Influence of the rock massif physical properties variability on the localization of its disturbances with GPR

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Abstract. An integrated approach to studying the influence of the physical properties of a rock mass on the localization of its disturbances by GPR sounding is considered. The performed studies have established that, during GPR sounding of rock masses, there is a distortion of the induced electromagnetic field in areas with different physical properties of rocks (such as: massif heterogeneity, rock fracturing, zones of increased water saturation, etc.). Regularities in the formation of wave patterns of GPR model data (changes in the in-phase axes and amplitude characteristics of the signal) of a rock mass containing structural inhomogeneities are revealed. During GPR sounding of such a rock mass, reflections from the edge parts of inhomogeneities appear in the wave patterns in the form of branches of hyperbolas. The intensity of the wave field distortion is determined by the contrast of the physical properties of rocks, as well as the spatial orientation and depth of heterogeneities, which is a key parameter of GPR sounding. It has been established that the variability of the physical properties of rocks in a rock mass near faults introduces significant distortions in the parameters determined by GPR sounding, including the angle of incidence of faults.

1 Introduction

For efficient and rational development of minerals in rock massifs by quarries, detailed information about the structure and condition of rocks is required in order to promptly detect potentially dangerous zones that affect mining operations. One of the important tasks is to identify disturbed areas on ledges, which significantly affects the stability and functionality of structures of this type. Reliable knowledge about the structure and state of the rock mass is obtained through specially drilled geological wells, but here it is possible to obtain only point data, and increasing the number of wells to obtain sufficient completeness of data leads to high production costs. In this regard, the use of non-destructive research methods that provide a continuous (profile) picture is preferable and much more economically profitable. To study the geological and structural structure of rock

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masses, GPR sounding is actively used [1-4]. This method is based on the radiation of an electromagnetic field to study changes in the physical properties of rocks within a massif.

Non-destructive GPR sensing has proven its effectiveness in studying the physical properties of rock deposits and can be successfully used to study the structure of rock masses. Non-destructive GPR sensing has proven its effectiveness in studying the physical properties of rock deposits and can be successfully used to study the structure of rock masses. For example, to identify and study zones of tectonic disturbances (faults) in the earth's crust, combining ground penetrating radar with the radio impedance method is successful [3]. The use of the GPR method made it possible not only to identify the locations of faults, but also to determine their thickness and angles of incidence [4]. Much attention is paid to the use of computer modeling of GPR operation in the interpretation of vertical faults in South Korea [5]. Using numerical modeling of the GPR operation, the features of the wave pattern in the fault zone were identified, and the issues of interpreting GPR data based on various models in the fault zone were considered, where it was noted that the identification of such structures is extremely difficult [6]. From the experience of using ground penetrating radar, works related to the study of large fault structures stand out: Fossodella Valle Fault (Italy) [7], SonginoFault (Mongolia) [8], Narmada-SonFault (India) [9]. In the foothill region of the Pir-Panjal ridge to the north-west of the Himalayas, an analysis of neotectonic structures was carried out by integrating geomorphological indicators in combination with ground penetrating radar data [10]. Despite the fact that GPR sensing is widely used by researchers to study the physical properties of rocks, questions related to the influence of these properties on the accuracy of fault localization by this method still remain open. The use of standard approaches for identifying and localizing zones of structural disturbances when interpreting GPR data is not suitable for all cases, which is associated with a wide variety of geological and geophysical conditions. The article analyzes the results of GPR r sounding of rock sections of the Lovozero and Kovdor mountain range.

2 Materials and methods

Subsurface GPR sensing equipment operates on the basis of emitting ultra-wideband pulses of electromagnetic waves in the meter and decimeter range, and then receiving reflected signals that arise at the interfaces between layers of the probed medium with different electro physical properties. The main physical parameter of rocks, in this case, is their dielectric constant, which affects the speed of passage of electromagnetic waves. It depends on the dielectric properties of rock components such as mineral particles, air, water and ice. Rocks are complex multiphase formations consisting of various components in different phase states. This leads to local changes in physical properties in different zones and heterogeneities in the structure of rocks. The dielectric constant of dry rocks depends only on the density and dielectric properties of minerals, while for wet rocks it also depends on the amount of water in the rock (degree of water saturation) [11].

