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Influence of physical properties of a soil medium on locating with the use of geo-radar of underground installations

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Abstract: A geo-radar method is used for detection of underground installations with the use of electromagnetic waves. Results of investigations of installations depend on physical properties of soil media, which properties result in suppression, reflection and refraction of electromagnetic waves. Three parameters, electric permittivity ε, magnetic permittivity μ and the medium conductivity σ play the major role in establishing electric features of a material medium.

Suppression of the electromagnetic wave has the basic influence on detection of underground installations with the use of the geo-radar, and, in particular, on the depth range of the method. Relation between designing parameters of the geo-radar equipment and its depth range is determined by the basic equation of the geo-radar method. Solution of the basic equation of the geo-radar method for the needs of detection of underground installations requires performing experimental measurements.

Measurements of the maximum depth of detection of underground installations with the use of the geo-radar have been performed in media of known physical properties, i.e. in the air, water and water solutions of NaCl of various concentrations. Two steel pipes of diameters of $\phi = 0.03$ m and 0.10 m were the objects for testing. Measurements were performed with the use of antennae of frequencies of 1000 MHz and 200 MHz. The results obtained in the form of echograms were analysed in order to determine the maximum distances for which the tested pipes were recorded. Experiments allowed to state that the maximum measurements of the depth range of the geo-radar equipment is rapidly decreased with the decrease of the background's specific resistance below 50 Ωm. An increase of the soil resistance above 500 Ωm results in slight increase of the depth range of measurements.

Tests and analyses performed concerned homogenous media, i.e. metal installations, for which the electromagnetic wave is fully reflected.

Keywords: Geo-radar, locating underground installations, depth range, dielectric constant, suppression of electromagnetic waves

1. Introduction

An electromagnetic pulse is suppressed, reflected and refracted in the soil medium. Those phenomena are described by Maxwell equations. Suppression of the electromagnetic wave has the basic influence on detection of underground installations by means of the geo-radar. The knowledge concerning the influence of the soil medium on detectability of underground installations of specified parameters is required for selection of the geo-radar method as a method of measurements. Detection of underground installations with the use of the geo-radar depends, among the others, on the type of equipment applied, frequencies of electromagnetic waves propagating in soils, size and materials used for construction of installations and the depth of their location.

Manufacturers of recent geo-radar equipment specify technical data that allows for calculating measuring parameters of those instruments. Calculations are simple in the case of the electromagnetic wave reflecting from a flat surface of investigated objects. They are however, complicated for objects of complex shapes. If data required for calculations is missing, it is not possible to recognise theoretical parameters of measurements.

The subject literature contains complicated theoretical calculations of model echograms for localised installations, which occur in media of diversified physical properties (Carcione and Schoenberg, 2000; Wang and Oristaglio, 2000). Performance of such calculations is difficult in the case of commercial works conducted for the needs of surveying inventory of underground installations. The majority of publications concerning location of underground installations are dedicated to particular examples of detection of installations in specified soil media (Annan et al., 1984).

Suppression of electromagnetic waves, which has the basic influence on the depth range of geo-radar measurements in soils are presented in publications (Hipp, 1974; Bergmann et al., 1998). The subject literature does not present any analyses and tests concerning methods of experimental determination of parameters, which specify the depth range of the geo-radar in the case of location of underground installations for specified conditions of soil media and types of installations.

Tests presented in this paper allowed for specification of depth ranges of the geo-radar applied for location of metal pipes. The diagram of relations between pipe diameters, frequencies of electromagnetic waves, specific resistance of the medium and depth of radar penetration, has also been developed. Methodology of measurements, proposed by the authors may be useful for various types of geo-radar equipment.

2. Influence of physical properties of the medium on suppression of electromagnetic waves

Electric features of a material medium are influenced by three parameters: electric permittivity ε, magnetic permittivity μ and the conductivity of the medium σ. For the majority of rocks and minerals (dielectrics) that compose the Earth's crust, the magnetic permittivity μ is approximately equal to the magnetic permittivity of vacuum.

The relative electric permittivity ε_r and the relative magnetic permittivity μ_r are determined by the following equations

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{1}$$

$$\mu_r = \frac{\mu}{\mu_0} \tag{2}$$

where

$\varepsilon_0 = 8.859 \cdot 10^{-12}$ F/m is an electric permittivity of vacuum,

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m is a magnetic permittivity of vacuum,

ε is an electric permittivity of the medium [F/m],

μ is a magnetic permittivity of the medium [H/m].

