Journal of Applied Geophysics 71 (2010) 53–61

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

Application of GPR to the monitoring of river embankments

Monica Di Prinzio [a], Marco Bittelli [b,1], Attilio Castellarin [a,*], Paola Rossi Pisa [b,2]

[a] DISTART — Department of Civil and Environmental Engineering — University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy
[b] DISTA — Department of Agroenvironmental Sciences and Technologies — University of Bologna, Viale Fanin 44, 40136 Bologna, Italy

ARTICLE INFO

Article history:
Received 18 June 2009
Accepted 7 April 2010

Keywords:
Ground Penetrating Radar
Flood-risk mitigation
Levee monitoring
Void detection
Animal burrows

ABSTRACT

Ground Penetrating Radar (GPR) can assist decision making in a number of fields by enhancing our knowledge of subsurface features. Non-destructive investigations and controls of civil structures are improving day by day, however the scientific literature reports only a few documented cases of GPR applications to the detection of voids and discontinuities in hydraulic defense structures such as river embankments and levee systems. We applied GPR to the monitoring of river levees for detecting animal burrows, which may trigger levee failures by piping. The manageability and the non-invasiveness of GPR have resulted to be particularly suitable for this application. First because GPR is an extensive investigation method that enables one to rapidly cover a wide area, locating voids that are difficult and costly to locate using other intrusive methods. Second, GPR returns detailed information about the possible presence of voids and discontinuities within river embankments. We document a series of successful GPR applications to detect animal burrows in river levees.

1. Introduction

Ground Penetrating Radar (GPR) is a geophysical technique to detect and identify structures, either natural or man-made, below the ground surface. The GPR technique has been in use for about a century. The original incentive for its development was military in nature, for the detection of tunnels and buried mines (Daniels, 2004).

Nowadays, GPR is applied in a wide range of engineering surveys as a non-invasive method for mapping subsoil features. GPR surveys can assist decision making in a number of fields in geosciences and engineering by enhancing our knowledge of underground patterns and discontinuities. The literature reports many documented applications of GPR to a vast number of practical problems; a few examples are listed below:

- Utility locating: water, sewer and storm drains lines, electric, telephone, cable TV, etc. (e.g. Al-Nuaimy et al., 2000);
- Concrete detection: localization of reinforcing bars and metallic ducts, rebar radius measurements, slab thickness and other properties detection (e.g. Bungey, 2004; Barrile and Paccinotti, 2005; Chang et al., 2009);
- Bridge and railway monitoring (e.g. Hugenschmidt, 2002);
- Road inspection: pavement structure analysis (e.g. Evans et al., 2006);
- Geological investigation: bedrock profiling, fracture mapping, sedimentology (e.g. Davis and Annan, 1989; Beres and Haeni, 1991; Neal, 2004);
- Environmental assessment and hydrogeophysical studies: underground storage tanks location, soil contamination, water table mapping, soil water content (e.g. Mellet, 1995; Pyke et al., 2008; Gerhards et al., 2008).

In recent years, non-destructive investigations and controls of civil structures are increasingly improving and they are now supported by national and international standards. However, the literature on the applicability of GPR techniques to the problem of levees and river embankments monitoring is still limited. Levees, dykes and river embankments prevent rivers from flooding, mitigating the risk in flood-prone communities. Determining their state-of-health in a non-destructive and, possibly, fast way is a critical issue for a number of public bodies and institutions (e.g., river basin authorities, bureaus of reclamation, civil protection agencies, etc.). Detection and characterization of underground voids within hydraulic defense structures is one of the major issues to deal with. These anomalies may threaten the integrity and the stability of the structure itself. Levees monitoring consists of the identification of potential weaknesses and, currently, is mainly carried out through direct visual inspections along kilometers of levees, which is neither a time nor a cost efficient technique. Moreover it only allows collecting information about the external condition of the investigated area. The detection of hidden voids in river embankments at the earliest possible stage during dry periods is a fundamental

* Corresponding author. Tel.: +39 51 209 3354.
E-mail addresses: marco.bittelli@unibo.it (M. Bittelli), attilio.castellarin@mail.ing.unibo.it (A. Castellarin), ppisa@agrsci.unibo.it (P.R. Pisa).
[1] Tel.: +39 51 209 6695.
[2] Tel.: +39 51 209 6656.

0926-9851/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jappgeo.2010.04.002

requirement, and the identification of an efficient technique for this purpose is a critical issue.

There are a variety of geophysical techniques that are suitable for the general task of delineating voids within the ground (not necessarily in river embankments). Nevertheless, they tend to be mainly used for a local characterization of buried structures. All of them are based on a physical contrast between void and the surrounding material, and they are characterized by advantages and disadvantages depending on the problem at hand.

A gravity survey is one of the most inexpensive geophysical methods when investigating a wide area with relative big cavern (Butler, 1984). Resistivity methods have also been applied for this purpose because the electrical resistance of the void is higher than the surrounding substrate (e.g. Roth et al., 2002 and Lagabrille et al., 2003). Pioneer research on application of the high resolution seismic reflection method to cavity detection was conducted in late 1980s in the US (Branham and Steeples, 1988). However, the resolution of these methods is insufficient for detecting small holes in river embankments, which may facilitate piping and levee breaching during major flood events, therefore producing catastrophic consequences and incalculable damages.

