

Study of changes in the induced wave field in mining waste storage facilities

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Abstract. An integrated approach to analyzing changes in the induced wave field in mining waste storage facilities for mineral waste is considered to localize potentially dangerous zones in the body of bulk structures using georadar sounding. It has been established that the zone of possible water saturation of rocks is perceived by the georadar signal as a transition to a medium with a higher dielectric constant and is reflected by the maximum amplitude of the signal. The boundaries of water saturation zones are not always sharply defined, but change smoothly depending on the degree of water saturation from a natural state unsaturated with moisture to complete saturation of soil pores. During GPR sounding, below the expected zone of water saturation, the soil structure is noticeably smoothed out, where, due to increasing attenuation, the signal amplitude sharply drops, which manifests itself in a noticeable decrease in the contrast of the wave pattern of the radargram. The use of intra-method integration by profiling on a permanent base and a common depth point with simultaneous synchronization of groundwater level measurements in a piezometer made it possible to identify and identify zones of increased water saturation in the dam body.

1 Introduction

Mining waste storage facilities, such as tailings dumps, are potentially hazardous. The most important task here is the safe operation of dams, which are an integral part of such objects, which is not possible without studying the structure and condition of the rocks and soils composing them. The use of geophysical survey methods makes it possible to obtain operational information about the structural features of such structures and the degree of water saturation of the soils composing them. One of the operational geophysical methods for studying the structure and condition of these objects is georadar sounding, which makes it possible to study changes in physical properties in a mass of rocks and soils.

The experience of using geophysical research in studying the physical properties of rocks and soils at mining sites shows that the resulting changes in the induced wave field during non-destructive subsurface georadar sounding can be effectively used to study their structure and condition. For example, at the Kangalas coal mine, as part of the geophysical monitoring of the dam, the boundaries of filtration flows that seep through the body and

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base of the dam were established [1]. The effectiveness of geophysical methods of operational non-destructive testing on an earth dam located in the Sverdlovsk region has been shown for assessing the stability and predicting its physical condition [2]. Examples of integrating geophysical methods, such as electrical prospecting in the modification of electrical tomography and ground penetrating radar profiling, are considered to obtain information about the lithological structure of the dam, identifying possible zones of high humidity and areas of decompaction on an earth dam as part of small hydroelectric power station structures (Karelia) [3]. Conductive zones associated with enhanced water filtration through geophysical monitoring of the reservoir's soil dam were discovered, and the feasibility of conducting seasonal geophysical monitoring for a more reliable assessment of the condition of soil hydraulic structures was noted [4]. An analysis of the information content of geophysical methods in studying the structure of dams was carried out with the rationale for the optimal complex for diagnosing and predicting the technical condition of earthen dams in the Republic of Kazakhstan [5, 6]. It is worth noting the use of electrical resistivity and ground penetrating radar methods at the Tapira mining complex in the state of Minas Gerais, Brazil, where they were used to determine the groundwater level, identify local zones of water saturation, and show the effectiveness of this type of monitoring for soil dams [7]. The integration of geophysical methods in the Linares-La Carolina region (southern Spain) made it possible to assess the internal structure of mountain dams [8]. At Gadwalan Dam, Northern Pakistan, mapping of near-surface cavities was carried out using integrated geophysical methods [9]. When examining the Monte Cotugno dam (southern Italy) using geophysical methods, infiltration zones were localized and the effectiveness of using non-destructive methods for diagnosing and monitoring critical infrastructure facilities was shown [10]. Based on georadar sounding, the groundwater level at the Sutami Dam, Indonesia was determined, and the values of soil dielectric constant were determined by comparing the obtained data with the values of piezometers [11]. Although the integration of geophysical methods improves the quality of the information obtained, it also leads to significant labor costs and increased costs of work [12].

2 Materials and methods

The georadar sensing method is based on studying the propagation of electromagnetic waves in the studied rock mass, through the analysis of reflected signals that arise at the boundary of objects with different electrophysical properties. The key property of a rock mass during GPR sounding is its dielectric constant, which affects the speed of passage of electromagnetic waves. As a result of GPR sounding, radargrams are obtained, which are time sections. The horizontal axis of the radargram shows the distance traveled by the georadar, and the vertical axis shows the time of arrival of the reflected signals in nanoseconds [13].

