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The application of non-standard GPR techniques for the examination of river dikes

Zastosowane niestandardowych technik georadarowych do badania wałów przeciwpowodziowych

Abstract

A standard measurement procedure currently applied in the ground penetrating radar (GPR) method is short-offset reflection profiling. As this procedure delivers data that is suited only for qualitative interpretation, its application should be limited exclusively to reconnaissance surveys. There are various other techniques used in GPR surveying that may be regarded as non-standard, such as multi-offset and adaptable-polarisation surveying and tomography. Because these techniques deliver information that allows for quantitative interpretation, they could be applied for the detailed examination of geological media and investigations of various buried anthropogenic targets. This paper focuses on the application of non-standard GPR techniques for the detection of high-porosity zones in river dikes. Results from both field surveys and numerical modelling are presented.

Keywords: GPR, ground penetrating radar, non-standard surveys, river dike

Streszczenie

Standardową techniką pomiarową stosowaną obecnie w metodzie georadarowej (GPR) jest krótko-offsetowe profilowanie refleksyjne. Technika ta dostarcza jedynie informacji do interpretacji jakościowej, więc powinna być stosowania tylko w badaniach rekonesansowych. W metodzie GPR jest kilka technik pomiarowych, które można uznać obecnie za niestandardowe, tzn. badania zmienno-offsetowe i zmienno-polaryzacyjne oraz tomografia otwór–otwór i otwór–powierzchnia. Techniki niestandardowe dostarczają informacji do interpretacji ilościowej więc powinny być stosowane w szczegółowych badaniach ośrodka geologicznego i obiektów antropogenicznych. W artykule skupiono się na zastosowaniu niestandardowych technik pomiarowych do wykrywania stref podwyższonej porowatości w wałach przeciwpowodziowych. W pracy przedstawiono wyniki pomiarów terenowych oraz modelowań numerycznych.

Słowa kluczowe: GPR, georadar, badania niestandardowe, wał przeciwpowodziowy

1. Introduction

There are a variety of electrical and electromagnetic geophysical methods that may be applied for the subsurface examination of river dikes, such as electrical resistivity tomography (ERT), electromagnetic profiling (EMP), ground penetrating radar (GPR) and occasionally capacitively-coupled resistivity method [2, 9, 10, 11, 12, 16, 18, 23, 24, 25, 29, 36]. Increasingly, the seismic technique known as multichannel analysis of surface waves (the MASW technique) is also applied to study river dikes [20, 27, 28]. This paper is exclusively devoted to the application of the GPR method for examining the geotechnical condition of river dikes, specifically for the detection of poorly consolidated zones characterised by anomalously high porosity located within the bodies of dikes.

A standard GPR measurement technique that is often applied for the examination of river dikes is the short-offset reflection profiling technique (the SORP technique). In the SORP technique, there is a fixed short distance between the transmitter (Tx) and the receiver (Rx) antennae which move simultaneously along a profile during the surveys (Fig. 1A). The transmitter antenna emits an electromagnetic (EM) wave while the receiver antenna (Rx) records the waves that are reflected back to the surface from anomalous bodies (Fig. 1A) as well as geological boundaries and structures. During SORP surveys, three types of EM waves are recorded in a radargram, these are direct air wave (DAW), direct ground wave (DGW) and short-offset reflected waves (soRW); only the latter are interpreted in the radargram. Depending on the specific circumstances, different types of antennae utilising different frequencies can be used. A disadvantage of the SORP technique is that, while it may be used for the detection of natural and anthropogenic objects, there is no information about the properties of the detected objects contained in the amplitudes of reflections. For this reason, the SORP technique should only be applied for reconnaissance surveys.

Regulations concerning the periodic examination of the geotechnical condition of river dikes require engineers to conduct in-situ soundings and laboratory analysis of ground samples obtained from boreholes. In such boreholes, SORP downhole surveys may also be carried out (Fig. 2A). The principle of such measurements is the same as that of surface surveys (Fig. 1A) except that the Tx and Rx antennae (Fig. 2B) move vertically within the borehole. Unfortunately, the antennae that are currently used for borehole measurements have omni-directional radiation patterns, which precludes the detailed localisation of anomalies on the basis of measurements taken from a single borehole. To resolve this limitation, measurements can be made from several boreholes in different locations (which may be impractical in the case of river dikes) or directional GPR system can be apply.

In the next part of the paper, we present other (non-standard) measurement techniques that can deliver additional information for river dike investigations beyond that provided by the standard SORP technique.

Many of the non-standard techniques require the transmitter (Tx) and receiver (Rx) antennae to be separated. An ideal solution is to deploy a multichannel GPR system using multiple antennae (Fig. 3A). A multichannel system can involve a land streamer (Fig. 3B), such that terrain surveys may be efficiently carried out. Non-standard techniques may also include:

