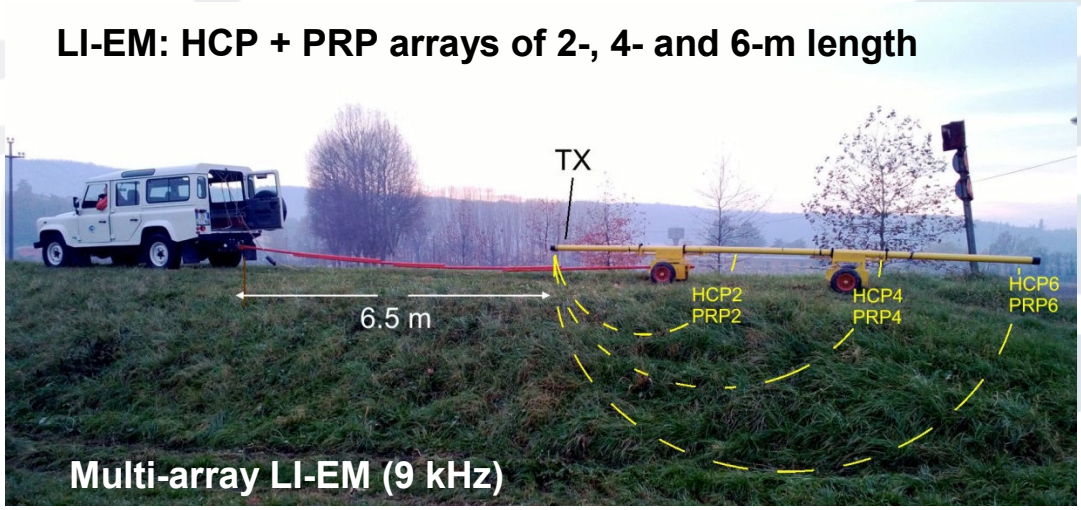
Damages (rough estimate):
450 Million Euro
mostly due to levee failures

As a result of severe losses, several pilot projects in different countries were undertaken to image the internal composition of levees to predict the potential for collapse.

The geophysical imaging system

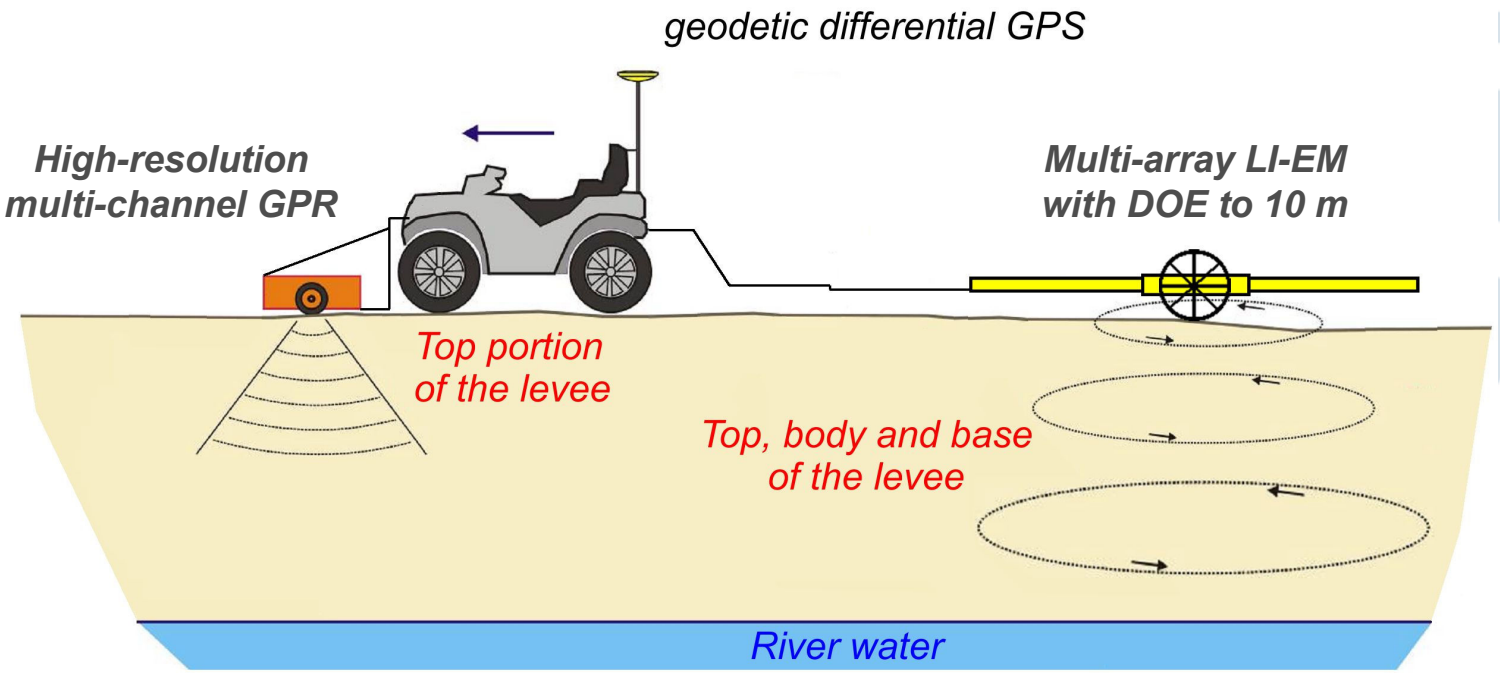
OGS

Several methods and geophysical techniques were tested and a dual imaging system, based on multi-channel GPR and multi-array low induction (LI) EM, proved to be the most flexible and efficient approach.

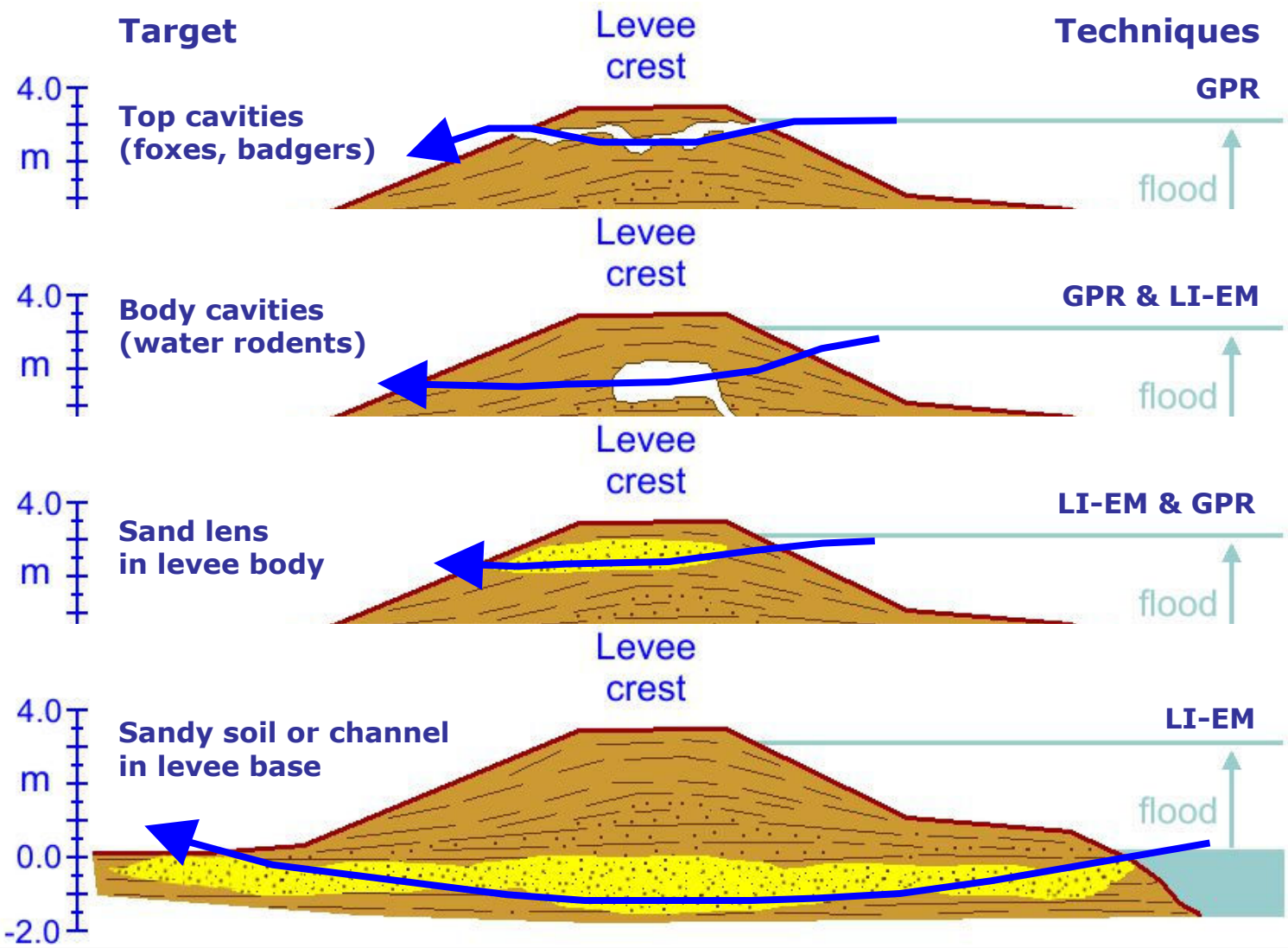


The geophysical imaging system

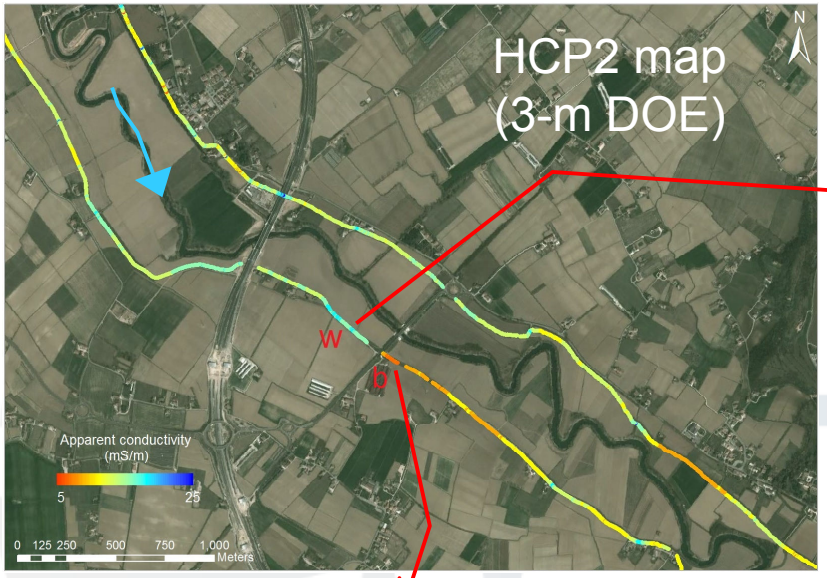
The dual techniques of the system have complementary combinations of resolution and depth of exploration (DOE) to the base of the levee. The techniques can provide detailed data while in motion so the system can image several km per day of levee, perhaps in a single pass.