The parameters of the resulting GPR sounding signal are informative regarding the internal variability of properties and heterogeneity of the structure of rocks and soils. The results of instrumental measurements showed that the induced electromagnetic field is distorted in areas where their dielectric constant differs (for example, zones of massif heterogeneity, zones of increased water saturation, etc.). The dielectric constant of dry rocks depends only on the density and dielectric properties of the minerals, while for wet rocks it also depends on the amount of water in the rock (degree of water saturation).

Recalculation of time sections for depth reference is carried out in three ways: according to the hodograph of a diffracted wave - conventionally called the hyperbola method, and is applicable when wave effects in the form of hyperbolas are clearly visible on the georadargram; according to the reflected wave hodograph - a method for estimating velocities can be implemented using data from multi-channel measurements or single-

channel radars operating with a variable distance between the transmitting and receiving antennas (constructing a signal delay hodograph); calculation of the average value of dielectric constant based on geological or piezometric well data, the so-called “calibration principle” [12].

The use of a structural approach, based on an analysis of the dynamic and kinematic characteristics of the wave field, to identify various filtration or deformation processes at mining sites can significantly improve the accuracy of their determination and localization based on non-destructive georadar sounding data.

3 Results and Discussion

At the observation site of the embankment dam of the tailings dump located in the Khibiny mining region, a study of changes in the induced wave field was carried out, which made it possible to determine the structure of the embankment structure with the localization of water saturation zones (Figure 1). The results were obtained using the Loza 1V georadar complex, equipped with an unshielded 100 MHz antenna, using the profiling method on a permanent base with a step of 1 meter.

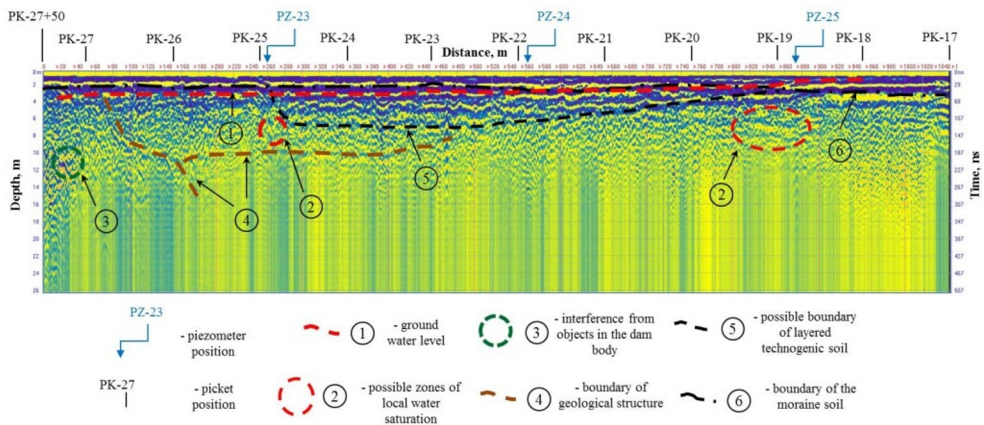


Fig. 1. Radargram of the GPR survey of the tailings dam.

The results were obtained by profiling on a permanent basis with a step of 1 meter. The groundwater level (1) varies from 4 meters at the beginning of profile PK27+50 to 1.1 meters at level PK18+10, at key points in the vicinity of the piezometers it corresponds to the values at the time of measurements: PZ23 – 3.1 m; PZ24 - 2.1 m; PZ25 – 1m. The near-surface zone to a depth of 2 meters is a uniform wave pattern, which indicates the presence of dense soils without any anomalies and is moraine soil. The profile identifies two supposed zones (2) of possible water saturation of 255-275 and 800-880 meters, which are characterized by the presence of strong low-frequency interference, which, as a rule, is directly related to the water saturation of the host rocks. At the beginning of profile PK 27+25 at a depth of 10 meters, a contrasting local interference (3) was detected, which was caused by the presence of a pipe or metal debris in the dam body. A possible geological boundary of soils (4) differing in its dielectric properties has been identified. Throughout the entire profile, at a depth of 2 meters, the boundary of compacted soils, which are moraine deposits, is clearly identified (6). At the profile interval of 260-880 meters, an area with a typical type of recording of layered technogenic soils is identified (5).

