THE USE OF GPR FOR THE DETECTION OF NON-HOMOGENEITIES IN THE RENO RIVER EMBANKMENTS (NORTH-EASTERN ITALY)

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RÉSUMÉ
L'utilisation de techniques non-invasives lors de l'analyse des berges artificielles des fleuves est essentielle pour la sauvegarde du fleuve lui-même. Récemment, ce thème a fait l'objet d'une attention particulière lors de l'utilisation de méthodes géophysiques. Contrairement aux autres méthodes, le GPR offre la possibilité d'étudier des zones étendues sur un laps de temps relativement court. Lors de l'analyse de berges, il permet de détecter des anomalies pouvant être étudiées plus tard en détails. La sécurité hydraulique du fleuve Reno, l'un des plus importants du Nord-Est de l'Italie, constitue une priorité pour l'administration de la région Émilie-Romagne. Au cours des dernières décennies, de nombreux événements hydro-météorologiques ont provoqué des dommages structurels dans les berges du fleuve Reno et ses affluents. Le potentiel du GPR a été testé à différentes fins : détection de la stratigraphie des berges, étude du développement de cavités creusées par des animaux, localisation de conduits inconnus et de zones réparées. Les premiers résultats montrent que le GPR est, en termes de rapidité d'acquisition et de précision, une technique efficace pour la détection d'anomalies telles que les zones réparées, les niveaux de construction, les éléments cachés et les principaux horizons stratigraphiques peu profonds.

ABSTRACT
The use of non-invasive techniques in the monitoring of man-made river embankments is of primary importance for the safety of the embankment itself. Recently, a noticeable attention for this topic has been addressed to many geophysical methods. The GPR method respect to the others gives the possibility to investigate spread areas in a relative short time; in the study of river embankments, it allows to detect anomalies that can be thoroughly studied later on. The hydraulic safety of the Reno River, one of the main rivers in North-Eastern Italy, is of primary importance for the Emilia-Romagna regional administration. In the last decades, several hydro-meteorological events caused structural failures of the embankments of the Reno River and its tributaries. The GPR capability has been tested in several test areas, along more than 15 km on artificial embankments for several issues: detection of river embankment stratigraphy, study of the development of cavities produced by animals, localization of unknown pipelines and repaired areas. Preliminary results show that GPR is a suitable technique for the detection of anomalies like levels of construction, recently repaired areas, hidden objects, important shallow stratigraphic horizons.

1. INTRODUCTION

The problem of the safety of river embankments can be easily underestimated, particularly if a relative dry period persists for a long time. The Reno river together with its tributaries covers, in the alluvial plain area, a length extension of more than 500 km. Some crisis events happened in the past highlighted how most of problems that can interest embankments occur along discontinuities hardly detectable with traditional techniques. Piping and seepage problems along fractures, cavities, differently compacted and settlemented areas, cannot be easily recognised through destructive methods which provide precise but punctual information. Non-invasive techniques, such as geophysical methods, result largely diffused for this topic and in constant development. In particular, seismic refraction and MASW (Multichannel Analysis of Surface Waves) techniques are the most suitable both for detecting different compacted areas and for estimating geotechnical properties of the materials; however, they are ineffective for identifying the presence of cavities and burrows (Morris, 2005). Electric tomography methods are able to resolve almost all the problems mentioned above with good resolution, mostly as regard to the structure and soil moisture content; but they require long time acquisition, because the spacing between the electrodes should be equal to or below 1 m. Innovative electromagnetic method as GMS (Geophysical Monitoring System), employing the GEM-2 (Boukalová and Beneš, 2007), was tested and verified in European Projects; it carries out basic assessment of the dikes condition and their material composition in large areas with quick and not highly money-consuming measurement. Looking for a higher resolution for the detection of non-homogeneities, the attention has been turned to alternative methods such as ground-penetrating radar (GPR). After an experimental period concerning mostly archaeological and urban purposes (Al-Quadi and Lahouar, 2005; Loizos and Plati, 2007), interest in GPR survey for geological issues increased considerably in the 1990s. As an example, the GPR has unquestionable advantages, respect to other techniques for the estimation of scree thickness of hardly accessible mountain areas (Otto and Sass, 2005). Moreover, GPR capability in the determination of buried geological structures makes this technique a powerful tool in sedimentology (Smith and Jol, 1995); even if the extraction of meaningful information on

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the deposition style and on the sedimentary structures needs systematic and accurate data processing (Neal, 2004).
In geological and geomorphological studies, Schrott and Sass (2008) suggest using the GPR technique integrated with other geophysical techniques, in order to avoid interpretation misunderstandings. In regard to the application of GPR to river embankments, very few applications are to date known for this issue (Morris, 2005; Niederleithinger *et al.*, 2007).
The knowledge of the existence and the position of eventually non-homogeneity zones into the embankment are relevant problems in term of hazard and hydraulic risk, especially if river embankments themselves are old (more than one century), inserted in a densely populated area, subjected to periodic important floods and at last, detailed information on history and structure are missing. The need to carry out a survey of hundreds of kilometres of river embankments for identifying, primarily, these weakness zones, is also a requirement of the regional government authorities. Just in this context, GPR suitability has been tested in the study of river embankments. The detection of stratigraphy, animal cavities and burrows, buried pipelines, non-homogeneities related to different phases of construction and repaired areas of the embankment itself represent the main purpose of our research. Even if some of these aims need further investigation, it is possible to outline GPR capability in the study of river dikes.

