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Lithological Profiling of Rocky Slopes Using GeoReader Software Based on the Results of Ground Penetrating Radar Method

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Abstract

The paper presents the Ground Penetrating Radar (GPR) technique for the survey of deforming rocky slopes of the railway subgrades. The developed software GeoReader allows the delineation of the boundaries in soils, which compose the slope, and definition of the possible slip surface. We have summarized the results of the use of the technique in certain sections of the Far Eastern Railway.

The current level of development in the sphere of geo-survey does not allow for the complete abandonment of costly and labor-intensive conventional survey techniques, such as boring. Nevertheless, in the near future geophysical methods will be able to provide complete information on the object of investigation.

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Keywords: ground penetrating radar, common-offset reflection survey, common-midpoint method, subgrade;

Introduction

Large amounts of work on the reconstruction of operation lines are being conducted in the Eastern polygon of the railways of Russia. Among others, reconstruction resolves the tasks of extending the station tracks, laying second tracks and increasing curve radiuses. These jobs involve widening of the subgrade, displacing the center line

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of the track and determining the design parameters that will ensure the stability of the newly formed slopes. High quality engineering geological survey results are crucial for laying out such jobs.

Unfortunately, the performance of high quality survey jobs on an operating railway track is very complicated. Some sections do not have a developed motor-road network which sometimes makes delivery of the equipment and machinery to the work site impossible and, consequently makes implementation of the work tasks impossible also.

The ground penetrating radar survey offers the possibility of solving some of the problems, emerging in the process of the survey. Portability, high speed and low labor cost are the main advantages of the geophysical methods in comparison with the traditional geological-engineering survey methods. In our view, geophysical methods do not cancel traditional ones, but complement them and allow specialists to provide a higher quality of results.

Ground penetrating radar (GPR) is a geophysical method for the non-destructive detection of ground layers by electromagnetic waves. GPR measures the two-way travel-time of the reflected electromagnetic wave propagating through the ground layers. The thickness of these layers is estimated after the determination of the EM velocity, *V*, propagation which, in turn, is controlled by the relative dielectric permittivity ε_r [1]:

$$V = \frac{c}{\sqrt{\varepsilon_r}} \tag{1}$$

where c is the EM velocity in vacuum, 0.3 m/ns.

GPR has been proved to be an effective non-destructive tool for solving a variety of engineering tasks [1]. The benefits of the method include development of a continuous GPR section, high efficiency and low cost. However, the complexity of the processing of the results is dependent on the experience of the engineer, which may significantly reduce the accuracy.

Materials and methods

There are very few papers dedicated to the use of the ground penetration radar method in the survey of unstable rock slopes. The theoretical basis of the GPR method from the point of view of resolving this task was given in the work of T. Toshioka [2]. Research [3] conducted within the frameworks of the research project "Landslide Hazard Assessment and Cultural Heritage", describes the employment of the GPR method when monitoring landslides in Austria. The paper [4] is devoted to GPR surveying of road failures as they relate to filling slope stability (using in particular a three-dimensional survey method). This paper describes ground penetrating radar method as an efficient, non-destructive and cost effective tool in characterizing the nature of slope stability problems as they relate to road construction. The work of British scientists [5] gives an example of using GPR methods for studying the influence of badger setts on the stability of slopes prone to landslide. The research paper [6] gives a theoretical basis for forecasting landslide deformation based on the interpretation of the amplitude-frequency characteristics of the returned GPR signal.

The practice of employing LOZA GPR units produces good results under very different conditions [7, 8]. Antennae with a carrier signal frequency of 100-150 MHz are used under common conditions. In order to increase the depth of the cross-section, the radar is equipped with antennae with frequencies of 25 and 50 MHz. We used the LOZA-N GPR unit with a 3.0 meter long 50 MHz antennae. The time-base was 1024 ns and the sampling frequency was 1 GHz. The antennae are not cable-connected which allows the performance of GPR measurement to determine the velocity of wave propagation in ground layers.

The research described in the paper is based on the results obtained by the research workers of the Far Eastern State Transport University [9, 10, 11].

Two groups of profiles are assigned and performed on the research object. The cross-sectional profiles are assigned from the base of the slope upwards. They are usually used to determine the possible slip surface on deforming or potentially dangerous slopes. The longitudinal profile is assigned along the slope or along the axis of the existing railroad. These profiles are essential for detecting the delineation of a landslide ground massif and correcting the boundaries detected on cross-sectional profiles. Combining the results of processing the cross-sectional and longitudinal profiles allows us to obtain a 3-D object model.

