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Procedia Engineering 143 (2016) i

Procedia Engineering

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Advances in Transportation Geotechnics III

Guest Editor:

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Procedia Engineering 143 (2016) vi–xii

Procedia Engineering

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Procedia Engineering
Volume 143, 2016, Pages 1236–1243
Advances in Transportation Geotechnics 3 . The 3rd International Conference on Transportation Geotechnics (ICTG 2016)

Soil Formation Lithological Profiling Using Ground Penetrating Radar

Yuri A. Sukhobok, Viktor V. Pupatenko, Gennady M. Stoyanovich and Yulia V. Ponomarchuk
Far Eastern State Transport University, Khabarovsk, Russia
yuri.sukhobok@gmail.com

Abstract
The paper presents a modified technique for generation of the high-contrast sub-horizontally layered earth depth sections which is based on the common offset and common midpoint GPR methods. The iterative algorithm for fitting and correction of the reflection and refraction time-distance curves, as well as identification of the basic layer parameters, is suggested. Some results of the technique's implementation on railroads and highways in the Russian Far East are summarized.

Keywords: Ground penetrating radar, common-offset reflection survey, wide angle reflection and refraction method, geotechnical investigations, data processing

1 Introduction

One of the most widely recommended method of geophysical survey is a ground-penetrating radar (GPR). It is based on radio frequency broadband signal emission into medium by a transmitter and response signal registration by a receiver. The response signal is a superposition of amplitudes of forward, reflected, and refracted waves, which reach a receiving antenna.

One of the important GPR applications in surveys of transportation facilities subsurface or subgrade is construction of a depth section of the surveyed medium. Generally the medium is non-uniform, however, it can be considered to be constructed of uniform subhorizontal layers of finite quantity with precision, which is sufficient for practical use. According to this model the electrophysical properties of ground layers change step-wise. For instance, filled and foundation soils in different conditions (watered, thawed out or frozen), engineering structures, reinforced, insulating, and separating layers and constructions can be found in subgrade surveys of railroads and highways, runways and other structures.

In order to construct a depth section of an extensive site usually GPR survey is conducted. A linear profile is marked on the surveyed area and a GPR unit, which has a constant distance between its transmitting and receiving antennae, is moved from one point to another within a given step along it. At each point a signal (trace) is registered. Signals, received from all the points, form a radargram.

 Selection and peer-review under responsibility of the Scientific Programme Committee of ICTG 2016

doi:10.1016/j.proeng.2016.06.110

The main problems of a cameral treatment are as follows: detection of interface boundaries on a radargram and detection of the depths, where these boundaries are located. The first problem, which was thoroughly studied in [1, 2], is out of the scope of this paper. It is further assumed that the interface boundaries are detected previously. The goal of this research is to advance the detection technique of depths, where the interface boundaries are located, that is transformation technique of the source reflection-time section to the depth section.

2 Related Work on Transformation Techniques of the Source Reflection-Time Section to the Depth Section

In order to transform the source reflection-time section to the depth section, first of all, it is necessary to calculate the velocity of electromagnetic wave propagation in each layer (strata velocity). Since the reflected signal propagates through the whole ground layers, in order to evaluate the strata velocity in a given stratum the notion of a root-mean-square (RMS) velocity is introduced. It represents the mean velocity of electromagnetic signal propagation at a given point on the ground surface (emission source) to a given point of ground depth. The strata and RMS velocities are related to each other.

Nowadays a few techniques have been developed in order to estimate RMS velocities and, therefore, strata velocities. The simplest method relies on velocity calculation according to the diffraction curves [2]. Its idea is based on the fact that if there are local diffractors in the section area (big rocks, pipes, cables), the curve of arrival time versus distance has a hyperbolic form on the GPR radargram.

The disadvantage of this technique is that in order to have a success in its implementation a sufficient number of local diffractors are needed to be situated in different depths. Frequently these objects are located only in the upper layer of the section and non-uniformly along the profile length. The forms of hyperbolic time-distance curves are not reliably detected when there is a large interference that leads to errors in velocity estimation.

Another technique for estimation of the signal propagation velocities in different strata is based on amplitude fluctuations on strata boundaries [4]. The main drawback of the method is the measurement complexity of the decaying signal amplitude, which leads to significant errors with the increase of the reflecting boundary depth. Moreover, there may be no significant change in amplitude values on the boundaries of layers when the dielectric constants of ground layers change insignificantly. In the meantime due to interference and re-reflections "false" jumps may occur, which do not depend on the ground layers boundary surfaces.

