DOI: https://doi.org/10.30932/1992-3252-2020-18-6-88-107

Evaluation of Electrophysical Properties of Soils in the Slope Zones of the Foundation During GPR Survey

Victor V. PUPATENKO **Yuri A. SUKHOBOK** **Gennady M. STOYANOVICH**

Pupatenko, Victor V., *Far Eastern State Transport University, Khabarovsk, Russia.*
Sukhobok, Yuri A., *Far Eastern State Transport University, Khabarovsk, Russia.*
Stoyanovich, Gennady M., *Far Eastern State Transport University, Khabarovsk, Russia*.*

ABSTRACT

The article describes a new method for conducting a ground penetrating radar survey of slope zones of soil objects of transport infrastructure. In the lithological section of these objects, there are sub-horizontal and inclined soil boundaries, as well as slope zones. Traditional survey methods (drilling, pitting), as well as the standard GPR method, make it possible to reliably survey at these objects, as a rule, only the zones under the horizontal main ground of the subgrade and sub-horizontal sections of the ground outside its boundaries. Survey under inclined surfaces is often difficult or technically impossible; geophysical methods, just like traditional ones, provide initial information that is exceedingly difficult for further decoding. The sections are filled with re-reflections and noises, and the process of decoding them is associated with great methodological problems.

This paper presents a new method for determining speed of propagation of radio waves in the slope zones of the foundation. The initial information is the data obtained during the survey using the common depth point (CDP) method, using a well-known survey technique and a standard set of hardware. The novelty of the article results is determined by the algorithm for processing the measurement results developed by the authors. The software implementation made on its basis makes it possible to obtain the hodograph equation considering the slope of the layers. Defining geometric characteristics of embankments associated with the presence of slopes of variable steepness have been considered. A technique for calculating propagation speed of radio waves for a two-layer medium with a boundary inclined to the scanning surface has been proposed. The validity of the developed method was verified using finite-difference time-domain modelling.

The article provides examples of practical application of the developed method in the GPR survey of real track foundation objects (transport infrastructure objects). The method proposed in the article makes it possible to increase the informative area of the surveyed diameters. At the same time, the accuracy of the GPR method is preserved, the area of its application for obtaining reliable information is increased to 60 % of the cross-sectional area of the foundation.

Keywords: *transport, railways, georadiolocation, georadar, foundation, common depth point method, hodograph, dielectric constant, slope.*

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*Information about the authors:
Pupatenko, Victor V. – Ph.D. (Eng), Associate Professor at the Department of Railway Track of Far Eastern State Transport University (FESTU), Khabarovsk, Russia, pvv@festu.khv.ru.
Sukhobok, Yuri A. – Ph.D. (Eng), Associate Professor at the Department of Railway Track of Far Eastern State Transport University (FESTU), Khabarovsk, Russia, yusukhobok@mail.ru.
Stoyanovich, Gennady M. – D.Sc. (Eng), Professor at the Department of Railway Track of Far Eastern State Transport University (FESTU), Khabarovsk, Russia, oif@festu.khv.ru.

Article received 26.10.2020, accepted 27.12.2020.

For the original Russian text of the article please see p. 88.

Background. Good engineering solutions should be based on reliable background information. To design the foundation, to ensure its strength and reliability, not only the strength and deformation characteristics of soils are required, but also data on the geometry of soil layers. The task of obtaining objective information during the engineering-geological, geophysical, and other survey of an object is urgent. The ground penetrating radar (GPR) method allows solving the problem of determining the boundaries of soil layers of the roadbed, its ground [1; 2], identifying the features of the structure of the object, restoring the history of its construction, the sequence of works on its reconstruction and restoration. No less urgent are the problems of finding surfaces of displacement of landslide massifs [3; 4]. Under special conditions, for example, in the presence of long-term permafrost soils in the foundation and its ground [5], GPR survey in combination with other geophysical methods makes it possible to determine layers of different physical characteristics.

The advantages of a GPR survey include its low cost (compared to traditional methods), the ability to perform work in the environment where the use of, for example, a drilling rig is difficult or even impossible. The low weight of the equipment and little staff of performers (as a rule, two or three people), high speed of the survey of lengthy transport structures are also important advantages.