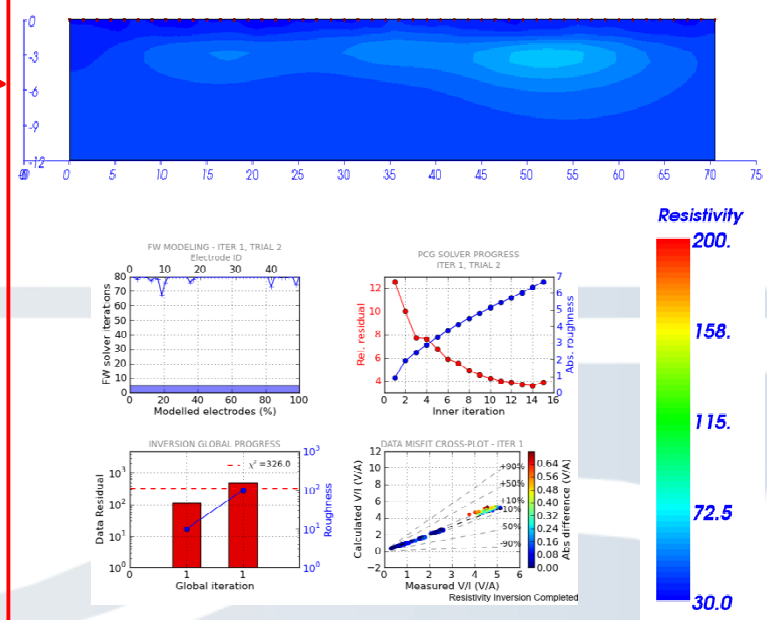
The geophysical imaging system: target features of levee failure

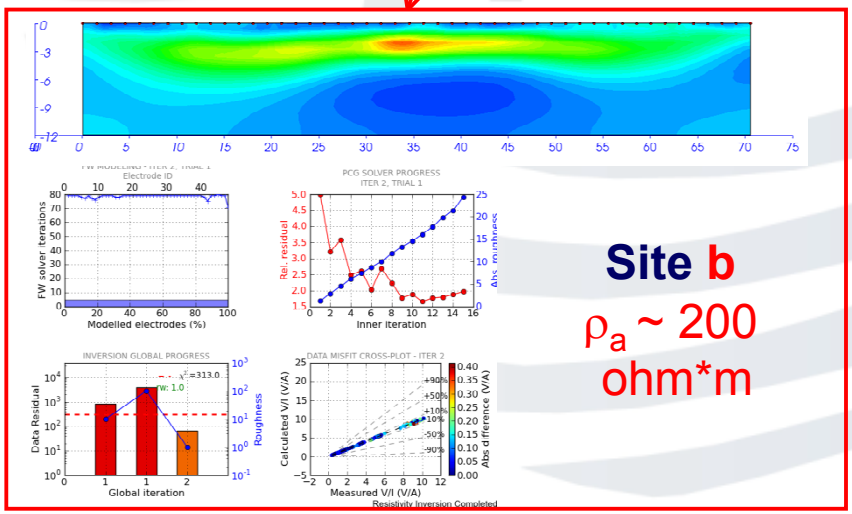


Data analysis and validation - multi-array LI-EM



Site w (reference)





Site b

ρ_a ~ 200 ohm*m

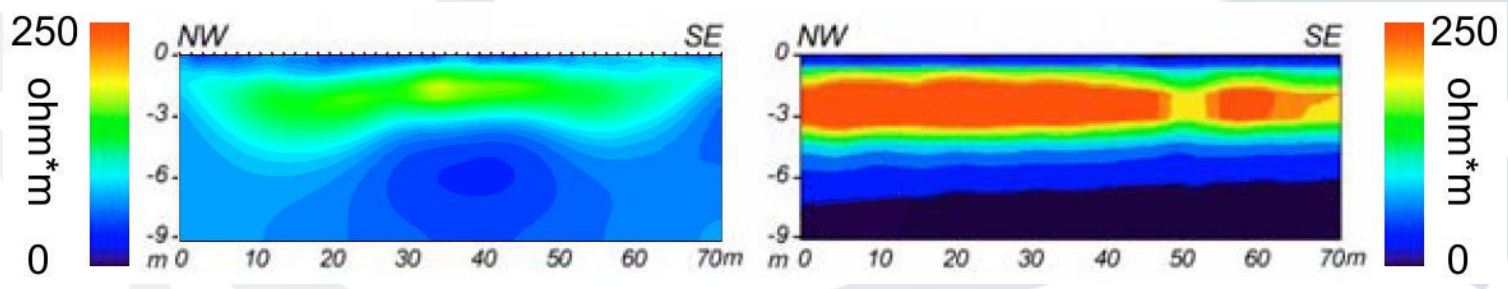
In a test survey, LI-EM identified moderate resistivity at **site w** and high resistivity at **site b**. Resistivities were confirmed by electrical resistivity tomography (ERT).

Data analysis and validation - multi-array LI-EM

OGS

The LI-EM data were also inverted and compared to the ERT profiles.

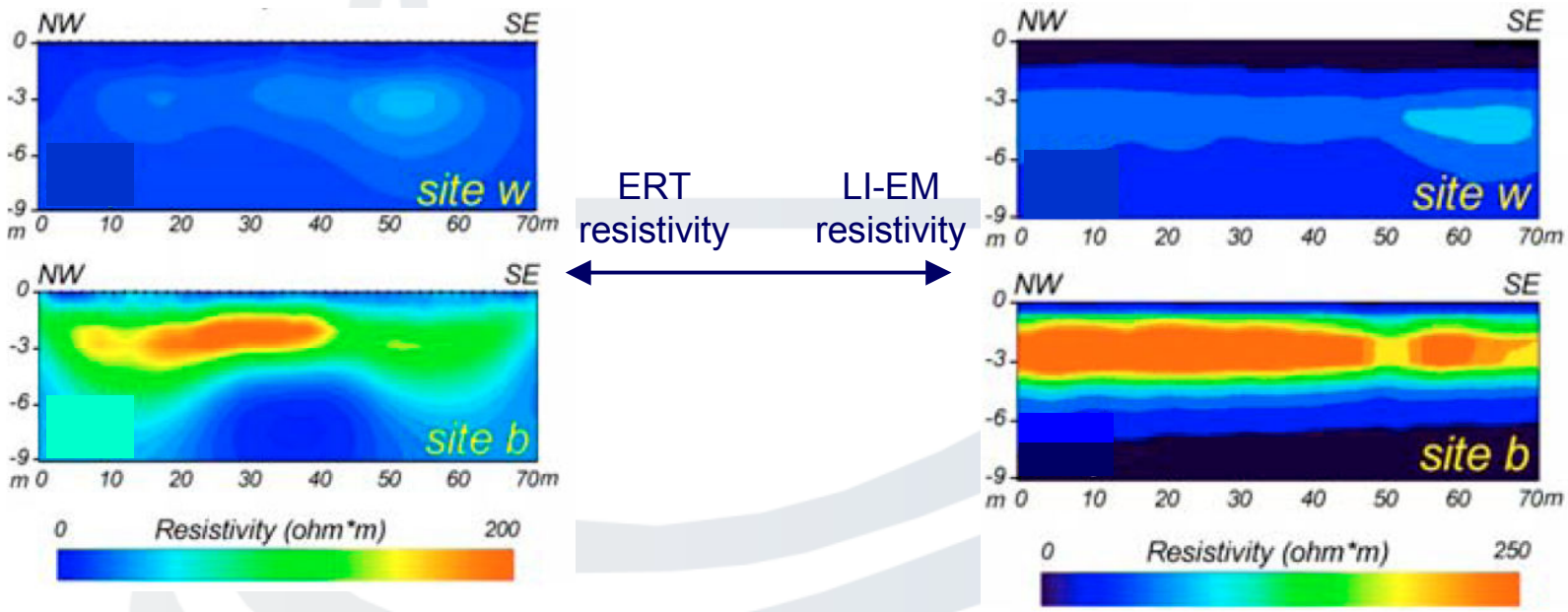
Inversion was carried out with a smooth quasi-2D algorithm (*Monteiro Santos and El-Kaliouby, 2011*) using a homogeneous initial model of 30 ohm*m and allowing for a maximum of 10 iterations. The sections exhibit a good similarity although the resistivities in the LI-EM inversion are somewhat larger (*Francese and Monteiro Santos, 2014*).



At site b the difference in the resistivity level is not an issue as it does not affect interpretation. At other sites such a difference could be significant as silt and sandy silt layers could be interpreted as pervious sands.

Data analysis and validation - multi-array LI-EM

At site w, where resistivities are low to moderate, the LI-EM and the ERT inversions are almost identical.



For site b a better correspondence in resistivity level has been obtained by lowering the number of iterations to 8 and using a three layer initial model.

