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Estimation Methods for Obtaining GPR Signal Velocity

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Abstract—**Ground Penetrating Radar (GPR) has proven to be a promising nondestructive measurement methodology in transport infrastructure diagnostics as well as in many other fields. Thanks to the upgraded hardware and software technology, GPR is fast becoming a key instrument to obtain the properties of subsurface materials/layers with different relative permittivity by making use of the reflected electromagnetic energy. An important element in the use of GPR technology is the knowledge of the signal velocity of above-mentioned energy in the examined building materials, soil and rock layers. If this velocity is known, and time between sending and receiving the reflected signal is measured, the depth of the object or dielectric interface (as well as the thickness of the various layers of materials) can be estimated. Present study attempts to characterize and compare the available methods for acquiring the GPR signal velocity used in transport infrastructure evaluation.**

Keywords—**ground penetrating radar (GPR), signal velocity, relative permittivity, transport infrastructure**

I. Introduction

In the early stages of Ground Penetrating Radar (GPR) use, the main objective was not beyond detecting subsurface anomalies, utilities and existence of reflectors to be excavated later, rather than to determine the accurate depth of the said objects. The focus has shifted gradually from this superficial "subsurface object detection" to more specific surveys where the goal is to map subsurface in real depth removing the necessity of subsurface excavation as much as possible. [1], [2]

The essential prerequisite of determining the depth of object or interfaces is the knowledge of the signal velocity of electromagnetic radiation emitted into the investigated materials and layers of soil and rock. If the signal velocity is known and time between sending and receiving the reflected signal is measured (two way travel time - TWT), the depth of the object, or dielectric interface (as well as the thickness of the various layers of materials) can be estimated.

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Travel time of the GPR signal is substantially the only direct measurement obtained in the field. The signal velocity, however, is variable and dependent on the physical properties of the medium among which relative permittivity (ε_r) is the most significant one.

In the literature many tabular values of this variable can be found, such as in Table 1.

TABLE 1. RELATIVE PERMITTIVITY, CONDUCTIVITY AND PROPAGATION VELOCITY OF GPR IN DIFFERENT MATERIALS [3]

Materials	ε_r	σ (S/m)	v (m/ns)
Air	1	0	0.3
Distilled water	80	0.01	0.033
Water	80	0.5	0.033
Marine water	80	0.003	0.01
Dry sand	3–5	0.01	0.15
Wet sand	20–30	0.1–1	0.06
Limestone	4–8	0.5–2	0.12
Shale	5–15	1–100	0.09
Silt	5–30	1–100	0.07
Clay	5–40	2–1000	0.06
Granite	4–6	0.01–1	0.13
Dry salt	5–6	0.01–1	0.13
Ice	3–4	0.01	0.16
Frozen ground	3–6	–	–
Concrete	4–10	–	–
Metal	1–2	–	–

However these values should be used only for reference, due to the complexity of the EM wave behavior issues and characteristics of each site and material. It can be also determined by a direct measurement on samples in the laboratory or in situ by e.g. percometer.

Once relative permittivity is known, the relative signal velocity can be computed from (1):

$$v = \frac{c}{\sqrt{\varepsilon_r}} . \qquad (1)$$

Where
v = the signal velocity,
c = the speed of light,
ε_r = the relative permittivity. [2]

II. Available Methods Characterization

Above mentioned approaches do not obviously require GPR usage to estimate relative permittivity; however there are many methods using GPR how to acquire this variable from radar recorded data. Generally there are two groups of methods which are methods using the reflected waves and methods using direct waves.

A. *Reflected Wave Methods*

The methods using reflected waves require that sent energy is reflected back by objects or stratigraphic interface of known (measured) depth. In this case, it is necessary (in order to accurately measure the signal velocity) to provide multiple measurements with burying strong reflector at varying known depths. This is because the velocities calculated in each case could be different due to the variations in water saturation and/or ground composition with depth. In order to obtain direct measured depths, core drills, probes etc. can be utilized. Once signal velocity is known, the depth of object or interface can be computed from (2):

$$d = v \cdot \frac{t}{2} . \qquad (2)$$

Where

d = the depth of object or stratigraphic layer of interest,

t = two way radar travel time to and from the target. [2]

Reflected wave methods can be used either at one point where only one trace signal is measured (this record is called the A-scan) or on profile with repeated consecutive measurements with the specific stationing increment by moving the antenna along the measured profile (this record is called B-scan as can be seen in Fig. 1) [14]. In this case the transmitter and the receiver simultaneously move along the measured profile with a constant mutual spacing. This method is called profiling or fixed offset method (FOM), and also common offset method (COM).

