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Detecting moisture damage in archaeology and cultural heritage sites using the GPR technique: a brief introduction

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Abstract: Moisture damage is the most important issue in the preservation and integrity of cultural heritage. This paper discusses the ability of geophysical instruments to detect this problem. Non-destructive techniques (NDTs), such as Ground Penetrating Radar (GPR), use electromagnetic (EM) impulses to investigate archaeological sites and building structures that are affected by moisture and can be used to locate and estimate the extent of damage and to develop restoration plans before permanent damage occurs. The main objective of this paper is to introduce the capacity of surface GPR to rapidly and non-invasively estimate physical soil properties, develop novel processing strategies and provide valuable information about the investigated material in archaeological and cultural heritage sites. This new approach analyzes the amplitude attributes of the GPR pulse obtained from conventional single-offset surface-coupled profiling. To achieve the objective of this study, the technique is examined in two different experimental test settings to show that GPR analyses clearly highlight dampness as ringing anomalies with a very low EM signal amplitudes that are caused by high attenuation, poor antenna coupling, and temporal stretching. These indicators are important for diagnosing cultural heritage sites by allowing for the correct and precise visualization of radargrams and time-slices of the moisture anomalies.

Keywords: GPR; Moisture; Amplitude, Attenuation; Time stretching; NDT; Archaeology; Cultural Heritage; Restoration

1. Introduction

Dampness is one of the most common problems found in cultural heritage sites. Structural dampness refers to the presence of unwanted moisture in the structure of a building as the result of either the intrusion of moisture from outside or condensation within the structure.

A high proportion of dampness problems in buildings is caused by the "big three" factors: condensation, rain penetration, and rising damp. Other causes of dampness, such as pipe leakage and construction moisture, are also important [1].

Ground Penetrating Radar (GPR) is a non-destructive geophysical technique that is frequently used to investigate the interior of a medium, in particular for cultural heritage issues [2]. It can also accurately assess the level of moisture inside structures, such as ancient walls or decorated pavement. An autoptic survey of a historical building can only record the presence of surface moisture, but this type of geophysical technique can be used to determine the true moisture content below the surface, document problems caused by construction techniques, diagnose the condition of the artifact and plan for restoration.

Comparisons of autoptic and architectonic surveys (which highlight large and superficial cracks) to GPR surveys confirm not only the presence of the cracks but also the presence of areas that have been altered by the infiltration of water.

Moisture affects building materials due to their porosity and ability to absorb water. All traditional building materials (ancient to modern) have levels of porosity that vary from low to high. The primary sources of water ingress are related to several problems. Rainwater and groundwater (rising damp) can leak into the enclosure (through the roof, walls, windows or foundation) and can often result in mold growth, peeling paint, brick and concrete decay or corrosion. The presence of modern plumbing leaks and spills, which can be the result of improper design, installation, operation or maintenance, can create many dampness-related problems. In general, the most common dampness problems are the wicking of water (so-called capillary suction) through porous building materials (such as concrete or bricks), rainwater, condensation or plumbing water running along the top or bottom of a material, and the infiltration and exfiltration of warm outside and inside air, respectively, through cracks and holes in the enclosure due to a lack of ventilation or insufficient dehumidification by heating, ventilating and air-conditioning systems [3] [4] [5] [6].

2. Materials and Methods

In a bistatic GPR configuration, the signal that is emitted by the transmitting antenna (Tx), which travels along the air/material interface, is composed of two waves: the direct air wave and the direct ground wave [7]. These two waves arrive separately at the receiving antenna (Rx) (i.e., they do not interfere) if the wavelength is smaller than the Tx-Rx offset, particularly when the permittivity of the material is sufficiently high. The ground wave arrival time can be used to estimate the permittivity of the material (by measuring the wave velocity) and therefore its water content [8, 9, and literature therein].

In contrast, for low material permittivities, the first signal that arrives at the Rx is the superposition of the two direct waves, and the ground wave velocity cannot be measured. However, other antenna parameters, such as the signal amplitude of the wavelet, can be used to evaluate the EM properties of the material in the region near the antennas, where the signal propagates through a surface material [10] and [11]. The potential of estimating the soil's dielectric parameters using the high attenuation and temporal stretching of the EM signal amplitude has been demonstrated experimentally and validated by numerical simulations and on-site measurements [12]. In particular, the dielectric permittivity affects both the amplitude and duration of the GPR signal, so higher amplitudes and shorter wavelets are associated with lower permittivities [9, 13, and literature therein].