Zhang-qiang et al. (2004) have discussed the main features of high density seismic wavelengths method for the detection of underground cavities. However there still remains ambiguity in their interpretation of cavities.

Another way for detecting voids is to make use of short wavelengths comparable to the GPR (Bachrach and Nur, 1998). However the higher the resolution of the data we intend to acquire, the larger the impact of small heterogeneities on the data and therefore the harder the interpretation of the results.

A method often utilized for extensive survey is the remote sensing. This technique is now employed in several areas of applied research, mainly because of its distinguishing feature of synopticity. Among optical sensors utilized in remote sensing, the hyperspectral scanner MIVIS (*Multispectral Infrared and Visible Imaging Spectrometer*) could be successfully used for the detection of large cavities that could undermine levees stability (Lechi et al., 2001).

Considerations reported above point out that the characteristics of traditional geophysical techniques technically or economically limit their applicability to levee monitoring.

Concerning GPR applications to levee monitoring, in 2000 the usefulness of the GPR for rapid and non-destructive monitoring of earthen flood banks has been proved. Very reliable information was obtained about the lithology and the internal structure of river banks, such as the identification of a flood terrace and a buried paleomeander, the detection of damage failures due to water percolation, fluation, rinsing, outwashing, sinking and erosion, and the localization of old buried cables and pipes (Szynkiewicz, 2000).

Laboratory tests over buried pipes were compared to field applications at the river levee, showing a similar phenomenon of multiple reflections on void-detecting radar images (Sheng Huoo et al., 2002). Biavati et al. (2008) have tested GPR for the detection of non-homogeneities along river embankments. On the one hand, the authors found the GPR survey a useful tool for preliminary investigation of recently repaired areas, characterization of shallow stratigraphy horizons and detection of shallow isolated objects. On the other hand, they encountered some difficulties in the detection of animal burrows because of their unpredictable layout inside the embankments and the variability in depth.

Our study aims primarily at testing the feasibility and the effectiveness of GPR survey on levees or earthen embankments, in particular for the detection of animal cavities and burrows. The presence of these tunnels represents a hazard and it can noticeably worsen the performance of the flood-risk mitigation structures, therefore increasing risk in the flood-prone area protected by the levee itself. The possibility to employ GPR to acquire a detailed knowledge of the integrity of these structures could hold a relevant role from a practical viewpoint. For instance, Italian institutions and public bodies in charge of monitoring hydraulic structures safety (e.g., National Agency for Civil Protection — Dipartimento di Protezione Civile; Interregional Authority for the Po river — Agenzia Interregionale per il Fiume Po) periodically check the state-of-health of the above mentioned structures. The manageability and the non-invasiveness of GPR result to be particularly suitable to this application. In this study, we illustrate a series of successful application of the GPR technique to this problem for minor river embankments.

2. GPR technique: theoretical principles

GPR is a very efficient tool for mapping shallow targets. The best results are obtained when the topographic cover is rather smooth and when the material penetrated is dry (Reynolds, 1997). One of the major advantages of GPR is the capability to perform scans in a continuous way, over a wide area in a relatively short time. In addition GPR data can be viewed in real-time, enabling one to assess the quality of the acquired data directly in the field, and eventually adjust acquisition parameters and settings.

Most commonly, the GPR technique exploits the reflection of high-frequency electromagnetic pulses generated and transferred into the ground. This way, it enables one to detect dielectric discontinuities existing into the material through which the pulse travels. It is the contrast in the dielectric permittivity at the layer boundaries between the bulk medium and the buried targets that causes reflections: the greater the difference in dielectric permittivity, the greater the coefficient of reflectivity (Conyers and Goodman, 1997). These differences are often associated with change in textural, lithology, porosity and density of materials, but especially with water content. Water content mainly controls the signal energy, causing a loss in the wave energy, and changes in water content may produce abrupt jumps in relative dielectric permittivity.

The transmitting antenna broadcasts over the ground electromagnetic pulses at a certain frequency, the pulse spreads into the ground at a velocity typical of that terrain. When the transmitted wave encounters a discontinuity in the dielectric properties, a certain amount of energy is reflected and picked-up by a receiving antenna, the remaining part of the wave continues to travel towards deeper areas.

Two important dielectric parameters for the electromagnetic waves propagation are conductivity and relative dielectric permittivity:

$$\sigma = \frac{1}{\rho} \tag{1}$$

$$\varepsilon_r = \frac{\varepsilon_b}{\varepsilon_0} \tag{2}$$

where σ is the conductivity (1/Ω m, S/m), ρ the resistivity (Ω m), ε the material permittivity (F/m) and ε_0 the vacuum permittivity ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m). ε_b of a porous medium can be considered as the sum of the ε_r the different phases:

$$\varepsilon^\alpha = \theta_l \varepsilon_l^\alpha + \theta_a \varepsilon_a^\alpha + \theta_s \varepsilon_s^\alpha \tag{3}$$

where ε_l, ε_a, and ε_s are dielectric permittivity of liquid water, of air and of the solid phase, α is a geometric parameter (usually equal to 0.5) that depends on the mineral particles positioning and θ_l, θ_a, and θ_s are the volumetric fraction of the respective phases. This relation is called mixed dielectric model (Birchak et al., 1974).

As reported in Table 1, liquid water has the highest value of ε_r (~80), for this reason it plays an important role to the bulk dielectric permittivity of a terrain. This feature can be seen as an advantage if dealing with the measure of the water content and as