In the 2D matrix of a B-scan (this is actually a vertical cut by the material or construction), each row represents one sample point (pulse) on a column which represents each individual trace. The value of the matrix element is the voltage amplitude for a given trace and the sample. Assigning color bar to voltage amplitudes can display matrix as the image.

Most recently, the measurement can be performed on large areas, either by repeating the measurement on parallel profiles with the constant spacing, or using antenna arrays. A record of such 3D measurement is then called C-scan, and allows easier data interpretation and identification of targets (e.g. to create horizontal or vertical cuts at any point). [5]

Data analysis of above mentioned methods uses only single trace on each location, so it is called a single trace analysis (STA).

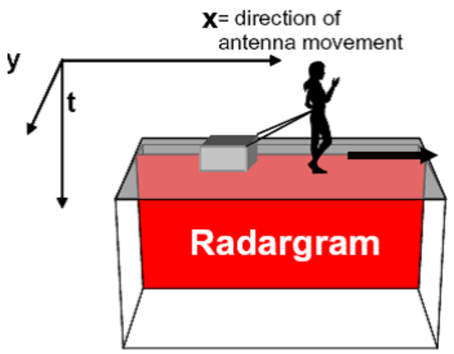

Figure 1. Schematic view of a B-scan [4]

When above mentioned B or C-scan is performed over point source reflections (pipes, walls, rocks, etc.) we can use velocity analysis based on geometric evaluation of generated hyperbolic reflections (as depicted in Fig. 2). The shape of created hyperbolas is a function of the average signal velocity in the material and the size of the point source that caused the reflection. [2]

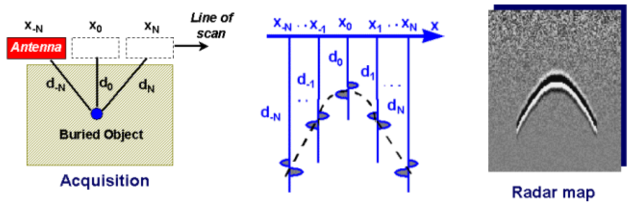

Figure 2. Hyperbolic reflection principle [5]

The hyperbolic reflection is formed due to fact that EM signal is emitted from antenna in a shape of a cone. Transmitted energy is thus reflected from objects that are not directly below the antenna, but these reflections are recorded in the position (stationing), wherein the antenna is currently located (directly below current position of the antenna). As a result of longer trajectory (higher TWT) of oblique wave, these reflections are recorded at greater depths than they are actually located. The peak of hyperbola indicates current target position and shape of a hyperbola depends on horizontal step and signal velocity in the material (the higher velocity/lower dielectric permittivity causes wider hyperbolas and vice versa). Size of the target can be estimated by the width of the flat top of hyperbola. [5]

Another type of reflected wave methods is called Reflection Coefficient Method (RCM). This method uses comparison of the reflected signal amplitudes at the air/surface layer interface with amplitudes on the air/total reflector interface [6]. In most cases a metal plate is used as a total reflector. This way you can determine the dielectric constant of the material (signal velocity) for surface layer according to (3):

$$\varepsilon_a = \left[\frac{1 + A_1 / A_m}{1 - A_1 / A_m} \right]^2 . \qquad (3)$$

Where

ε_a = the dielectric value of the surfacing layer,

A_1 = the amplitude of the reflection from the surface,

A_m = the amplitude of the reflection from large metal plate (100% reflection case) [7]

For the second layer and the following layers the calculation of its relative permittivity is based on above mentioned equation. For the second layer (4) is used:

$$\sqrt{\varepsilon_b} = \sqrt{\varepsilon_a} \cdot \left[\frac{1 - \left[\frac{A_1}{A_m}\right]^2 + \left[\frac{A_2}{A_m}\right]}{1 - \left[\frac{A_1}{A_m}\right]^2 - \left[\frac{A_2}{A_m}\right]} \right] . \qquad (4)$$