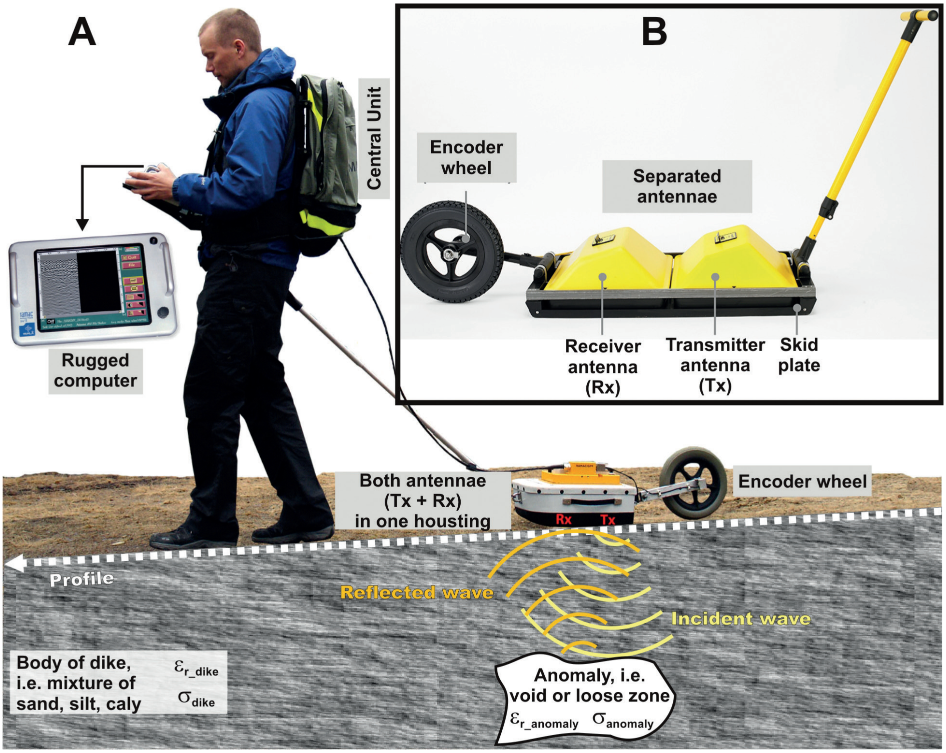

Fig. 1. A) standard, short-offset GPR system for reflection survey [38]; B) separate transmitter (Tx) and receiver (Rx) antennae for non-standard surveys [37]

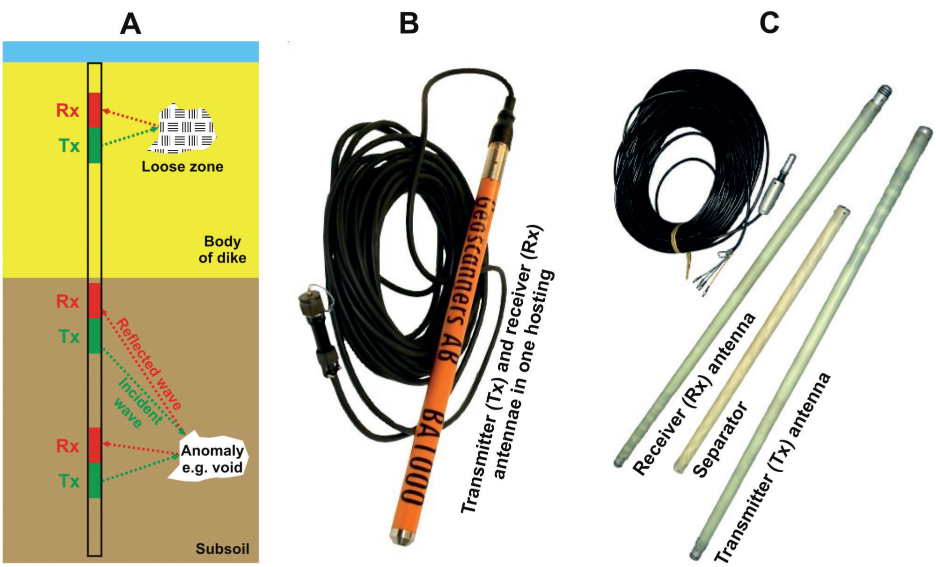

Fig. 2. A) methodology of reflection profiling in borehole; B) standard, short-offset borehole system for reflection survey [40]; C) separate transmitter (Tx) and receiver (Rx) antennae for non-standard borehole surveys [38]

- multi-offset surveys, which enable: wide-offset reflection profiling, the analysis of refraction and direct ground waves, as well as the analysis of velocity;
- adaptable-polarisation surveys;
- separate transmitter (Tx) and receiver (Rx) borehole antennae (Fig. 2C), which allows users to carry out GPR tomography.

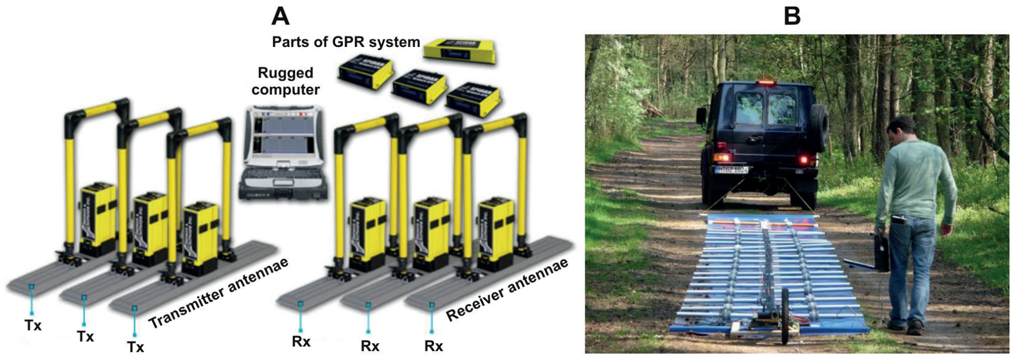

Fig. 3. Fig. 3. A) elements of a multichannel GPR system [37], B) terrain surveys with the use of GPR land streamer [39]

The above techniques are described in more detail later in this paper. The advantages of their application for river dike investigations are presented on the basis of results from numerical modelling and terrain surveys.

2. Wide-offset reflection profiling

The wide-offset reflection profiling (WORP) technique is similar to the SORP technique (Fig. 1A, Fig. 2A); however, during WORP surveys, the transmitter antenna (Tx) is separated from receiver antenna (Rx) at a fixed distance, typically several meters. Regardless of whether short-offset or wide-offset reflection profiling is applied, the fundamental physics of EM wave propagation in a geological medium is the same. The difference of relative electrical permittivity ε_r (Table 1), between the anomalous zone (e.g. a void or poorly consolidated zone in a river dike) and the surrounding medium (e.g. the intact body of the dike) determines the value of the reflection coefficient R and, consequently, the amplitude of reflections recorded on the radargram. For the WORP technique, the reflection coefficient is defined by formulae (1, 2) below, whereas for the SORP technique, it is defined by the simplified formula (3). The relative electrical permittivity ε_r and electrical conductivity σ [S/m] (Table 1) determine the values of velocity v [m/s] and attenuation α [dB/m] of the EM wave (Table 1) according to formulae (7, 8) below. As GPR surveys are presumed to be conducted in non-magnetic media, the value of relative magnetic permittivity μ_r =1.