Theory

Unstable rock slopes have a well-marked sandwich layer structure. The upper layer consists of a mixture of rocky ground with loamy or sandy aggregate. The slip surface is, as a rule, water saturated, and goes along the loose ground interlayers. The lower layer may have an undisturbed structure. Layer geometries may be random and, frequently, very complicated. The strength, deformative (and velocity) properties of each layer differ significantly.

Thus, the model of a deforming rock slope is represented by a stratified medium with significantly differentiated velocity properties of adjacent layers. Such a model can be applied to calculate the ground facilities of a transport infrastructure on a stable or loose base, under the conditions of spread permafrost and buried/ground ice [7], and extended structures crossing water areas, rivers and lakes [12, 13].

We have developed a methodology for transforming source GPR data into the depth sections. The central idea of this methodology lies in using the multi-offset measurement to calculate the propagation of electromagnetic waves in each layer. The results of transformation serve as a basis for the transformation of the source reflection-time section into the depth section.

When carrying out full-scale field investigations, field tests are performed in such variants as the common midpoint (CMP) or wide angle refraction and reflection mode (WARR) technique. According to this technique, the distance between the antennae increases from 0 to a maximum value (usually up to 10 meters). At each point of measurement an electromagnetic impulse is generated and then a signal is registered at the receiving antenna.

The time-distance curves of reflected waves are detected on the radargram. The velocity estimation from the multi-offset the GPR dataset is based on a hyperbolic assumption, where the reflecting interface is horizontally layered and the medium is homogeneous [14]. The relationship between the reflected wave time t, the antenna offset x and rms velocity V_{rms} is given for each horizon time by:

$$t = \sqrt{t_0^2 + \frac{x^2}{V_{rms}^2}} \tag{2}$$

The required interval velocity in the layer can be calculated by Dix's equation [15]:

$$V_{\mathrm{int},i} = \sqrt{\frac{V_{rms,i}^2 \cdot t_{0,i} - V_{rms,(i-1)}^2 \cdot t_{0,(i-1)}}{t_{0,i} - t_{0,(i-1)}}} \tag{3}$$

where $V_{rms,i}$ and $V_{rms,(i-1)}$ are the rms velocities at the layer boundaries *i* and *i-1*, respectively; and $t_{0,i}$ and $t_{0,(i-1)}$ are the horizon times at these layer boundaries.

The depth of the *n*-th boundary layer can be computed as follows:

$$z_n = \frac{\sum_{i=1}^{n} V_{\mathrm{int},i} \cdot t_i}{2} \tag{4}$$

We have developed a GeoReader software for the practical employment of the described survey technique [16]. The software is written in Python 2.7 programming language using the Python(x,y) library for numerical calculations, analysis and data visualization (numpy, scipy, and matplotlib libraries tied with the graphics framework PyQt were used).

The software implements a design procedure that calculates the velocities of propagation of electro-magnetic signals in stratified media, including those having inclines towards the boundary horizon. On the basis of the computed model, an engineer can delineate the boundaries of the ground layers and transform the time section into a depth section.

The software contains the following major algorithms for processing radargrams:

- Compensation of attenuation along traces; vertical and horizontal normalization of amplitudes;
- Spectral analysis (including constructing/plotting and analyzing spectrograms and periodograms according to fixed signals);
- Distinguishing of the statistical parameters of traces;
- High-frequency and low-frequency signal filtering;
- Hilbert transform, plotting a signal envelope curve;
- Topographic correction (Fig. 1, a) and compiling the results of processing the coordinates of the boundaries of ground layers (Fig. 1, b) for cross-sectional and longitudinal (Fig. 2) profiles.

a) b)