The parameters of the resulting GPR sounding signal are informative regarding the internal variability of properties and heterogeneity of the structure of rocks. The results of instrumental measurements showed that the induced electromagnetic field is distorted in areas where the physical properties of rocks differ (for example, zones of massif heterogeneity, areas of increased fracturing, zones of increased water saturation, etc.) [11].

One approach to reducing ambiguity when interpreting GPR data is mathematical modeling of radar grams. To solve the direct problem of GPR sensing, finite-difference modeling is used, based on solving Maxwell's equations, which is implemented in various software products, for example GPRMAX and MatGPR [11,12]. Computer modeling of the electromagnetic field induced by GPR probing is used to theoretically substantiate approaches to assessing the influence of the physical properties of rocks on the localization of its disturbances by GPR probing. Modeling significantly reduces the ambiguity in the interpretation of GPR data, making it possible to understand the mechanism of formation of wave characteristics (in-phase axes, amplitude values) and compare model data with natural ones.

3 Results

Studies of the internal structure of the rock massif and the localization of its structural disturbances were carried out at the Lovozero and Kovdor mining massifs.

In the Lovozero massif, the adopted methodological approach was tested and used to identify structural disturbances in the interpretation of water-saturated zones of the rock massif in the vicinity of the “Karnasurt” mine. To determine hidden zones of water saturation in the rock mass, field geophysical studies were carried out in the Lovozero mountain range, where the operating “Karnasurt” mine and the closed flooded “Umbozero” mine are located, using the GPR sounding method. A GPR survey of a section of a rock massif was carried out along the bed of the Alluive stream, in the elevation range of 475-500 meters, using the “Loza 1V” georadar complex, equipped with unshielded 50 MHz and 100 MHz antennas. The dielectric constant value for recalculating time sections in depth is taken to be 9 units, which corresponds to the average value for rocks.

As can be seen in figure 1, at 18 m from the beginning of the profile, a clear reflection can be traced, going at an angle of 22° deep into the massif, interpreted as a structural disturbance through which water flows (the place where water flows into the bedrock). This reflection is repeated in the results obtained with the 50 MHz antenna unit. Also, in the interval of 0-25 m, there are presumably three disturbed structures with a length of 25 m, at a depth of 42-48 m, 52-60 m and 65-72 m, with the same angle of incidence.

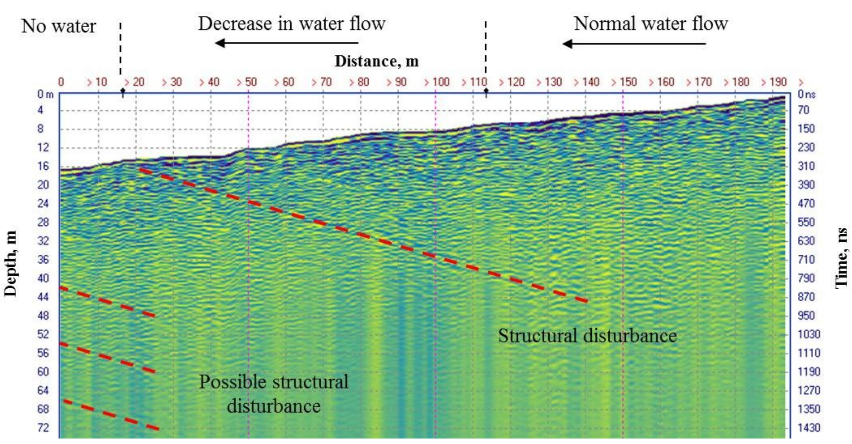

Fig. 1. Radar gram obtained by the "Loza- 1V" georadar with a 100 MHz antenna.