A feature of the initial original GPR data (radarograms) is that they are time sections, i.e., they display the dependence of the signal amplitude on time of its return to the receiving antenna. However, to solve engineering problems, it is required to build a depth section. To transform the initial time section into a depth section (migration), it is necessary to select the correct velocity model of the environment [6–8].

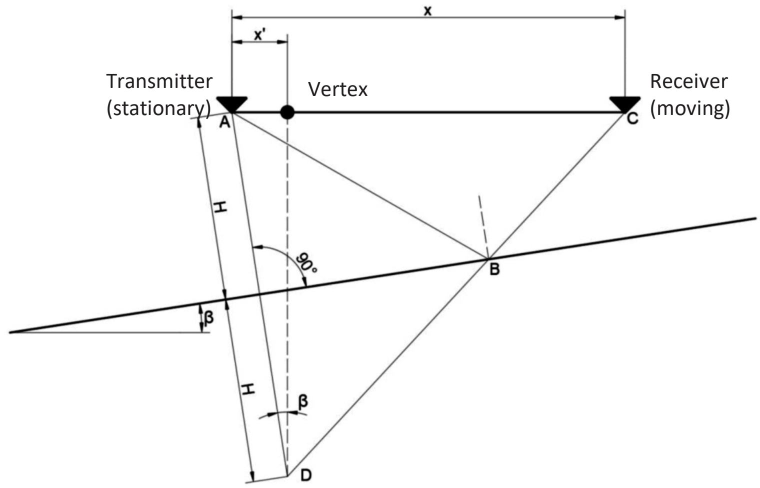
Speed of propagation of electromagnetic waves in a medium depends on its electrophysical properties, in particular, on relative dielectric constant ε. The dielectric constant, in turn, is determined by the type of soil and its physical properties. Experiments have established [6; 7; 9] that the greatest influence on the dielectric constant is exerted by soil moisture and, to a lesser extent, by soil temperature, density, and other parameters.

There are reference tables, which can be used to estimate speed of propagation of radio waves, depending on the type of soil and qualitative assessment of its condition (wet, dry, thawed, or frozen condition) [6; 9]. However, analysis of data shows that even for one and the same type of soil, the range of changes in characteristics is significant. This leads to an error in determining the geometry of soil layers. Besides, the type of soil and its condition are often unknown in advance. Therefore, methods are needed that make it possible to determine velocity characteristics of the media directly in the field conditions. Several such methods have been recently developed.

Trial and error method [10] is based on using the results of control drilling. Layers are fixed from top to bottom, along the line-ups. Each line-up on the radarogram presumably correlates with the boundary of the layers in the well. The desired speeds are calculated from the known layer thickness and time stamps. If the resulting values are unreliable, the current line-up is rejected, and the process is repeated. The disadvantage of this method is that drilling operations are expensive, time consuming and often not so prompt; when works are executed at several sites, it is not always possible to be sure of reliability of data provided by geologists. Also, there is no guarantee that the selected line-up correlates precisely with the boundary between the layers, and not with a noise or re-reflection. In addition, engineering-geological drilling provides information only at one point (cross-section) of the section, while the velocity characteristics of soil media can vary significantly along the profile.

A number of other methods are based on direct measurement of the dielectric constant. A sample is taken, which is then tested under laboratory conditions with a reflectometer [6]. The complexity of this method lies in the need to use expensive laboratory equipment. A modification of this method is known [11], that is associated with excavation of a pit and with testing using a GPR, the design of which allows the antennas to be spaced apart. However, this method is also laborious, and the results are tied to a specific point. In addition, it can be used to determine the speed only in the near-surface layers of the foundation.

The most common method for determining velocities is based on selection of diffraction hyperbolas on a radarogram. Diffraction



Pic. 1. Calculated scheme for conducting GPR multi-offset profiling for a two-layer medium with one inclined boundary (compiled by the authors).

hyperbolas arise when there is an object in the medium whose transverse dimensions do not exceed the length of the radio wave [6]. The sought speeds are determined from the angle of inclination of the branches of the diffraction hyperbola. The disadvantage of this method is that often these objects are located unevenly along the length and depth of the profile. The outlines of hyperboles cannot always be distinguished with confidence.