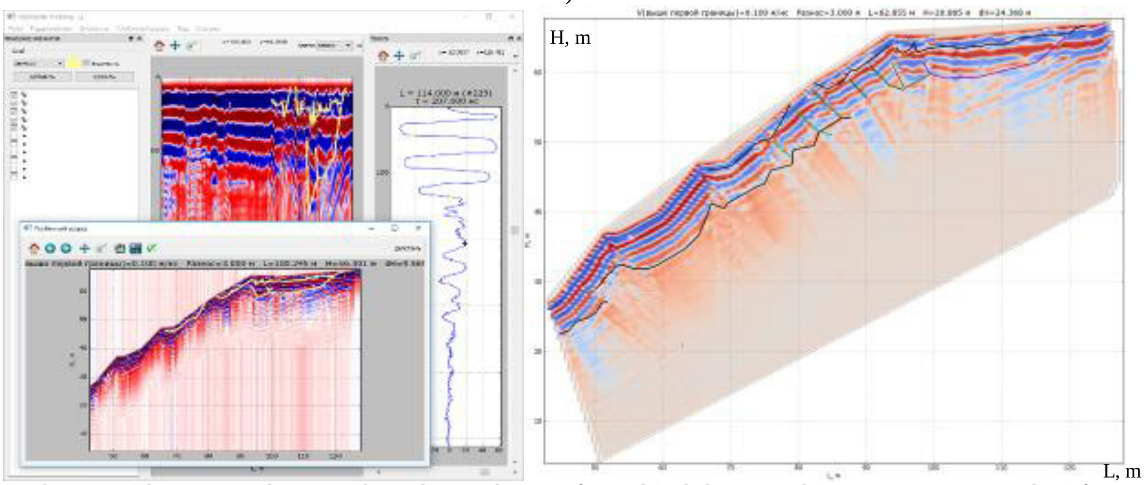

Fig. 1. The source radargram (a) and corresponding radargram (b), geo-referenced (with the topographic survey correction carried out) for cross-sectional profile.

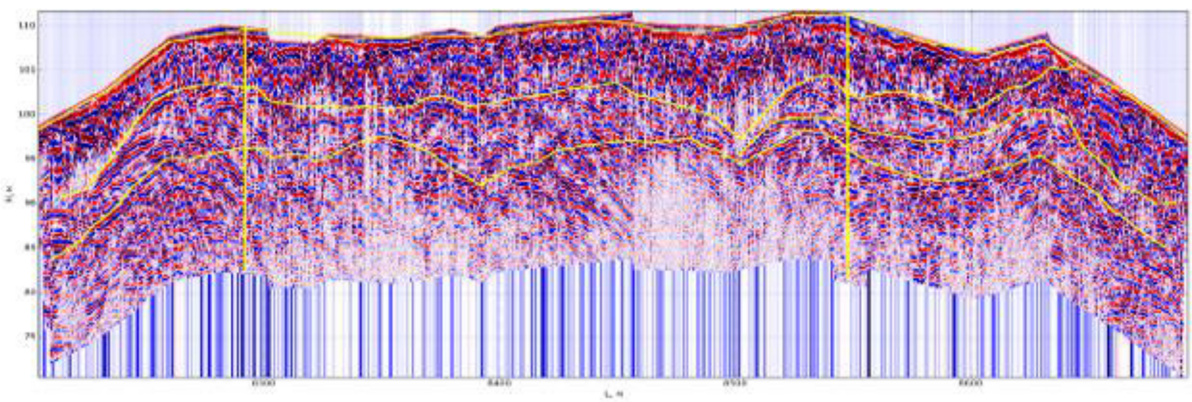

Fig. 2. Radargram of longitudinal profile with geo-referenced topographical survey correction.

The obtained coordinate data for all assigned borders of layers in the object under research is important information that allows us to determine the possible positioning of a single or several displacement surfaces.

Results

The coordinates of the boundaries have been obtained. Velocity parameters for each delineated layer have been transformed according to given dependencies into strength and deformation parameters. The detailed results of the geo-survey of one of the landslide sections of the Far Eastern Railway are described in [8]. Fig. 3 shows an example of the processing results. The geometry of the ground layers in the landslide massif is complicated. No less complicated is the task of delineating a possible slip surface in the slope. It should be taken into consideration that slip surfaces may be numerous lying at different depths from the slope surface. Additional information obtained in the course of the survey helps the analysis of the results.