2. GEOGRAPHICAL AND GEOLOGICAL SETTING

The study area belongs to the structural domain of the Apennine belt, in particular to its front portion, covered by recent alluvial deposits and underlain by terrigenous layers of Plio-Pleistocene sediments. The tectonic uplift of the Apennine mountain chain is considered the main reason for the northward migrations of the Po River, occurring during the last 3000 years (Bondesan, 2001). The evolution of the study area has been strongly influenced by this change, together with political and social events of the last centuries. As one of its right tributaries, the Reno River has been keeping a transversal direction to the Po (SW-NE), swamping and over flooding in the alluvial plain. From the Middle Ages to the present, the hydraulic network completely changed respect to the natural attitude of those areas: the Reno river was forced to flow partially along an abandoned Po River trace. Some important hydraulic structures were designed in order to protect the plain from recurrent destructive floods; among artificial structures, the Napoleonic Channel (completed in 1965) still permits to switch the exceeding part of the greatest flood of the Reno River in the winter, acting as a water reservoir for agriculture in the summer. Generally, embankments are still affected by many different problems like subsidence, erosion, animal excavations, human impacts, but over all by the inappropriate building techniques that have been used throughout their history. Earth materials were usually taken directly from the river-bed and transported and compacted on the natural river banks using only wheelbarrows or other poor means of work. As a result the flood defence system of the complex Reno River network does not operate as it should in many important nodes.
The GPR methodology has been applied to the Reno River and its tributaries, together with the Napoleonic Channel (Fig. 1). Tests were carried out both in well known areas in order to verify specific issues (stratigraphy, animal cavities, repaired zones) and in areas with no information.

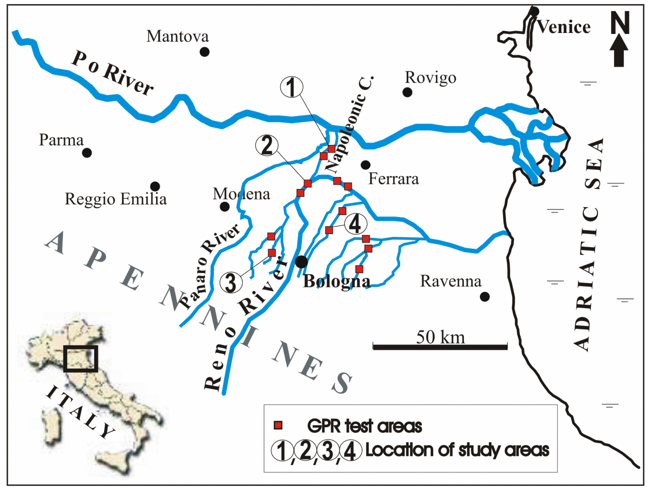

Figure 1. Geographical setting of the study area and location of GPR surveys.

3. METHODOLOGY

The main GPR campaign survey was carried out in October 2007 with a RIS-MF (IDS) georadar using a bistatic 100 MHz antenna and a multifrequency 200-600 MHz antenna. More than 15 km of embankments had been investigated in approximately ten working days. Results from GPR test areas (numbered from 1 to 4 in Fig.1) are presented.
GPR investigation depth is defined as the depth beneath which the signal received is too week to be detected in presence of noise. Reno River and Napoleonic Channel embankments are about 10 m high, Reno River tributaries embankments are 5 m high. Even if a frequency of 30 MHz is suggested for such investigation depths (Morris, 2005), the scarce resolution entailed the choice of antenna frequencies not lower than 100 MHz, so that, ground-coupled and shielded antennas were used. The size of the minimum target (pipelines, animal cavities) can be hypothesized as 30 cm, which is consistent with the physical relationship between spatial sensitivity (S) and wavelength (λ): S= 1/3λ. For these kind of soils may be considered S = 0,33 m and S = 0,16 m for antenna frequency equal to 100 MHz and 200 MHz, respectively.
A distance of at least 1,5 km has been covered with GPR for every test site, both along the top and on the downward side of the embankment, performing longitudinal sections.
For each site, many data from in situ direct measurements (boreholes stratigraphy and/or cone penetration test with porewater pressure management (cptu) are available. These kind of data are fundamental for geophysical data calibration: it allowed us to estimate some physical

properties of the soil and to derive their relative dielectric constant (ε_r). Most of the investigated soils are sandy clayey silts (50% silt, 30% sand, 20 % clay on average). Typically, such a kind of soil has an ε_r value range from 5 to 30, depending on the saturation conditions (Daniels, 2004). GPR in situ tests, performed burying a metal object at a known depth, reveal that a ε_r value of 9 may be considered reliable for these soils.
At some test sites, GPR results have been compared with other non-invasive techniques, such as MASW and dipole-dipole electric tomography.