If the design of the georadar allows changing the distance between the antennas, then speed can be determined using GPR multi-offset profiling by the method of the common depth point [2; 10; 12]. When processing radarograms obtained during such a test, hyperbolic hodograph curves of reflected waves are identified. They are used to determine the root-mean-square values of the wave propagation velocity, which are then converted into layer velocities in the layers using Urupov–Dix equation [13; 14]. Working with this method requires a good quality of the input information, since with a large amount of interference and incorrectly selected characteristics of the equipment, the hodograph curves are detected uncertainly (if they are identified at all), which leads to errors in determining the values of velocities.

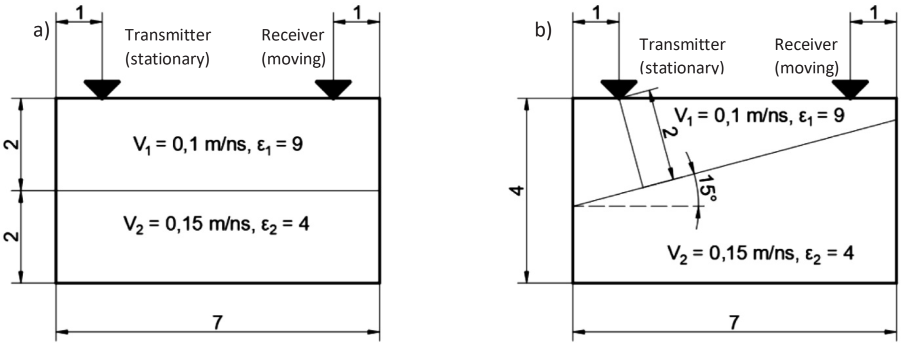
There are other methods associated with the analysis of the amplitudes of reflections from the boundaries [15; 16]. However, they also work mostly only regarding the upper part of the surveyed environment. Thus, modern methods make it possible to determine velocities only in the upper part of the section. This feature is also inherent in the most, in our opinion, universal and inexpensive method which is GPR multi-offset profiling. When performing work on the main ground of the foundation, the propagation speed of radio waves in its upper layers is determined reliably, and in the middle and lower parts of the section, velocity is often only estimated.

At the same time, GPR sounding can also be performed on embankment slopes. The main obstacle to conducting GPR multi-offset profiling on slopes is that the basic CDP method assumes that the media boundaries are horizontal or sub-horizontal (their slope can be neglected). However, below embankment slopes, media boundaries are not parallel to the survey surface (slope).

Thus, the *objective* of the work is to develop a method for determining propagation speed of radio waves in near-slope zones based on the results of multi-offset GPR profiling. For this, a *method* has been developed for calculating propagation speed of radio waves in an environment with inclined boundaries.

Method for calculating propagation speed of radio waves for a medium with an inclined boundary

Testing with GPR multi-offset profiling can be carried out in two ways. Following the first method, both antennas are simultaneously removed from a common centre (common depth point/CDP method). With the second



Pic. 2. Design schemes: a – horizontal boundary between the layers; b – inclined boundary between the layers (β = 15°) (compiled by the authors).

method, one of the antennas does not change its position, and the second is gradually moved away from the first one. When examining the slope of the foundation, it is convenient to use the second modification.

The design scheme for conducting multi-offset profiling with one inclined boundary between the layers is shown in Pic 1. Let us denote the current distance between the antennas of the GPR as x, the thickness of the upper layer as H, the sought speed of propagation of radio waves in it as V, and the angle of inclination of the boundary as β. Layer height H is measured in the position of the stationary transmitter along the normal to the layer boundary. The electromagnetic signal emitted by the transmitting antenna is reflected from the media boundary and is recorded by the receiving antenna some time t after emission.