$$R_{\parallel} = \frac{Z_{anomaly} \cdot \cos\theta_{anomaly} - Z_{dike} \cdot \cos\theta_{dike}}{Z_{anomaly} \cdot \cos\theta_{anomaly} + Z_{dike} \cdot \cos\theta_{dike}} \quad (1)$$

$$R_{\perp} = \frac{Z_{anomaly} \cdot \cos\theta_{anomaly} - Z_{dike} \cdot \cos\theta_{dike}}{Z_{anomaly} \cdot \cos\theta_{anomaly} + Z_{dike} \cdot \cos\theta_{dike}} \quad (2)$$

$$R = \frac{Z_{anomaly} - Z_{dike}}{Z_{anomaly} + Z_{dike}} \quad (3)$$

$$where: \; Z = \sqrt{\frac{\mu}{\varepsilon}} \quad \mu = \mu_r \cdot \mu_0 \quad \varepsilon = \varepsilon_r \cdot \varepsilon_0 \quad (4, 5, 6)$$

In the above equations, R is the reflection coefficient; the symbols $||$ and $\perp$ denote parallel and perpendicular polarization of the EM wave relative to the plane of incidence. The quantity Z is the impedance of the intact body of the dike, or that of the anomalous zone. The quantity θ_{dike} is the angle of incidence, equal to the angle of reflection, of the EM wave in the body of dike. The quantity $\theta_{anomaly}$ is the angle of transmission of the EM wave into the anomalous zone; σ is the electrical conductivity; ω is the angular frequency of the transmitter antenna, and μ, μ_r, μ_0 are the magnetic permittivity, relative magnetic permittivity and magnetic permittivity of vacuum, respectively; and finally, ε, ε_r, ε_0 are the electric permittivity, relative electric permittivity and electric permittivity of vacuum, respectively.

$$v = \frac{c}{\sqrt{a \cdot \left[(1+\delta)^2 + 1 \right]}} \quad \alpha = \omega \sqrt{a \cdot \left[(1+\delta)^2 + 1 \right]} \quad a = \frac{\varepsilon \cdot \mu}{2} \quad \delta = \frac{\sigma}{\omega \cdot \varepsilon} \quad (7, 8, 9, 10)$$

In the above equations, c is the velocity of an EM wave in a vacuum while α is the attenuation of the geological medium in which the EM wave propagates.

Table 1. Properties of media analysed in the paper [1]

	Relative electrical permittivity	**Velocity of EM wave**	**Electrical conductivity**	**Attenuation of EM wave**
	ε_r [-]	v [m/ns]	σ [mS/m]	α [dB/m]
Air-filled void or loose zone	1	0.3	0	0
Fresh-water-filled void or loose zone	80	0.03	0.5	0.2
River dike (i.e. mixture of sand, silt and clay)	from 5 (dry - d) to 36 (water saturated - ws)	from 0.13 (d) to 0.05 (ws)	from 0.1 (d) to 1 (ws)	from 0.1 (d) to 1 (ws)

In paper [1], the simplified formula (11) below is proposed, which enables determining the ideal distance (offset) between the transmitter and receiver antennae for a WORP survey:

$$S = \frac{2 \cdot h_{anomaly}}{\sqrt{\varepsilon_{r\_dike} - 1}} \tag{11}$$

Where: S is the ideal offset, $h_{anomaly}$ is the depth to the anomalous zone, and ε_{r_dike} is the relative electrical permittivity of the medium under investigation.

Papers [9, 10, 12] present the results of the application of the WORP technique for the investigation of river dikes. Figure 4 shows example results from WORP surveys carried out on a selected part of a dike on the Vistula river in Poland. Terrain measurements were made using the standard, short-offset profiling technique (Fig. 4A). Offset S was determined by formula (11) and wide-offset profiling (Fig. 4B) was also performed at the same location using the same GPR system with the same acquisition parameters. In Fig. 4A, only minor indications of a poorly consolidated zone within the river dike can be identified, whereas using Fig. 4B, the zone is easy to identify. The main poorly consolidated zone is located between distances x=40-120 m along the profile and depths h=1–2 m below the surface.

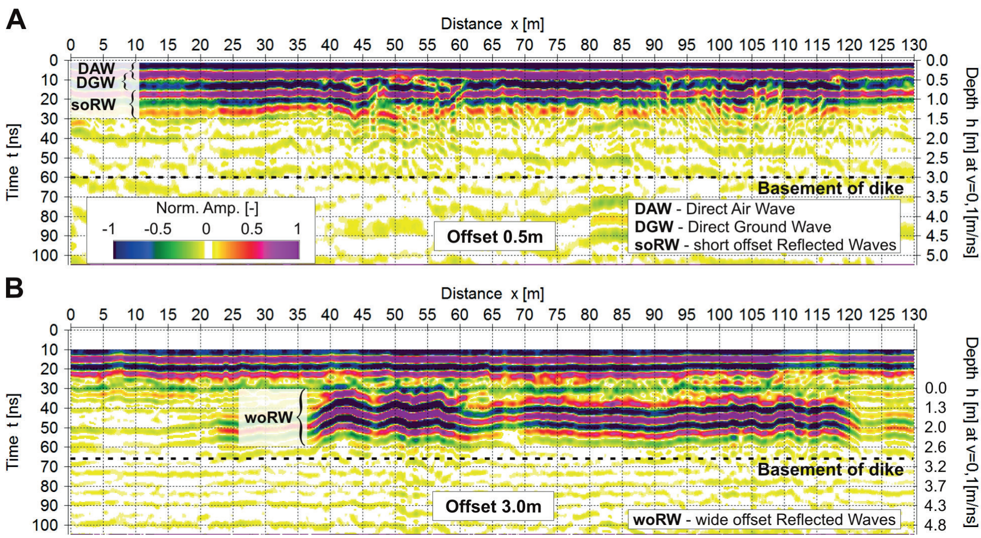

Fig. 4. Results of GPR surveys carried out on the Vistula river dike with the use of SORP (A) and WORP (B) techniques

3. Adaptable-polarisation surveys

The majority of GPR systems that are currently available on the market (such as the system presented in Fig. 1A) enable users to carry out SORP surveys using the standard orientation of antennae (Fig. 5A – option A1). However, this configuration only permits a single polarisation of an EM wave. We do not present a theoretical description of the propagation of EM waves of various polarisations in geological media as the complexity of the physics exceeds the scope of the paper. Readers interested in this problem will find adequate information in [4, 13, 15, 22, 31, 32, 33].

