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Experimental testing of geo-radar resolving power for detection of underground installations

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Abstract: A geo-radar image of a recorded underground conduit has a hyperbolic shape in an electrically homogeneous background. Echograms of conduits, which are located close to one another, overlap leading to possible interpretation errors.

The paper presents a method of experimental determination of resolving power capabilities of a given type of geo-radar equipment for the needs of detection of underground installations.

It has been proved, basing on performed experiments that the horizontal resolving power of detection of underground installations depends on the type of applied geo-radar equipment and on the frequency of electromagnetic waves. Together with the increase of the dielectric constant of the medium, where underground installations are located, the horizontal resolving power also increases.

Keywords: Geo-radar, resolving power, underground installations

1. Introduction

It is the geo-radar that is used for subsurface penetration of the terrain. Its operations consist of transmitting high frequency impulses from an antenna and of recording those waves when they are reflected by objects or by, so-called, subsurface borders.

A geo-radar image of a recorded underground conduit has a hyperbolic shape in an electrically homogeneous background; the size of such a hyperbole considerably exceeds the size of the conduit. This results in overlapping of echograms of conduits which are located close to one another. For a given type of equipment and properties of ground soil environment there exists a distance between two located conduits, which is the minimum distance required for correct interpretation of those conduits. When that distance is shorter than the minimum value, the echogram of both conduits may be interpreted as an image of a single installation.

Recognition of relations between parameters of the applied equipment, properties of the soil media and location of underground installations, allows for correct evaluation of the accuracy of their localization.

The subject literature contains theoretical calculations of model echograms for installations, which occur in media of diversified physical properties (Carcione and Schoenberg, 2000; Wang and Oristaglio, 2000). Models of echograms discussed in those publications are not analysed with respect to resolving power.

Interpretation of the influence of construction of geo-radar antennas on the resolving power is presented in (Daniels et al., 1988).

The papers (Alberti et al., 2001) and (Groenenboom et al., 2001) present accuracy analysis of geo-radar measurements of two parallel conduits. Their authors, however, do not consider the resolving power of equipment for various measuring conditions.

Investigations presented in this paper aimed at determination of approximate resolving power capabilities of a specified geo-radar with respect to detection of two parallel metal installations, located in soils of diversified electric properties.

2. Environmental factors influencing geo-radar measurements

The electromagnetic wave that falls on a border between two media is both reflected and refracted. Those phenomena are described by Maxwell equations, and, assuming specified conditions of consideration, they may be interpreted by means of geometrical optics. In typical media which are not ferromagnetic materials, variations in propagation of the electromagnetic wave depend mainly on their electric properties.

The soil background behaves more or less as the perfect dielectric. From the physical point of view, borders of heterogeneity in such a background will be the borders of media which differ in the parameter of the dielectric constant ε_r. For the majority of materials that are the components of the soil medium, the dielectric constant varies between 1 and 88 units. The larger the difference in the dielectric constant between two media, the clearer is the variation in propagation of electromagnetic waves on the borders of those media.

Suppression of electromagnetic waves depends on the conductivity σ of the medium, in which the wave is propagated. Rocks characterized by the high conductivity and suppression include clays and silts; lower conductivity and suppression is characteristic for dry sands. Together with increase of the media moisture, its conductivity also grows.

3. The essence of geo-radar measurements

Reflection of the electromagnetic wave is the basic property of a geological medium which is used for geo-radar measurements. If the, so-called, geological interbedding, exists under the terrain surface in the form of variable layers, e.g. a silt layer occurs under a layer of sands, radar impulses are reflected on the subsurface borders.

The essence of geo-radar measurements is presented in Fig. 1. It consists of moving the antenna along the determined profile between assumed field points, for example, between points No 1 and 2. An electromagnetic wave impulse of the specified frequency and amplitude is transmitted by the antenna. That wave is reflected on the border of both media and returns to the equipment, where it is electronically processed and recorded. Successive impulses, transmitted in the course of antenna moving, scan the background and create its image which is called the echogram. Figure 1 presents lines of the signal recording level; interval of those lines is the decisive factor concerning the quality of the obtained echogram.