The hodograph equation of the reflected wave $t(x)$ was obtained from geometric relationships (Pic. 1), where $ABC = DC$:

$$t(x)=\frac{\sqrt{(x-2H\sin\beta)^2+(2H\cos\beta)^2}}{V}, \quad (1)$$

$$x' = 2H \cdot \sin\beta. \quad (2)$$

When the distance between the antennas is equal to zero, formula (1) is reduced to the form:

$$t_0=\frac{2H}{V}. \quad (3)$$

After expressing the values of H and β from (2) and (3) and substituting them in (1), the hodograph equation is obtained:

$$t(x)=\frac{\sqrt{x^2-2\cdot x\cdot x'+t_0^2\cdot V^2}}{V}. \quad (4)$$

In the case of a horizontal boundary, when β = 0 and, therefore, x' = 0, this equation is reduced to the well-known equation of the hodograph of the reflected wave with a horizontal arrangement of layers [2]:

$$t(x)=\sqrt{t_0^2+\left(\frac{x}{V}\right)^2}. \quad (5)$$

Equation (4) is a hyperbolic function. However, if for the case of a horizontal boundary the vertex of the hyperbolic travel time (hodograph) curve corresponds to zero separation (x = 0), then for the case of an inclined boundary the top of the hodograph curve is shifted by the value x'.

Thus, the following sequence of processing GPR data is proposed:

1) On the initial radarogram, the hodograph of a hyperbolic outline with a displaced vertex is revealed.

2) The found hodograph is automatically approximated by the hyperbola equation in accordance with equation (4).

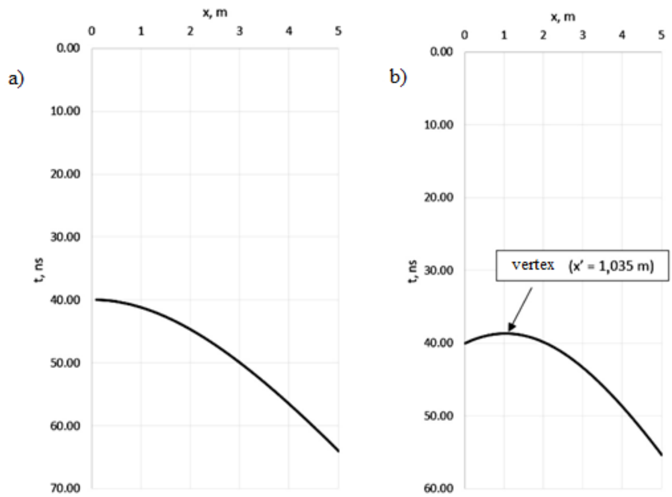
3) The parameters t_0, V and x' are determined by equation (4).

4) According to equation (3), the layer thickness H is calculated.

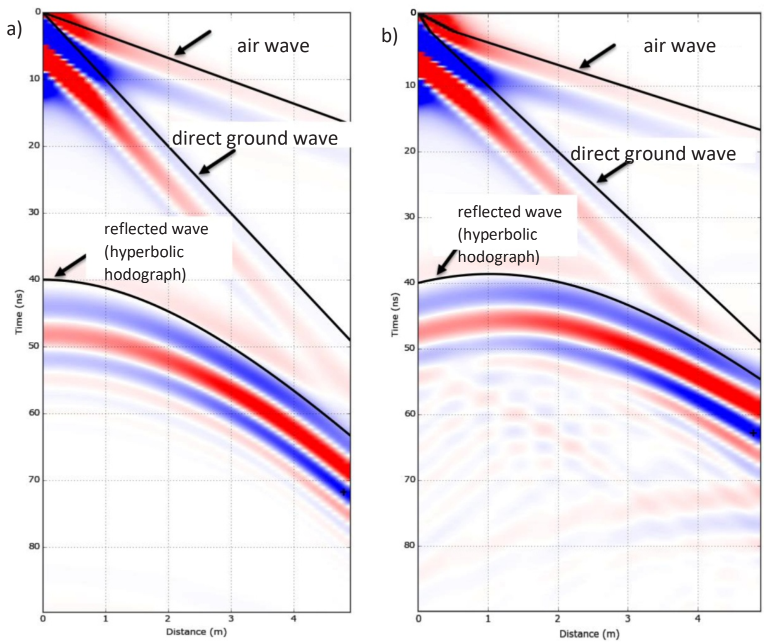
5) According to equation (2), the angle of inclination of the layer β is determined.