An analysis of previous geophysical studies carried out by the Geological Survey of Finland (GTK), parallel and 300 m north of the current study, also showed the presence of a powerful structural fault extending from the surface with an angle of incidence of approximately 20°. Thus, a comprehensive analysis of two independent studies in this area suggests that the front of the identified structural heterogeneity of rocks with a thickness of 20-40 cm can extend 300 m further to the north.

Thus, as a result of GPR probing, a structural disturbance was revealed that goes deep into the massif to the east, along which the Alluive stream continues to move, as a result of which the influx of water into the underground workings of the mine has sharply increased.

The heterogeneity of rocks and the variability of their properties lead to changes in the recorded parameters of the electromagnetic signal during GPR sounding. The contrast of reflections during GPR sounding depends only on the change in dielectric constant at the boundary "host rock - structural heterogeneity", where the difference in properties in its vicinity introduces significant zonal changes in the wave field. These changes significantly complicate the identification of position in space and the precise location of structural disturbances by ground penetrating radar probing. The lack of detailed geological data in a given area and visual contact with a disturbance on an outcrop of a rock mass, as well as the use of average reference values of dielectric constant during processing, can lead to a significant error in localizing disturbances in a rock mass.

New research methods, including computer modeling of induced electromagnetic fields and the generation of synthetic radar grams, provide additional opportunities for analyzing wave patterns and resolving ambiguities in data interpretation [5, 9, 11-12]. The use of modeling the electromagnetic field induced by ground penetrating radar sounding made it possible to significantly reduce the uncertainty in the interpretation of the data obtained by understanding the mechanism of formation of the wave characteristics and comparing synthetic data with natural ones.

In Figure 2 presents the stages of computer modeling of the electromagnetic field induced by GPR sensing. The modeling was carried out by simulating the operation of a GPR equipped with a 100 MHz antenna. The rock mass includes a group of inclined structural heterogeneities located at an angle of 22° to the surface. The geometric diagram of the model of the environment of the rock section (Figure 2a) is presented in the form of a vertical section measuring 25x10 m, which includes a group of four inclined heterogeneities with a thickness of 0.1 m. Three parallel ones, lying at a depth of 4 to 8 m in at the beginning of the model, 3 m long and extending to the surface 15 m long.

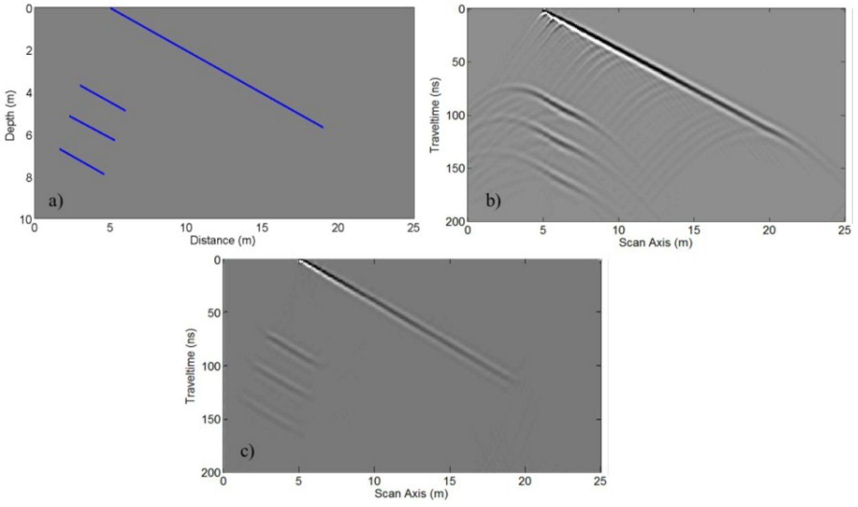

Fig. 2. Modeling stages: a - geometric scheme of the model, b - synthetic unprocessed radar gram, c – radar gram using processing procedures.

At the stage of creating the model, in accordance with the data on the physical properties of rocks [11], the average value of dielectric constant for the host rocks was used, which amounted to 9 units. To increase the contrast of the obtained data, the value of the dielectric constant of structural damage was taken to be 2 times larger and amounted to 18 units.