Where

ε_b = the dielectric of the layer 2 (base layer),

A_2 = the amplitude of reflection from the top of layer 2 [7]

This method is applicable to air coupled antennas. Also equation 4 can be used with the assumption of no attenuation in surface layer. The most accurate results of this approach can be for example obtained on asphalt layers thicker than 60 mm without any thin layers in between the asphalt and the second layer. [7]

B. *Direct Wave Methods*

Methods using direct waves (principle shown in Fig. 3) operate with the wave that travels from the transmitter directly via the material to the receiver over a known path. [2]

The direct wave methods include primarily Wide Angle Reflection/Refraction (WARR), and the Common Midpoint (CMP) method. In the first case, one antenna remains stationary while the other moves along the measurement profile. In the latter case, two antennas simultaneously move away from each other on both sides from a common center point. In case of relatively homogeneous environment, CMP generally provides realistic approximation, but for multilayer terrain with variable porosity or with different degrees of saturation, it delivers only a rough estimation [3]. In most cases, the CMP and WARR tests are usually used only to determine the velocity in near surface layers. For greater depths they should be used only in cases where it is somehow possible to determine the actual path of GPR signal [2]. Also Common Source and Common Receiver methods can be included in direct wave methods [9]. All these methods, due to their nature, are known as variable offset methods (VOM). Since more traces are used in above mentioned methods, the data analysis method is called multiple trace analysis (MTA) [4].

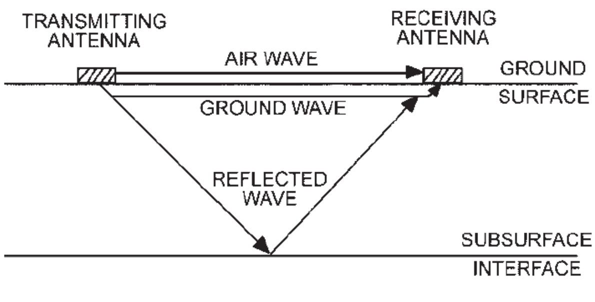

Figure 3. Direct wave method principle **[8]**

Another direct wave velocity test is called Trans illumination (principle indicated in Fig. 4), where transmitter and receiver antennas, facing toward one another, are placed on the opposite sides of earth body in between two trenches. The walls of the trenches should be parallel. It is preferable to also perform measurements as soon as possible after excavation works to avoid leakage or evaporation of water, which could result in changes in the dielectric properties of the material. The thickness of the body between the transmitter and receiver should be greater than the used wavelength (eliminating the effect of near-field zone). The disadvantage of this method is, as with other direct wave methods, the uncertainty in determining the exact path of GPR signal. [2]

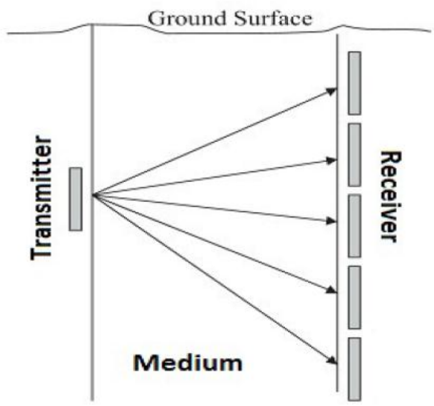

Figure 4. Transillumination principle **[9]**

III. Data Acquisition, Processing and Interpretation

All the tests were conducted in the Educational and Research Centre in Transport, Jan Perner Transport Faculty, University of Pardubice. Tests were performed on material samples stored in IBC containers (clay, sand and gravel), concrete floor of the laboratory and asphalt road (with known layers) in adjacent area.