4. RESULTS

Along the Napoleonic Channel data relative to three sections have been studied in detail (Fig. 2). The internal structure of the embankments can be referred to a general model, such those represented in Fig. 3A, B and C.
The stratigraphic sequence consists of: i) the artificial river embankment, 8 m height (silt prevalent); ii) in situ alluvial deposit, 2-10 m thick (silt prevalent); iii) paleochannel, variable thickness (medium sand). For section A (Fig. 2), GPR was used to check the embankment structure. Because of the silty soil, both 100 MHz and 200 MHz antennas suffered a strong diffraction process in the signal. Anyway, the 200 MHz antenna has permitted to identify a non-homogeneity structure (20 m wide and 1,5 m deep) on the downward side of the embankment (SCAN A in Fig. 2 and 3). The well recognized concave shape may be referred to a repaired area; in situ samplings have evidenced the presence of filling soil and heterogeneous elements.
Along its course, the Napoleonic Channel crosses repeatedly a Po paleochannel (Mazzini *et al.*, 2006). GPR capability for the detection of the top of the sandy body, in order to verify its lateral continuity (Section B and C in Fig. 2). In respect to the base of the embankment, cptu tests identify the top of the sand respectively at 2 m (cptu 1) and 10 m below (cptu 2) going northward (Figg. 2 B and 2 C).
The GPR survey (100 MHz antenna) has been carried out for about 2 km between sections B and C (Fig. 3). For the entire length of the GPR profile, the road asphalt covering the silty soil level is recognizable. In the first hundred meters of the survey (SCAN B in Fig. 3), it is possible to clearly recognize, at a depth of 2 m, a sandy layer. The signal becomes too weak at 4 m deep because of the presence of the water table, confirmed by piezometers in the vicinity. This strong contrast becomes more and more discontinuous going northward and, at the end of the survey line, it disappears (SCAN C Fig. 3).
Along the Reno River (site 2 in Fig. 1), a comparison of GPR survey with other geophysical techniques has been carried out. The geotechnical section of the embankment (Fig. 4) is characterized by a major complexity structure in respect to the Napoleonic channel ones. Borehole stratigraphy evidences the presence, besides the artificial embankment (silt prevalent), of in situ alluvial deposits (silt and sand) covering the basement (clay). The MASW survey has covered a length of 23 m, with 1 m spacing geophones (Fig. 5 A).

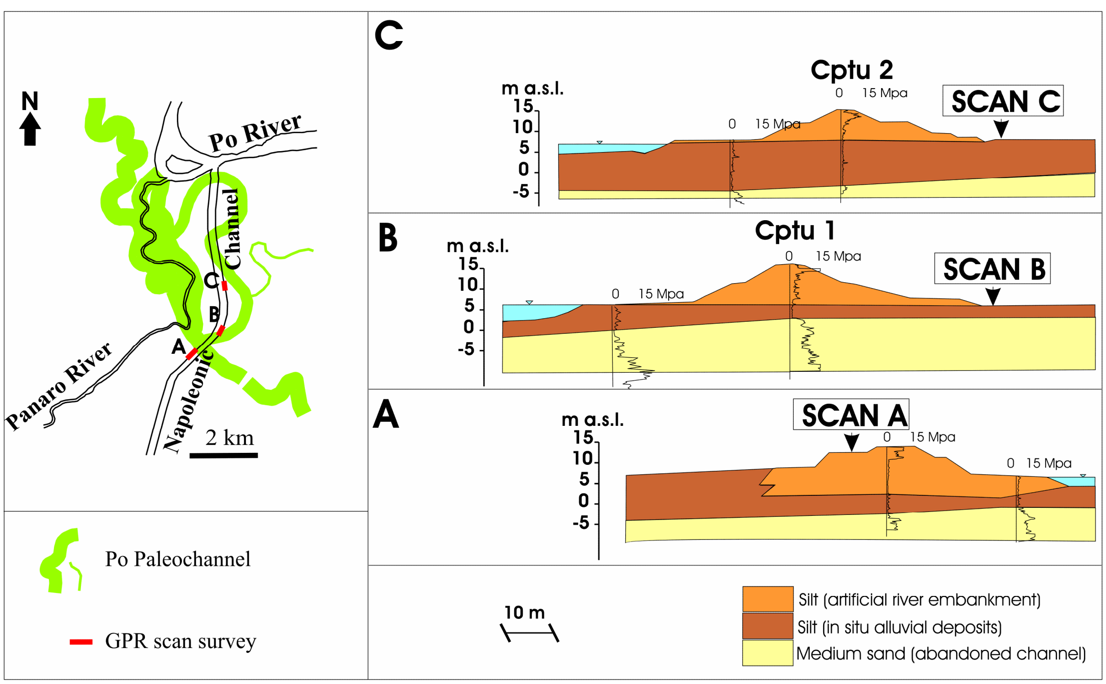

Figure 2. GPR surveys location along the Napoleonic Channel (site 1 in Fig. 1) and stratigraphic sections of the embankments obtained by in situ direct measurements. SCAN A, B, C: location of the GPR survey.