This technique is implemented with the GeoReader software package [17].

To check reliability of the developed technique, we will consider two design schemes for an environment with two soil layers. In the first design scheme, the media boundary is horizontal (Pic. 2a), in the second one, it is located at an angle of 15° to the scanned surface (Pic. 2b). All dimensions are given in meters. The transmitting antenna of the georadar is stationary, the receiving antenna moves with a step of 10 cm in the direction away from the transmitter.



Pic. 3. Results of calculating the hodographs of the reflected waves: a – horizontal boundary between the layers; b – inclined boundary between the layers (β = 15°) (compiled by the authors).



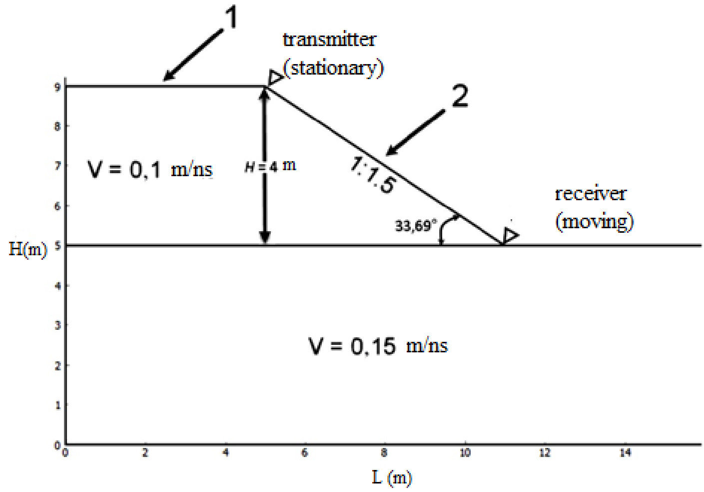
Pic. 4. Synthetic radarograms obtained by finite-difference time-domain simulation: a – horizontal boundary between the layers; b – inclined boundary between the layers (β = 15°) (compiled by the authors).

The results of calculations by the traditional method [2] for a medium with a horizontal boundary and by the method presented in this work for a medium with an inclined boundary are shown in Pic. 3. As can be seen, for a medium with an inclined boundary, the vertex of the hyperbola is displaced by $x' = 1{,}035$ m. In this case, the time value for $x = 0$ for both schemes is constant and equal to 40 ns.

To check correctness of the calculation, a finite-difference time-domain (FDTD) simulation was performed in the gprMax software environment [19]. A pulse in the form of an MHAT wavelet was used as a probe sounding pulse in the model.

The simulation results are shown in Pic. 4.

The simulation results are fully consistent with the calculation. The position of the



Pic. 5. Design scheme of the embankment; areas of GPR multi-offset profiling are: 1 – a section with a horizontal boundary (traditional version), 2 – a section with an inclined boundary (compiled by the authors).

Table 1

Results of comparing the calculated parameters with simulation data (compiled by the authors)

Parameter	Calculated value	Specified value	Error, %
Radio wave propagation speed, m/ns	0,096	0,1	4
Layer thickness, m	3,86	4	3,5
Boundary inclination angle, °	32,103	33,69	4,7

calculated hyperbolas (Pic. 3), determined by formulas (1–5), completely coincides with the results of numerical simulation (Pic. 4).

Determination of speed of radio waves in the slope zones of the foundation

It is shown in [14] that for a multilayer medium with several boundaries, which are not parallel to each other, the hodograph curves of reflected waves cannot be represented as hyperbolic functions and the velocity characteristics cannot be determined. To overcome this constraint, it is proposed to determine propagation speed of radio waves directly in the near-slope zone for a medium with one inclined boundary.

Let us consider how, according to the developed method for determining the speed characteristics of the environment, it is possible to calculate speeds in the slope zones of the foundation. Pic. 5 shows the design diagram of the embankment and the ground. The slope of the boundary between the embankment and the ground in relation to the slope is 33,69° (slope ratio 1:1.5).