A. *Used Equipment and Software*

For all GPR measurements RIS Hi-Pave system provided by Ingegneria Dei Sistemi S.p.A. (IDS) was used. This system consists of DAD MCH Fast-Wave control unit, air coupled shielded dipole antenna HN-2000 with central frequency of 2 GHz, ground coupled TR Dual Frequency antenna with central frequency of 400/900 MHz, and accessories. While air coupled antenna was placed 30 cm above surface, ground coupled one was placed directly on the surface without an air gap during the tests. Both antennas are monostatic (both transmitter and receiver are placed in same antenna with fixed offset), thus only Reflected Wave Method tests were possible to be performed. For data acquisition during the tests K2 Fast Wave software (IDS) was used. Both wheel driven and auto stacking (time based) modes were used during data acquisition. Then those recorded data were viewed and processed in Mr. Sandmeier's Reflex W software (http://www.sandmeier-geo.de).

B. *Data Processing*

Following data processing steps were used in above mentioned Reflex W software to better display data and to get usable outputs.

- Dewow (subtract-mean) function in 1D filter sub menu to remove low frequency content.
- Envelope function in complex trace analysis sub menu to confirm identification and exact position of surface reflection.

- For air coupled antenna, correct max phase function in static correction sub menu was used to compensate antenna bumping and make the surface reflection horizontal.
- For air coupled antenna, move starttime in static correction/muting sub menu was used to adjust surface reflection to time zero level.
- Background removal in 2D filters sub menu to remove background noise and to enhance signal-noise ratio.
- Gain function in gain sub menu was used according to the attenuation properties of materials to amplify desired reflections.
- Running average in 2D filter sub menu was used to better display horizontal interfaces (to highlight horizontal consistent energy and avoid trace dependent clutter).
- Subtracting average in 2D filters sub menu was used to better display hyperbolic reflections by highlighting signals which change laterally (e.g. diffractions)

C. *Measurement procedure*

1) Hyperbolic reflections

To acquire signal velocity using hyperbolic reflections, ground coupled antenna was used only. The reason is that the above mentioned geometry principle assessment cannot be applied properly while using air coupled antenna due to the fact that transmitted signal travels through different media (air, evaluated material). In obtaining hyperbola reflection, it is necessary, of course, to move antenna above the target on the measured profile with continuous recording of the traveled distance as mentioned before. This movement can be done by attaching the antenna to a car (or a cart) with using GPS or odometer device (referred as wheel driven mode). Example of hyperbolic reflections velocity assessment (antenna attached to a cart) in Reflex W can be seen in Fig. 5.

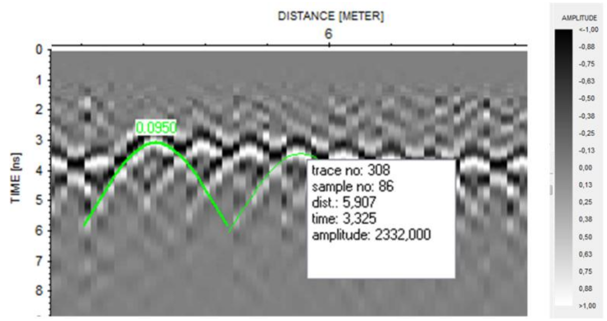

Figure 5. Hyperbolic reflections of steel mesh in concrete floor

Since some of the tests were conducted on laboratory samples in IBC containers only, above mentioned approach could not be used. In this case (when it is not possible to use wheel driven mode due lack of space), it is possible to move antenna manually over the sample in auto stacking (time based) mode. However, it is required to move antenna with constant speed on pre-measured line. Besides, it is significant to start data recording at the precise moment that the antenna starts to move and similarly to stop recording when the antenna stops to move at the end of the pre-measured line. After data recording, it is also important to change trace increment in the radargram in order to fit the line length to recorded data distance. Only after these steps, shape of the hyperbola corresponds to its real shape as if the measurement was performed in wheel driven mode. In order to attain the most precise shape of the hyperbola over point source reflection, higher central frequencies (related to maximum range and depth of the reflector) should be used.

2) Calculation based on known depths

Tests based on this method were performed on several construction material samples stored in IBC containers with variable layer thicknesses. In every case, surface reflection and metal plate reflection (placed at the bottom of the box with known/measured depth) were identified on radargram. On both interfaces TWT values were noted and time difference was determined. Then based on the known depth and determined time difference, signal velocity was calculated according to (2). Example of thus obtained radargram together with trace is shown in Fig. 6.