For the majority of rocks and minerals (dielectrics) that compose the Earth's crust, the relative magnetic permittivity $\mu_r = 1$.

If one assumes the unlimited, linear, isotropic, uniform and low-loss material medium, the suppression factor α is defined by the following equation (Morawski and Gwarek, 1985)

$$\alpha = \frac{1.69 \cdot 10^3 \cdot \sigma}{\sqrt{\varepsilon}} \text{ [dB/m]} \tag{3}$$

The equation for the electromagnetic wave velocity has the form

$$v = \frac{c}{\sqrt{\varepsilon_r}} \text{ [m/s]} \tag{4}$$

where c is light velocity in vacuum.

It turns out from (3) that the suppression factor is directly proportional to the conductivity. For the majority of soil media, where the conductivity σ is lower than several hundreds mS/m, the equations (3) and (4) may be applied. For non-uniform media of high diversification of ε and σ parameters, equations (3) and (4) have more complex forms.

The level of suppression of electromagnetic waves in a given medium depends on its:

- mineral and chemical composition,
- structure and moisture,
- applied wave frequency.

An increase of suppression is influenced by the increase of porosity of rocks and temperature of the medium. The conductivity of the medium, and, therefore, the suppression, increases with the increase of the moisture of the soil medium. Suppression resulting from that factor grows rapidly with high frequencies of electromagnetic waves (higher than 1 GHz). It is caused by oscillation of water particles, which absorb some parts of energy.

3. Theoretical foundations of measurements performed by means of the geo-radar method

The phenomenon of reflection of the electromagnetic wave occurs on the border of two media of different dielectric constants. In the geo-radar equipment, the impulse of the electromagnetic wave is transmitted by an antenna into the investigated medium.

A receiving antenna records reflection of that wave from the so-called, "subsurface border". The known time t, between the moment of transmission of the wave impulse and the moment of recording of its return allows for determination of the depth using the following formula

$$D = \frac{c \cdot t}{2\sqrt{\varepsilon_r}} \text{ [m]} \tag{5}$$

For the majority of background materials, the value of dielectric constant varies between 1 and 88 units. The higher the differences of the dielectric constant between two media, the clearer is the change of distribution of the electromagnetic wave on the border of those media.

The basic equation of the geo-radar method determines the relation of construction parameters of the geo-radar equipment with its depth range (Skolnik, 1990; Noon, 1996). The following formula allows for calculating the power P_R of the received signal

$$P_R = \frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2 \cdot \sigma_T}{(4 \cdot \pi)^3 \cdot D^4 \cdot L} \text{ [W]} \tag{6}$$

where

- P_T – power of the transmitted impulse of electromagnetic wave [W],
- G_T – amplification of the transmitting antenna [abstract units],
- λ – length of electromagnetic wave [m],
- G_R – amplification of the receiving antenna [abstract units],
- L – coefficient responsible for suppression of waves in a geological medium [abstract units],
- σ_T – effective surface of reflection of the localised object [m^2],
- D – the distance from the reflecting object [m].

Assuming P_R equal to the minimum power ($P_{\min}$) that may be recorded by the receiving antenna, the maximum depth range ($D_{\max}$) will be calculated.

After transformation of (6) one obtain:

$$D_{\max} = \left(\frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2 \cdot \sigma_T}{(4 \cdot \pi)^3 \cdot P_{\min} \cdot L} \right)^{\frac{1}{4}} \text{ [m]} \tag{7}$$

The majority of parameters on the right hand side of (7) depend on constructional features of the geo-radar. Only the effective surface of reflection σ_T and the coefficient L depend on the geological medium and on parameters of the localized object.

The coefficient L will be determined by the equation

$$L = e^{4\alpha \cdot D} \tag{8}$$

where α is the coefficient of suppression calculated with (3).

The effective surface σ_T of the localized object depends on its shape, on the length of the electromagnetic wave, on the contrast of the dielectric constant ε_r between the object and its surrounding environment and on other factors.

