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Detecting steel rods and micro-piles: A case history in a civil engineering application

Luciana Orlando

Dept. DICEA, Sapienza University of Rome-via Eudossiana, 18-00184 Rome, Italy

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ABSTRACT

Investigating engineered structures with GPR is challenging because quite often the scale of important features is similar or smaller that the natural scale of heterogeneity in the material.

In this paper I summarize the key factors and use numerical simulations and real data examples to illustrate the tradeoff between detection and resolution. The targets were micro-piles and steel bars with diameters 0.13 m and 0.02 m, respectively, and embedded in an ancient wall that consists of an aggregate of stones ranging in size from 1 cm to half meter, mortar and air. The data were collected with center frequency antennas of 200, 600, 2000 MHz which provide increasing resolution. The model and measurement results indicate that lower resolution may result in a better understanding of the structure imaged with GPR. In fact, high resolution profiles show enhanced anomalies caused by heterogeneities in the host material, making data interpretation more difficult.

This study shows that GPR survey design must be clear about the particular engineering objective and requires selecting the optimal frequency and bandwidth depending on the target dimension.

1. Introduction

Ground Penetrating Radar (GPR) is well known for investigating subsoil with high lateral and vertical resolution, as well as for drawbacks related to the depth of penetration, because the signal under many circumstances is strongly attenuated. Resolution and penetration depend on antenna performance, emitted energy and the frequency bandwidth, as well as the electric parameters (conductivity and permittivity) of the medium and antenna-medium coupling (Shari et al., 1997). In a homogeneous medium, attenuation depends mainly on the medium's conductivity, while resolution depends on bandwidth and the velocity of the electromagnetic wave. Commercial GPR instruments work with antenna center frequencies ranging from 10 to 3000 MHz, and bandwidths of about two octaves. For such frequencies, free-space wavelengths range from 0.10 m to 30 m, which are reduced by about 1/3 (0.03–10 m) for a material with a relative permittivity of 9. Higher-frequency antennas are normally needed for the detection of small targets. In this paper I examine the response of typical targets in civil engineering application.

Many GPR studies have approached the problem of small target detection with the aim of improving the resolution and signal penetration. Indeed, resolution is improved by increasing the wide band frequency by working on hardware, acquisition and data processing (Soldovieri and Orlando, 2009; Turner, 1992), while penetration can be increased by acquiring multi-fold data (Berard and Maillol, 2007; Fisher et al., 1992; Malagodi et al., 1994; Orlando, 2009; Pipan et al., 1996, 1999).

Often, GPR high-resolution performance is regarded as a quality index of the GPR method, and as commercial antennas are band-limited, a selection of the optimal operating frequencies is chosen as a function of the electric parameters of the host material and of the depth and dimension of the targets to be detected. Generally, low-frequency antennas are preferred for deeper investigations, while high-frequency antennas are preferred for shallower ones.

The high resolution achieved with GPR has led to its widespread use in civil engineering investigation of small targets, such as wire mesh, rods, piles, sewers, etc., ranging in size from a few millimeters to more than half a meter. Because most of the host structures are built with resistive materials (concrete, stone, etc.), the selection of antenna frequency is based mainly on the desired lateral and vertical resolution.

The choice of antenna frequency is often made without taking into account the heterogeneity of the host material, which in most cases is assumed to be homogeneous, even if it consists of aggregated materials of different size and electromagnetic properties. The material classification – homogeneous or heterogeneous – is closely related to the wavelength of the signal. In fact, materials can be homogeneous for low frequencies and heterogeneous for high. On increasing antenna frequency, resolution is enhanced and anomalies from the heterogeneity of the host material arise in the GPR section. These anomalies affect the signal backscattered from the target in two ways: 1) obscuring and/or reducing target detection; and 2) causing a loss of transmitted energy by scattering. Both phenomena are extremely frequency-dependent and can become more important than

E-mail address: luciana.orlando@uniroma1.it.

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electrical loss (Annan, 2003). In general the backscattered electromagnetic energy depends on the electromagnetic parameters of the host material and target, the relative size of the target in relation to the signal wavelength, the incident angle of the signal, the reflected angle of the signal, the strength of the radar transmitter and the distance between transmitter–target–receiver.

All these parameters add to complexity of the GPR antenna frequency selection. Indeed, the interpretability of the GPR section is not a simple task as it is not related to the signal wavelength in a straightforward way.

The purpose of the paper is to study the influence of antenna frequency on the ability of GPR to detect steel rods (0.02 m in diameter) and micro-piles. The latter are about 25 m long, 0.13 in diameter, spaced 1.6 m apart and drilled in a heterogeneous stone wall. The micro-piles are themselves heterogeneous because they are formed by an iron casing filled with concrete. Here I draw particular attention to the influence of heterogeneity on the interpretability of the GPR data. To achieve the objective, I recorded and modeled the response of steel rods in concrete beams and micro-piles drilled into the wall of an ancient building. The wall consists of an aggregate of stones ranging in size from 1 cm to 0.5 m, mortar and air. The employed antenna frequencies were 200, 600 and 2000 MHz. I selected two cases which differ greatly in the properties of the matrix in which these targets were embedded: one in a simple homogeneous concrete and the other a stone wall that can be considered homogeneous for low antenna frequencies and heterogeneous for high frequencies.