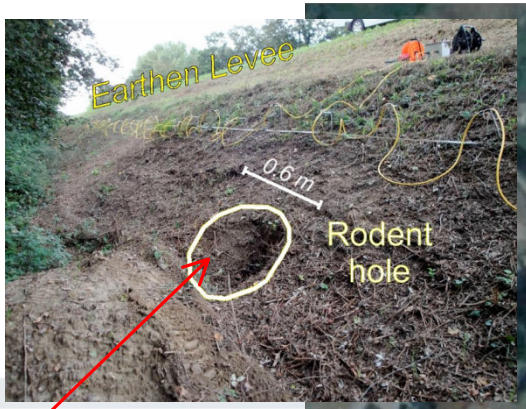
Data analysis and validation – multi-channel GPR

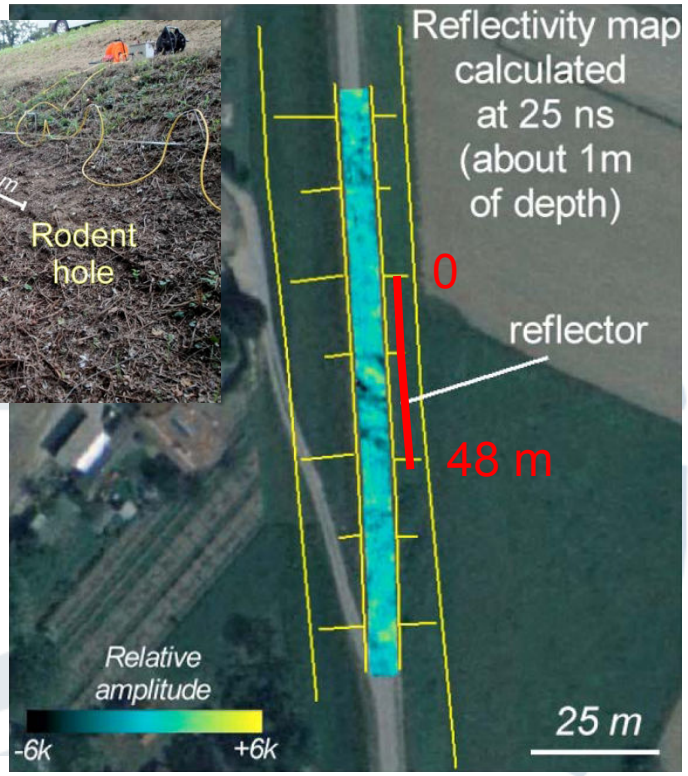
OGS

Two GPR test-sites

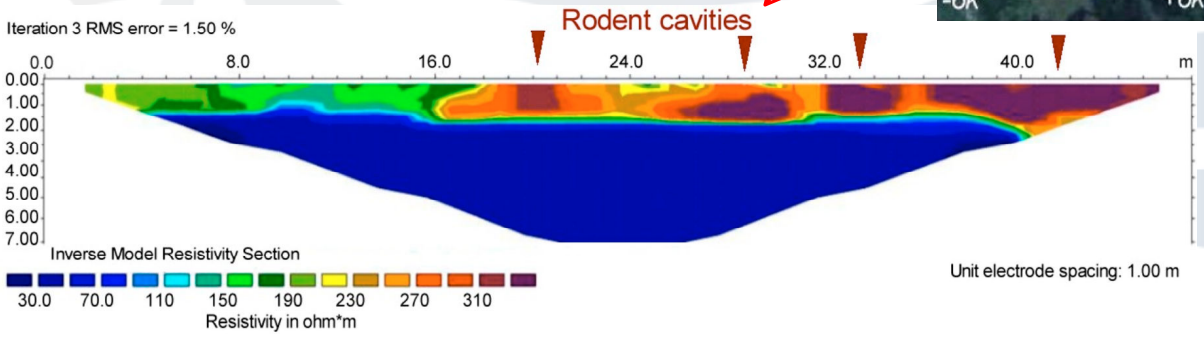
Test Site I

The GPR reflectivity map calculated at an approximate depth of 1 m below the levee crest showed a series of linear reflectors.





These reflectors were caused by cavities as confirmed by visual inspection and ERT profiling.



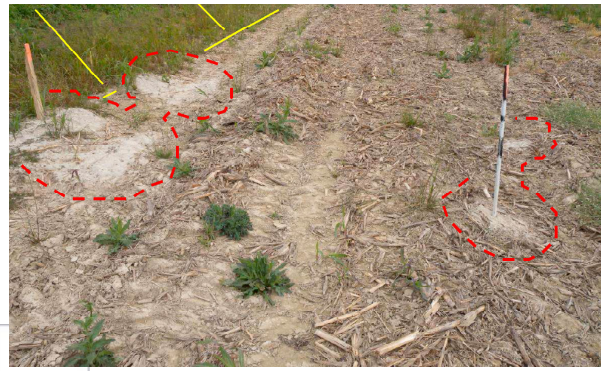
The ERT data were collected on the side of the levee.

Data analysis and validation – multi-channel GPR

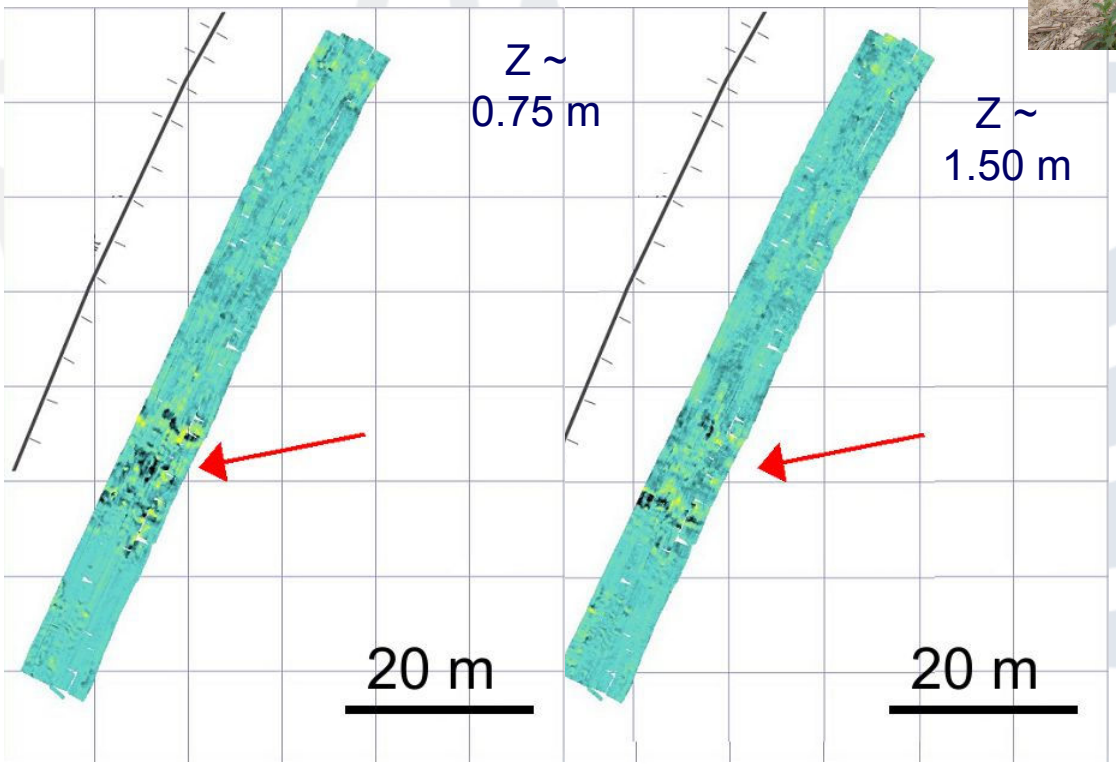
OGS

Test Site II

Several sand mounds were identified at the foot of the levee. The reflectivity map showed some clear anomalies coincident with associated sand pipes.



sand mounds



15-antenna GPR provides images with high lateral resolution, and 200 MHz frequency enables some penetration into levee material.

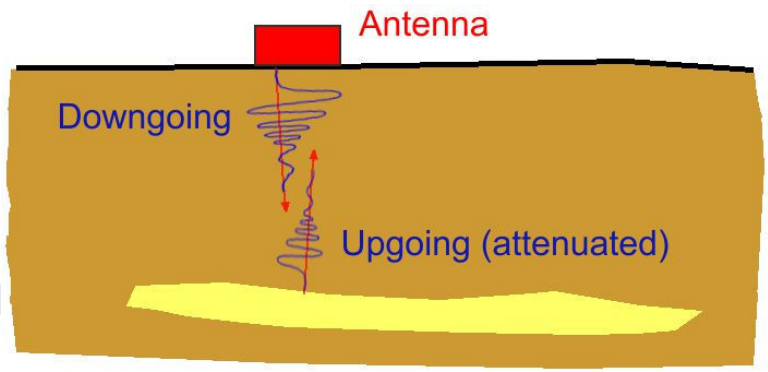
Relative amplitude

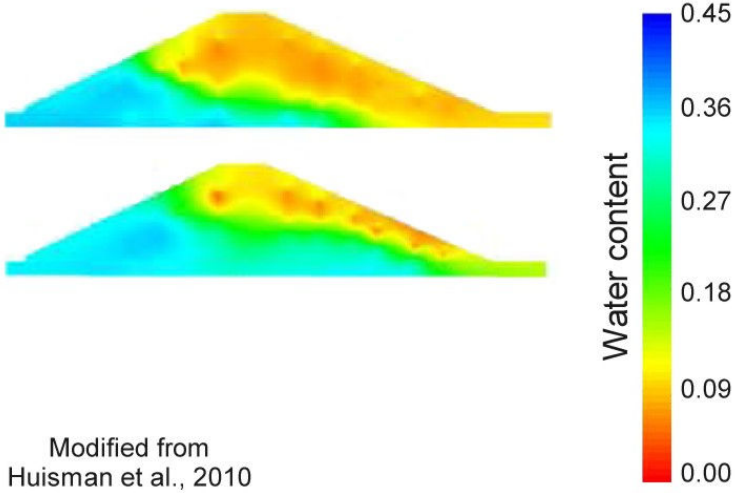
-6000 6000

Data analysis and validation - residual drawbacks

The tests validated the system although there are still some drawbacks ...

Penetration. 200 MHz GPR signal still has low penetration in conductive silts and clays. On the other hand GPR is the only geophysical technique capable of delivering enough spatial resolution to detect the animal cavities in the top portion of the levee.





Modified from Huisman et al., 2010

Moisture variation. Changes in the water content of the levee itself could significantly influence the LI-EM measurements and the effect could be of the same order of magnitude as a sand/clay contrast.

Data analysis and validation – compromise solution

OGS

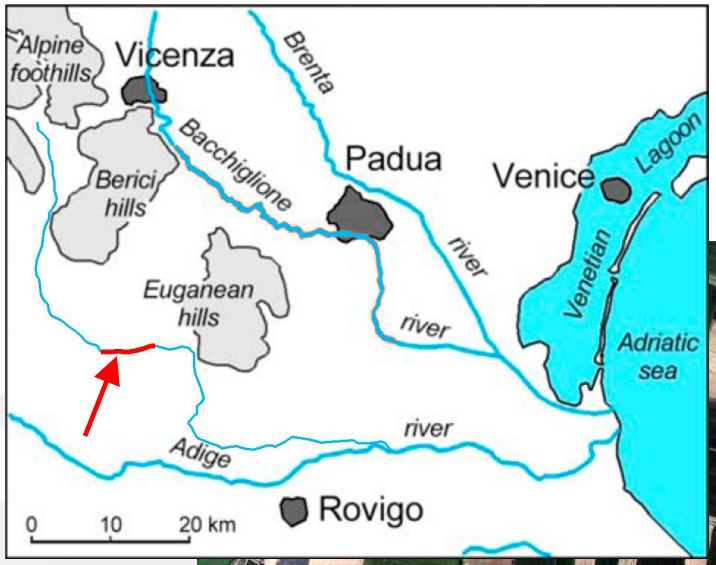
Penetration. In many cases the resistivity of the moist levee body is lower than 50 ohm*m. In order to increase the depth of penetration of the GPR, surveying should be carried out after a dry period (typically during the Italian summer).