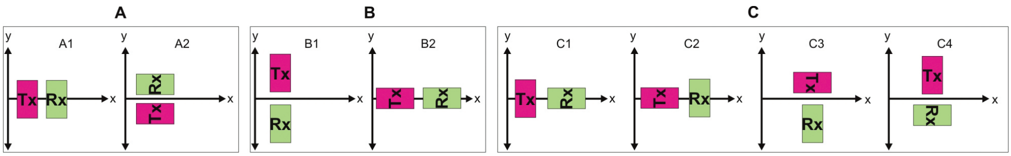

Fig. 5. Different orientations of GPR antennae: A) 'co-pole' orientations; B) 'end-fire' orientations; C) 'cross-pole' orientations

Unfortunately, in many cases, the application of the standard orientation of GPR antennae delivers information of a lower quality than obtained through applications using a non-standard antennae configuration. For illustrative purposes, Fig. 6 presents the results of SORP surveys carried out at a former industrial facility. In Fig. 6A (with antennae in the 'co-pole' orientation), the remains of a concrete tank pad located underground are partially visible. A trenched area (where leakage of creosote from the tank took place) is also distinguishable. In Fig. 6B (antenna in the 'cross-pole' orientation), the full extent of the tank pad is much more apparent than in Fig. 6A. The trench (marked by the break of lateral continuity of the tank-pad radar signature) is also prominently displayed. Additionally, in Fig. 6B, a rebar that is located in the concrete tank pad can also be distinguished. The application of the non-standard orientation of antennae (Fig. 6B) also allowed the depiction of a creosote-filled vault; this anomaly is not as easily distinguished in Fig. 6A.

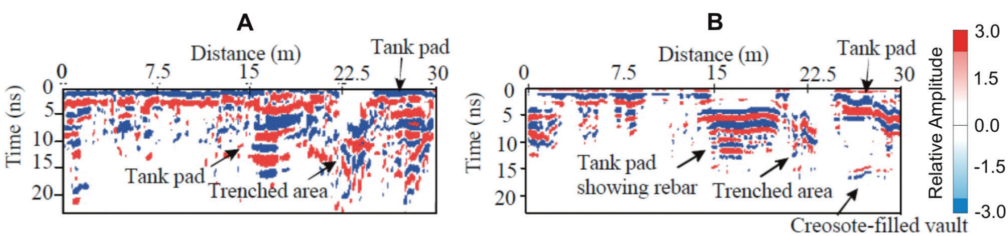

Fig. 6. Results of SORP surveys with the use of standard 'co-pole' (A) and non-standard 'cross-pole' orientation of antennae [15]

As a general rule, the antenna orientation should be adequately suited to explore the heterogeneity and anisotropy of the host medium as well as to characterise the spatial distribution and geometry of any known or suspected underground objects. Unfortunately, this information is not always available in terrain surveys; therefore, test measurements should be carried out in order to select the optimal antenna orientation (Fig. 5) for a specific site. The time and labour necessary for this operation may be reduced through the use of a multichannel GPR system (Fig. 3) in which antennae of various orientations are connected to several channels. During multichannel surveys of a river dike, for example, it might be empirically found that the best results are delivered at the beginning of a long profile by, for example, an 'end-fire' orientation, in the central part by, for example, a 'co-pole' orientation and at the end of the profile by, for example, a 'cross-pole' orientation.

In the next part of this paper, we present the results of GPR surveys of a river dike in which the multi-offset and adaptable-polarisation configurations were jointly applied.

4. Multi-offset surveys

Applications of GPR system with separate receiver and transmitter antennae (Fig. 1B) enable users to carry out multi-offset surveys. These types of survey may be more effective when multichannel GPR is applied (Fig. 3). There are two main types of multi-offset survey [1, 5, 19]. The first type is WARR – wide-angle reflection refraction profiling (Fig. 7A) and the second type is CMP – common mid-point profiling (Fig. 7B). During multi-offset surveys, different kinds of waves are generated and they propagate within the examined medium (Fig. 7C) allowing for additional analysis in comparison with SORP surveys.

Multi-offset surveys generate and record the same categories of EM waves as SORP and WORP surveys, i.e. direct air wave (DAW), direct ground wave (DGW) and short-offset reflected waves (soRW), as shown in Fig. 7C. In the case of a sufficiently large Tx-Rx offset, a wide-offset reflected waves (woRW) are also generated and recorded (Fig. 7C). Neither SOPR nor WORP surveys generate a significant air refracted wave (ARW) - Fig. 7C. This wave has no application in the examination of geological media and will not be considered further.

Another type of wave is the ground refracted wave GRW (Fig. 7C). Thus far, it has rarely been investigated in the GPR method [3, 9, 11, 24]. The GRW may be important, however, for the examination of the basement of a river dike (Fig. 7C) and, more importantly, for the investigation of horizontally extended, poorly consolidated zones located in the body of a dike (Fig. 8A). A GRW may be generated if three criteria are met: (a) there is a sufficiently high reflection coefficient for a wave that is incident on an underground boundary; (b) there is an adequate Tx-Rx offset, beyond the so-called 'critical offset'; (c) there exists a low-velocity medium overlying a higher-velocity medium. For GPR surveys conducted on a river dike, all these criteria are commonly met when the body of the dike is saturated with water and when a poorly consolidated zone overlies a compacted, dry medium (Fig. 8A). The publications mentioned earlier present the theoretical background of the refraction phenomenon.

Figure 8 shows an example of a multi-offset WARR survey designed for the examination of a river dike. The hodograph, or synthetic shot gather, presented in Fig. 8B was generated by numerical modelling based on the model shown in Fig. 8A. More information about the modelling of EM wave fields may be found in [6, 7, 8]. Similar to radargrams recorded during SORP and WORP surveys, the hodograph (Fig. 8B) delivers information about the location of the boundary between the poorly consolidated and the compacted zones. As opposed to a radargram, a hodograph contains information about the velocities within the examined medium, thereby enabling a quantitative interpretation. The velocity of the reflected wave v_{RW}=0.05 m/ns (Fig. 8B) constrains (on the basis of formula 7) the value of the relative