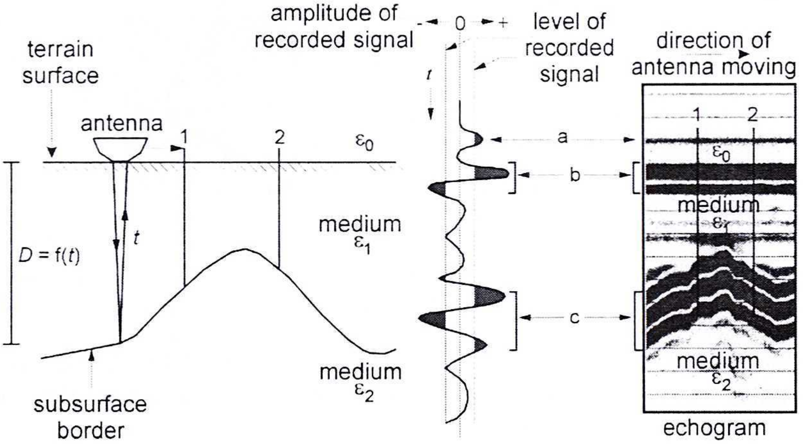

Fig. 1. Overall diagram of measurements using the geo-radar method; a – initial impulse, b – impulse reflected from the Earth surface, c – impulse reflected from the subsurface border, D = f(t) – depth as the function of time, ε_1, ε_2 – dielectric constants of media

The depth of the "subsurface border" is calculated by the formula:

$$D = \frac{c \cdot t}{2\sqrt{\varepsilon_r}} \quad [\text{m}] \tag{1}$$

where:

c – the light velocity in vacuum [m/s],

t – time required by the recorded electromagnetic impulse for going through the path [s].

In an electrically homogeneous background, the geo-radar echogram of the underground conduit has the hyperbolic shape. The overall diagram is presented in Fig. 2.

Let us consider the following example. Electromagnetic waves transmitted by the antenna propagate in the space. The electromagnetic impulse transmitted from the antenna at point No 1 passing the distance D_1 to the conduit is reflected (Fig. 2a). Coming back to the antenna, it passes the same distance. The transmitted and reflected impulse will pass the distance $2D_1$ within time t_1. Moving the antenna to the point No 2, the time required by the impulse for passing the distance to the conduits, is shortened. Moving it further along the direction to the point No 3, the antenna records the image in a similar way (comparable to Fig. 2b).

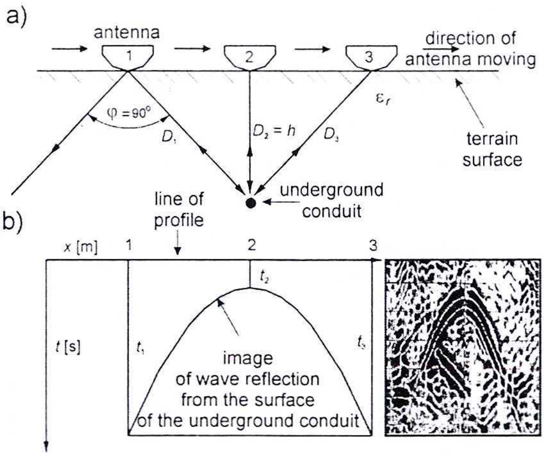

Fig. 2. Overall diagram of construction of the echogram of underground installations for measurements with the use of the geo-radar method

On a radar image, this distance will correspond to the time, when it was passed by the wave. Transforming (1), one obtains the equation (2) that was used for calculation of the time of passing of the analyzed wave.

$$t = \frac{2D\sqrt{\varepsilon_r}}{c} \quad [\mathrm{s}] \tag{2}$$

Let us consider the theoretical model of the echogram for a conduit of a circular cross-section. The following assumptions are taken:
- the electromagnetic impulse should propagate in the infinite, linear, isotropic, homogenous medium, without any loss,
- the line of measuring profile should be perpendicular to the axis of the linear object,
- dimension of the cross-section do not affect the shape of the echogram (the cross-section diameter is considerably smaller than the depth of the conduit location).