The calculation was carried out in two versions: respectively, with a two-layer medium with a horizontal boundary and a two-layer medium with an inclined boundary. In the first version, the traditional method of velocity analysis [2] is used, in the second the developed method for determining the velocities for a medium with an inclined boundary is applied.

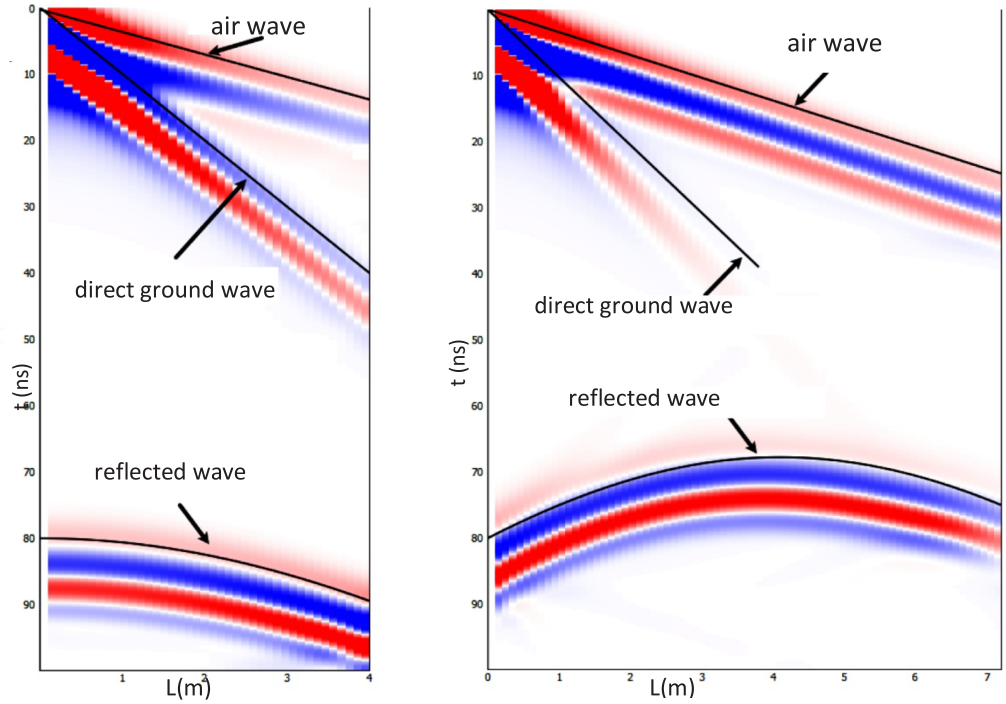
To check the calculation results, a synthetic simulation was performed using the gprMax software [19]. The obtained synthetic radarograms (Pic. 6) show a direct air wave, a direct ground wave and hyperbolic outlines of the hodograph of reflected waves.

The results of comparing the calculated parameters with simulation data are shown in Table 1.

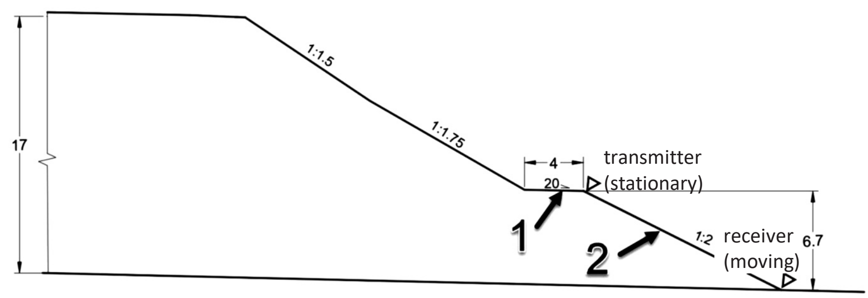
The errors in determining the parameters determined for the first and second sections in the section of the edge and the slope do not exceed 5 %. Thus, by installing a stationary transmitter at any point of the slope, it is possible to determine the layer thickness under the installation point and the slope of the soil boundary.