When GPR data are acquired using a fixed-offset ground-coupled GPR antenna configuration, the ringing anomalies in the radargrams with very low EM signal amplitudes due to high attenuation, poor antenna coupling, and temporal stretching can be analyzed to estimate the physical properties of near-surface materials in archaeology and cultural heritage sites. Note that as discussed above, the signal amplitude is affected by variations in the EM parameters and particularly by permittivity changes, so it is also possible to determine the soil's volumetric water content using an appropriate petrophysical relationship [12].

The theoretical bases of this radar technique are described in [9], [13]-[16], and literature therein. One of the main findings of these studies was an explicit expression for the amplitude of the direct signal that propagates between the antennas, which is related to the relative soil dielectric permittivity. The waveform amplitude has an inverse linear dependence on the permittivity. In particular, [14] and [15] confirmed that because the first arrival of the GPR signals is strongly dependent on variations in the shallow subsurface permittivity, the signal to noise ratio can be maximized by minimizing the interference from reflections caused by shallow interfaces.

3. Discussion

The capability of a non-destructive technique (NDT) such as GPR to probe and detect the dampness distribution in the subsurface of archaeological sites and buildings is discussed here using several examples. The speed, sensitivity to moisture, and relatively low cost of GPR make it one of the best diagnostic NDT methods for archaeological and cultural heritage sites. In particular, this method can be used to accurately determine areas of rising damp, which creates many problems for preservation. Moreover, this type of geophysical approach allows a correct and precise restoration plan to be designed before permanent damage occurs.

The first case focuses on the presence of moisture in the soil of an archaeological feature. Well-drained materials, such as sands and gravels, give rise to relatively high conductivity of the EM signal, whereas moisture-retaining materials, such as clays and silts, generally have lower conductivities [17].

Figure 1 shows an example of an anomaly of a GPR signal in the presence of moisture. The archaeological site near Rome is partially covered by a structure with columns and supporting beams that support the roof. However, the middle of this structure lacks a roof. The figure shows a representation of the covered and uncovered areas. This creates a problem during rainy days. The GPR radargrams show how the NDT instrument can detect a time-stretched signal due to the presence of high levels of moisture after rain. This represents a clear preservation problem because the ingress of this dampness beneath the soil can damage the integrity of the ancient structure.

The second case illustrates the diagnosis of a cultural heritage site that involves the evaluation of the moisture level in a thick travertine wall of an ancient church in Italy. In particular, the presence of different restorations of this portion of the church has caused instability of the static structure. As can be observed in Figure 2, a pad door is visible in the middle of the acquired GPR profile. In particular, the analysis of the radargram of the wall highlighted several detachments and water ingress issues in correspondence of this part of the wall at a depth of 0.5m below the surface. The time-stretching phenomenon that was described previously is slightly attenuated by the restorations, but the dampness is evident as ringing anomalies with a very low intensity EM signal due to high attenuation, poor antenna coupling, and temporal stretching. Figure 3 clarifies this concept and shows the penetration map and a pseudo-3D reconstruction of the moisture within the shallow part of the wall.

Note that this portion of the wall, inside the church, has a relevant lesion and some detachments in the same position of the GPR anomaly detected from the outside surface (Figure 4). These are probably because the dampness, coming from the partially collapsed roof, is recently concentrated in the part of the wall more fragile as the pad door.