After substituting the coefficient L (calculated from (8)) to (7), one obtains

$$D_{\max} = \left(\frac{P_T \cdot G_T \cdot G_R \cdot \lambda^2 \cdot \sigma_T}{(4 \cdot \pi)^3 \cdot P_{\min} \cdot e^{4\alpha \cdot D_{\max}}} \right)^{\frac{1}{4}} \tag{9}$$

Assuming P_T, G_T, G_r and $P_{\min}$ constant values for the given geo-radar equipment, the following constant K may be introduced

$$K = \frac{P_T \cdot G_T \cdot G_R}{(4 \cdot \pi)^3 \cdot P_{\min}} \tag{10}$$

After substituting K to (9) the following non-linear equation is obtained

$$D_{\max} = \left(K \cdot \frac{\lambda^2 \cdot \sigma_T}{e^{4\alpha \cdot D_{\max}}} \right)^{\frac{1}{4}} \quad [\mathrm{m}] \tag{11}$$

4. Experimental measurements of geo-radar parameters

The measurements of the maximum depth of detection of underground installations by means of the SIR-8 type geo-radar required that tests for a medium of known physical properties were performed. The air environment has been assumed for measurements, for which $\varepsilon_r = 1$ and $\sigma = 0$ S/m.

Two steel pipes of diameters $\phi = 0.03$ m and 0.10 m were tested. Measurements were performed separately for each pipe. The antenna and the pipe tested were located in the air. Tests consisted of averting of the pipe from the antenna and simultaneous recording of its echogram. Obtained echograms were analysed in order to specify the maximum distances of recording. Measurements were performed with the use of antennas of frequencies of 1000 MHz and 200 MHz. The results of measurements lead to the following conclusions for the 1000 MHz antenna:

– the pipe of 0.03 m diameter is recorded within the distance $D_{\max} = 1.7$ m from the antenna,

– the pipe of 0.10 m diameter is recorded within the distance $D_{\max} = 2.2$ m from the antenna.

Measurements performed by means of the 200 MHz antenna proved that:

- for the 0.03 m diameter pipe the maximum recorded distance equaled to $D_{\max} = 3.9$ m,
- for the 0.1 m diameter pipe the maximum recorded distance equaled to $D_{\max} = 5.2$ m.

Measurement results were applied for calculations performed with the use of "the basic equation of the geo-radar method" (6).

The value of α calculated for the air by means of (3) equals to 0.

Since K is constant for a given antenna, then substituting the values of $D_{\max}$, calculated earlier, to (11) gives

$$\frac{D^4_{\max 0.03}}{\sigma_{T0.03}} = \frac{D^4_{\max 0.1}}{\sigma_{T0.1}} \tag{12}$$

where

$D_{\max 0.03}$, $D_{\max 0.1}$ – maximum depth ranges for pipes $\phi = 0.03$ m and $\phi = 0.1$ m,
$\sigma_{T0.03}$, $\sigma_{T0.1}$ – effective surfaces of reflection for pipes $\phi = 0.03$ m and $\phi = 0.1$ m.

The ratio $\frac{\sigma_{T0.03}}{\sigma_{T0.1}}$ for the 1000 MHz antenna equals to 0.35, and for the 200 MHz antenna it equals to 0.36. The results obtained from experimental measurements prove that for the medium with $\varepsilon = 1$ and for steel pipes, the ratio of effective surfaces of reflection approximately equals to the ratio of diameters of tested pipes.

5. Geo-radar experiments

It turns out from (11) that the parameters, that influence mostly the depth range of the geo-radar, are the suppression coefficient α and lengths of electromagnetic waves λ. The suppression coefficient α specified by (3) depends on the value of the dielectric constant ε_r and conductivity σ. The relation between conductivity σ and specific resistance ρ of the geological medium is specified by the formula

$$\rho = \frac{1}{\sigma}\ [\Omega\mathrm{m}] \tag{13}$$

The length λ of electromagnetic wave that propagates in the given environment, is calculated by means of the formula

$$\lambda = \frac{c}{\sqrt{\varepsilon_r \cdot f}}\ [\mathrm{m}] \tag{14}$$

where

c – light velocity in vacuum [m/s],
f – frequency of the wave [Hz].

After substituting to (11) conductivity σ and the wavelength λ, specified by (13) and (14), respectively one obtains

$$D_{\max} = \left(K \cdot \frac{c^2 \cdot \sigma_T}{\varepsilon_r \cdot f^2 \cdot e^{4 \cdot 188.5 \cdot \frac{1}{\sqrt{\varepsilon_r} \cdot \rho} \cdot D_{\max}}} \right)^{\frac{1}{4}} \tag{15}$$

Transformation of (15) leads to

$$K \cdot \sigma_T = \frac{D^4_{\max} \cdot \varepsilon_r \cdot f^2 \cdot e^{4 \cdot 188.5 \cdot \frac{1}{\sqrt{\varepsilon_r} \cdot \rho} \cdot D_{\max}}}{c^2} \tag{16}$$

The values of K and f are assumed constant for a given geo-radar equipment. It is also assumed that σ_T does not change for an underground installation of known parameters. Determination of the maximum depth range D_{max} of the geo-radar equipment in the suppressing medium required the performance of experimental measurements.