Moisture variation. In a wetter levee, moisture distribution is more consistent and contrasts between sandy and clayey material are enhanced. In order to minimise temporal resistivity fluctuation and improve target definition, LI-EM data should be collected after a wet period (typically during fall, winter or spring).

Thus, separate GPR and LI-EM surveys are indicated, despite increased operational cost.

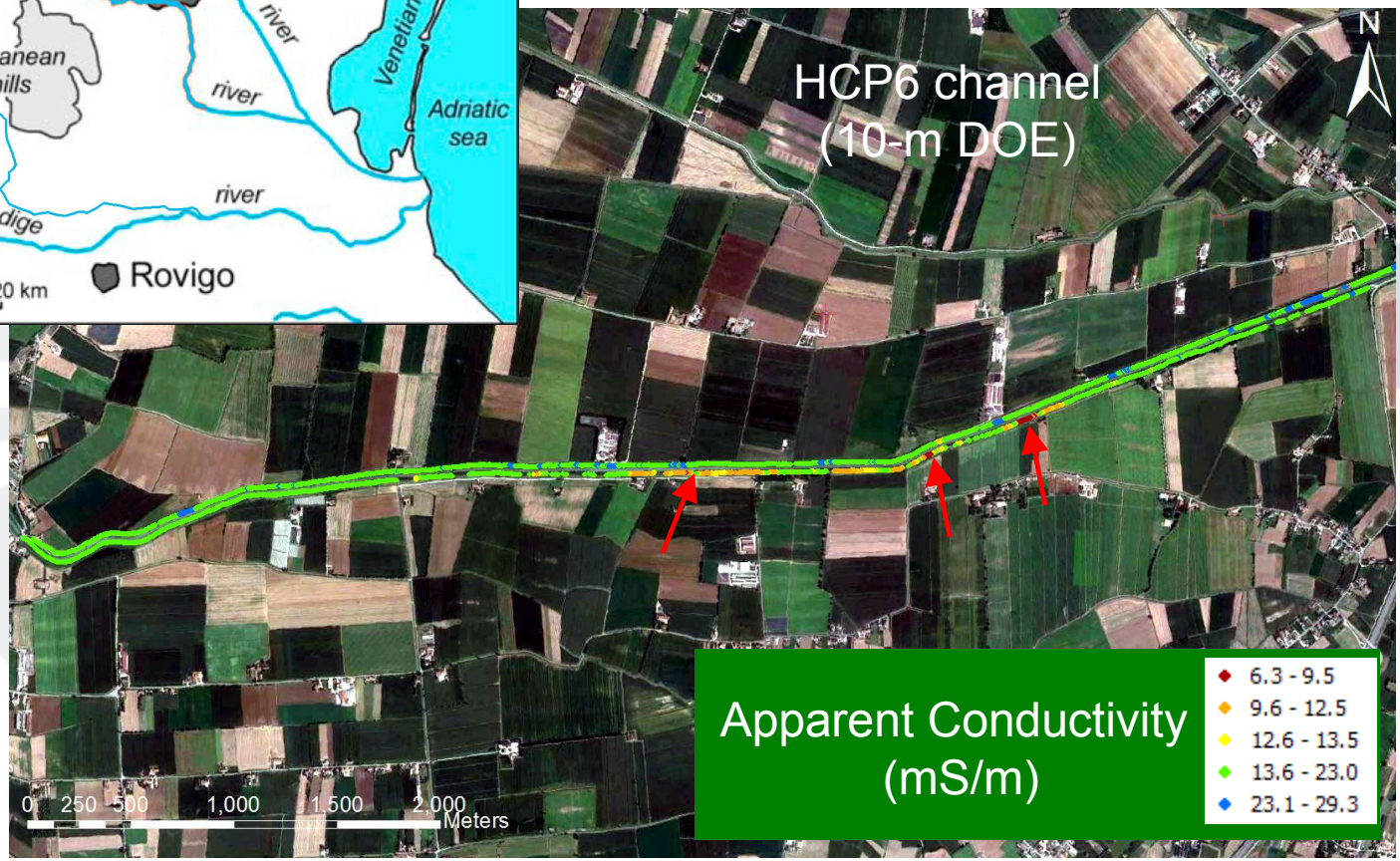
Two case studies in Veneto Region

OGS



7 km of *Frassine* river: dual surveys on north and south levees

Zones of high resistivity in southern levee

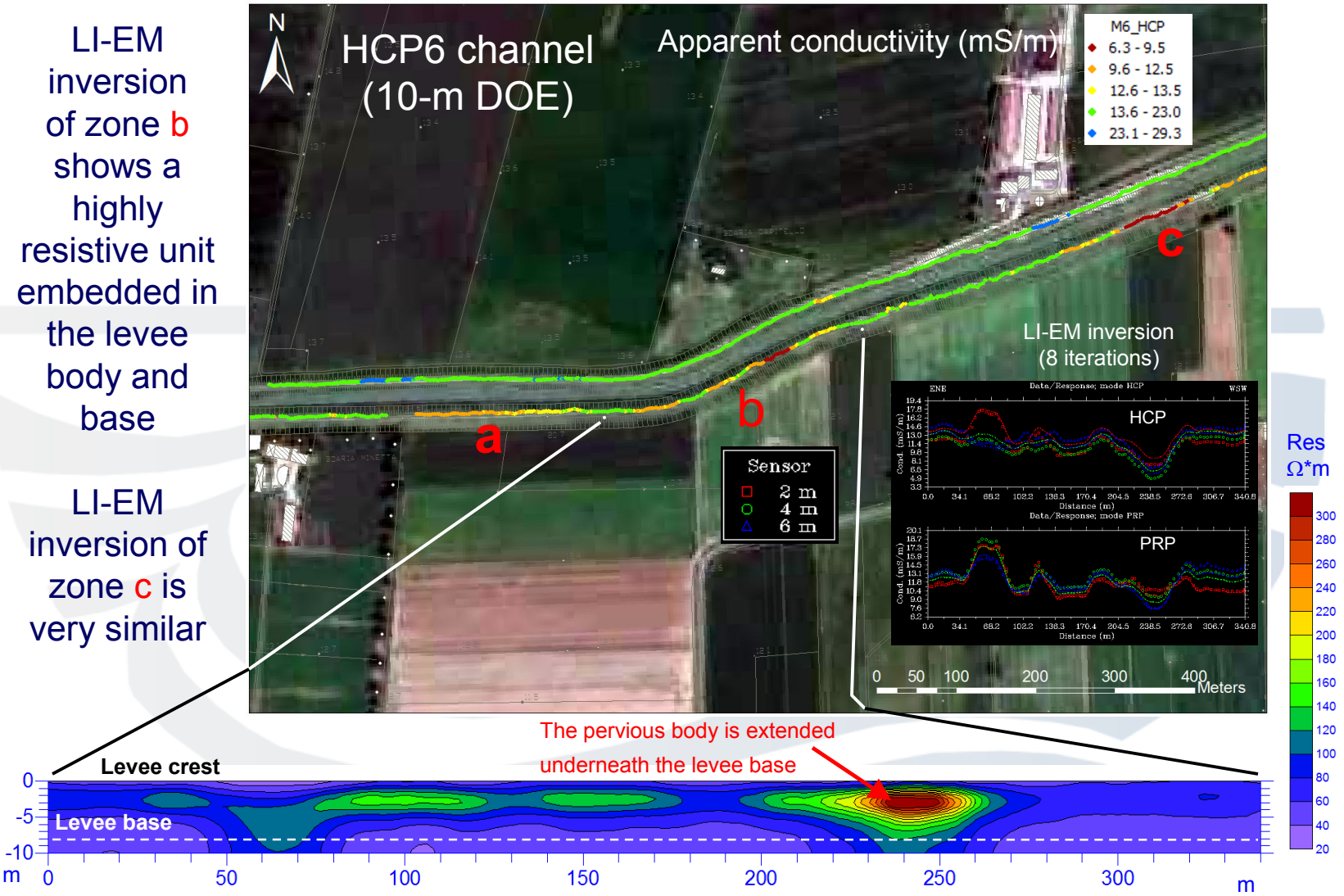


Results from some study cases near Venice (case 1)

OGS

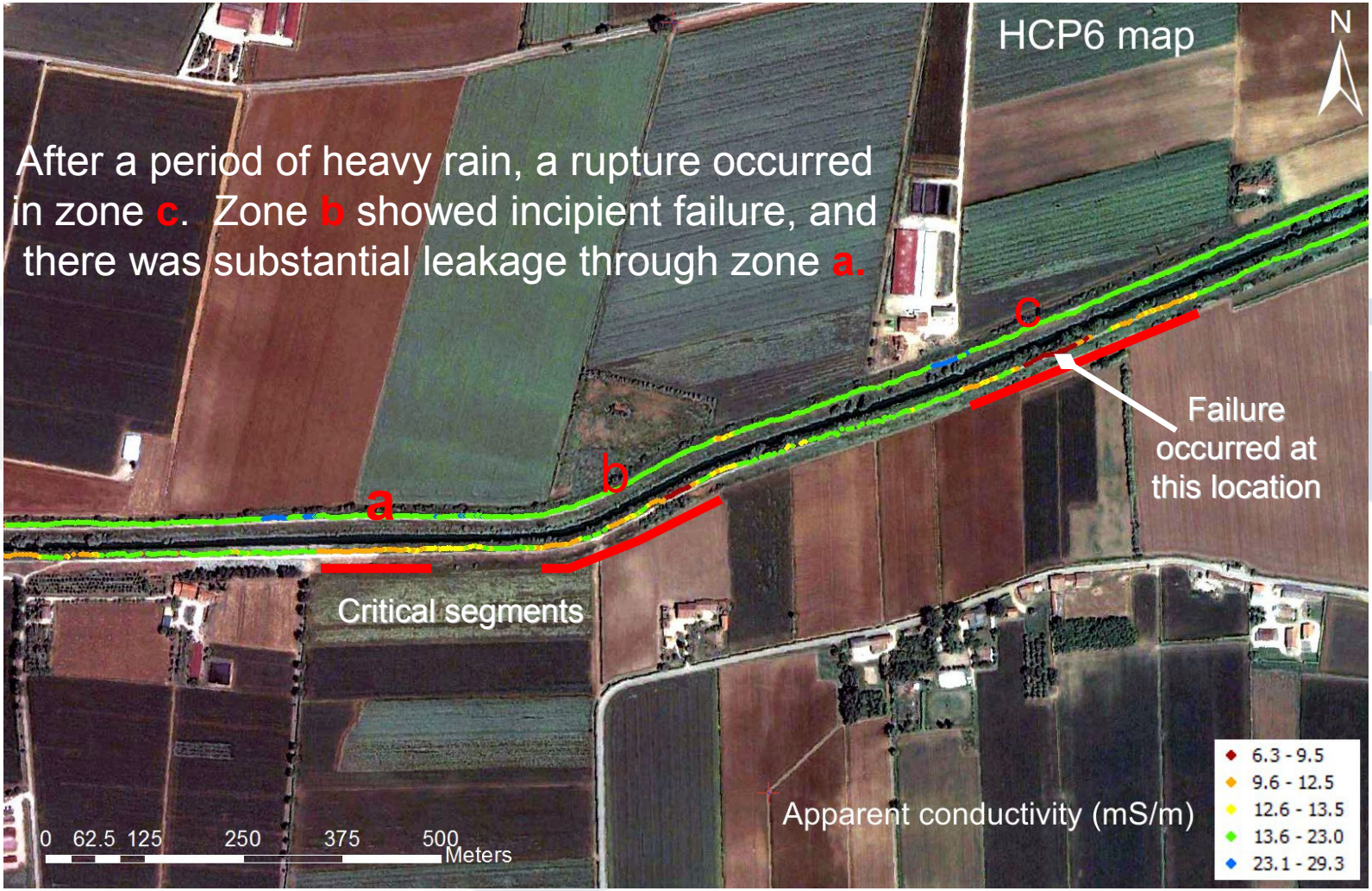
LI-EM inversion of zone b shows a highly resistive unit embedded in the levee body and base