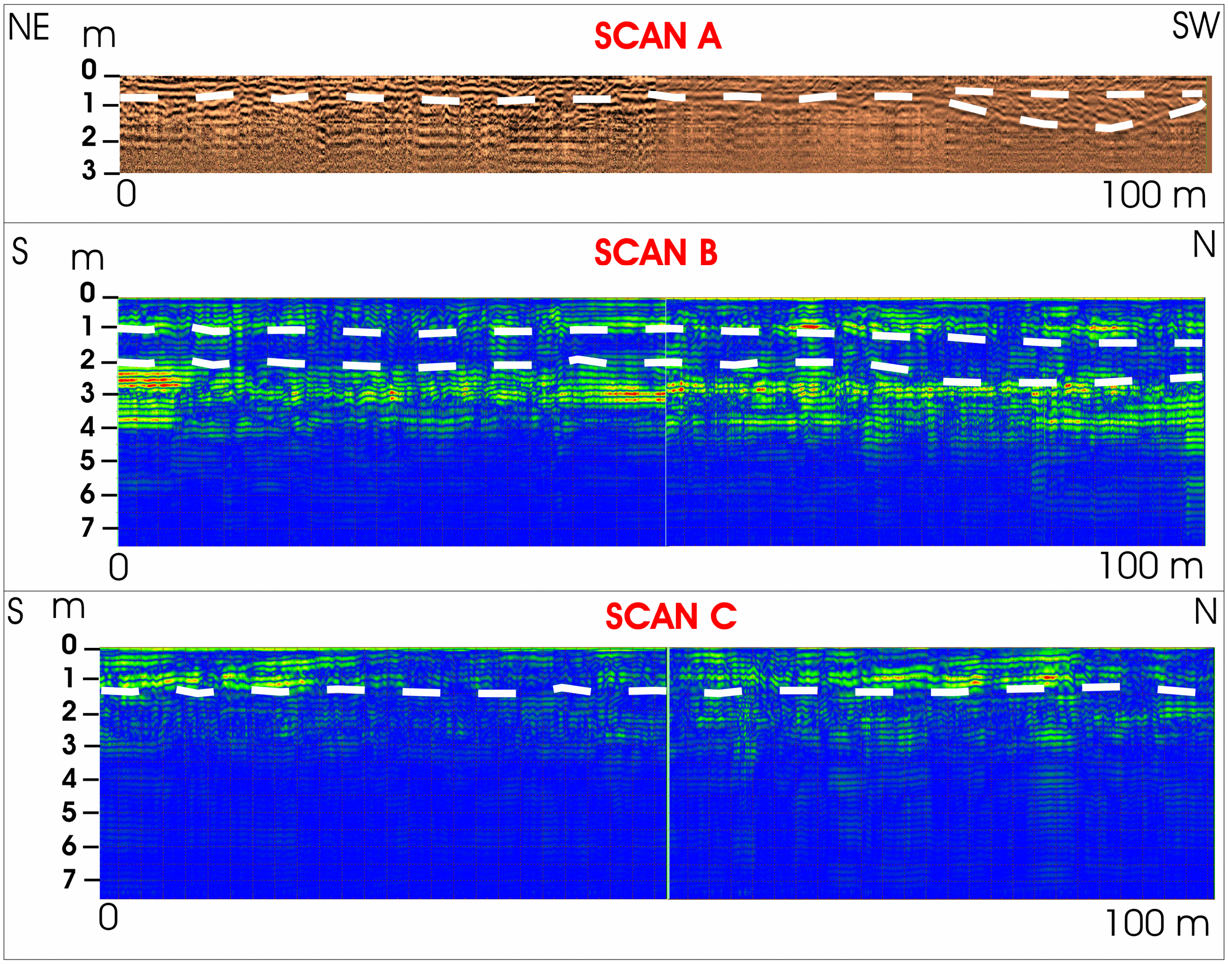

Figure 3. Non-homogeneity horizons (white dashed lines) detected with GPR along the Napoleonic Channel (see Fig. 2 for location). SCAN A (200 MHz antenna): channel form repaired area; SCAN B and C (100 MHz antenna): it is possible to notice how the contact between silt and sand at 2 m depth disappear passing from SCAN B to C.