Water environment was the medium which best suited to the conditions of measurements. The specific resistance of that medium may be freely modelled by adding appropriate amounts of various chemical compounds that are soluble in water. Basing on performed measurements the specific resistance of water was obtained $\rho = 50\ \Omega$m.

Basing on the above considerations the following research criteria were assumed:

- measurements should be performed by a non-movable antenna of the frequency of 1000 MHz, located in a tank filled with water of the dielectric constant $\varepsilon_r = 81$–88 (depending on the level of water mineralization),
- the distance between the level of antenna and water level should be constant and equal to 0.15 m,
- the measured object, such as the steel pipe of the diameter of 0.1 m, should be placed on the water surface,
- the specific resistance of the medium should be changed by adding soluble chemical compounds, between 1 and 50 Ωm.

The objective of research was to determine the specific resistance of the medium, for which the geo-radar equipment stops recording the electromagnetic impulse, reflected from the steel pipe. Measurements were performed in the following way. Soluble chemical compounds were added to the water medium that filled the space between the geo-radar antenna and the pipe located within the distance of $D = 0.15$ m from the antenna. Then, the specific resistance of the given solution was determined and geo-radar recording was performed with simultaneous measurements of power of the recorded impulse P_R. That value was compared with power P_W, obtained in measurements performed for the clear water. Results of measurements are listed in Table 1, where ratios of P_R to P_W impulses are given in percentage.

Table 1. Relation between the ratio of power of recorded impulses P_R and P_W, and the specific resistance of solution

Type of compound dissolved in water	Na_2CO_3		$MgSO_4$		NaCl		NaOH		$NaHCO_3$	
Volume of compound dissolved in 1 litre of water [g]	ρ [Ωm]	$P_R/P_W \times 100\%$	ρ [Ωm]	$P_R/P_W \times 100\%$	ρ [Ωm]	$P_R/P_W \times 100\%$	ρ [Ωm]	$P_R/P_W \times 100\%$	ρ [Ωm]	$P_R/P_W \times 100\%$
0.4	12.0	50	18.0	60	11.0	40	4.0	6	27.0	80
0.8	6.0	22	8.0	30	5.0	17	2.0	–	12.0	50
1.2	4.5	10	6.0	20	4.0	7	1.5	–	9.0	40
1.6	3.0	5	4.5	8	3.0	5	1.2	–	7.0	25

Tests were performed for the following chemical compounds: Na_2CO_3, $MgSO_4$, NaCl, NaOH and $NaHCO_3$. Concentrations of the solutions were equal to 0.4; 0.8; 1.2 and 1.6 g/l, respectively. Figure 1 presents example echograms performed for various solutions of NaCl.

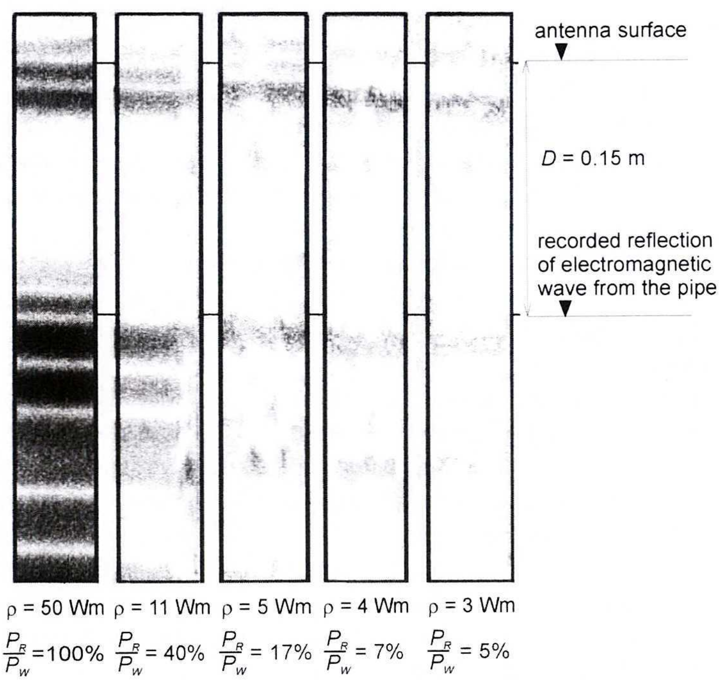

Fig. 1. Echograms of variations of power of recorded signals reflected from the pipe of 0.1 m diameter, located in media of various specific resistance