Application of the developed technique when inspecting the foundation

The developed technique is applied in the GPR survey of the foundation construction sites. The survey was carried out by the staff of



Pic. 6. Synthetic radarograms obtained by finite-difference time-domain simulation: a – the first section, b – the second section (compiled by the authors).



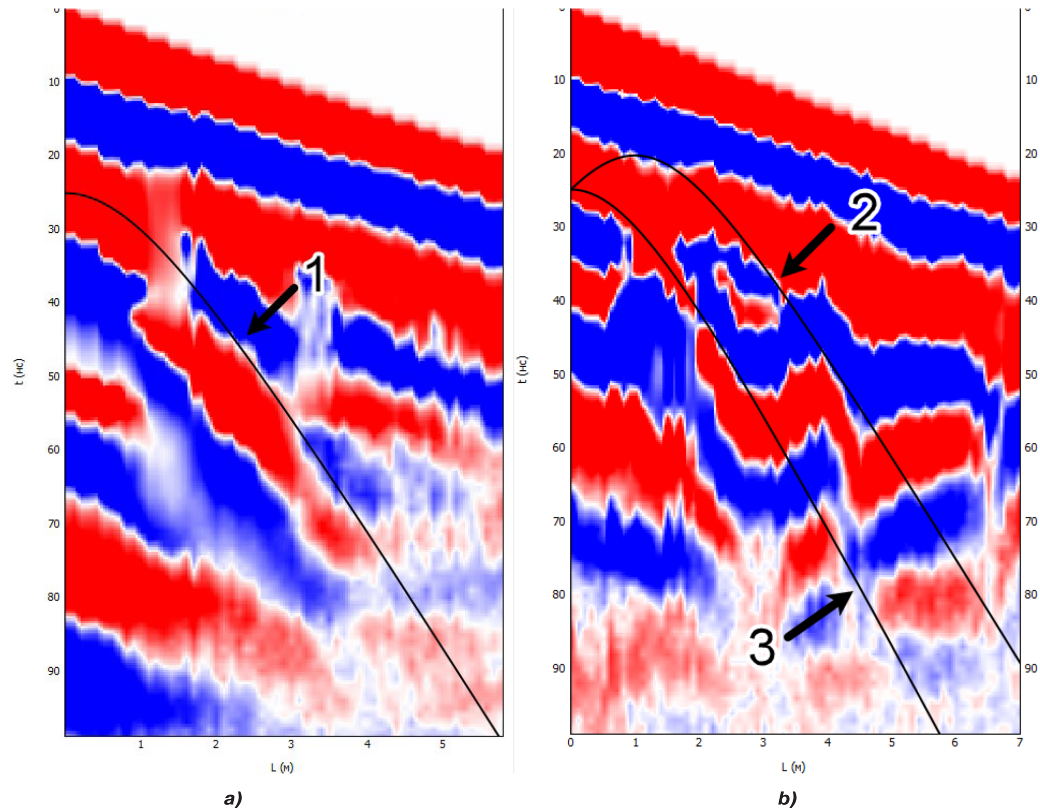
Pic. 7. Fragment of the cross-section of the surveyed embankment; areas of GPR multi-offset profiling are: 1 – on the berm, 2 – on the slope of the berm (compiled by the authors).

the Railway Track department of Far Eastern State Transport University. The georadar «LOZA-V» was used complete with antennas of various lengths from 1,5 to 6 m. Several longitudinal profiles were surveyed along the main site of the foundation with antennas long respectively of six and three meters (the central frequencies of the signal were respectively 25 and 50 MHz). When examining the transverse profiles, antennas with a length of 1,5 m (central frequency of the signal 100 MHz) were used. In the area under the main ground, due to the use of low-frequency antennas, sections with a depth of up to 18...20 m were obtained. The depth of the GPR section in the slope zones turned out to be lower. There were «blind» zones, in which it was not possible to determine the position of the boundaries outside the main ground. Control drilling was performed only on the ground of the foundation. To determine the velocity characteristics of soils under the surface of the slopes, the proposed method was applied.

On the transverse profile (Pic. 7), GPR multi-offset profiling was performed in two versions.