The elaboration has evidenced a strong *Vs* attenuation at a depth of about 3 m. This confirms the presence, supported by the borehole data, of the latest level of construction, made up of silty sand in respect to the former underlained sandy silt level. The MASW survey allows to highlight this slight difference in lithology being able to detect the higher compaction of the upper level and to confirm its lateral continuity. The electric tomography (Fig. 5 B) has been made with an electrode distance of 2 m, attaining a total length of the scan of 220 m. Results are coherent with the borehole data and definitely more accurate than MASW information. The depth of investigation reached about 20 m, allowing also to detect the base of the embankment at about 11 m depth. The difference in electric resistivity at this depth is due to the sandy-silt to clay passage and to the presence of the water table. The GPR survey has been carried out for 450 m with a 100 MHz antenna (SCAN D Fig. 5 C). Despite the investigation depth is limited to the first 3-4 m, it is possible to mark the contact at about 3 m depth between two differently levels. This contact is visible for the entire length of the scan: a stronger or a weaker signal may be related to soil differences, to moisture changes or/and higher or lower material compaction state. In this case, GPR technique allows to catch the electrical properties difference, but it is only thanks to the multidisciplinary approach adopted, that this feature can be well determined.

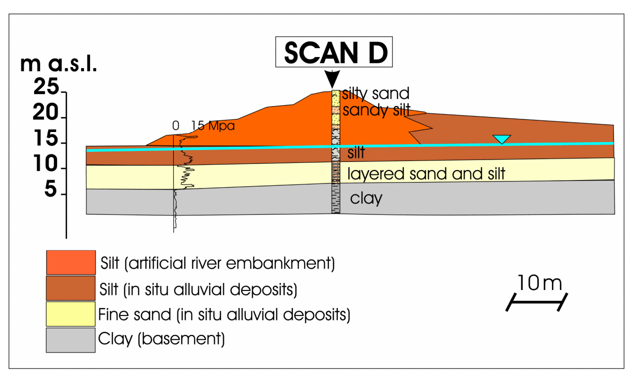

Figure 4. Schematic section along the left side of Reno River (site 2 in Fig. 1) with the location of GPR survey.