The determination of the dielectric constant and the speed of propagation of electromagnetic waves in the body of the dam were carried out using the hodograph of the

diffracted wave by analyzing the section of the radargram in Figure 1, where a diffracted reflection in Figure 2 was detected at 50 m. The study was carried out using the comparative method, which is based on the use of diffracted waves [12-13]. The field measurement data was processed in the Krot program, where the mathematically calculated hyperbola was combined with the in-phase axis of the diffracted wave hodograph on the screen, its parameters were adjusted by iteration until complete alignment. Thus, through iterations, the average speed of wave propagation in the overlying rock strata was determined, which was $V = 5 \text{ cm/ns}$, which corresponds to the dielectric constant $\epsilon = 9$ (Figure 2). The dielectric constant value for recalculating time sections in depth is taken to be 9 units, which also corresponds to the average value for minerals and rocks of the Khibiny deposits [11].

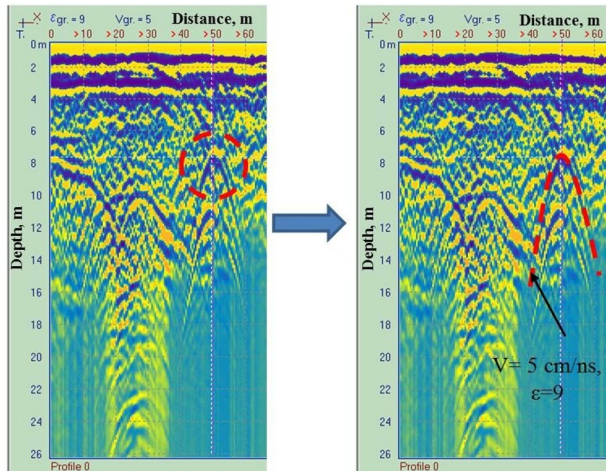


Fig. 2. Combination of a theoretical hodograph with a diffracted wave.

The use of intra-method integration by profiling on a constant base and a common depth point with simultaneous synchronization of groundwater level measurements in a piezometer made it possible to identify and identify zones of increased water saturation in the dam body, which made it possible to obtain additional justification for the reliable interpretation of ground penetrating radar data when solving this kind of problems.

To accurately calibrate the results, at 260 meters of the profile, in the immediate vicinity of piezometer 23, a hodograph of the reflected wave was constructed using the common depth point method (Figure 3), in order to determine the true values of velocities in the bulk rock mass in depth and in relation to the groundwater level in the body of the dam.

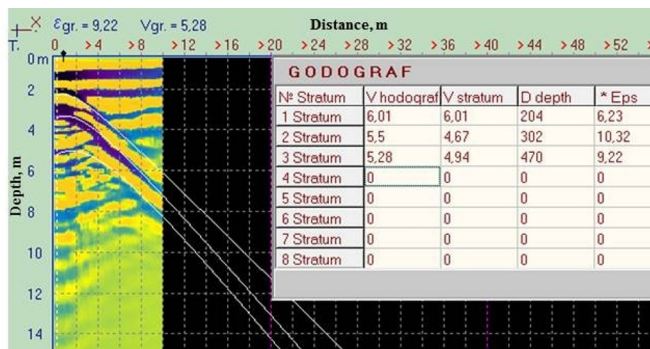


Fig.3. Reflected wave hodograph using the common depth point method.

It is worth noting that this kind of measurement is carried out exclusively on open, flat terrain, in arrays with parallel horizontal layers. The value of dielectric constant in the near-surface layer (up to a depth of 2.04 m) is at a fairly low level $\epsilon = 6.23$ units, which may be due to the dense state of the rock mass. The speed of the electromagnetic wave here is $V=6.01$ cm/ns. Analysis of changes in the speed of the electromagnetic wave and dielectric constant showed a significant drop in speed (almost 1.5 times) at a depth of 3.02 meters, from 6.01 cm/ns to 4.67 cm/ns, which may indicate the presence of water saturation at this mark (Figure 3). The water level according to the piezometer at the time of measurements was 3.1 meters. Thus, this approach makes it possible to most accurately determine the groundwater level in the body of the dam, where a significant drop in the speed of the electromagnetic wave indicates the presence of water saturation. The average value of dielectric constant to a depth of 5 meters was $\epsilon=8.6$ units, which actually corresponds to the data obtained at 50 meters of the profile using the profiling method on a permanent basis by analyzing the diffracted wave of the object (Fig. 2.), where $\epsilon=9$ units.