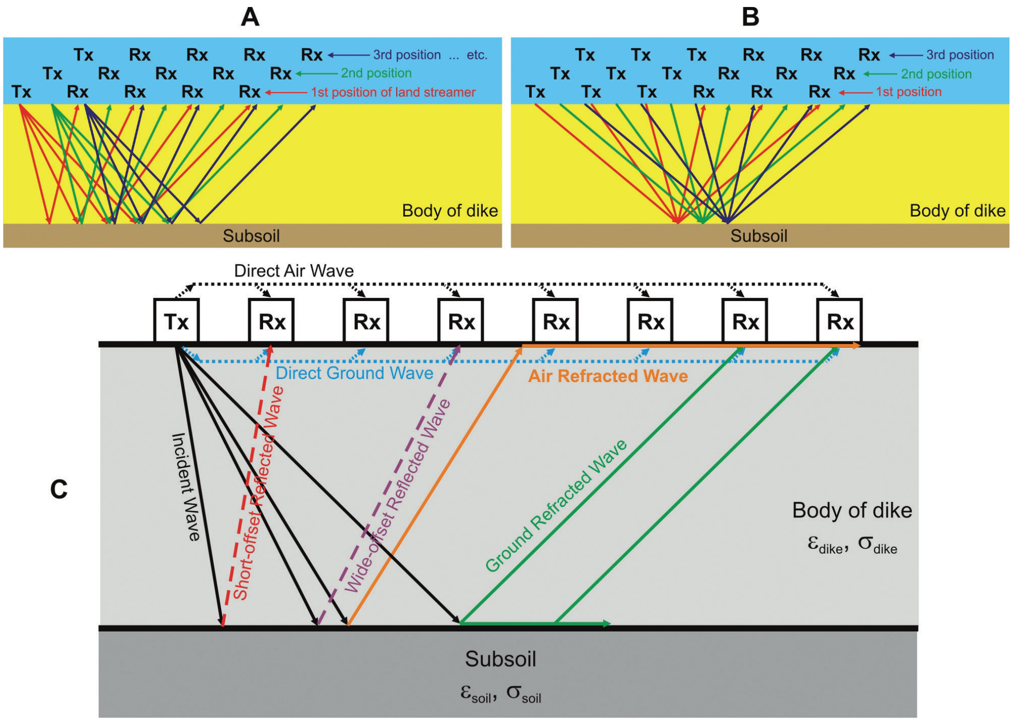

Fig. 7. A) WARR profiling; B) CMP profiling; C) different waves created during multi-offsets profiling

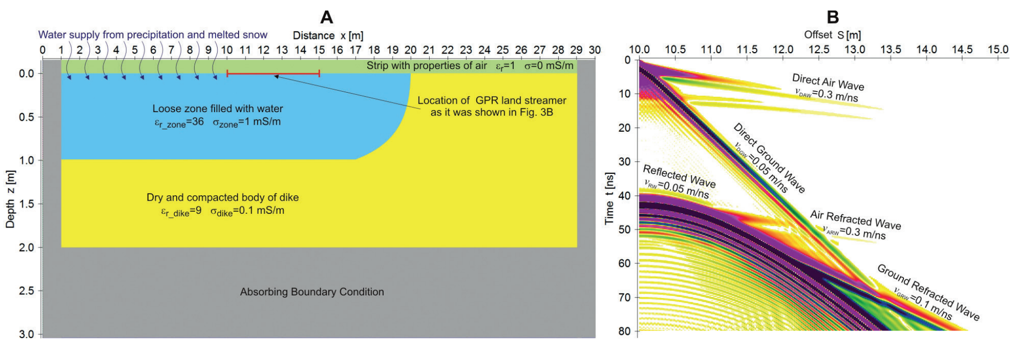

Fig. 8. A) situation when GPR refraction surveys should deliver satisfied results during the examination of river dikes – electromagnetic properties of media were taken from Table 1; B) hodograph generated by numerical modelling for situation presented in Fig. 8A

electrical permittivity of the water-saturated poorly consolidated zone, i.e. ε_{r_zone}=36 (Fig. 8A); the velocity of the ground refracted wave v_{GRW}=0.1 m/ns (Fig. 8B) constrains the value of relative electrical permittivity for the compacted part of the river dike, i.e. ε_{r_dike}=9 (Fig. 8A).

If the value of ε_{r_zone} is known, we can determine, on the basis of the well-known Topp formula (12), the volumetric water content θ_w in the poorly consolidated zone. The value of ε_{r_zone} also permits the determination of porosity n based on a number of established formulae, such as the complex refractive index model (CRIM), the Maxwell-Garnet theory (MGT), the effective medium theory (EMT), the Looyenga model (LM), and the Bruggemann-Hanai-Sen (BHS) model [19]. Equation (13) was constructed on the basis of formula (7) and the CRIM model and relates porosity to the EM wave velocity.

$$\theta_w = 4.3\cdot 10^{-6}\cdot \varepsilon^3_{r\_zone} - 5.5\cdot 10^{-4}\cdot \varepsilon^2_{r\_zone} + 2.92\cdot 10^{-2}\cdot \varepsilon_{r\_zone} - 5.3\cdot 10^{-2} \tag{12}$$

$$v = \frac{c}{\sqrt{\left[\theta_w\cdot \varepsilon^{\alpha}_{r\_water} + (1-n)\cdot \varepsilon^{\alpha}_{r\_grain} + (n-\theta_w)\cdot \varepsilon^{\alpha}_{r\_air}\right]^{\frac{1}{\alpha}}}} \tag{13}$$

Where: ε_{r_water} is the electrical permittivity of the pore water (usually ~80); ε_{r_grain} is the electrical permittivity of grains comprising the solid matrix; $\varepsilon_{r\_air}=1$ is the electrical permittivity of air; α is a factor of anisotropy which assumes values between -1 and 1. For an isotropic medium, $\alpha=1/2$.

Fig. 9 shows the results of terrain surveys carried out on the Vistula river dike, where joint WARR profiling (Fig. 7A) and adaptable-orientation measurements were applied (Fig. 5). An analysis of the hodographs presented in Fig. 9 indicates that the 'end-fire' orientation of antennae delivered the most encouraging results and that such an orientation should be applied for GPR examination of this part of the river dike. Unfortunately, GRW was not generated due to the site conditions. An analysis of Fig. 9C allows the determination of the position of the principal reflector (i.e. the boundary between the body of a dike and the underlying subsoil) at depth of ~5 m. In addition, the velocity of the reflected and ground waves (Fig. 9C) allows the determination of the relative electrical permittivity equals 6 for the body of the dike. This value indicates that the dike is in a dry condition (Table 1).