2. Theory and forward modeling

2.1. Simple theory

GPR signals propagating through complicated media encounter heterogeneous electrical and magnetic properties at many different scales. The heterogeneities capture the energy and scatter it in all directions, often generating weak or undetectable responses (Annan, 2005, 2009). The most suitable antenna frequency is chosen by taking into account the desired lateral and vertical resolution, the target depth and the electromagnetic properties of the materials. The effectiveness of a GPR investigation, in the field or for civil engineering, depends on the interaction of many factors that are often not simple to analyze. An important factor is the relation of the signal frequency to the dimension and shape of the target, and the heterogeneity of the host material.

2.1.1. Backscattered energy

The complexities associated with the interaction between waves radiating from dipole antennas placed near a dielectric half-space and the electrical heterogeneities within the dielectric medium often assume the far field approximation to model propagation phenomena. Despite the proximity, the short dipole length D and wavelength λ often satisfy the far field criterion $= 2D^2/\lambda$. For example a typical D = 22 cm, 400 MHz dipole with $\lambda = 75$ cm gives a far field distance of only 13 cm. Inside a dielectric of relative permittivity $\varepsilon = 4$, the far field distance is <7 cm. Civil engineering investigations are often concerned with targets located in the near-field zone that may not be detected or detected with distortion, because of the overload of receiver electronics and the overlapping of direct and ground waves with the desired signal.

In the far-field, a target reflects a limited amount of energy, and the type of backscattered energy depends on the radar cross section (RCS) and wavelet spectrum. Basic results for a simple metal sphere, (Fig. 1, after Skolnik, 1970), and a single-frequency excitation, show how the scattering cross-section (σ) normalized by the geometric cross-section (πr^2) varies as a function of the sphere circumference normalize to the wavelength

$$S = 2\pi \cdot r/\lambda, \quad (1)$$

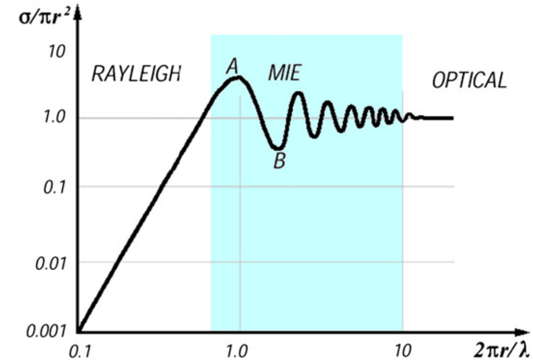

Fig. 1. Scattering cross-section as a function of the object dimension normalized (2π·r) by the geometric cross-section (πr2) and the signal wavelength (λ), respectively. The sphere of arbitrary dimension is a perfectly conducting and excited for a single frequency signal (Skolnik, 1970).

where r is equal to the sphere radius, and λ = wavelength. The target may scatter a fraction or nearly all of the power of the incident field that intersects the sphere (Fig. 1). For $S << 1$ the signal is diffracted (Rayleigh region), and for $S >> 1$ it is reflected (optical region). In the transition zone (Mie zone, Fig.1) resonance of signal occurs. In some cases the diffracted energy analysis is the only way to detect targets of a size below the resolution and to characterize particular materials (Al-Qadi et al., 2008) but it is not able to resolve the dimension of the target.

As an antenna emits a broad band of frequencies, it is possible that, during signal propagation, a fraction of the high-frequency energy is diffracted and a fraction of the low-frequency energy is reflected, depending on the size, shape and orientation of the buried target (Balanis, 1989; Daniels et al., 1988; Knapp, 1991; Radzevicius and Daniels, 2000). Moreover, the re-emitted energy also depends on the incident energy (which is controlled by the transmitter power, directivity and distance away).

In most civil engineering cases the host material is heterogeneous and the backscattered energy fall into the Rayleigh and resonance regions (Mie), depending on the dominant wavelength of the pulse. In this case, the amount of scattered energy can change rapidly with the signal wavelength for a given target. The inappropriate choice of antenna frequency may reduce ability to detect the target.

2.1.2. Resolution

The resolution is normally divided into two components, namely vertical or radial and lateral resolutions (Yilmaz, 2001), both of which are controlled by the signal wavelength.

Vertical resolution is controlled by the dominant wavelength (λ) of the signal and defines how close two layers can be vertically distinguished. Generally, the threshold for vertical resolution is a quarter of the dominant wavelength ($\lambda/4$) which is independent of depth. With equal bandwidth, resolution increases upon increasing the dominant frequency. In real applications the resolution also depends on data noise.

Lateral resolution refers to how close two reflecting points must be separated horizontally to be detected. This resolution depends on the Fresnel radius (Fr), given by

$$Fr \cong \sqrt{((h+\lambda/4)^2 - h^2}, \quad (2)$$

where λ is the wavelength, and h is the depth of the target (Yilmaz, 2001). For a target substantially far away from the measurement point ($\lambda << h$), Eq. (2) can be approximated with the following relation:

$$r \cong \sqrt{\lambda h/2}. \quad (3)$$

Lateral resolution decreases with increasing depth, and therefore the depth of the target is also important in the choice of antenna