It is further assumed that electromagnetic waves are transmitted by the antenna into the space that is limited by a cone of the apex angle $\varphi = 90°$. Objects may be recorded on the echogram, if they fall within the cone of the wave influence. This condition is met when the distance between the points $x(1)$ and $x(2)$ is shorter or equal to the depth h (Fig. 2).

The shape and size of a linear object of the circular cross-section on the geo-radar image depends on:
- the depth of the object location,
- the dielectric constant of the medium, in which the electromagnetic wave propagates,
- the vertical and horizontal scales of the echogram.

It is the diagram calculated using (2). The value of D in (2) will be calculated with the use of the formula

$$D = \sqrt{x^2 + h^2} \quad [\mathrm{m}] \tag{3}$$

where

x – distance between the antenna and the point on the profile which is located over the object [m],

h – depth of the object [m].

The D value calculated using (3) will be substituted to (2). As a result one obtains the formula

$$t = \frac{2\sqrt{x^2 + h^2}}{c} \cdot \sqrt{\varepsilon_r} \quad [\mathrm{s}] \tag{4}$$

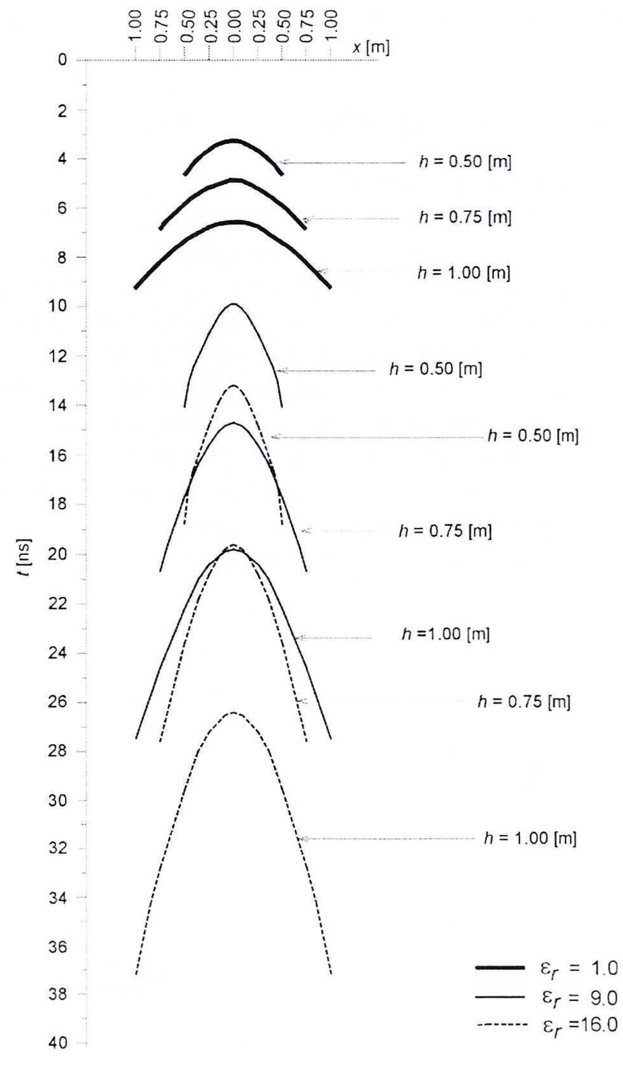

Fig. 3. Model of echograms of a linear object of circular cross-section for various values of the dielectric constant ε_r and various depths h

In order to make diagrams of model echograms of a pipe, dielectric constant values $\varepsilon_r = 1$, 9 and 16 were substituted to (4). Those constants are typical for the natural media of propagation of electromagnetic waves. Depths of location of a model pipe $h = 0.5$ m, 0.75 m and 1.0 m were assumed for calculations (Fig. 3).