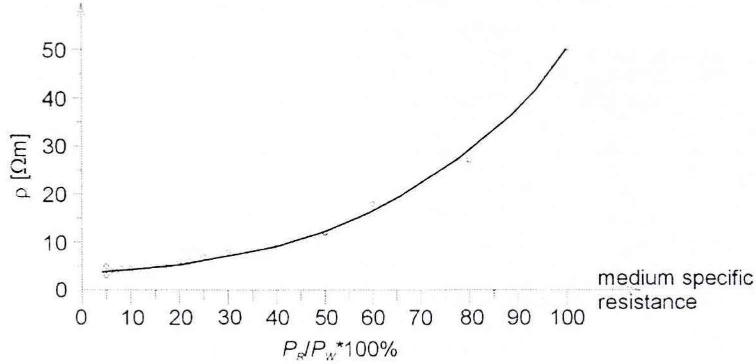

Fig. 2. Diagram of relations of power of recorded impulses of electromagnetic waves and the medium specific resistance

Results of tests (compare Table 1 with Fig. 1) allow for evaluation of the influence of variations of the specific resistance of the medium, of the dielectric constant $\varepsilon_r = 81–88$, on the level of recorded impulse of the electromagnetic wave, reflected from the steel pipe of the diameter $\phi = 0.1$ m. The percentage decrease of the impulse power, depending on the specific resistance of the medium, is presented in Fig. 2.

After analysing of obtained results it has been stated that, for the specific resistance $\rho = 2\ \Omega$m and the dielectric constant $\varepsilon_r = 81–88$, the geo-radar equipment does not record the investigated object located within the distance $D = 0.15$ m. Thus it turns out that for those parameters of the medium, the determined distance has the maximum value $D_{\max}$.

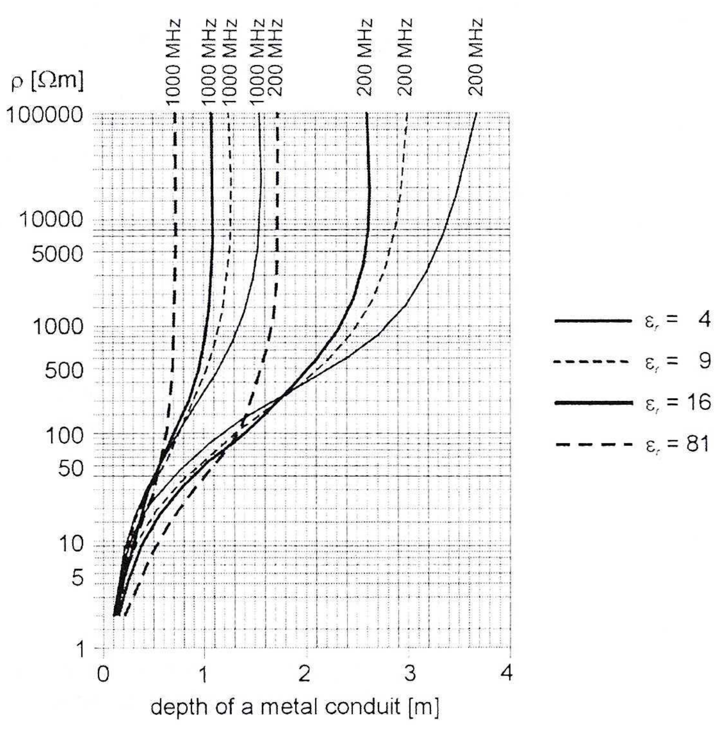

Fig. 3. The scope of measurements of depth of a metal conduit of diameter $\phi = 0.1$ m with the use of geo-radar antennae 200 and 1000 MHz in media of various specific resistance ρ and dielectric constant ε_r

