

Geophysical signs of hard rock disturbance

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Abstract

Introduction. Development of deep open pits requires reliable knowledge on conditions of rocks at the hard rock mass to locate potentially hazardous sectors which have considerable impact on efficiency and rationality of a deposit's development. Definition of disturbed zones at the open pit benches is an actual scientific and practical task in terms of supporting stability and functionality of such facilities.

Research aim is to study geophysical signs of disturbance of hard rocks by data of nondestructive ground-penetrating radar (GPR) observation of the surrounding rock mass at the working open pit benches in order to estimate their geological structure and differentiate by disturbance degree.

Methodology. Nowadays, GPR data is overwhelmingly interpreted based on comprehensive analysis of amplitude, frequency and phase characteristics of an electromagnetic signal and without an attribute analysis of the wave field. When using the structural approach, based on the analysis of the dynamic and kinematic characteristics of the wave field, to identify hard rock disturbance areas, it becomes possible to significantly increase the accuracy of their determination and localization according to the nondestructive subsurface GPR research.

Results. Based on GPR measurements, the author has studied geophysical signs of disturbed rock zones identification at the open pit benches which consist in a quantitative estimation of change in reflection response amplitude characteristic, permittivity of a section and Q factor attribute.

Conclusion. Using the established relationships with the proposed analysis of geophysical signs, the GPR study data can contribute to the adoption of differentiated and providing greater stability parameters of benches and mining operations.

Key words: open pit; bench; hard rock mass; ground-penetrating radar; radarogram; disturbance.

Introduction. Development of deep open pits requires reliable knowledge on conditions of rocks at the hard rock mass to locate potentially hazardous sectors which have considerable impact on efficiency and rationality of a deposit's development. Definition of disturbed zones at the open pit benches is an actual scientific and practical task in terms of supporting stability and functionality of such facilities. Reliable data on hard rock mass state may be obtained from exploratory boreholes, however, only point data is obtained this way, and increased number of boreholes aimed at obtaining more complete information results in high extraction costs. In this regard, nondestructive and providing continuous (profile) picture of research methods are preferable and economically more attractive.

Research aim is to study geophysical signs of disturbance of hard rocks by data of nondestructive ground-penetrating radar observation of the surrounding rock mass at the working open pit benches in order to estimate their geological structure and differentiate by disturbance degree.

Methodology. Analysis of literature on hard rock disturbance estimation using nondestructive geophysical methods written in the past decade has shown that there

have been developed no fundamentally new technologies in these methods. At the same time, successful application of the GPR method for these aims has been recorded making it possible to get information efficiently in situ [1–6]. It should be noted that there have been numerous improvements of the GPR method, particularly, improvement of the obtained data depth and information value by means of reducing the frequency of the emitted signal and increasing the transmitter's power, which have significantly enhanced the opportunity of obtaining field results. The number of innovations has grown significantly in GPR data office study as well, firstly due to 3D systems realization. Much attention has been given to the improvement of the information value and accuracy in hard rock mass structure estimation based on data processing algorithms development with the use of the methods of statistical analysis, signal decomposition procedures, and various types of filtration. Meanwhile, the main drawback of GPR is the intricacy of obtaining distributed velocity data. GPR data is overwhelmingly interpreted based on comprehensive analysis of amplitude, frequency and phase characteristics of an electromagnetic signal, and the comparison of the signal common mode axes inside the highlighted sections and regions in the radarogram, which differ in the character of the image, unconformity interface and reflectors intensity. However, an innovative technology of automated analysis of the backscattered electromagnetic fields (BSEF) may be distinguished among new GPR data processing technologies; it is realized in GEORADAR-EXPER program which makes it possible to significantly improve the quantitative and qualitative indicators of the resulting parameters by means of wave field attribute analysis. The practice applying the wave field attribute analysis to solve some mining problems has shown significant improvement in the quality of GPR data interpretation and may be an effective means of timely detection of hazardous zones in pit benches [7, 8]. So, the integrated analysis of wave field dynamic and kinematic characteristics is an important tool dealing with such problems with the help of GPR.

Results. The research presented in this work were fulfilled at the producing sections of Zhelezny open pit slopes of JSC Kovdorsky GOK mining enterprise in close cooperation with the specialists of the enterprise with the use of GPR complex Ramac/GPR X3M equipped with screened aerials. The obtained data were processed with specialized RadExplorer and GEORADAR-EXPER programs, interpreted separately and further on an integrated analysis was made of the obtained data in space-depth relationship.

Many instrumental measurements over the years of benches study in this facility revealed that within the zones of rock mass inhomogeneity (fault tectonics, areas of increased jointing) the induced electromagnetic field distorts in the degree of difference between the physical properties of rocks in the zone and main rock mass. It has been stated that the intensity of wave field distortion is determined by the contrast (ratio) of rock physical properties and the depth of the zone [1, 9, 10].