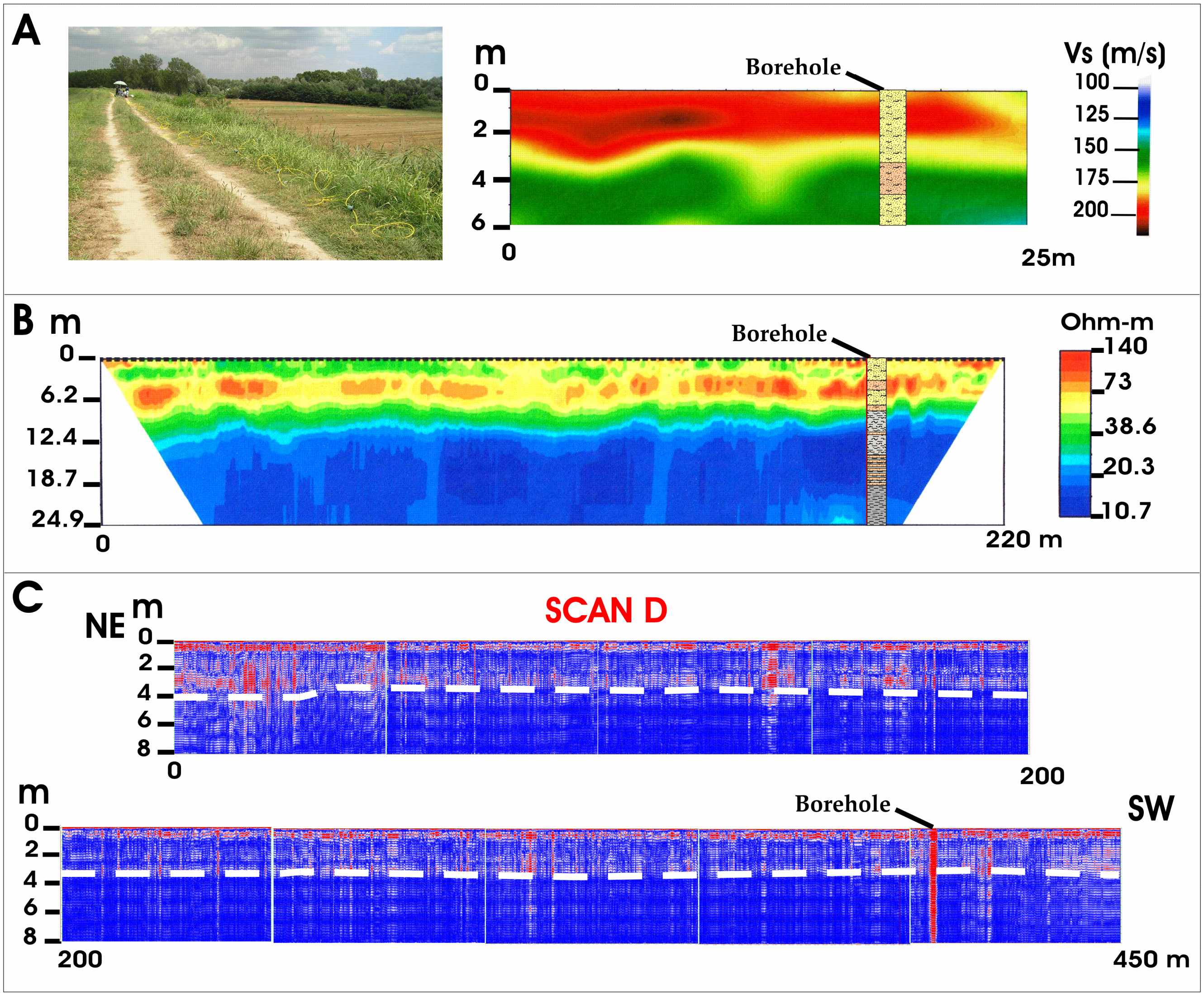

Figure 5. Geophysical investigations along the Reno River; A: Multichannel Analysis of Surface Waves (MASW) is able to detect the higher compaction of the upper level; B: Electric tomography easily reached the base of the river bank; C: GPR survey with a 100 MHz antenna highlight the lateral continuity of the two differently compacted levels.

Along a Reno River tributary (site 3 in Fig. 1), the GPR capability for the detection of repaired portions and animal cavities, has been tested. Along the GPR profile at the top of the embankment (Fig. 6, SCAN E), it was possible to clearly identify zones with strong reflections till the depth of 4 m. These areas correspond to known recently repaired areas. In this case, higher GPR reflections correspond to less compacted soil (Fig. 6, SCAN E). Holes excavated by animals (foxes and nutrias) can seriously compromise the hydraulic safety of river embankment as they may trigger seepage or piping phenomena. Several tests were implemented for the determination of holes development inside the embankment. Along this Reno river tributary, many entries of animal holes were seen at the base of the embankment itself, at a depth of 1 m from the embankment step. A 100 MHz antenna was used in GPR survey. The main aim was to see if, as well as the entrance, the main developing of the hole inside the embankment was recognizable. Respect to many trials on holes, only the biggest one, with a size of about 40 cm, has been detected (Fig. 6, SCAN F). Together with the entrance, another non-homogeneity close to the main, is evident: this may be a portion of the hole inside the embankment. The difficulty for detecting other cavities is due to the size of the holes, which are probably slightly lower than the antenna resolution.

In homogeneous soil the GPR is able to clearly identify shallow isolated objects with a size higher than the maximum resolution. As a matter of fact, it was possible to identify pipelines at unknown depth (Fig. 7 A) and objects having a high permittivity contrast. In case of several anomalies without repeated reflection at depth (Fig. 7 B, C), they have been interpreted as isolated blocks inside filling soil; isolated small anomalies with strong reflection at depth are probably related to metal objects (Fig. 7 D).