Therefore, after substituting the dielectric constant value $\varepsilon_r = 81$, the specific resistance $\rho = 2\ \Omega$m and $D_{\max} = 0.15$ m to (16), the product $K \cdot \sigma_T = 239$, for the frequency of 1000 MHz was calculated. The product $K \cdot \sigma_T$ calculated same way for parameters $\varepsilon_r = 1$, $\rho = \infty\ \Omega$m and $D_{\max} = 2.0$ m equals 260. If $K \cdot \sigma_T = 239$ is substituted to (16), then $D_{\max}$ will be equal to 2.15 m. Analysed values of $K \cdot \sigma_T$ product, were experimentally determined for the radar antenna 1000 MHz. As a consequence it has been assumed that $K \cdot \sigma_T$ product is constant for a given geo-radar equipment with the antenna of the specified frequency and specified effective surface of reflection σ_T. Using it, one may calculate and state whether it is possible to detect underground installations at the given depth in the soil of specified physical properties. This allows for calculating $K \cdot \sigma_T$ product for the antenna of the frequency 200 MHz. Basing on experimental measurements the value of 325 was obtained for the discussed product.

Values of $K \cdot \sigma_T$ calculated for both antennae, substituted to (15) were the basis for making diagrams of the maximum depth ranges of geo-radar measurements (Fig. 3). Calculations were performed for dielectric constants $\varepsilon_r = 4, 9, 16$ and 81 and $\rho = 2, 10, 30, 60, 100, 200, 1000$ and ∞ Ωm. The $K \cdot \sigma_T$ product has been assumed from measurements performed for the pipes of 0.1 m diameter.

Considering relations described by (12), it is possible to perform similar calculations for other diameters of metal conduits.

Conclusions

Experiments allow for stating that the maximum range of depth measurements of the geo-radar equipment rapidly decreases with the decrease of the specific resistance of the background below the value of 50 Ωm.

The effectiveness of detection of installations in soils of low specific resistance (below 50 Ωm) by means of the geo-radar equipment is low.

The developed diagram (Fig. 3) of the maximum depth ranges for geo-radar antennae of various frequencies, allows for stating that slight increase of the measurement range is obtained with the increase of soil resistance above 500 Ωm.

Performed tests and analyses concerned uniform media. They were performed for metal installations that fully reflect electromagnetic waves. Depth ranges decrease for non-uniform media and non-metal installations.

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Wpływ właściwości fizycznych ośrodka gruntowego na lokalizację przy użyciu georadaru instalacji podziemnych

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Streszczenie

Metodą georadarową wykrywane są instalacje podziemne z zastosowaniem fal elektromagnetycznych. Wyniki badań instalacji zależą od właściwości fizycznych ośrodka gruntowego, którego własności powodują, że fala elektromagnetyczna ulega tłumieniu, odbiciu i załamaniu. O cechach elektrycznych ośrodka materialnego decydują trzy parametry: przenikalność elektryczna ε, magnetyczna μ oraz jego przewodność σ.

Tłumienie fali elektromagnetycznej ma zasadniczy wpływ na wykrywanie instalacji podziemnych georadarem, a zwłaszcza zasięg głębokościowy metody. Związek parametrów konstrukcyjnych aparatury georadarowej z jej zasięgiem głębokościowym określa podstawowe równanie metody georadarowej.

Rozwiązanie podstawowego równania metody georadarowej dla potrzeb wykrywania instalacji podziemnych wymaga przeprowadzenia pomiarów eksperymentalnych. Pomiar maksymalnej głębokości wykrywania instalacji podziemnej z zastosowaniem georadaru, wykonano w ośrodkach o znanych właściwościach fizycznych tzn. w powietrzu, wodzie i roztworach NaCl o różnych stężeniach. Obiektami badanymi były dwie rury stalowe o średnicach $\phi = 0.03$ m i 0.10 m. Pomiary wykonano z zastosowaniem anten o częstotliwościach 1000 MHz i 200 MHz.

Otrzymane wyniki w postaci echogramów, poddane zostały analizie, celem określenia maksymalnych odległości, w jakich zarejestrowano badane rury. Badania eksperymentalne pozwoliły na stwierdzenie, że maksymalny pomiar zasięgu głębokościowego aparatury georadarowej zmniejsza się intensywnie wraz ze spadkiem oporu właściwego podłoża poniżej 50 Ωm. Wzrost oporności gruntu powyżej 500 Ωm, powoduje nieznaczne zwiększenie zasięgu głębokościowego pomiarów.

Przeprowadzone badania i analizy dotyczyły jednorodnych ośrodków. Wykonano je dla instalacji metalowych, od których fala elektromagnetyczna odbija się całkowicie.