The next method is based on direct velocity measurement with the help of the common-midpoint (CMP) or the wide angle refraction and reflection mode (WARR) techniques. According to these techniques, the distance between the antennae increases from 0 to a maximum value, usually up to 10 meters. It should be noted that the CMP technique operates with the both antennas which are moved equidistantly from the midpoint. However according to the WARR technique the position of the one antenna is fixed while the other one is moved step-by-step away from the fixed one. According to both methods an electromagnetic impulse is generated and then a signal is registered at the receiving antenna at each point of measurement. The types of waves representing the received signal can be classified as direct, refracted and reflected ones. These waves could be represented in the form of the time-distance curves. These curves are detected from the radargram (Fig. 1).

Generally the CMP technique is more accurate than WARR for obtaining velocity. The cause of this difference is that moving both antennas equidistantly from the midpoint ensures that the average velocity is being measured using the same reflection interface, at the same location. Since the reflection surfaces of subgrade are assumed horizontal, the WARR technique could be used for a subgrade survey. In addition, the recording surface is horizontal in the longitudinal direction, for subgrade surface and berms, which allow to conduct WARR tests. This technique, in addition, is two times faster than CMP for the considered types of GPR units.

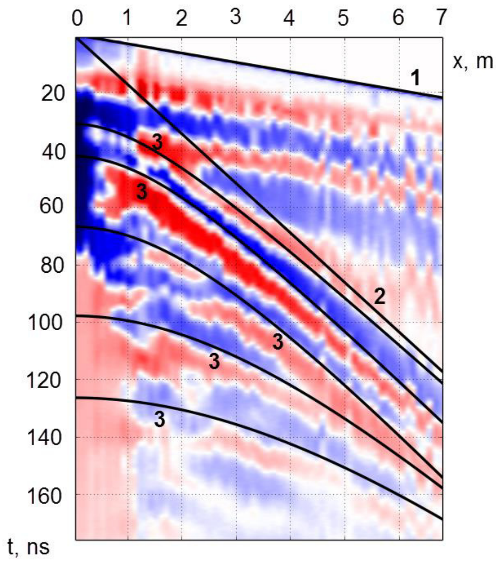

Fig.1. An example of radargram, which was obtained after the WARR measurement. Rectilinear time-distance curves of direct air wave (1), direct ground wave (2) and hyperbolic time-distance curves of reflected waves (3) are detected; *x* – the axis of distance between the antennae, m.

The time-distance curves of reflected waves are approximated by hyperbolic functions, and for each of them a corresponding equation can be found. If it is assumed that the trajectories of beams are rectilinear (i.e., do not change while propagating from one medium to another), then the time-distance curve equation is expressed in engineering seismicity as [6]:

$$t_{refl-n}(x) = \frac{1}{V_{stack}} \sqrt{4H_n^{\ 2} + x^2} , \tag{1}$$

where t_{refl-n} – is a 2-way time of reflected wave propagation, ns; x – distance between antennae, m; H_n – depth of nth layer's top, m; V_{stack} – stacking velocity of electromagnetic waves propagation in the medium; in this case it is equal to the RMS velocity of electromagnetic waves propagation in the medium from the surface to the top of the nth layer V_{RMS} , m/ns.

The estimation of the RMS velocities of electromagnetic waves propagation and boundary depths leads to the problem of the coefficients fitting in equation (1). These values can be adjusted by time-distance curves approximation of the direct and refracted waves. Then, the each layer thickness is evaluated according to the estimated strata velocities.

One significant drawback of this method is based on assumption that the beam trajectories are rectilinear. However, when propagating from one layer to another the beams are refracted and, therefore, deviate from the initial direction.

Therefore the technique can be used only for media, in which the velocities of electromagnetic waves propagation do not differ more than by 10-15% from each other. If a surveyed ground area significantly differs in velocities, the deviation of the beam trajectory from a straight line can not be neglected.

The technique, which is based on WARR results processing, is versatile. In the simplest implementation this method does not allow to estimate the ground model with significant velocity variation between different layers. Therefore the goal of this research was to modify the transformation of the source reflection-time section into depth section according to the results of the WARR technique without the mentioned constraint.

3 Modification of the Transformation Technique of the Source Reflection-Time Section into Depth Section according to the WARR technique

Let us consider the model of reflected wave propagation in a multilayered medium, which consists of separate homogeneous layers with horizontal boundaries (Fig. 2).