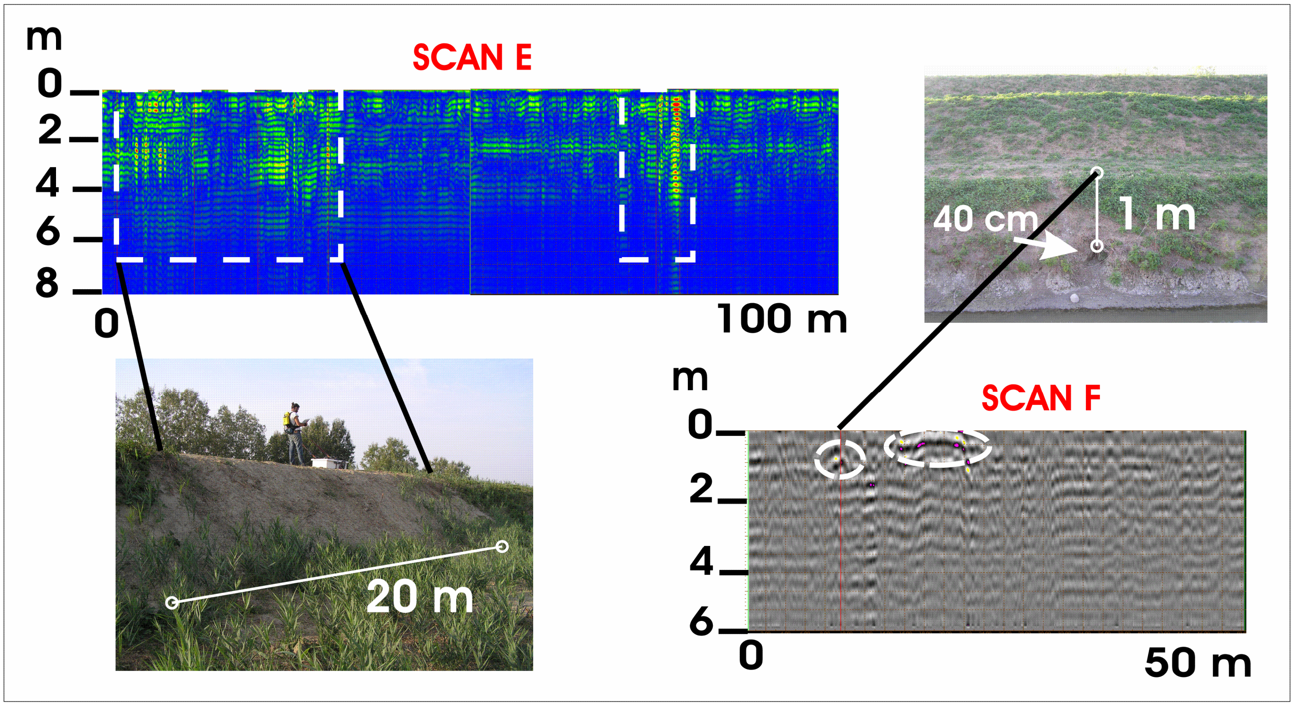

Figure 6. GPR scans carried out along a Reno River tributary (site 3 in Fig. 1) with a 100 MHz antenna; SCAN E: detection of repaired areas; SCAN F: detection of an animal cavity.

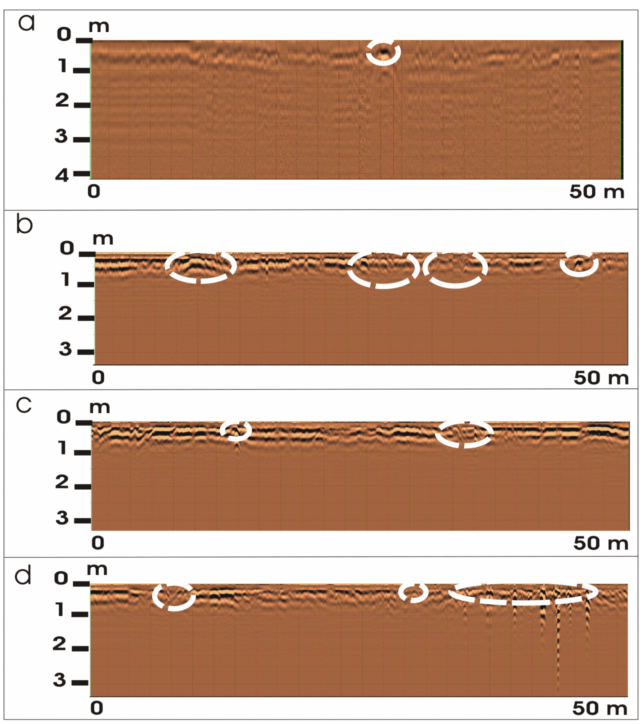

Figure 7. GPR scans carried out for the detection of metal objects (site 4 in Fig. 1); A: pipeline detected with a 100 MHz antenna; B, C: isolated blocks inside a filling soil; D: metal objects.

5. DISCUSSION

MASW and electric tomography are well known techniques for river embankments investigation; nevertheless, for a preliminary research in a spread study areas, also faster investigation methods are required. In the case of Reno River monitoring (scan D), GPR survey allowed to verify lateral continuity of borehole, MASW and electric tomography results to a length of almost 500 m.

The 100 MHz antenna has reached a maximum GPR investigation depth of 4 m which allowed to detect shallow horizontal stratigraphic levels (scan B in Fig. 3) and some isolated non-homogeneities. For this last purpose the 200 MHz antenna resulted more suitable (scan D Fig. 7), even if investigation depth decreased to only 2 m. In respect to typical GPR surveys for archaeological and urban purposes, non-homogeneities in river embankments are more difficult to be detected because of a slight difference in lithology and/or the presence of silty-clayey soil which damp the electromagnetic signal. MASW and electric tomography have required one day of acquisition each, while GPR, performing longitudinal sketches both along the top and on the downward side of the embankment, has been permitted to investigate 3 km of embankments per day. GPR time acquisition was about 7 km per day. Indeed random anomalies like that found along the Napoleonic Channel (scan A, Fig. 3), can be more easily detected with GPR rather than other methods.

The detection of animal cavities still remain an open issue: In respect to about 10 tests tried on observed cavities, GPR has clearly identified only one burrow. The difficulty is mainly due to the fact that animals excavate holes with a complex shape inside the embankments, with interruptions and changing in depth. These variations are hard to be detected with GPR. On the other hand, repaired areas are well recognizable if they have been executed recently, because new material is less compacted in respect to the old one. Reparations executed several years ago are difficult to detect with GPR because the soil compaction with time becomes similar to the surroundings.