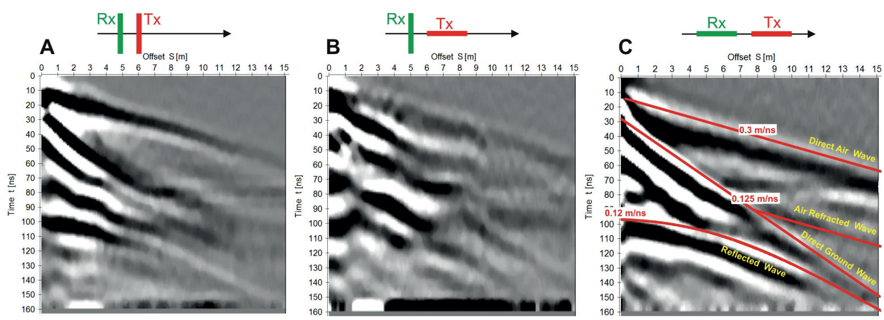

Fig. 9. The results of multi-offset surveys (i.e. WARR profiling) conducted on the river dike for different antenna orientations: A) 'co-pole' orientation; B) 'cross-pole' orientation; C) 'end-fire' orientation

An important type of wave that is generated during multi-offset surveys is the direct ground wave (DGW). As mentioned above, the DGW is also recorded during SORP surveys, but analysis of DGW is generally impractical. DGW propagates in the near-surface zone (Fig. 7C). The depth penetration h of this wave may be described by the simplified formula (14) below. The DGW may be used to evaluate the velocity (according to formula 15) of the shallow part of the dike. The theory of DGW in the GPR method may be found in [14, 17].

$$h = 0.5 \cdot \sqrt{\frac{v \cdot S}{f}} \quad v = \frac{S}{\Delta t} \tag{14, 15}$$

where:
S is the Tx-Rx offset; f is the frequency of GPR antenna, and Δt is the difference in arrival times of the DAW and DGW.

In Fig. 10A, an example is shown of the application of DGW for the examination of a river dike. Terrain surveys were carried out on the Rudawa river dike in Poland and the radargram was converted into the water saturation map. The spatial distribution of the water saturation of the poorly consolidated zones in this dike was determined on the basis of the Topp formula (12). The least consolidated part of the examined dike appears to be located between x=14m and x=36m along the profile, to a depth of 0.6m (depicted in Fig. 10A as anomaly 'A'). Note that data along the central part of the survey profile could not be acquired due to external noise interference. At a depth of ~1.6m, the effect generated by more compacted, drier material was recorded (depicted in Fig. 10A as anomaly 'B'). SORP surveys were also carried out in this site (Fig. 10B); however, they only allowed for the detection of the 'B' anomaly.

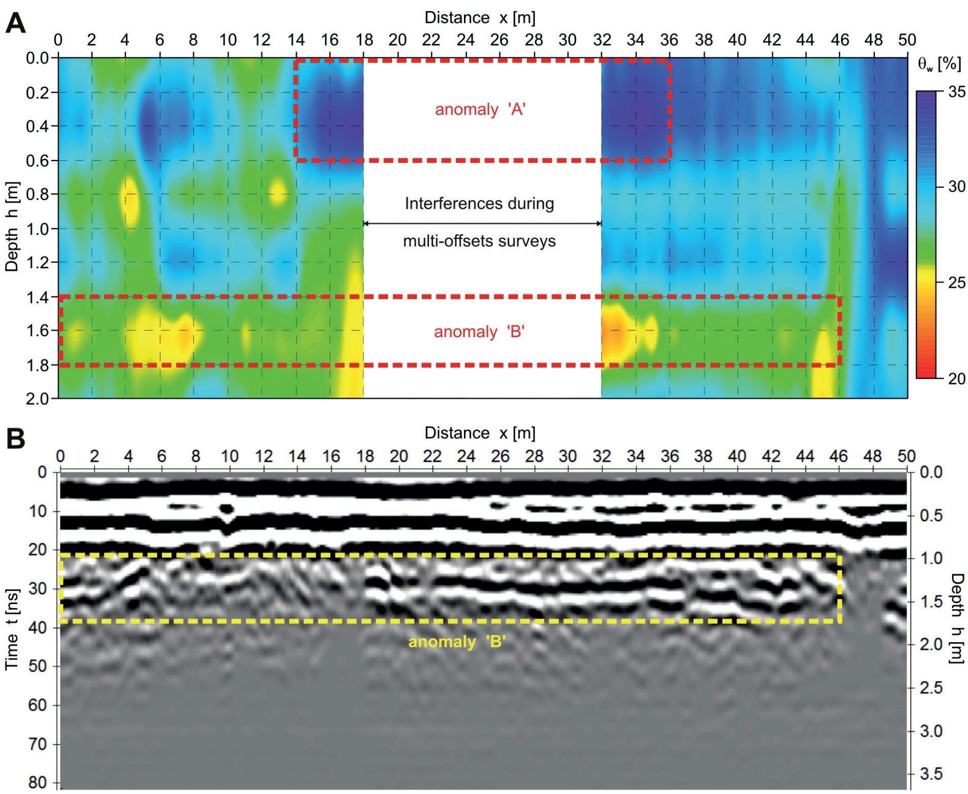

Fig. 10. GPR surveys in the Rudawa river dike: A) water saturation of loose zones solved on the basis of analysis of DGW; B) SORP survey

5. GPR tomography

GPR tomography may be applied to investigate the intervening space between boreholes that are located within the body of a river dike (Fig. 11) or drilled into the underlying basement (Fig. 11). This technique is called borehole-borehole tomography (BBT). In the case of a single borehole drilled into the body of dike, a simpler technique, borehole-surface tomography (BST), may be performed (Fig. 11). Transillumination is another type of tomography that will be discussed later in this section. The theoretical background for GPR tomography may be found in [11, 21, 26, 30, 34, 35]. BBT tomography requires separate transmitter and receiver antennae (Fig. 2C) and unfortunately, it is both time and labour consuming. The effort can be reduced by the application of 'fast' tomography (BBT-fast) in which both antennae move simultaneously within the same measurement step and only selected ray paths are analysed (Fig. 11). However, both BBT and BBT-fast surveys have a serious limitation; this is that the limited power of the transmitter allows for measurements between boreholes located in the ground only to a maximum distance of ~10-15 m. Another limitation of both the BBT and BBT-fast surveys is that a typical borehole antenna is very long (i.e. 1.5–2.0 m). As a consequence, such surveys may be applied only for the examination of tall river dikes and the underlying subsoil. Due to the limitations described above, BBT and BBT-fast surveys may only be carried out in specific situations.