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As a result of the analysis of amplitude changes in the waveform of the synthetic radar gram signal (Figure 2.b), a large number of secondary waves were identified that mask the useful signal, which significantly complicates the interpretation of the data obtained. The appearance of this kind of waves on radar grams is associated with the spherical front of propagation of an electromagnetic wave, and, therefore, objects whose dimensions are comparable to or smaller than the wavelength in a given medium will behave as point sources of secondary waves. Such objects will appear as hyperbolas on radar grams. In this case, flat reflective surfaces whose dimensions exceed the wavelength will retain their shape. To eliminate this effect, a migration procedure is used (Figure 2c), which consists of summing all waves from elementary sources along their hyperbolic in-phase axes. It is also worth noting that objects located deeper have a less contrasting reflection, which is associated with signal attenuation.

The results of computer modeling of the electromagnetic field induced by GPR sounding showed the wave pattern of the in-phase axes and amplitude characteristics of the GPR signal on the radar gram of a rock mass weakened by a group of structural heterogeneities. When the GPR approaches an inclined heterogeneity, reflections in the form of hyperbola branches from the angles of the heterogeneity appear in advance on the radar gram.

At the observation site of the Kovdor rock massif (in the area of the ledge of the active "Zhelezny" quarry), in order to identify the influence of the variability of physical properties in the vicinity of a structural disturbance on its localization, ground penetrating radar sounding was carried out in combination with a visual inspection of the ledge outcrop (Fig. 3). For the research, the "Loza-1V" georadar complex, equipped with an unshielded 100 MHz antenna, was used on an outcrop of a ledge, where a structural disturbance of the rocks was clearly visible visually and according to photographic data (Figure 3a).

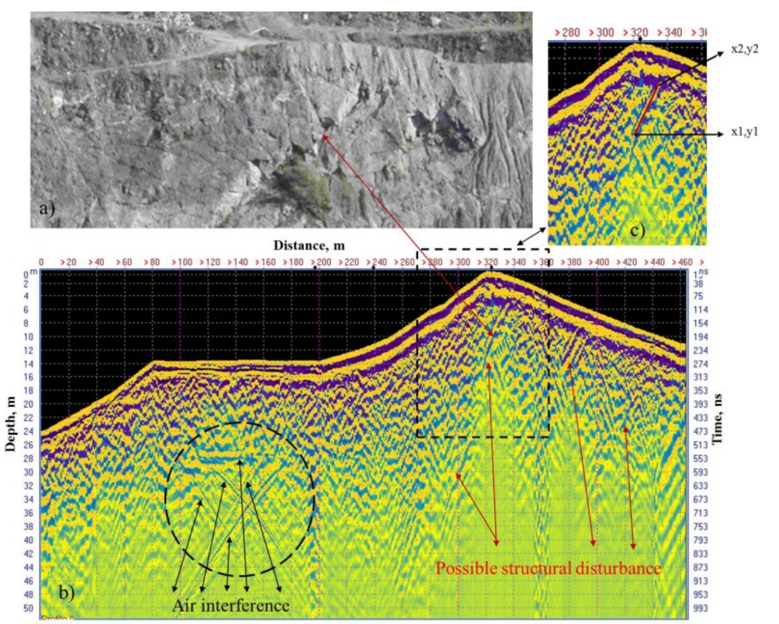

Fig. 3. Comprehensive survey of the rock massif of the ledge of the "Zhelezny" quarry: a - photography and visual examination, b - interpreted radargram, c - fragment of a radargram with a localized structural disturbance.

Analysis of the wave radargram obtained by profiling on a constant base (Figure 3b) showed that in the profile length interval of 100-200 m, at a depth of 15 m from the surface (28 along the vertical axis), a large number of hyperbolic reflections are recorded, which are confined to structures and structures located on the surface of the ledge. The velocities V calculated for this section using the theoretically calculated hyperbola lie in the range of 11-13.8 cm/ns, and are interpreted as air interference. On the right side of the profile, at marks 340, 400 and 440 m long, possible structural disturbances can be traced. The velocity values for this area according to the theoretically calculated hyperbola lie in the range of 5.6-9.13 cm/ns, which may indirectly indicate that these reflections were obtained from structures located directly in the rock mass. The structural disturbance revealed on the radargram in the distance interval of 300-340 m (Figure 3c) clearly correlates with the photographic data and visual inspection of the ledge (Figure 3a), which also clearly shows the structural disturbance.