To identify precise position of interface, it is necessary to estimate interrelation between interface materials. In the case that top layer has lower ε_r than lower layer, the position of the interface should be picked as a sample on the trace with the highest positive value of signal and vice versa. If this interrelation is not known (or materials have similar ε_r values), it is reasonable to pick the sample with value closest to zero to minimize the possible error in determining the interface position.

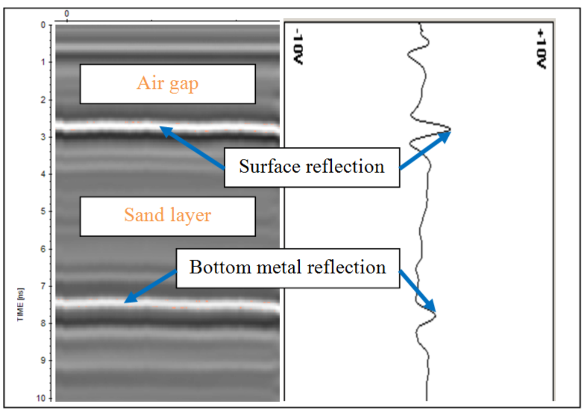

Figure 6. Recorded GPR data for known depth method use

In this method, not only precise identification of interfaces, but also precise depth measurement is necessary. For example, 1 % inaccuracy in measuring the depth on 1 m thick layer results in 1 % error in signal velocity calculation (as can be observed from (2)).

When using only half a thick layer, the error in result is doubled, and accordingly for other thicknesses.

3) Reflection coefficient method

To acquire signal velocity using this method, only air coupled antenna was used to prevent near field zone effect. This phenomenon is caused by strong electromagnetic field around the antenna within a radius of about 1.5 wavelength of the central frequency generated by EM energy emitted from the surface of the antenna. This zone is, due to using lower frequencies in case of ground coupled antennas, larger than in case of air coupled antennas, which usually operate with higher central frequencies. Also ground coupled ones are placed directly on the surface, thus the surface remains in the near field zone, while in case of air coupled one, there is an air gap. The compared amplitude values (used in (3)) are affected by air gap dimension, so it is required to keep the antenna at the same height during measurement both on a metal plate and the surface.

IV. Results and Conclusion

In most cases, it is not an easy task to determine the signal velocity. Many times it is also difficult to determine the causes of the differences in various materials and environments. Signal velocity values can be very different while measuring in laboratory conditions or in-situ. It is essential that any acquired velocity from in-place tests should be implemented to GPR profiles that were acquired at or about the same time and similar climate conditions. Also when using tabular values from literature, it is always necessary to keep in mind some uncertainties related to conditions while the data was recorded that may not be mentioned in those tables. Comparison of tabular data with data obtained based on reflection coefficient method performed in laboratory conditions with above mentioned equipment can be seen in Table 2.

TABLE 2. COMPARISON OF SIGNAL VELOCITY VALUES OBTAINED BY REFLECTION COEFFICIENT METHOD AND USED LITERATURE

Material	Signal velocity obtained by RCM [cm/ns]	Signal velocity tabular values (literature) [cm/ns]
Asphalt	10.1-11.1	13.0-17.0
Clay (Dry)	13.6-15.1	4.7-13.4
Concrete	10.2-10.3	9.5-15.0
Gravel (16/32 mm)	19.0-20.8	8.0-21.0
Sand (Dry)	14.8-15.6	13.4-17.3

Also choosing the most suitable method of determining the signal velocity can be a quite complicated task. Even with the same equipment and in same environment, results may differ due to the lateral and vertical variations in the material (which are not considered in RCM compared to known depth method). For example signal velocity obtained by known depth according to (2) for dry sand was varying from 12.9 – 13.8 cm / ns.

Observations from measurements and result discussions indicate that anyone who attempts to obtain the GPR signal velocity of some material has to bear in mind that not only selected method, environmental and/or equipment characteristics, but also material properties such as moisture content, grading, compaction, etc. can lead to data misinterpretations in utilization of each method which may result in erroneous determination of signal velocity. This error could then cause inaccurate time depth conversion and hence wrong positioning or dimension determination of detected object or interfaces.

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