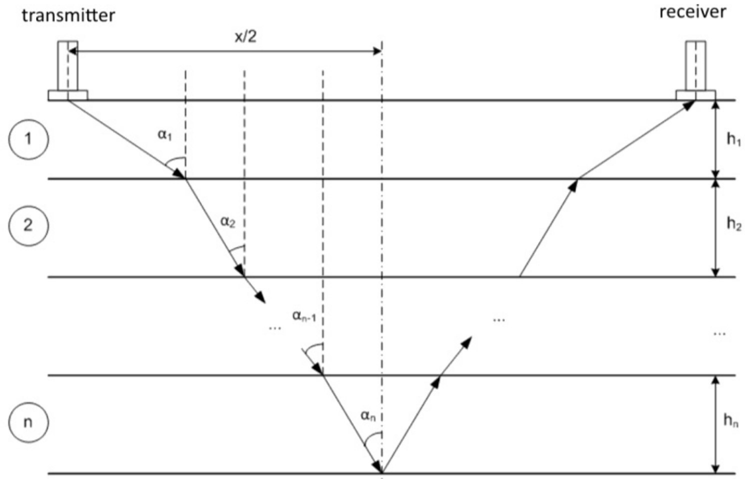

Fig. 2. The scheme of reflected wave propagation in a multilayered medium with horizontal boundaries: x – the distance between the antennae, m; h_i – the thickness of the ith layer, m.

In [5] it was shown that the time-distance curves cease to have hyperbolic form according to this model (Fig. 5, a). Their equation can be defined in parametric form:

$$\begin{cases} t_n(p) = 2\sum_{i=1}^{n} \dfrac{h_i}{V_i \cdot \sqrt{1-p^2V_i^2}} \\ x_n(p) = 2\sum_{i=1}^{n} \dfrac{p \cdot h_i \cdot V_i}{\sqrt{1-p^2V_i^2}} \end{cases}, \tag{2}$$

where n is the number of layers; V_i – the velocity of electromagnetic wave propagation in the ith layer (stratum velocity), m/ns; h_i – the ith layer thickness, m; p – ray parameter, which is defined according to the following expression:

$$p = \frac{\sin\alpha_1}{V_1} = \frac{\sin\alpha_2}{V_2} = ... = \frac{\sin\alpha_n}{V_n}, \tag{3}$$

where $\alpha_1, \alpha_2, \ldots, \alpha_n$ – the angles of incidence in the first, second, … , and nth layers respectively.

It was shown in [6] that it is impossible to obtain the expressions to calculate the strata velocity from (2). Moreover, equation (2) can not be represented in non-parametric from, as an expression $t = f(x)$.

This makes sure that it is impossible to evaluate adequate values of parameters for equation (2) on the basis of a selected time-distance curve and, therefore, precise computing of velocity values.

The technique, which uses the limiting efficient velocity, is used in engineering seismicity in order to estimate the strata velocities approximately [5]. This method is based on hyperbolic approximation of curve (2). According to expression (2) an effective velocity V_{stack} is obtained, which is not equal to the RMS velocity and which can not be transformed into the strata velocities.

However the author of [5] showed that with the approach to the time-distance curve axis, in the section of which the space between the antennae is equal to 0, the effective velocity is called the limiting effective velocity: $V_e = \lim_{x\to 0} V_{эф}(x)$ and it can be used to estimate the strata velocities using Dix formula [5]:

$$V_i = \sqrt{\frac{V_{e(i)}^2 \cdot t_{0(i)} - V_{e(i-1)}^2 \cdot t_{0(i-1)}}{t_{0(i)} - t_{0(i-1)}}}\,, \tag{4}$$

where $V_{e(i)}$ is the limiting efficient velocity according to hyperbolic form of the approximation of the time-distance curve of the wave, which is reflected from ith layer, m/ns; $t_{0(i)}$ – double signal propagation time of the wave, which was reflected from the boundary between ith and $(i+1)$th layers (which corresponds to the vertex of the hyperbola of the reflected wave), ns; $V_{e(i-1)}$ and $t_{0(i-1)}$ – the same values at $(i-1)$the layer.

Therefore, the limiting effective velocity V_e can be estimated, if the hyperbolic approximation is applied not to the whole time-distance curve of reflected waves, but to its part, which is the closest to its axis. Let us denote this approximating hyperbola as a *conditional time-distance curve* (Fig. 3, b). The ground model is developed according the conditional time-distance curves: the velocities of signal propagation in the layers, as well as the layer thicknesses, are computed.