Further analysis consisted of determining data on the localization of structural damage in space. Using an average dielectric constant of 9 units, for the host rocks, the further position in space of a structural disturbance emerging to the surface at an angle of incidence of 23° was calculated.

4 Discussion

A detailed analysis of the data obtained on the localization of the structural disturbance (Figure 3c), namely: the known distance between the boundaries x1, x2, the recorded time of reflection of electromagnetic waves from these boundaries y1, y2; showed that the localized incidence angle can vary (Figure 4a), depending on the dielectric constant values of the host rocks. A change in the physical properties of the host rocks, namely a decrease in their dielectric constant, leads to a significant increase in the angle of occurrence of the structural disturbance, but at the same time does not significantly affect their increase (Figure 4b). So, for example, with a decrease in dielectric constant from 8 to 3 units, the angle of inclination of the structural disturbance in space will be 25-37°, and with an increase from 10 to 15 units, will be 23 – 19°.

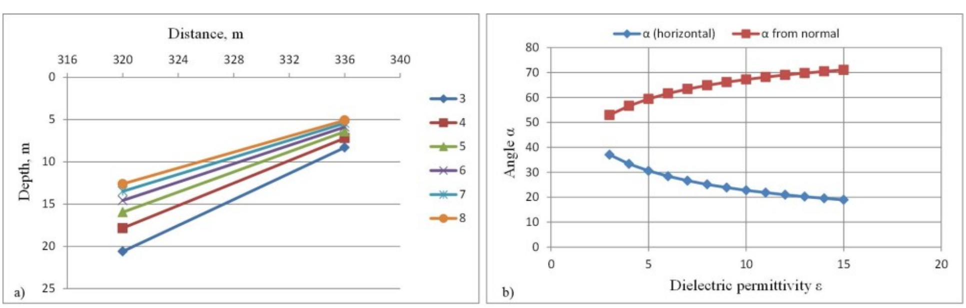

Fig. 4. Change in the angle of incidence (tilt) of the structural disturbance of the rock mass, depending on their physical properties: a - position in space, b - dependence of the angle of incidence on the dielectric constant.

It should be noted that low values of dielectric constant of rocks in most cases are characteristic of dense/monolithic areas, while higher values are associated with fractured rocks and possible water content in cavities and cracks.

Thus, the results of the study indicate that a change in such a physical property of a rock mass as dielectric constant can lead to a significant error in localizing structural disturbances in space, which should be taken into account when interpreting GPR data on the internal structure of the rock mass.

5 Conclusion

Studies of the internal structure of sections of the Lovozersky and Kovdorsky mining rock massifs in the area of active mines have been carried out. Wave radar grams reflecting the variability of the physical properties of rocks were obtained and interpreted. Identification of structural disturbances in the rock massif in the vicinity of the "Umbozero" mine was carried out. A structural disturbance has been localized, going deep into the massif to the east, along which the Alluive stream continues to flow, which could have served as an influx of water into the underground workings during the operation of the mine. The use of computer modeling of georadar probing of a rock mass in the vicinity of heterogeneities has made it possible to clarify approaches to the localization of structural disturbances in a rock mass by analyzing the in-phase axes of signals from the wave pattern of radargrams. Using the identified features of the change in the wave field, a structural disturbance was localized in the Kovdor rock massif in the section of the bench of the active "Zhelezny" quarry. It was revealed that a change in the value of such a physical property of a rock mass as dielectric constant has a significant impact (up to 50%) on the resulting localization of the angle of incidence (inclination) of structural disturbances using ground penetrating radar probing of the internal structure of the massif.

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