To implement the approach with calculating the average value of dielectric constant based on piezometric well data, GPR sensing data was calibrated using three piezometers of the dam: PZ23, PZ24 and PZ25. Each piezometer was compared with GPR readings and the dielectric constant values were calibrated to the groundwater level. Figure 4 shows an example of determining the depth of the water level in the body of a dam by analyzing the wave pattern of a fragment of a radargram obtained near piezometer 24. The groundwater level was identified based on a sharp change in signal amplitude caused by the presence of an aquifer between soils of varying degrees of moisture. This boundary between water-saturated and wet soils is quite clearly visible along the entire length of the radargram.

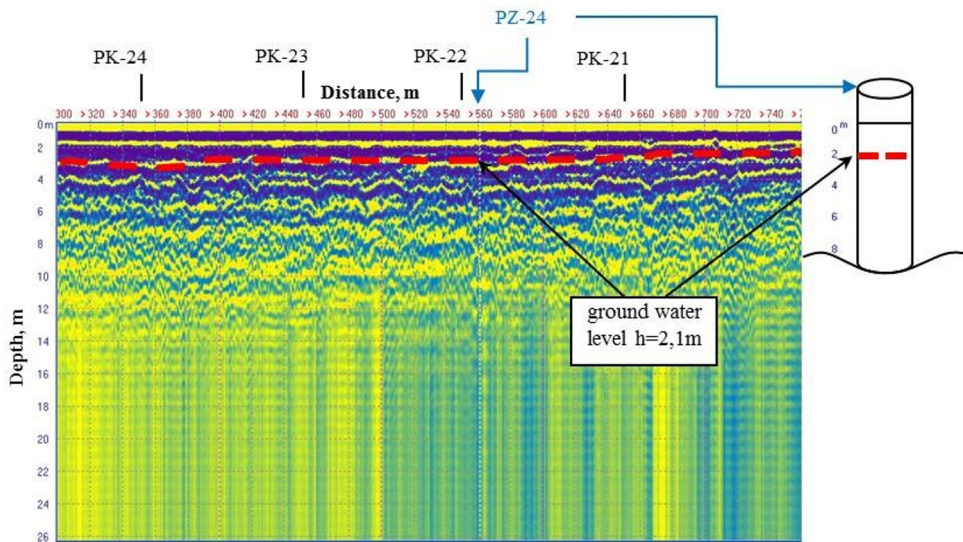


Fig.4. Calibration of dielectric constant based on groundwater level measured in a PZ24 piezometer.

As a result of calibration, the dielectric constant of soils was determined to be $\epsilon = 8.8$, which corresponds to the wave speed $V_{gr} = 5.06$ cm/ns. The depth of the water level in the piezometer according to the hydrogeological service is 2.1 m, the position of the water table on the radargram is 2.1 m (vertical resolution is about 0.05 m, the accepted accuracy is 0.1 m).

Analysis of the change in the induced wave field at the site for storing mineral waste from mining in the Khibiny mining region made it possible to identify the main signs of identifying potentially dangerous zones in the body of embankment structures and to identify approaches to their localization. The zone of possible water saturation of rocks is perceived by the georadar signal as a transition to a medium with a higher dielectric constant and is reflected by the maximum amplitude of the signal. However, the boundaries of water saturation zones are not sharply defined, but change smoothly depending on the degree of water saturation from a natural state unsaturated with moisture to complete saturation of soil pores. Below the expected zone of water saturation, the soil structure

noticeably smoothed out, where, due to increasing attenuation, the signal amplitude sharply drops, which manifests itself in a noticeable decrease in the contrast of the wave pattern of the radargram.

4 Conclusion

As a result of studying changes in the induced wave field in mining waste storage facilities, parameters and approaches were established that ensure the identification of water-saturated zones with sufficient reliability and their quantitative and qualitative interpretation. The use of intra-method integration by profiling on a permanent basis and a common depth point with simultaneous synchronization of groundwater level measurements in a piezometer made it possible to identify and identify zones of increased water saturation in the dam body, which made it possible to obtain additional justification for the reliable interpretation of georadar sounding data when solving such problems. The relationship between the change in the wave field and the dielectric permeability of soils with zones of increased water saturation and filtration of the dam has been revealed, which makes it possible to assess the condition of the tailings dam enclosure and identify local zones of increased water saturation and filtration in the absence of obvious signs of water saturation and the absence of contrasting boundaries on the wave field, with a smooth change in dielectric values permeability.

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