LI-EM inversion of zone c is very similar



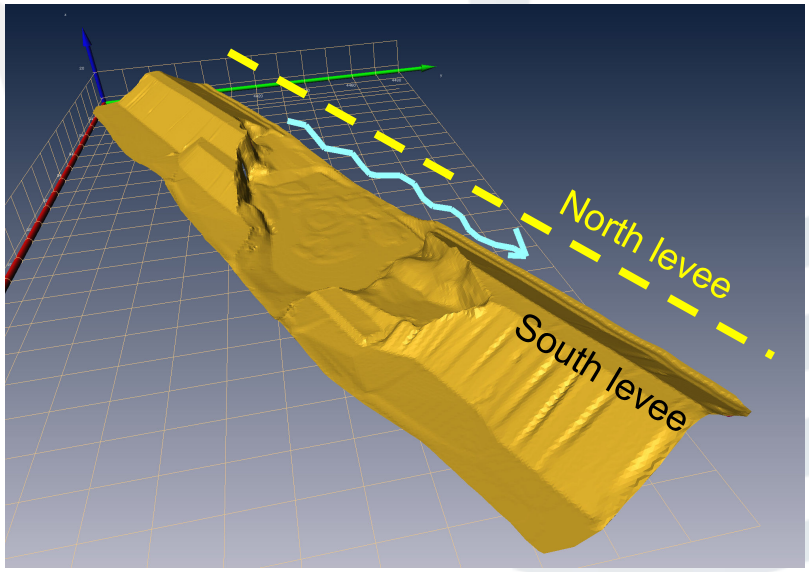
Results from some study cases near Venice (case 1)

OGS



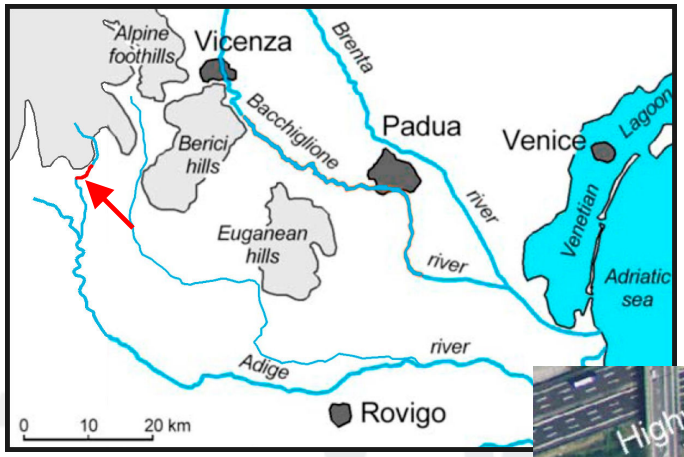
Results from some study cases near Venice (case 1)

The length of the breach after failure in zone c was roughly the same length as the high-resistivity segment mapped with LI-EM.



Results from some study cases near Venice (case 2)

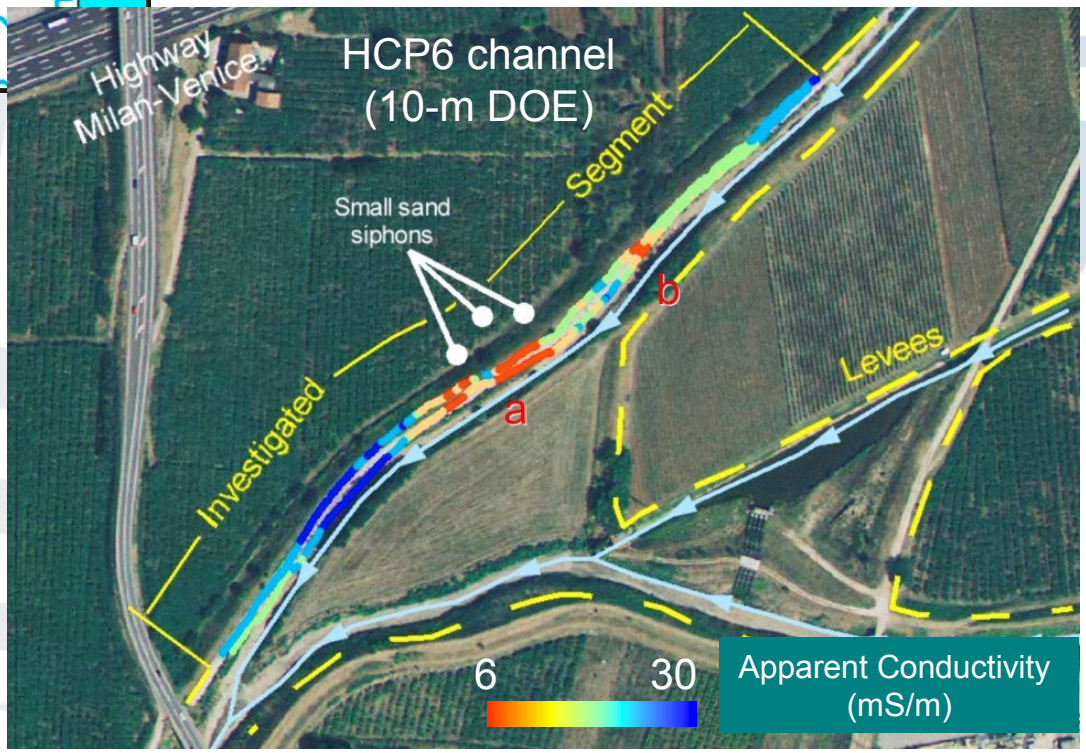
OGS



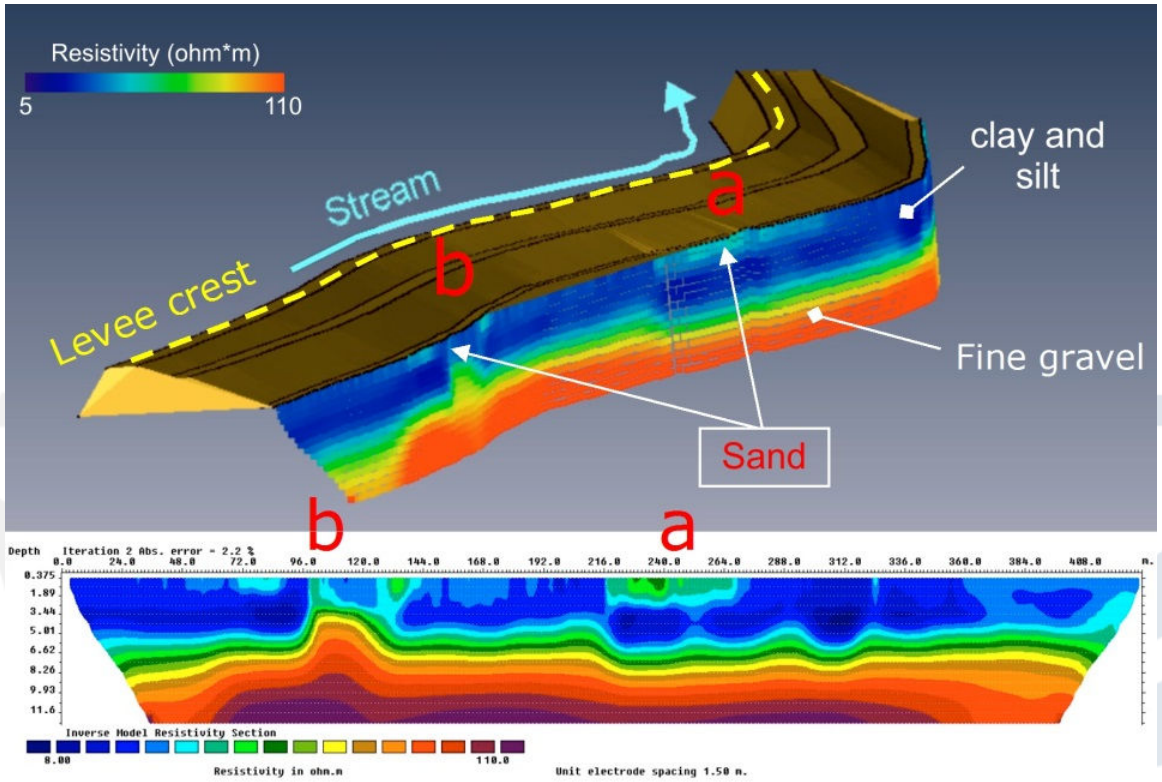
5 km of *Alpone* river

The deep-penetrating HCP6 channel showed two zones of high resistivity, broad zone a and narrow zone b.

Zone a was somewhat expected because of water piping around the levee base, while zone b was previously unknown.