The shape of the object recorded on the echogram depends on the horizontal scale of the profile line $x(1) - x(3)$ and on the vertical scale, that is the scale of time t [ns] (Fig. 3). The horizontal scale is the function of velocity V_p [m/s] of the antenna moving along the measuring profile and of the velocity V_e [m/s] of data recording on the echogram. The ratio V_e / V_p corresponds to the horizontal scale of the echogram.

Figure 3 presents the example of theoretical model echograms of a linear object of the circular cross-section, located on various depths in soils of specified dielectric properties.

4. Experiments concerning determination of resolving power

Vertical and horizontal resolution may be considered essential in the case of geo-radar measurements. The vertical resolution may be theoretically defined, using the Rayleigh criterion for geometrical optics. According to that criterion, two points, for which waves reflected by those points have the same amplitudes, may be distinguished when the minimum of the impulse reflection from the first point is located on the axis of time before the maximum of the impulse reflection from the second point.

The vertical resolution of the geo-radar method is inversely proportional to the bandwidth of the impulse transmitted by the transmitting antenna. Antennae of a wide frequency band have the high resolution, while antennae with narrow bandwidths are characterised by low resolution. The vertical resolution of the geo-radar method depends also on the dielectric constant of the medium. Dependence between the vertical resolution and the antenna bandwidth for various dielectric constants is shown in Fig. 4.

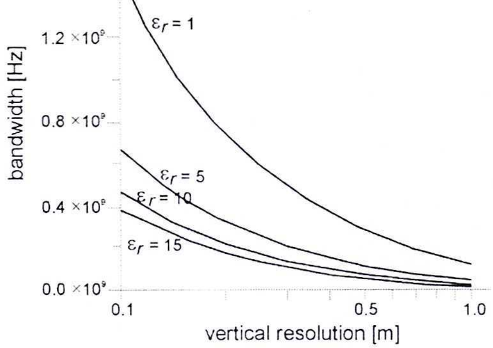

Fig. 4. Relations between the vertical resolution and the antenna bandwidth for various dielectric constants ε_r

Determination of the horizontal resolution of the geo-radar method is more complicated. It depends on:

- geometry of the measuring system (distance between transmitting and receiving antennae),
- depth of objects to be detected,
- dielectric constant and suppression of the medium where the electromagnetic wave is propagated.

5. Techniques of measurements for analytical determination of the horizontal resolution

It has initially been assumed that equipment factors and phenomena of diffraction of waves have the same effect on the horizontal resolution of geo-radar measurements. They depend on construction of equipment and on the frequency of electromagnetic waves. Therefore it has been assumed that the horizontal resolution for a given type of equipment depends on physical properties of the medium that surrounds the investigated objects.