In the first variant, the test was carried out on a berm, with a step of 10 cm. In the second

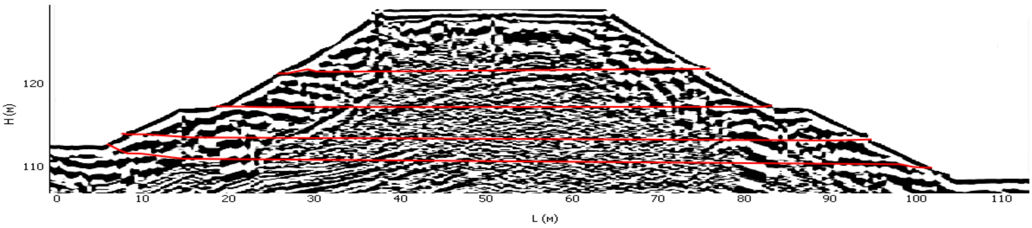
Pic. 8. Conducting GPR multi-offset profiling on a berm slope (provided by the authors).



Pic. 9. Radarograms obtained by GPR multi-offset profiling: a – first section, b – second section; 1, 2, 3 – hyperbolic hodograph curves of reflected waves (compiled by the authors).

variant, the test was carried out along the slope of the berm (Pic. 8); initially, the GPR antennas were located close to each other on the edge of the berm, then the transmitting antenna was moved away from the receiving antenna in the direction towards the bottom of the slope with a step of 10 cm.

The resulting radarograms are shown in Pic. 9.



Pic. 10. An example of processing the transverse profile of an embankment with a height of 17 m. The division of the section into boundaries with similar velocity characteristics is given (compiled by the authors).

When calculating the hodograph on the berm, the traditional method of velocity analysis was used. As a result of its use, it was obtained that propagation velocity of radio waves was 0,06 m/ns, the thickness of the layer was 0,756 m.

When calculating hodographs on the berm slope, it was found that there are two types of hyperbolic outlines. One of them (Pic. 9, 2) corresponds to an inclined boundary (with a displaced top), the other (Pic. 9, 3) – to a boundary parallel to the slope. The calculation for the first hodograph was carried out according to the traditional method of velocity analysis, the calculation for the second one was executed according to the method proposed in the work.

The calculation results for the inclined boundary are, respectively: propagation speed of radio waves – 0,069 m/ns; the angle of inclination of the layer – 35,43°; layer thickness – 0,863 m. Calculation results along the horizontal boundary: radio wave propagation speed – 0,058 m/ns; layer thickness – 0,72 m. Velocity characteristics are within the range of 0,058–0,069 m/ns, which corresponds to the soil in a wet condition.

The results obtained made it possible to determine the layers in the lower part of the surveyed embankment (Pic. 10). On the radarogram, tied to the marks of the transverse profile of the embankment, it was possible to plot the boundaries of soils, to trace their position in the middle part of the foundation, until reaching the opposite slope.

Due to propagation of radio waves in the soils, calculated using the proposed method, layers in a wet condition were identified and weak zones in the embankment were revealed.

The work performed has shown that the proposed method can be expanded and supplemented with a simplified method for determining the velocity characteristics of soils of the slope zone by recalculating the preliminary geometry of the layer boundaries obtained directly in the field conditions. It is also planned to use RFID tags embedded in the roadbed at the time of its construction.

Conclusions. The GPR method is widely used to survey transport infrastructure facilities. The problems solved by this method are diverse, so there is a need to develop new approaches to their solution. The proposed method for determining propagation speed of radio waves in soils in «blind zones» allows obtaining the speed characteristics of soils in the slope zones of embankments. The area of such zones can be up to 60 % of the total cross-sectional area of the embankment, depending on the steepness of slopes.

The developed technique not only expands the scope of application of GPR surveys, but also allows calculating the values of the speed characteristics of soils in slope zones. More reliable and high-quality information obtained as a result of the use of geophysical and traditional survey methods contributes to further improved quality of design decisions, and ensures strength and reliability of transport infrastructure facilities.

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Acknowledgments. The publication was carried out as part of a grant from JSC Russian Railways for development of scientific and pedagogical schools in the field of railway transport.