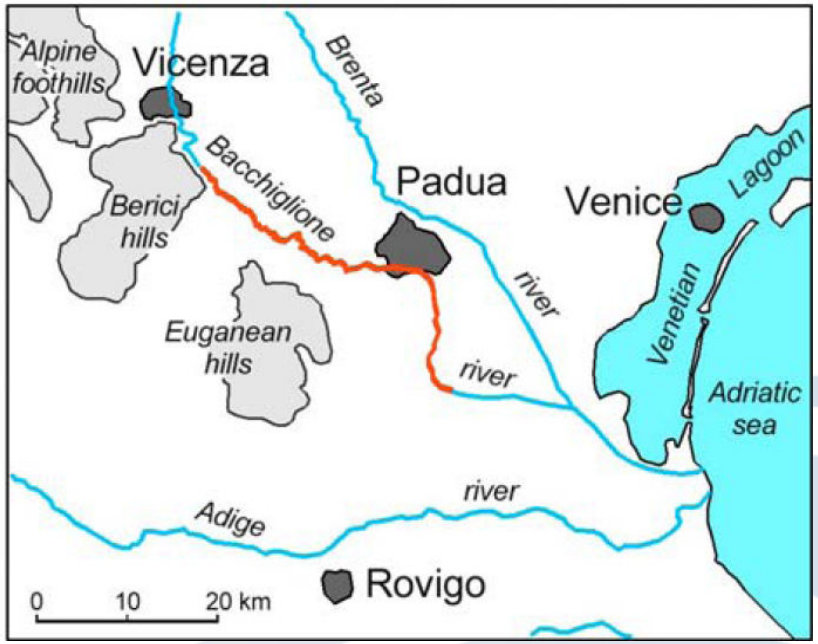
Results from some study cases near Venice (case 2)



Zones a and b were also investigated with an ERT profile.

The ERT profile confirmed the existence of two resistive bodies located just underneath the levee base. Trenches excavated in each zone confirmed the presence of a sand layer approximately 2-m thick.

Large scale project

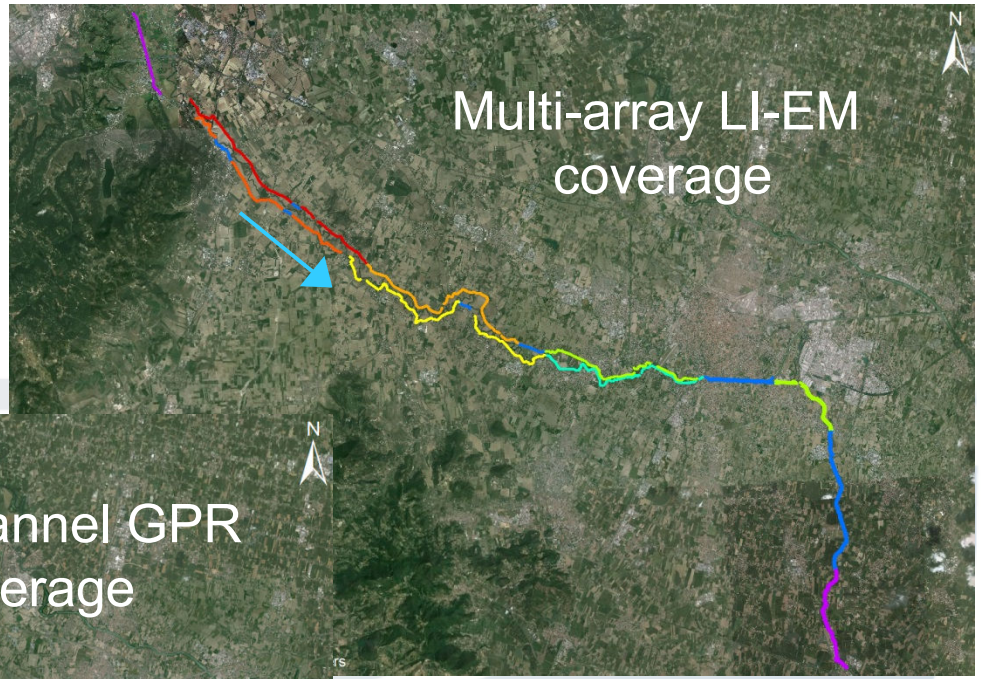


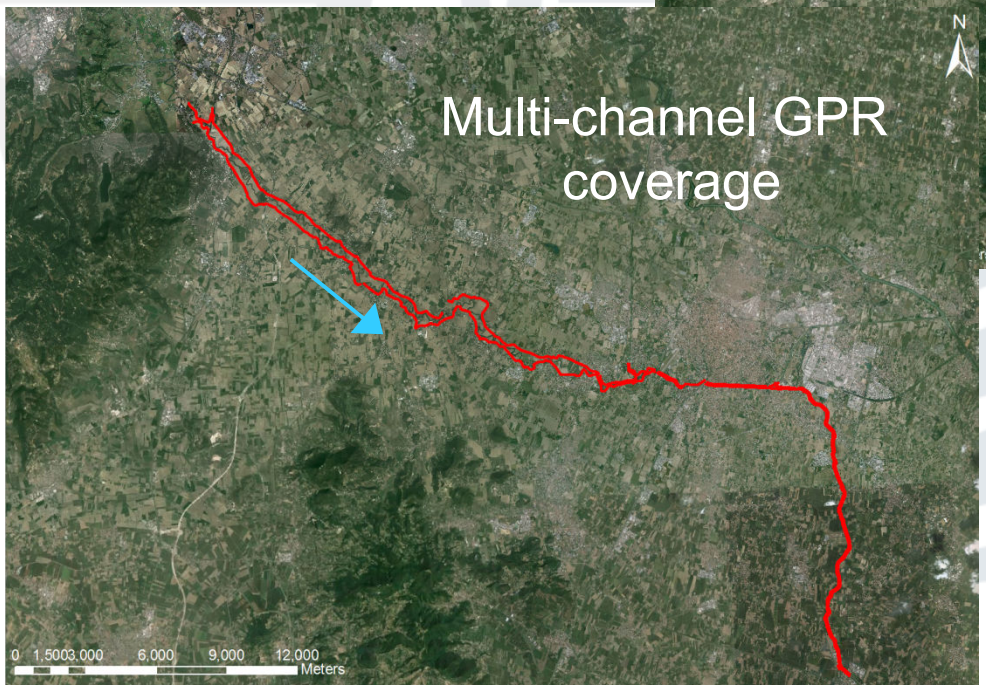
90 km of
Bacchiglione river

Large scale project data acquisition

OGS

Data acquisition:
Two-person crew, one week for each of:
~18,000,000 GPR traces
~3,000,000 LI-EM apparent resistivities

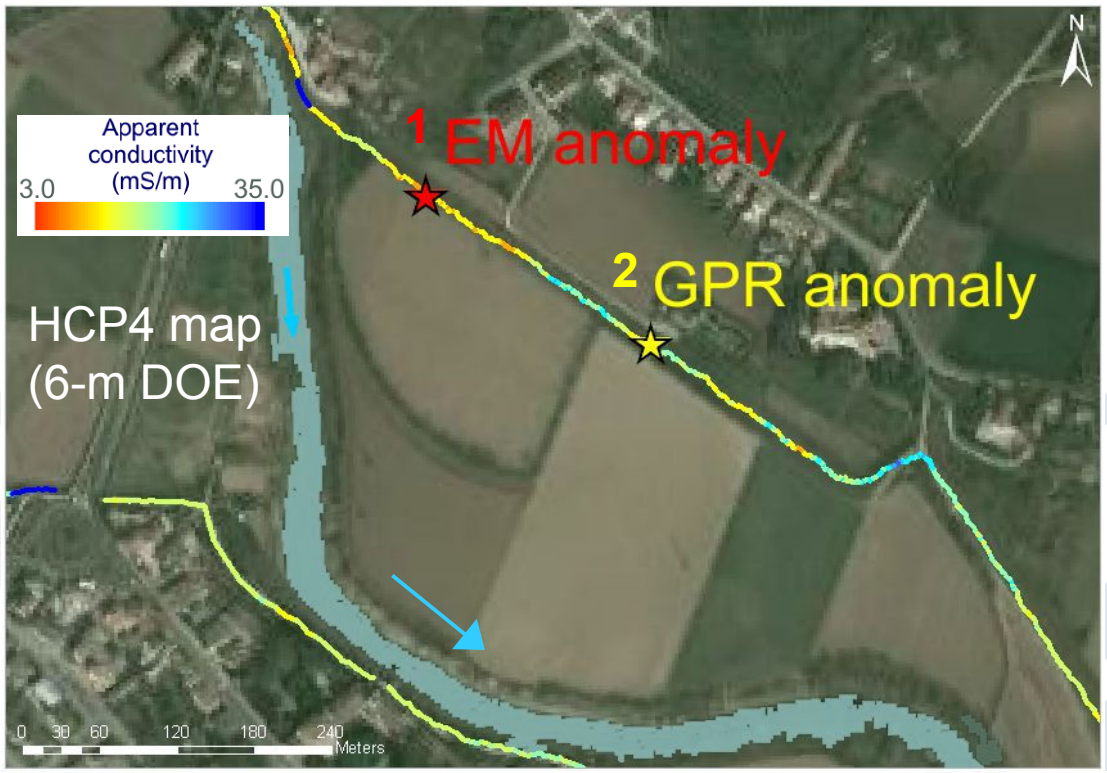




GPR measurements were carried out during the summer of 2013 while LI-EM data were collected during late autumn-early winter of the same year.

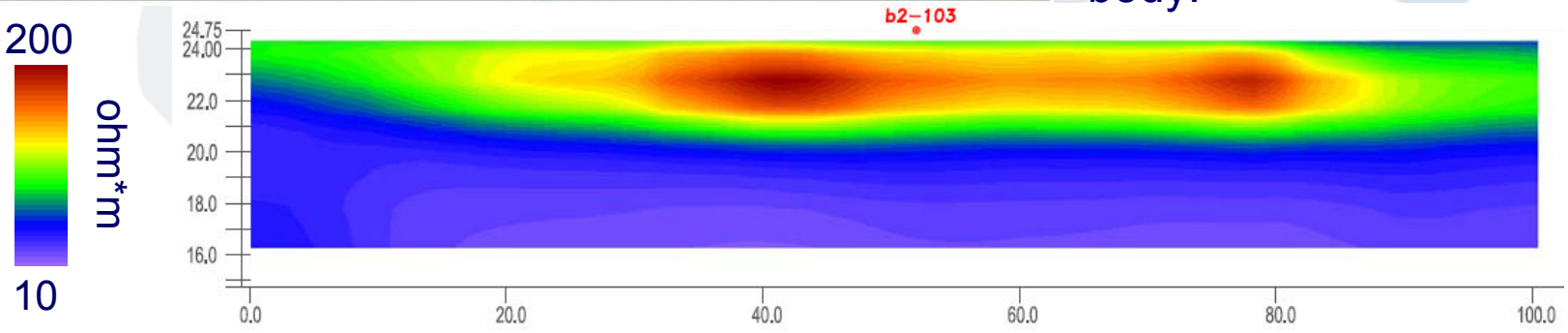
Results from a large scale project

OGS



An LI-EM anomaly with ρ_a > 200 ohm*m was evident in both the HCP2 and HCP4 data (4- to 6-m DOE).