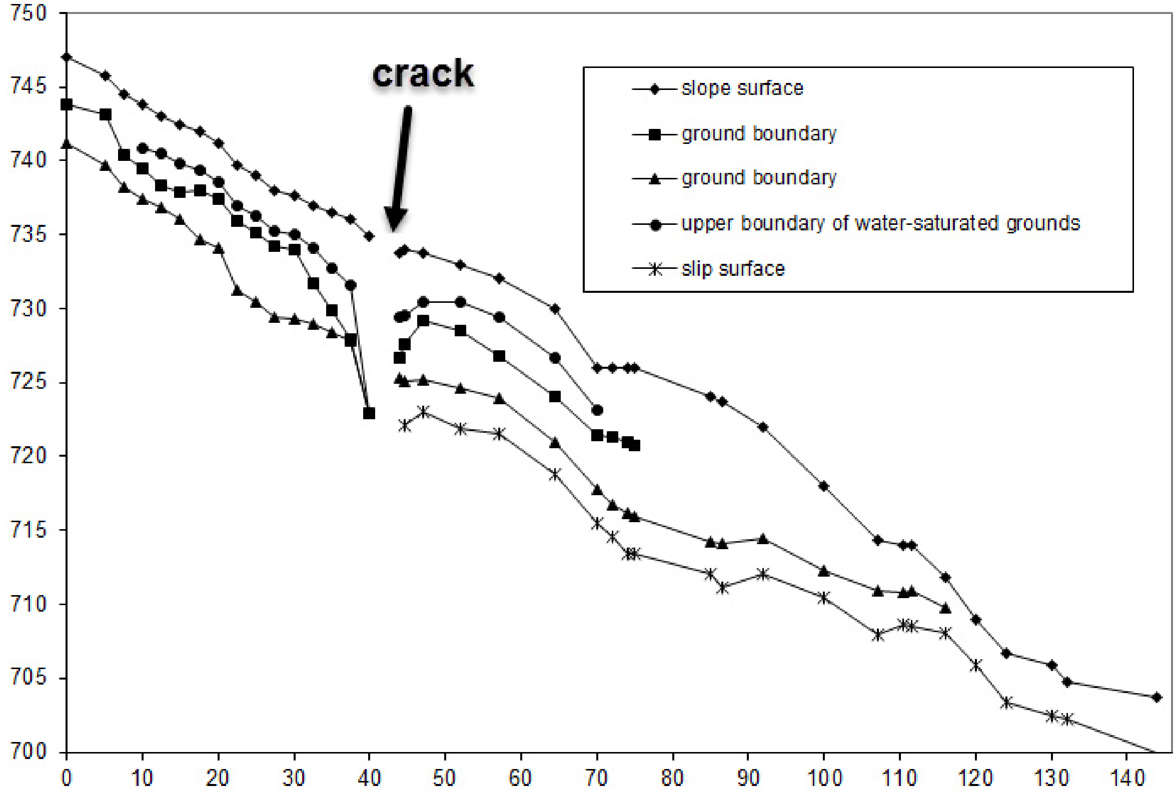

Fig. 3. Results of radargram processing: transverse profile with delineating boundaries between heterogeneous ground layers on a deforming rocky slope (beginning of frost retreat in spring)

The results analysis took into consideration additional information (Fig. 3) about the crack extension in the upper part of the slope.

Fig.4 Photographs of the crack in the upper part of the slope at the moment of its emergence and during its examining with GPR.

The configuration of the crack allowed us to choose only one slip surface out of all possible slip surfaces. The appearance of this crack is shown in (Fig. 4). As the slip surface goes from the bottom of the crack we were able to trace its exit onto the foot of the slope. The information on the upper boundary of the water saturated grounds is also of use. Information on the interlayers above the slip surface will have a lesser impact on the computation of stability.

Discussion

As a result of the conducted survey specialists gain an opportunity to generate design diagrams of an object. The demands of design organization and its survey specialists in structural calculations of the earth roadbeds depend on the personal experience and qualification of executive specialists and on the requirements set forth by the employer. Up-to-date software programs intended for calculating the stability of landslide slopes face the problem of the adequacy of the design solution. This problem is rooted not in the complexity of the design diagrams and computational resource requirements but in compliance with the real operation condition of an object under survey.

Conclusions

The described results allow us to formulate a conclusion that the examination of important and crucial objects of the transport infrastructure is a long-term and costly process. Significant results can be obtained only through the use of all survey techniques available to a designer. The current level of development in the sphere of geo-survey does not allow for the complete abandonment of costly and labor-intensive conventional survey techniques, such as boring. Nevertheless, in the near future geophysical methods will be able to provide complete information on the object of investigation. It is a matter of time and the speed of development of geophysical survey techniques.

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