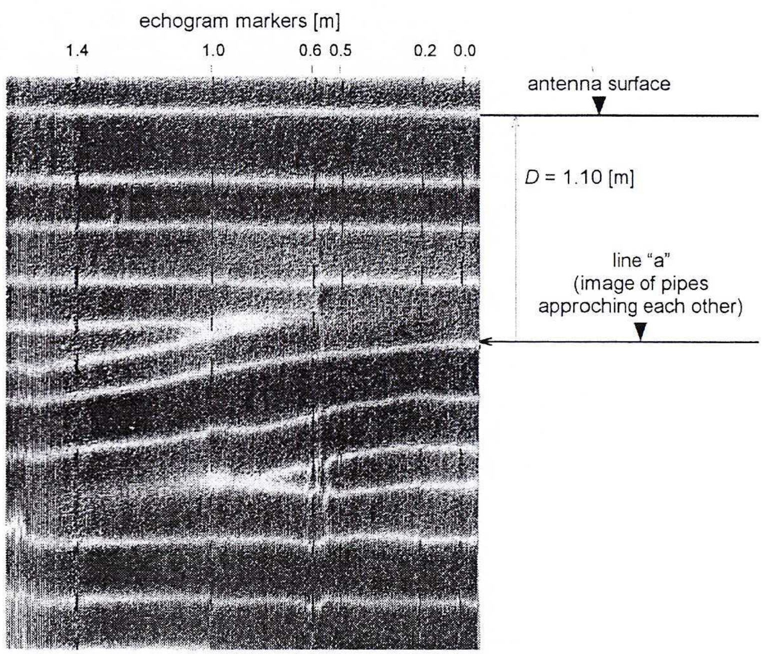

Fig. 5. Echogram from measurements of the horizontal resolution of two steel pipes

Model measurements of the horizontal resolution have been performed in the air for two steel pipes of the diameter of 0.03 m using the geo-radar with antennas of the frequency of 200 and 1000 MHz. The tests were performed in the following way. Five levels within the vertical distances: $D = 0.25$ m; 0.35 m; 0.70 m; 1.10 m and 1.50 m have been specified over the immovable antenna. Continuous registration of echograms of pipes, approaching one another, was performed at each level. The example echogram of such measurements is presented in Fig. 5. It has been made for two pipes located at the depth $D = 1.10$ m, with the use of the 200 MHz antenna. The inclined line "a" is the image of approaching pipes. At the time of measurements, the distance between the pipes is determined by means of markers at the top of the echogram that correspond to 1.4 m; 1.0 m; 0.6 m; 0.5 m; 0.2 m and 0.0 m.

Two detected objects were recorded on the echogram as separate objects, assuming that the marker of distance crosses the line "a" in such places where it is inclined to the line of the antenna surface. When it becomes horizontal, or almost horizontal, objects become non-distinguishable. For the discussed example, the marker 0.5 m marks the border that separates the inclined section and the straight section of the line "a". Therefore, it turns out that for $D = 1.10$ m, $\varepsilon_r = 1$ and 200 MHz antenna, the horizontal resolution equals to 0.5 m.

Resolutions for remaining levels of depth D were determined in the same way. Results of measurements are given in Table 1.

Table 1. Horizontal resolution values for 200 and 1000 MHz antennae in the medium of $\varepsilon_r = 1$ – experimental measurements

Vertical distance D [m]	Horizontal resolving power l [m]	
	1000 MHz	200 MHz
0.25	0.18	0.40
0.35	0.18	0.35
0.70	0.20	0.45
1.10	0.30	0.50
1.50	0.35	0.60

6. Analysis of results of measurements of model horizontal resolutions

Basing on experiments performed under ideal conditions (in the medium of the dielectric constant $\varepsilon_r = 1$ and specific resistance $\rho = \infty$ Ωm) and on (4) it has been stated that the factors that decide on the horizontal resolution of geo-radar equipment are the dielectric constants of the soil medium and the depth of objects detected in that medium.

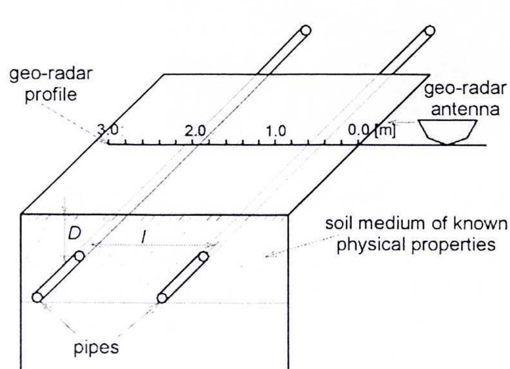

Fig. 6. Diagram of the research model

The procedure requires that calculations be performed by means of (4) for the following conditions. It has been assumed that the geo-radar antenna is located over one of investigated objects. Objects are located at the depth D under the terrain surface and within the distance l from one another (Fig. 6). It has also been assumed that the length of the section l is equal to the horizontal resolution for the depth D.