6. CONCLUSION

In this research, GPR capability for the study of river embankments has been tested. 15 km of the Reno River and its tributaries have been monitored both along the top and on the downward side of the embankment, taking about 10 working days. The total length of river network in the Reno plain basin is too spread (about 500 km long) for the use of common geophysics techniques in a preliminary phase of study, searching hazardous areas. Some important aspects in the use of GPR came out during the survey: the topography surface must be clean from vegetation and it is not possible to work with rainy weather or with wet soil; furthermore, it is always recommended a calibration with other direct and/or indirect measurements.

It is possible to assert that GPR survey for preliminary river embankment investigation has been a useful tool for the following issues:

-detection of areas with a strong difference in compaction, such as refurbished levels and recently repaired areas: it is important to mention that GPR cannot quantify the compaction state, as other non-invasive techniques like MASW does;

-detection of shallow stratigraphic horizons between soils with a noticeable difference in lithology or moisture content, like medium sand and silt. It has also been possible to check the lateral continuity of a paleochannel at the base of the embankment;

-detection of shallow isolated objects like blocks, metal objects and pipelines.

The detection of animal cavities still remains an open issue: nowadays the best way to assure the hydraulic safety related to the presence of cavities is a constant surveillance. With the chosen antenna frequency of 100 and 200 MHz, the survey results have been strongly influenced by the low investigation depth, due to the high silt fraction. This aspect is a strong limitation of the method: a maximum investigation depth of 4 m over an embankment height ranging from 5 m to 10 m is quite restraining. Spatial resolution is similar to the size of the expected targets: as a matter of fact, objects of known nature and shape have been clearly detected. Strong reflections referred to isolated objects are generally hardly detectable with other methods. Nevertheless, the recognition of animal cavities remains an open problem: cavity entrances at a depth of only 1 m, with a size smaller than 40 cm were not seen in GPR scan.

Considering the need of a preliminary monitoring of spread areas, other innovative geophysical methods such as Geophysical Monitoring System (Boukalová and Beneš, 2007) should be tested in the study area.

With the aware of the above mentioned limits, the GPR technique is a suitable preliminary investigation tool for the detection of potential hazardous areas. Other direct and indirect methods that assure a higher resolution need to be used later on for a thorough analysis.

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REFERENCES

Al-Qadi, I.L., and Lahouar, S. 2005. Measuring layer thicknesses with GPR – Theory to Practice. *Construction and Building Materials,* Vol. 19, pp. 763 – 772.

Bondesan, M. 2001. Hydrographical and environmental evolution of Ferrara Plain during the last 3000 years. *In* History of Ferrara. Vol. 1 “Cassa di Risparmio” of Ferrara, pp. 228-263. (in Italian).

Boukalová, Z., and Beneš, V. 2007. Dike break prevention as the process of flooding protection. *In* Proceedings of 32nd Congress of the International Association of Hydraulic Engineering and Research, Vol. 1, Venice, 1-6 July 2007.

Daniels, D.J. 2004. Ground Penetrating Radar. *Institute Electric. Engineers*, London. 2nd edition, 694 pp.

Elrick, D. E., and Reynolds, W.D. 1992. Infiltration from constant-head well permeameters and infiltrometers. *In* Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. *Edited by*: Topp, G.C., Reynolds, W. D. and Green, R.E., Madison, Wisconsin, Soil Sci. Soc. Amer. Proc., pp. 1–24.

Loizos, A., and Plati C. 2007. Ground penetrating radar as an engineering diagnostic tool for foamed asphalt treated pavement layers. *International Journal of Pavement Engineering,* Vol. 8, pp. 147 – 155.

Mazzini, E., Luciani, P., and Simoni, G. 2006 - The “Cavo Napoleonico” Channel: from the past to the present hydraulic risk reduction programs. *In* Proceedings of 10th International Congress of the IAEG, Nottingham, 6-10 September 2006.

Morris, M. 2005. Investigation of Extreme Flood Processes and Uncertainly, *Project IMPACT, Final Technical Report*, 72 pp. Project website: www.impact-project.net

Neal, A. 2004. Ground-penetrating radar and its use in sedimentology: principles, problems and progress. *Earth Science Reviews*, Vol. 66, pp. 261-330.

Niederleithinger, E., Weller, A., Lewis, R., Stötzner, U., Fechner, Th., Lorenz, B., and Nießen, J. 2007. Evaluation of Geophysical methods for River Embankment Investigation. *In* Proceedings of EFRM*,* Dresden, 6-7 February 2007.

Otto, J.C., and Sass, O. 2005. Comparing Geophysical Methods for Talus Slope Investigation in the Turtmann Valley (Swiss Alps). *Geomorphology*, Vol. 76, pp. 257-272.

Schrott, L., and Sass, O. 2008. Application of field geophysics in geomorphology: Advances and limitations exemplified by case studies. *Geomorphology*, Vol. 93, pp. 55-73.

Smith, D.G., and Jol, H.M. 1995. Ground Penetrating Radar: antenna frequencies and maximum probable depths of penetration in Quaternary Sediments, *Journal Of Applied Geophysics*, Vol. 33, pp. 93 – 100.