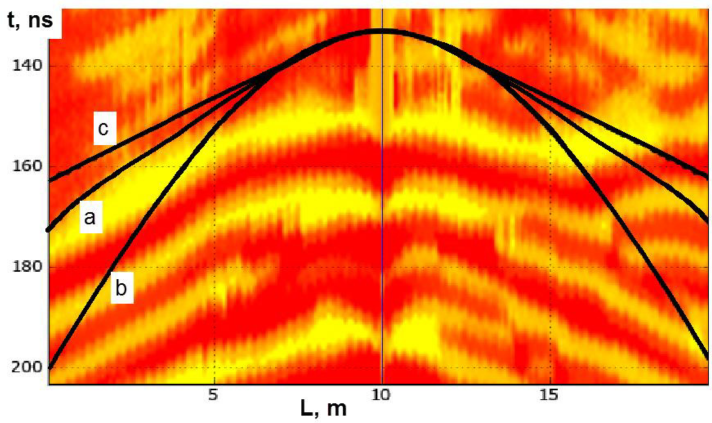

Fig. 3. A fragment of a radargram, which was obtained after the WARR measurement: a – the form of the original non-hyperbolic time-distance curve of the reflected wave; b – the conditional hyperbolic time-distance curve; c – the estimated time-distance curve.

On the basis of the technique, described above, an iterative algorithm was developed, which is based on step-by-step approximation of the ground model parameters $\{h_i, V_i\}$. According to the current values of the model parameters equation (4) is resolved numerically with respect to x and t (a direct geophysical problem is solved – an approximation of a *calculated time-distance curve* according to the ground model data). The solution of this equation consists of finding such values of angle α_1 and, consequently, parameter p, so that the value of x is to be equal to the corresponding distance between the antennae. By considering all the distance values between the antennae from 0 to the maximum value and solving numerically equation (4), a set of points (x_j, t_j) can be obtained for $0 <= x_j <= x_{max}$. These points form the calculated time-distance curve (Fig. 3, c), which is to be compared to the actual time-distance curve. If the calculated and the actual time-distance curves do not coincide, it is necessary to correct the conditional time-distance curve and solve again the inverse and direct geophysical problems.

If some a priori data on any layer thickness and velocity of electromagnetic wave propagation in any medium is available, it is necessary to introduce corrections into the ground model before solving the direct problem.

The iterative process is repeated till the actual and calculated time-distance curves coincide with sufficient accuracy. Methods of mathematical statistics, for example, the least square method are applied in order to minimize the residual.

The last stage is to transform the time section into the depth section according to the ground model. It is necessary to mark layer boundaries according to the estimated velocities of electromagnetic waves propagation in ground layers. This step is also implemented using the numerical solution of equation (2) separately for each GPR position and each boundary.

4 The Results of the Technique Implementation for the Transport Infrastructure Facilities

The proposed technique was implemented to survey various earth structures of the Russian Far East transportation facilities.

For example, the geophysical monitoring of the railway subgrade formation settlements was carried out at Kuznetsovo, Nakhodka – Khmilovsky section of the Far Eastern Railway in 2009 – 2011. The GPR units LOZA-N and LOZA-V were used provided with antennae, which have band center frequency from 25 to 100 MHz.

The WARR tests were carried out on the subgrade surface and the subgrade berms in the longitudinal direction. The test results were processed according to the proposed method (Fig. 4). As a result the ground model was developed and the ground profile of the subgrade formation settlements was obtained as longitudinal and cross-sectional profiles (Fig. 4). These results allowed detecting the locations of the maximum subsidence and monitoring the dynamics of soil settlements changes within the observation period. Moreover, the design decision – the placing of geotextile layers, was detected.

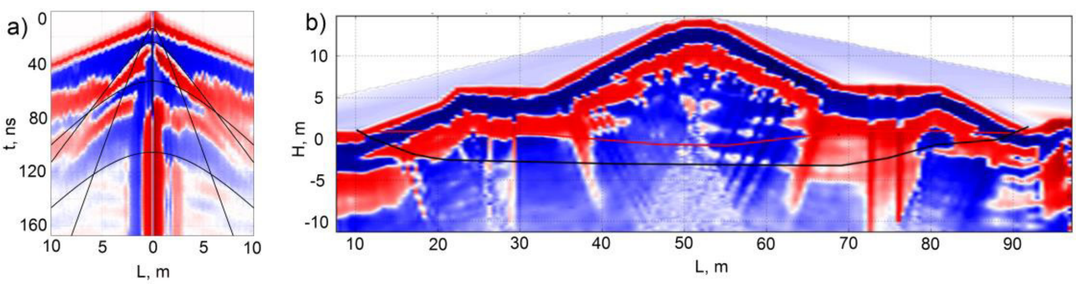

Fig. 4. The results of the geophysical survey of the railway subgrade formation settlements which was carried out at Kuznetsovo, Nakhodka – Khmilovsky section of the Far Eastern Railway: a – the radargram, obtained by the WARR measurement; b – GPR profile along the cross-section of the subgrade formation.