Time difference Δt between impulses of the electromagnetic wave which reach the geo-radar antenna after reflection from particular objects is equal to:

$$\Delta t = \frac{2 \cdot \sqrt{D^2 + l^2}}{c} \cdot \sqrt{\varepsilon_r} - \frac{2 \cdot \sqrt{D^2}}{c} \cdot \sqrt{\varepsilon_r} \quad [\mathrm{s}] \tag{5}$$

Simplifying (5) one obtains

$$\Delta t = \frac{2 \cdot \sqrt{\varepsilon_r}}{c} \cdot \left(\sqrt{D^2 + l^2} - D\right) \quad [\mathrm{s}] \tag{6}$$

After substituting $\varepsilon_r = 1$, D and l measured during experiments (see Table 1) to (6) the following average Δt values are obtained:
- 0.3 ns for the 1000 MHz antenna,
- 1.0 ns for the 200 MHz antenna.

It turns out from above considerations that for linear objects of circular cross-sections the horizontal resolution of the given equipment may be determined by Δt.

7. Measurements of the horizontal resolving power in real media

Results of the horizontal resolution obtained for ideal conditions were the basis for field tests. They were performed in real soil conditions. Those tests aimed at confirmation of the relation described by (6).

The SIR-8 geo-radar equipment has been used for experiments. Measurements were performed by means of 1000 MHz and 200 MHz antennae. The diagram of the experimental research model is given in Fig. 6.

Two steel pipes, of the diameter of 0.03 m and length of 4 m were the subject of testing. They were located in parallel to one another. The geo-radar profile, along which measurements were taken, was perpendicular to pipes; the distance l and the depth D were varying (Fig. 6). Measurements were taken in water and in embankment, sandy-and-clayey soil. Objects located in water were measured by the 1000 MHz antenna. For objects located in embankment soil 1000 MHz and 200 MHz antennae were used.

The dielectric constant of water equals to 81. The constant ε_r for embankment road was calculated by substituting results from field measurements to (2). The calculated dielectric constant equals to 19. In order to compare results of field measurements with theoretical results, the formula (6) should be transformed to the form

$$l = \sqrt{\left(\frac{\Delta t \cdot c}{2\sqrt{\varepsilon_r}} + D\right)^2 - D^2} \quad [\mathrm{m}] \tag{7}$$

Substituting the following Δt values to (7):
- $\Delta t = 1$ ns for the 200 MHz antenna,
- $\Delta t = 0.3$ ns for the 1000 MHz antenna,

theoretical resolving power of the geo-radar equipment for measurements of two parallel underground installations were calculated. The dielectric constant values $\varepsilon_r = 19$ and 81 were assumed. Calculations were performed for the depths $D = 0.25$ m and 0.42 m for the frequency of 1000 MHz, and for $D = 0.50$ m and 0.80 m for the frequency of 200 MHz. Results of calculations are given in Table 2. Values D and ε_r assumed for calculations equal to the values used for field measurements.

Horizontal resolution l for the depths of 0.25 m and 0.42 m and the dielectric constant $\varepsilon_r = 81$ were determined after analysis of echograms obtained from field measurements (Table 2).

Table 2. Horizontal resolving power

Depth D [m]	Dielectric constant of the medium ε_r	Horizontal resolving power l [m]	
		calculated	measured
200 MHz antenna			
0.5	19	0.19	0.22
0.8	19	0.24	0.25
1000 MHz antenna			
0.25	81	0.05	0.06
0.42	81	0.06	0.07
0.25	19	0.08	0.085
0.42	19	0.10	0.10

Both antennae were used for the soil medium that consisted of the sandy-and-clayey embankment.

Examples of echograms obtained from measurements for the depth $D = 0.8$ m and the distances $l = 0.2$ m and 0.3 m are shown in Fig. 7.

The results in Fig. 7 show that
- when the distance $l = 0.3$ m, two curves, being the images of two pipes, are visible on the echogram,
- when the distance $l = 0.2$ m, only one curve is visible on the echogram, being the image of both installations.