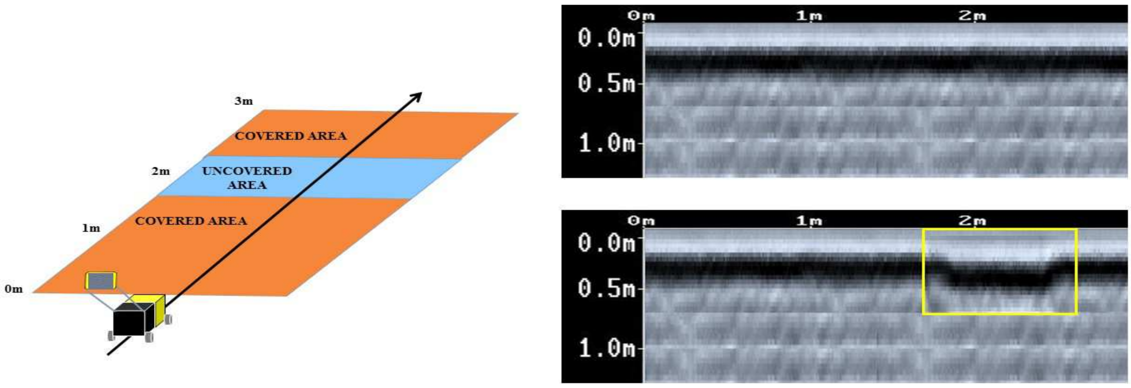

Figure 1. *The figure on the left shows a reconstruction of the archaeological area in which the GPR survey was performed. The radargrams on the right illustrate the differences in time stretching and attenuation of the EM signal in dry (top) and moist (bottom) conditions. The yellow rectangle highlights the anomaly caused by moist conditions.*

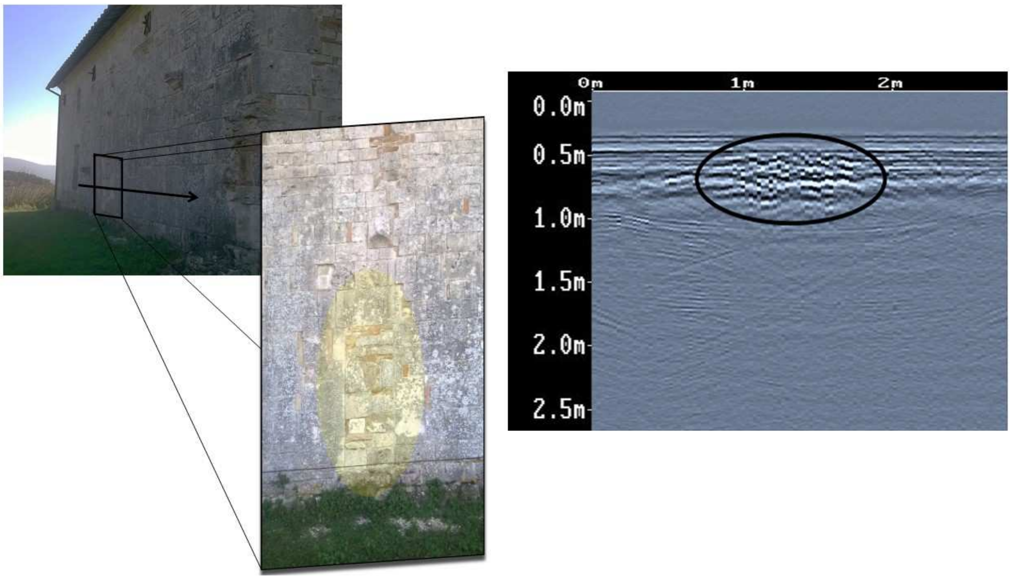

Figure 2. *The figures on the left show a travertine wall of a church with the pad door on which the GPR survey was collected highlighted in yellow. The figure on the right shows a radargram of this acquisition; the area of very low intensity EM signal due to high attenuation, poor antenna coupling, and temporal stretching is clearly located in the middle of the GPR section as strong ringing.*