A second type of tomography (BST) may be carried out using integrated antennae (Fig. 1A, Fig. 2B) or separate antennae (Fig. 1B, Fig. 2C). However, the BST technique delivers information about the examined dike from a limited volume around the borehole (Fig. 11). Another aspect of BST surveys is the limited transmitter power, as discussed in the previous paragraph.

Regardless of the type of tomography applied (i.e. BBT, BBT-fast, BST), the surveys enable users to map the distribution of spatial variations in EM wave velocity or attenuation

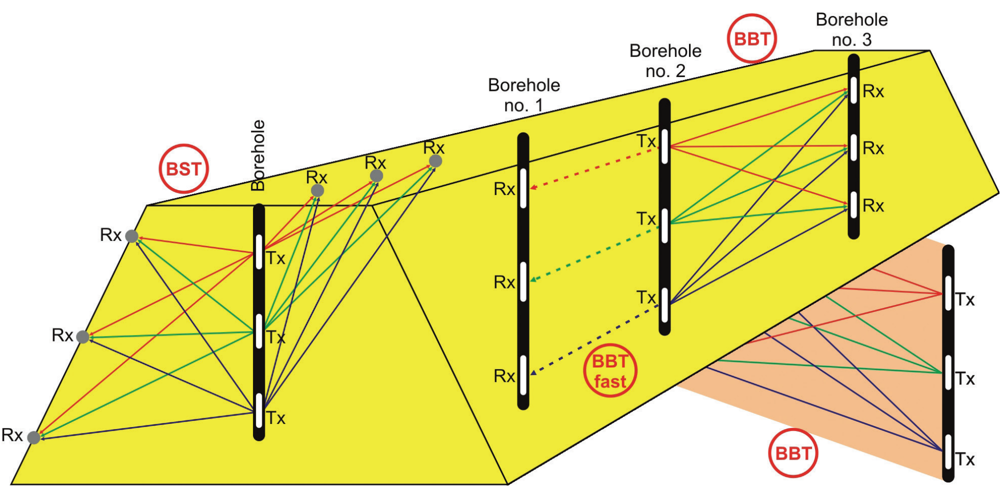

Fig. 11. Borehole-borehole tomography (BBT) carry out in body of dike and under dike; borehole-surface tomography (BST)

within the examined volume of a river dike. The poorly consolidated zones in the river dike may be filled with air or fresh water. Both of these scenarios have a significant impact on the contrast in EM wave velocity relative to the compacted part of dike (Table 1). As the saturation of the poorly consolidated zone with either air and fresh water does not markedly affect the attenuation of an EM wave (Table 1), the technique of attenuation tomography does not have any significant application for the examination of river dikes.

Figure 12A presents the results of the BBT survey. Measurements were carried out in three boreholes drilled into a water dam. The aim of the BBT surveys was to detect a possible leakage zone inside the dam. In Fig. 12A, the leakage zone is interpreted as a low velocity anomaly (dark blue). The fractured and water-saturated part of the dam was found to exhibit lower velocity in comparison with the enclosing solid dry material (Table 1).

Figure 12B presents the results of the BST survey. The aim of the study was to detect poorly consolidated zones that may be saturated with oil. The velocity of an EM wave in the oil-saturated zone was found to be higher than that in the surrounding medium. This contrast was responsible for the appearance of high-velocity anomalies in the 3D visualisation (Fig. 12B – red regions). Similar anomalies might appear during the detection of poorly consolidated zones in a river dike. The velocity in dry, poorly consolidated zones is likely to be considerably higher than the velocity in compacted material (Table 1).

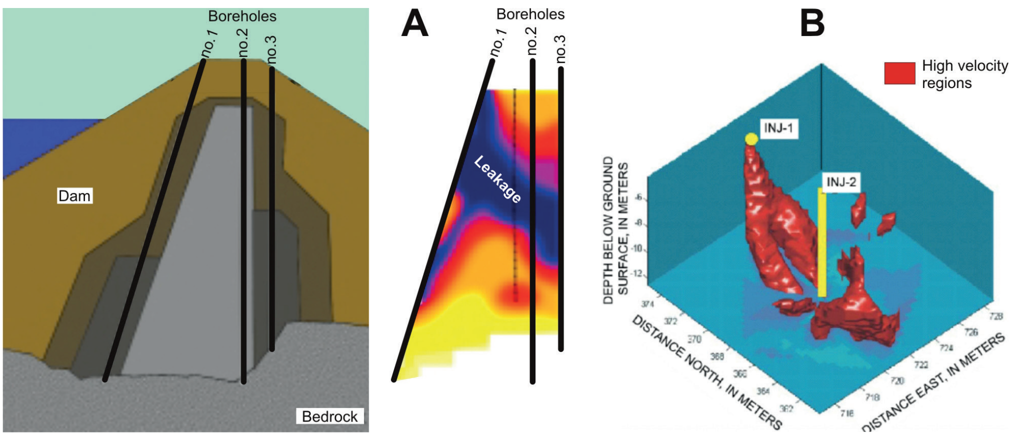

Fig. 12. A) application of BBT for detection of fractured zones filled with water in dam [21]; B) application of BST for detection of loose, oil-saturated zones located around boreholes INJ-1 and INJ-2 [35]

The combination of SORP profiling with a procedure known as transillumination, which produces the SORP-T technique (Fig. 13A), appears to offer a promising and useful GPR technique for the investigation of river dikes. Transillumination is based on similar physical principles as BBT. The SORP-T method has the following advantages: (a) it involves the application of surface antennae (Fig. 1), which are less costly than borehole antennae and may be applied to different kinds of surveys, i.e. SORP, WORP, adaptable-polarisation, multi-offset; (b) there is no need to drill boreholes – these weaken the structural integrity of dikes;

(c) the surveys are faster and less costly than borehole surveys; (d) joint measurements deliver 3D visualisation, which allows the detailed examination of the entire body of a dike (Fig. 13A); (e) continuous examination of the body of the dike is possible.