The highway monitoring in the Khabarovsk Territory of Russia was carried out in 2013. In order to conduct the survey the following GPR units were used: LOZA, OKO-2, and MALA GeoScience CX-11, provided with antennae of various frequencies (15-1700 MHz). The common-offset survey was carried out along the cross-sectional and longitudinal profiles. The distance between antennae was set to one meter. The multi-offset acquisition was also conducted at the specific points on the road surface.

The application of the proposed technique allowed obtaining a lithological section of the surveyed media. The results of comparison of borehole data with GPR data (Fig. 5) are satisfying generally. The occurrence of the second and the third reflection surface could be explained as at the discrepancy of the mineral composition of soils.

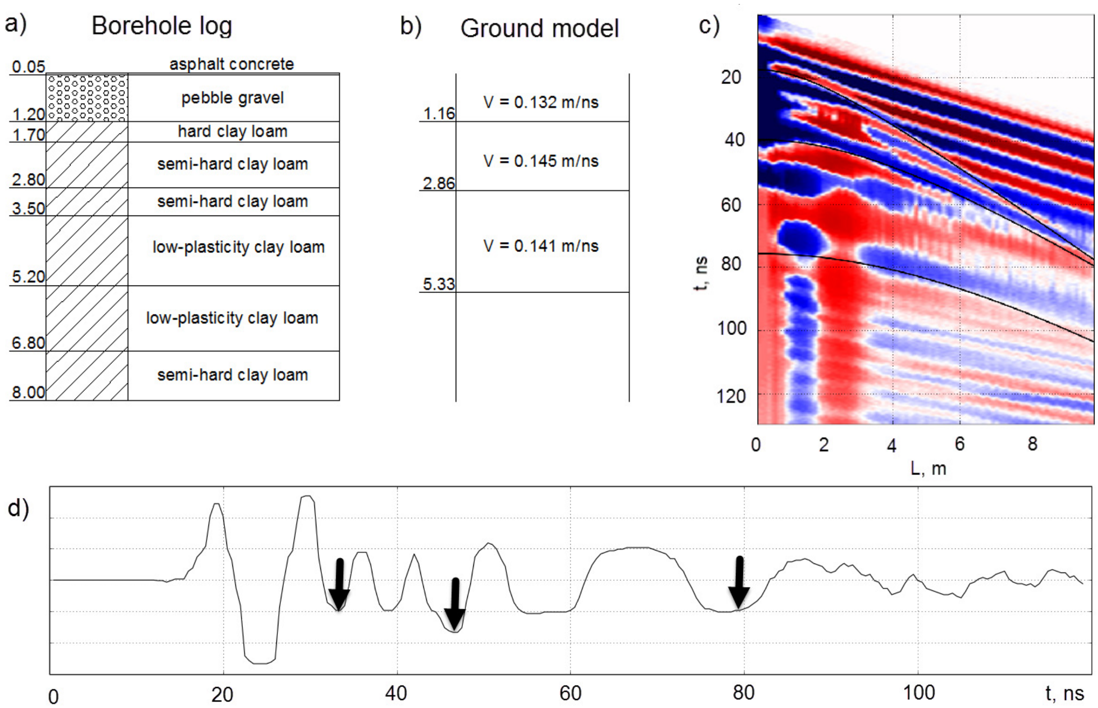

Fig. 5. The borehole data compared to the GPR data (highway section near Mukhen settlement): a – borehole log; b – ground model; c – radargram with marked time-distance curves of the reflected waves; d – the example of the GPR trace with 3.8 m offset: arrival time of the wavefronts is indicated by the arrows.

5 Conclusion

The research results allowed developing a technique for the heterogeneous media boundaries detection in order to do the lithological profiling of geological section. Besides the experiments on transport facilities presented in the previous section, the proposed technique was also tested in order to detect boundaries of filled-up ground while laying foundation, foundation pit contouring, displacement surface of downslopes, etc. The experience of implementation has shown that the integral use of traditional geotechnical methods (boring, test pit sampling) and geophysical methods (ground penetrating radar, seismic, etc.) allows providing the reliability of results and reducing labor costs and labor hours of geotechnical survey during construction of new facilities or reconstruction of objects, which are maintained for a long time.

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