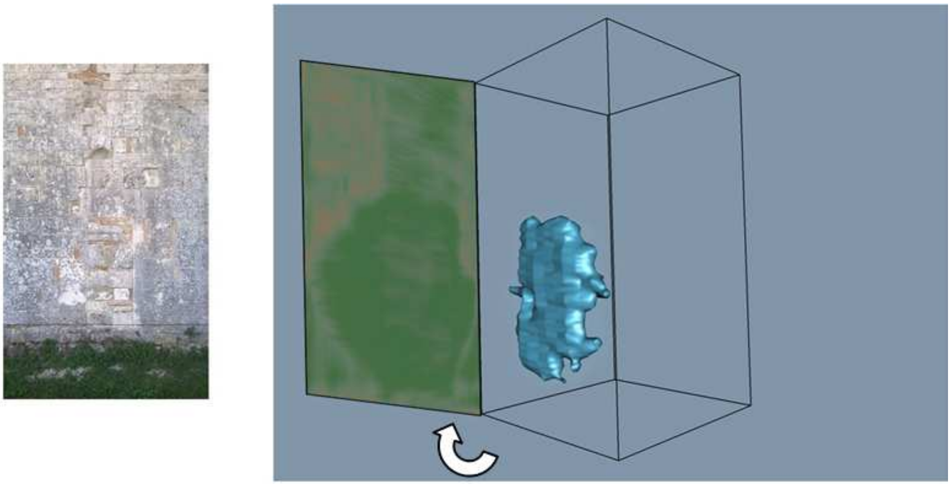

Figure 3. *The figure on the left shows the portion of the wall with the pad door. The figure on the right shows the volume of GPR data that was used to create a pseudo-3D reconstruction of a portion of the subsurface (i.e., a GPR data box). Opening this box allows a penetration map to be developed at a depth of 0.5 m inside the wall (in green), where the dark shadow indicates the presence of moisture. This moisture is also shown as an isosurface in light blue.*

Figure 4. *In these pictures, it is possible to recognize the detachments and the lesion visible in the internal part of the church, corresponding to the area in which the GPR survey is acquired.*

4. Final Remarks and Conclusions

This paper provides a brief introduction to the study and application of an EM technique that can be used to estimate material parameters and, in particular, to a novel use of GPR to obtain valuable information about the presence of moisture in an investigated medium. The novel data analysis approach uses the amplitude attribute information of the GPR signal that is acquired with a standard common-offset ground-coupled antenna configuration and applied to archaeological and cultural heritage sites.

Under these conditions, where the antenna offsets are small, the direct GPR signal is a complex combination of the air and ground waves and carries information about the physical properties of the surrounding material. This is because the amplitude, shape, and duration of the signal change as a function of the EM properties of the material [9].

The main results of this work verified that:

i) a systematic change in the amplitude and duration of ground-coupled GPR early time signals is induced by spatial variations in the shallow soil's dielectric properties, which in this case depend only on the water content distribution in the subsurface medium;

ii) this new GPR data analysis approach is highly suitable for creating detailed maps of variations in the shallow subsurface electric permittivity (e.g., water content);

iii) the evaluation of the shallow soil's dielectric properties using this novel technique instead of more traditionally configured radar systems could represent a practical way to rapidly characterize materials at high spatial resolutions.

This approach to evaluating variations in the shallow dielectric permittivity and conductivity (i.e., the presence of moisture) in a medium is more reliable and consistent than other methods. In particular, this diagnostic technique can be used as an efficient and high precision tool to characterize variations in the shallow subsurface.

Several controlled experiments, numerical simulations, and 'real-life' applications have been conducted to study the effects of EM parameter variations on antenna-material coupling [11].

This introductory paper shows archaeological and cultural heritage applications of examining very low EM signal amplitudes that are caused by high attenuation, poor antenna coupling, and temporal stretching. The obtained results demonstrate that based on the high attenuation of the GPR signal, it is possible to achieve near-surface permittivity information that is consistent with the results obtained from direct ground wave velocity measurements and to accurately predict shallow soil moisture conditions [16].

The advantage of this approach is the ability of GPR to assess soil moisture conditions in sites with different textures (soil and wall structures) under natural and manmade field conditions (rain and restorations) and unknown water contents.

The practical advantages of the use of this technique in an archaeological or cultural heritage context are its speed, non-destructive nature, and the use of relatively inexpensive and cart-mounted GPR systems without separable antennas for mapping the shallow soil water content. In addition, the technique can be combined with standard reflection profiling to extract shallow near-surface information while simultaneously obtaining reflection data from deeper targets.

The effectiveness of GPR-based moisture detection to determine the water content of shallow soil and buildings is based on relatively easy-to-determine EM material parameters. This new radar approach represents an efficient non-invasive soil dynamics monitoring tool, and the unique results that were presented in this paper could represent new operating and processing strategies to rapidly evaluate EM material parameters at high resolutions.

Further field studies should be conducted to provide a more detailed evaluation of the influence of a larger range of water damage in other ancient sites, which will further demonstrate the capacity of this GPR method for characterizing shallow moisture damage in archaeological and cultural heritage sites.

Nevertheless, even if additional improvements are necessary to further develop and test this approach, the GPR moisture detection technique has the potential to be an efficient means of using GPR data to estimate dampness damage information for use in preventive archaeology, restoration planning and time-lapse diagnosis of cultural heritage.

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