LI-EM inversion shows a resistive layer (ρ > 200 ohm*m) in the levee body.

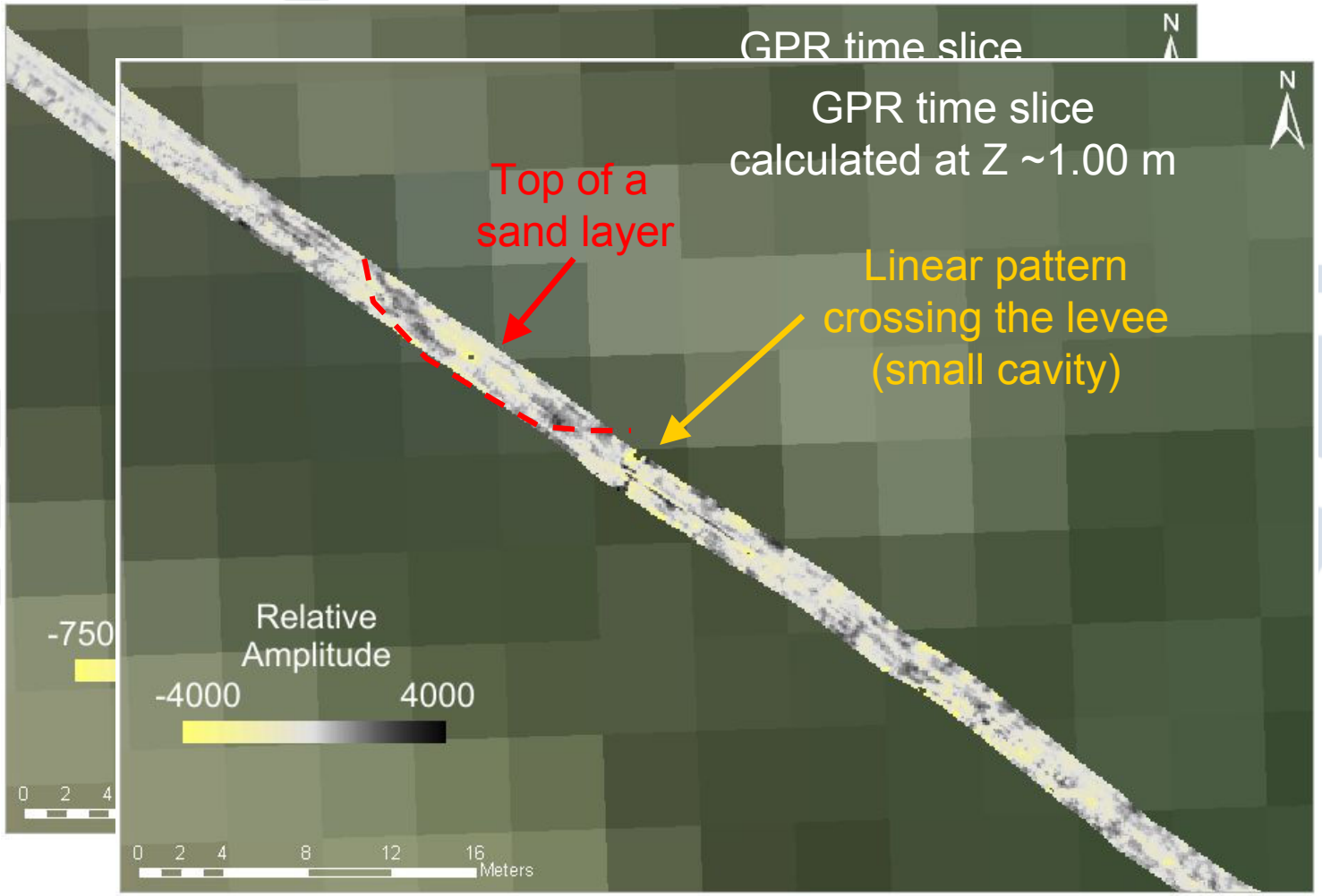


Gianfranco Morelli et al,, 2015

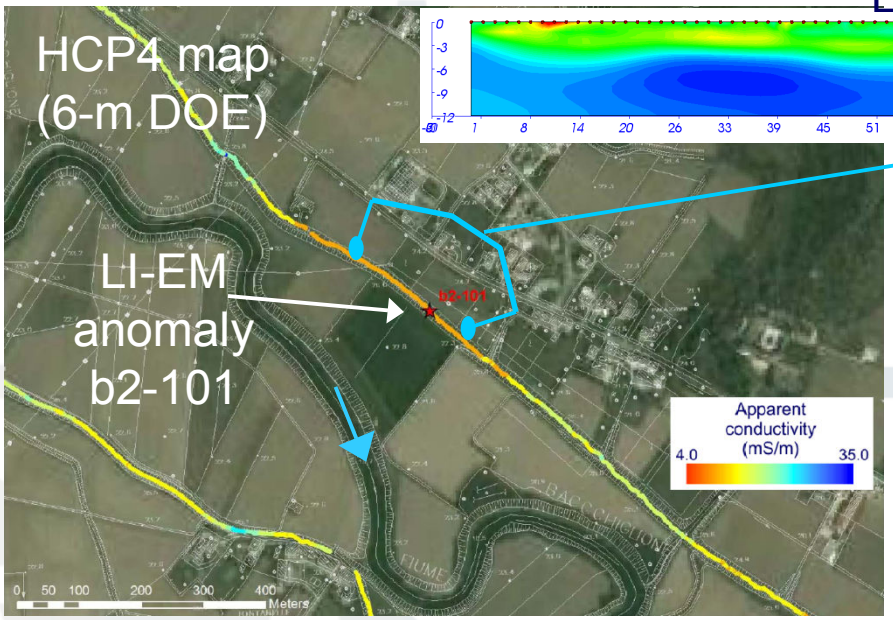
Results from a large scale project

OGS

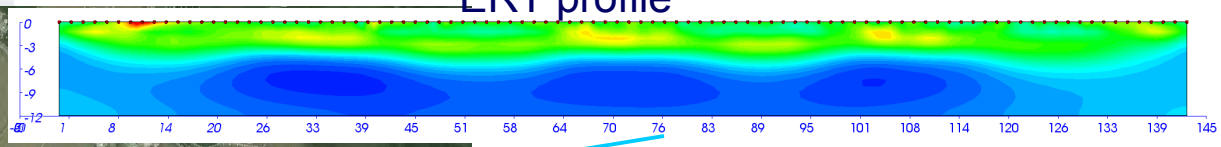
2. GPR anomaly:

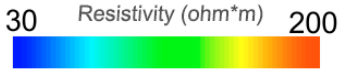


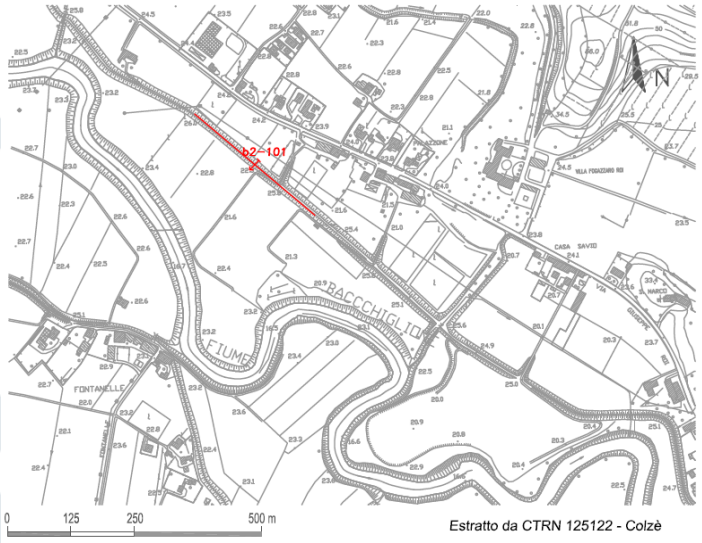
Results from a large scale project



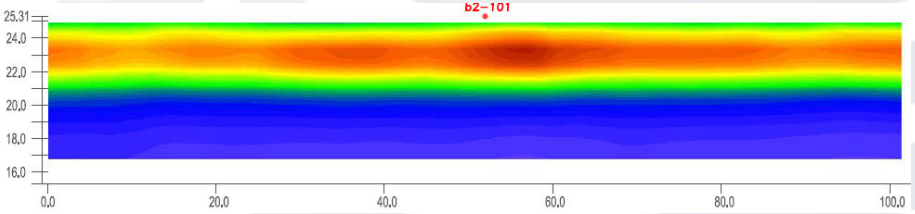
ERT profile

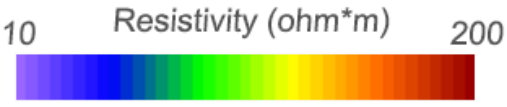


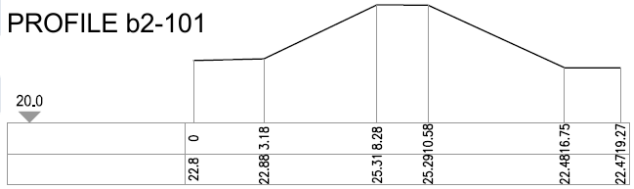




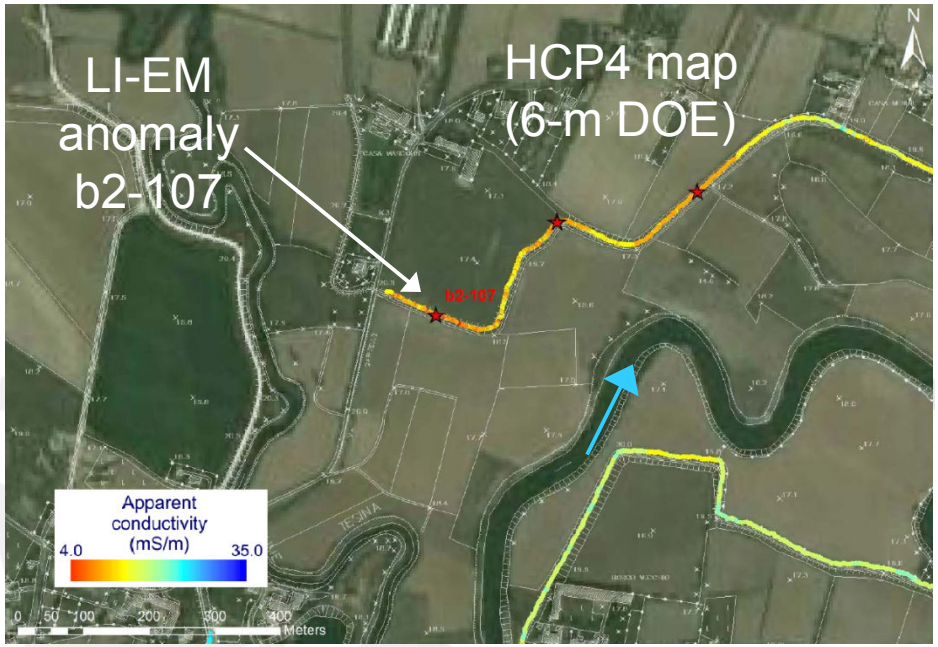
LI-EM inversion



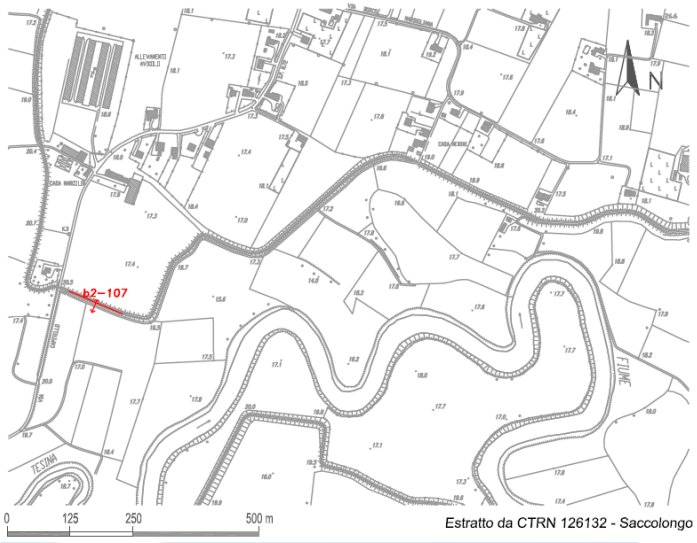




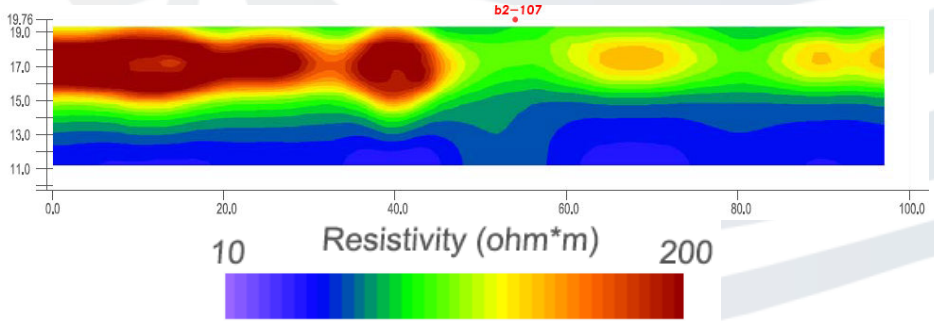
Results from a large scale project

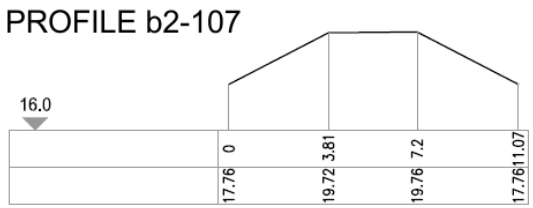


no ERT profile in this site

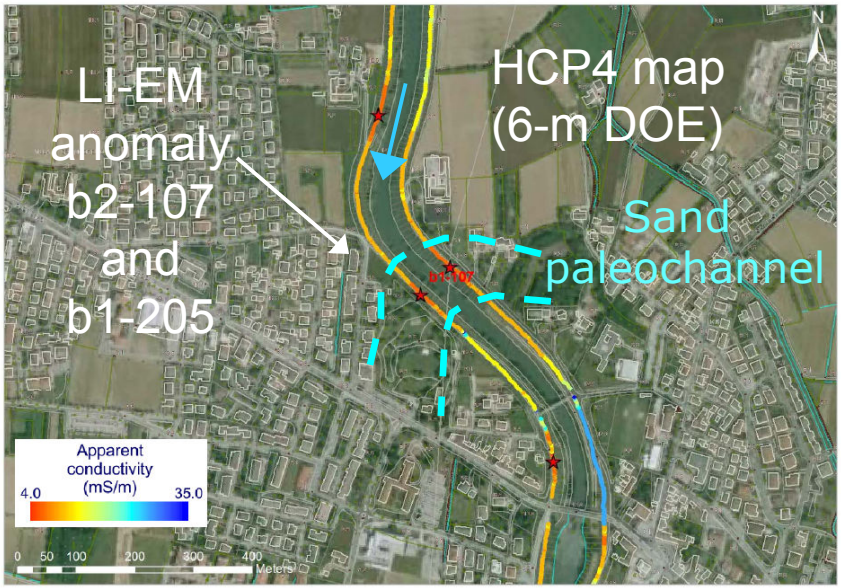


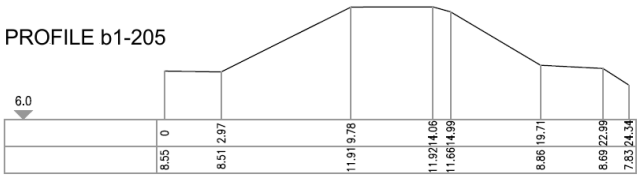
LI-EM inversion

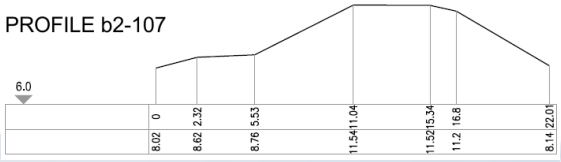


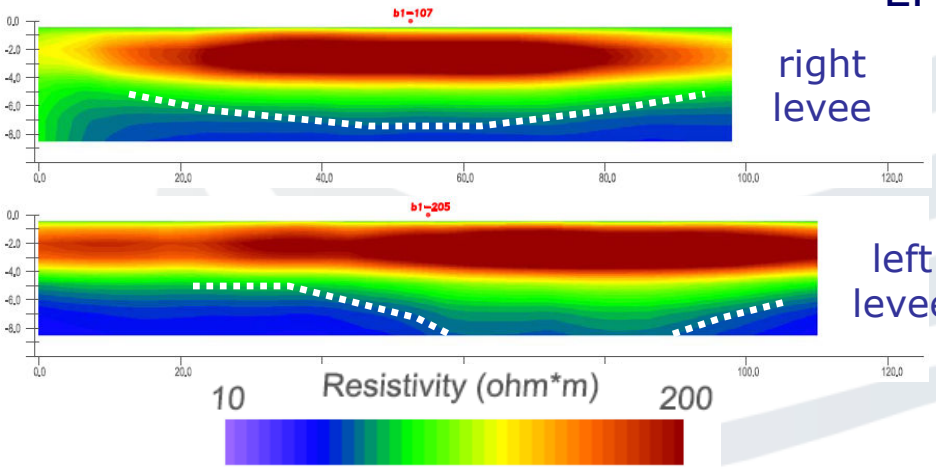


Results from a large scale project









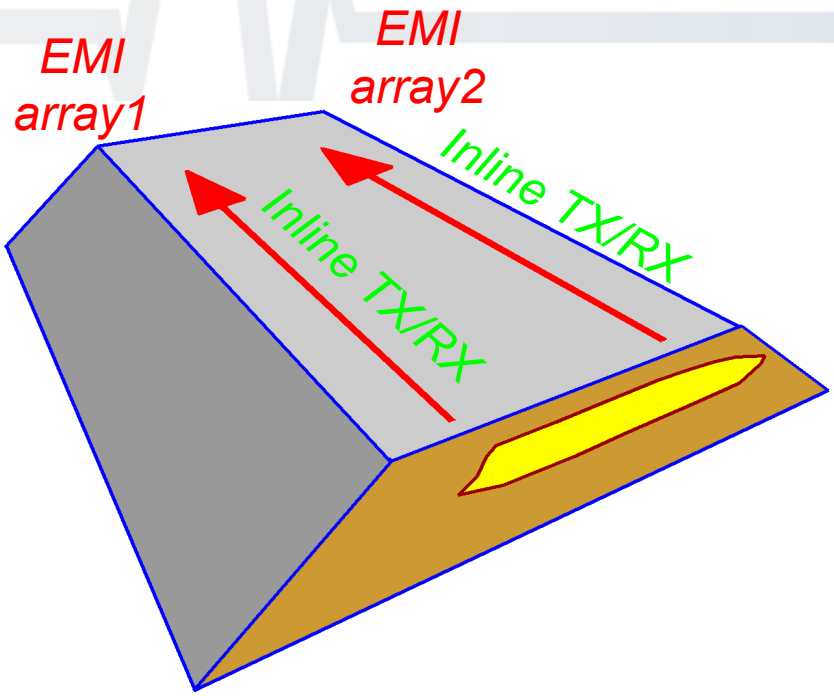
LI-EM inversions

In the resistive zones during high water, water piping was observed around the base of each levee.

Future improvements

OGS

One possibility for improving this approach would be operate a second LI-EM sensor in parallel with the first. This should improve lateral resolution of resistivity through the upper portion of the levee. Improved resolution should help define the lateral extent of sand lenses that might be present in the levee.



Alternatively, equivalent data could be obtained by round-trip surveying on each levee, with the two survey tracks offset by several metres.

Conclusions (1)

- A fast and efficient geophysical method to scan earthen levees has been tested and validated;

- The method is based on the dual techniques of (i) multi-channel GPR and (ii) multi-array LI-EM;

- Inversion of LI-EM data led to resistivity sections fully comparable to ERT imaging. This procedure still requires some tuning of the processing parameters but it is already in the range of robust interpretability and, as a result, there is no need to validate the LI-EM anomalies with time-consuming ERT profiles;

Conclusions (2)

OGS

-Single pass surveying improves the cost-effectiveness of the method. Where a GPR + LI-EM survey indicates low sand content through low resistivity, even in dry conditions, a subsequent pass in moist conditions is likely unwarranted.

- Since resistivity will be elevated in dry conditions, a second pass in moist conditions will be indicated for extensive lengths of levee. Given the economic consequences of levee failure, however, the cost of a second pass is easily justified.

-The volumes of data generated by complex sensors, perhaps on multiple passes, will demand greater use of quasi-3D EM inversion and other advanced interpretational techniques.

Acknowledgement and References

The authors thank the Veneto Region, Italy for making survey data available for our presentation.

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Thanks for your attention !!!

Gianfranco Morelli
gf.morelli@tin.it

Fernando A. Monteiro Santos
fasantos@fc.ul.pt

Roberto Francese
rfrancese@inogs.it
roberto.francese@unipr.it

Rick Taylor
rtaylor@dualem.com