In order to design effective SORP-T surveys of a river dike, the radiation patterns (Fig. 14A & B) and instrument footprint should be analysed. The radiation pattern is a superposition of the patterns generated by transverse magnetic (TM) and transverse electric (TE) modes of an EM wave (Fig. 14A & B). The pattern strongly depends on the properties of the examined medium; for a dry geological medium (i.e. for low value of relative electric permittivity) both TE and TM patterns are wide, while for water-saturated media, the patterns are narrower, or more tightly focused. In order to simplify analysis, both patterns can be enclosed by a cone with an elliptic base (Fig. 14C). Such an ellipse is called a 'footprint'. The shape of the footprint may be determined with the use of the simplified

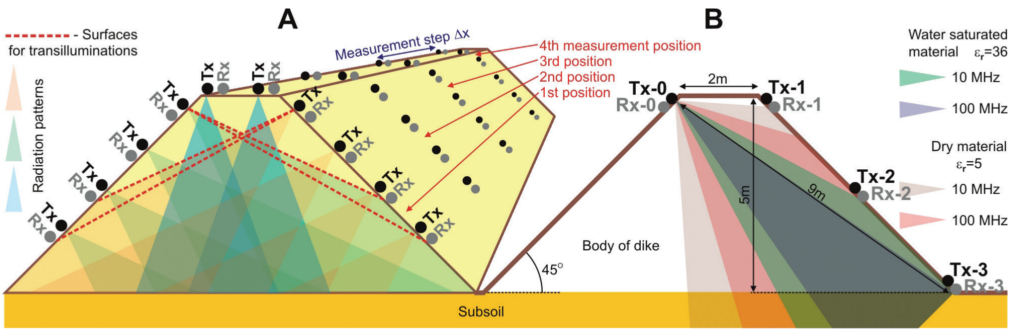

Fig. 13. A) joining of SORP profiling and transillumination (SORP-T surveys); B) analysis of radiation patterns for different antennae and changeable water saturation of body of dike

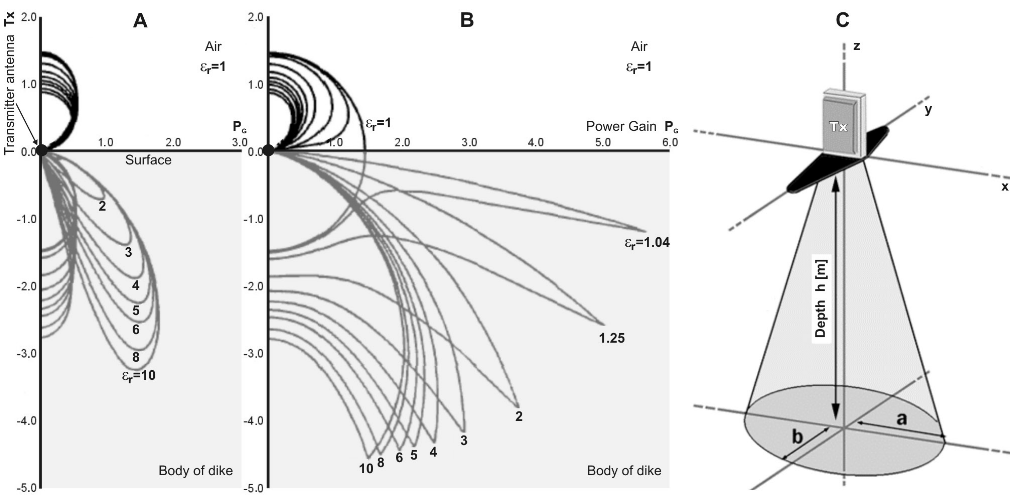

Fig. 14. A) TM pattern [1]; B) TE pattern [1]; C) envelope of both patterns and shape of footprint [38]

formulae (14, 15) below. Table 2 shows the radii (ellipse major and minor axes lengths) of the elliptical footprints for different types of dry and water-saturated medium (Table 1). Some representative radiation patterns are presented in Fig. 13B.

$$a = \frac{v}{4f} + \frac{h}{\sqrt{\varepsilon_r - 1}} \quad b = \frac{a}{2} \tag{14, 15}$$

Table 2. Shapes of footprints for situation analysed in the paper

River dike (a mixture of sand and gravel)	Footprints for distance between Tx and Rx equals 9 m (Fig. 13B) and for antennae with frequency:	
	10 MHz	100 MHz
dry medium (ε_r=5, v=0.13 m/ns)	2a=15.7 m 2b=7.9 m	2a=9.7 m 2b=4.8 m
water-saturated medium (ε_r=36, v=0.05 m/ns)	2a=5.5 m 2b=2.8 m	2a=3.3 m 2b=1.6 m

Taking into account the information presented in Table 2 and in Fig. 13B, the SORP-T technique may be applied for the examination of a river dike under the following conditions:

a) Antennae with very low frequency are used;
b) The angle of the slope is >45°;
c) The positions of the antennae are designed to detect direct signals in both wet and dry conditions;
d) Orientation of the antennae is specified with due regard to the elliptical shape of the footprint.

6. Conclusions

SORP surveys, applied as a standard technique of GPR examination of a river dike, are cost-effective and fast, but they can deliver only basic information about the location of dangerous poorly consolidated zones and voids. This paper demonstrates that, in many cases, the SORP technique fails to deliver satisfactory results. An important limitation of the SORP technique is that it only allows for qualitative interpretation. Modern GPR examination of river dikes should be carried out according to the following steps:

a) The first stage of GPR surveys should involve fast and continuous measurements of the river dike in a 3D mode with application of the SORP-T technique;

b) The second stage of GPR surveys should involve WORP, adaptable-polarisation and multi-offset measurements in a 2D mode performed in parts of the river dike that are identified in the first stage – all surveys proposed in this stage may be performed using a land streamer;
c) The third stage of GPR surveys should involve 2D GPR tomography of the most dangerous parts of a river dike, selected following the second stage of the surveys;
d) The above scheme allows for a detailed and three-dimensional analysis of the technical condition of a river dike that delivers critical information for quantitative geotechnical risk assessment.

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