It turns out from the above statements that the resolution l falls within the range between 0.2 m and 0.3 m. Similar analysis has been performed basing on echograms of measurements for remaining assumed depths D.

All results of field measurements of the resolution have been listed in Table 2 together with corresponding theoretical calculations.

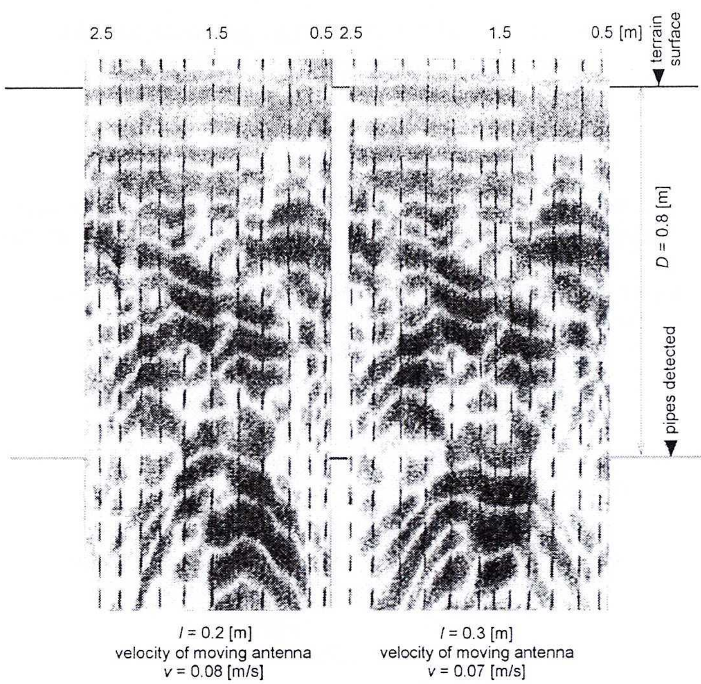

Fig. 7. Echograms of two steel pipes obtained using the 200 MHz antenna in the medium of the dielectric constant $\varepsilon_r = 19$

8. Conclusions

Performed tests and analyses allow for drawing the following conclusions.

1. Comparing results of field measurements and theoretical calculations obtained from experiments, their high compliance has been stated (Table 2).
2. The horizontal resolving power of detection of underground installations depends on the type of applied geo-radar equipment and on frequency of electromagnetic waves. It may approximately be determined by means of experiments, with the use of the method proposed in this paper.
3. Together with the increase of the dielectric constant of the medium where underground installations are located, the horizontal resolving power also increases. For example, for the SIR-8 equipment with the 200 MHz antenna, for $\varepsilon_r = 1$, it is equal to about 1/2 of the depth D of installation location, and for $\varepsilon_r = 19$ – about 1/3 D. For the 1000 MHz antenna they are equal to 1/3 D and 1/4 D, respectively.
4. Performed tests and analyses are new in the field of evaluation of the resolution of the geo-radar method, applied for location of underground installations.

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Eksperymentalne badania zdolności rozdzielczej georadaru przy wykrywaniu instalacji podziemnych

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Streszczenie

W jednorodnym elektrycznie podłożu, obraz (echogram) georadarowy zarejestrowanego przewodu podziemnego ma kształt hiperboli. Echogramy położonych blisko siebie przewodów nakładają się na siebie i powodują, że ich interpretacja może być błędna.

W pracy przedstawiono metodę eksperymentalnego wyznaczenia zdolności rozdzielczej danego typu aparatury georadarowej przy wykrywaniu instalacji podziemnej.

Na podstawie przeprowadzonych pomiarów wykazano, że pozioma zdolność rozdzielcza wykrywania instalacji podziemnych zależy od rodzaju stosowanej aparatury georadarowej i częstotliwości fal elektromagnetycznych. Wraz ze wzrostem stałej dielektrycznej ośrodka, w którym znajdują się instalacje podziemne, wzrasta pozioma zdolność rozdzielcza.