Fig. 1 represents an example of GPR data interpretation obtained by Ramac/GPR X3M radar with 100 MHz antenna unit using standard processing, as a result, the detailed analysis of frequency response of electromagnetic lines has made it possible to expose structural inhomogeneity and localize the rest water level (RWL). Against low-frequency noise caused by the presence of water in the rock mass (rest water level of 10–12 m from the surface), the boundary of structural disturbance of rock 2 m thick at the depth of 4–8 m is clear; it is presented in the form of an outburst of maximum amplitudes of the GPR signal.

Fig. 1 presents the detected disturbed zone (zone of weakness) according to GPR data which has been confirmed by the geological section according to the drilling data.

Standard GPR data processing includes the removal of the constant component of a signal, i. e. the direct wave, amplitudes correction due to signal divergence and

attenuation, and the use of specialized procedures of processing: deconvolution, the Fourier transform and the Hilbert transform, which, in some instances, improve greatly the accuracy of disturbed zones localization. Nevertheless, in a number of instances the discovered structural inhomogeneities do not agree and even go against the geological data. Data interpretation quality in this approach greatly depends on the interpreter's experience and skill.

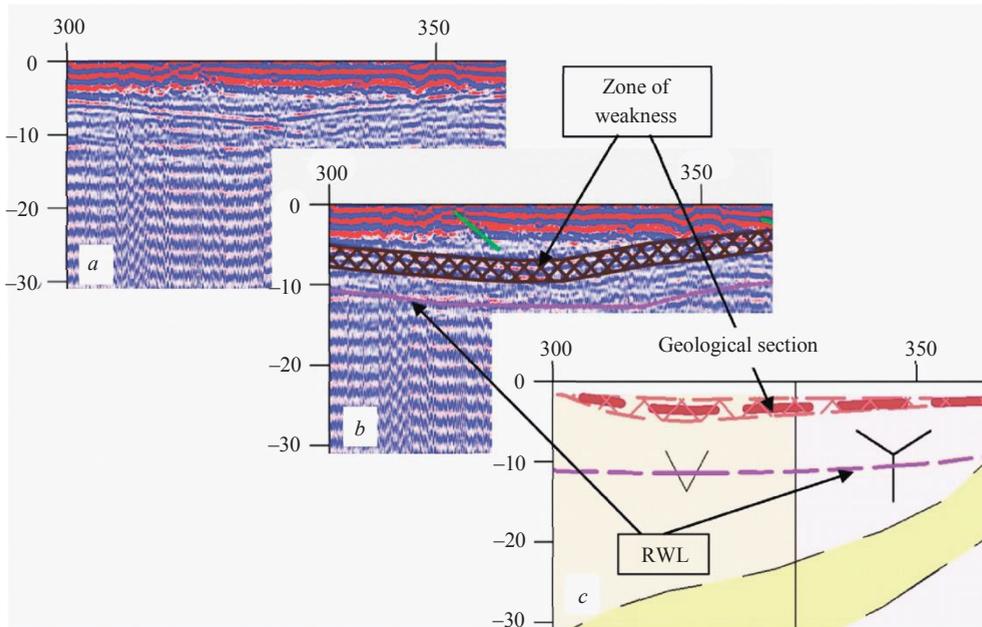


Fig. 1. An example of the GPR data interpretation:

a – processed radarogram; *b* – interpreted radarogram; *c* – geological section

Рис. 1. Пример интерпретации данных георадиолокации:

a – обработанная радарограмма; *b* – интерпретированная радарограмма; *c* – геологический разрез

In order to eliminate the given drawback, the author of the article carried out an independent comprehensive research on the geological structure of a bench, i. e. the GPR investigation of the bench surface by bore wells carrying out telemeasurement and registration of visually detected fissures and zones of excessive fissuring [9]. The obtained GPR data were processed by means of electromagnetic backscattered field automated analysis. As a result of BSEF automated analysis with the use of kinematic and dynamic characteristics of the signals, the GPR data array was created with a set of wave field attributes for further interpretation. As soon as the main parameter characterizing the opportunity of applying GPR in various spheres is the permittivity of rocks which influences electromagnetic waves propagation velocity [11, 12], it is essential to calculate the parameter and determine its correlation with the parameters of the medium (geological structure).

As a result of the obtained data comprehensive analysis and interpretation in the space-depth coordination, the correlation between the indicators of jointing intensity and rock permittivity has been revealed (fig. 2). It has been stated that rock jointing growth results in the increased recorded values of their permittivity [9].

Having applied this approach to process the GPR data in fig. 1, the author obtained the section in the values of the permittivity (fig. 3). Actually, it is a velocity section, as soon as the permittivity is the main parameter determining the electromagnetic wave propagation velocity in the geological medium [10].

As it can be seen in fig. 3, in the subsurface zone up to 1.5–2 m deep the values of the permittivity change within the range of 10.5 units (light blue palette). As a rule, this zone was disturbed by the blast at the previous stage of working the benches contour. At the depth of 2–4 m insignificant decrease in the permittivity is observed down to 9–9.5 units (yellow palette), rock here is less disturbed in accordance with earlier revealed regularities [9]. At the depth of 4–8 m of the profile a zone of increased permittivity values of 12 units is distinguished and in the profile interval of 0–15 and

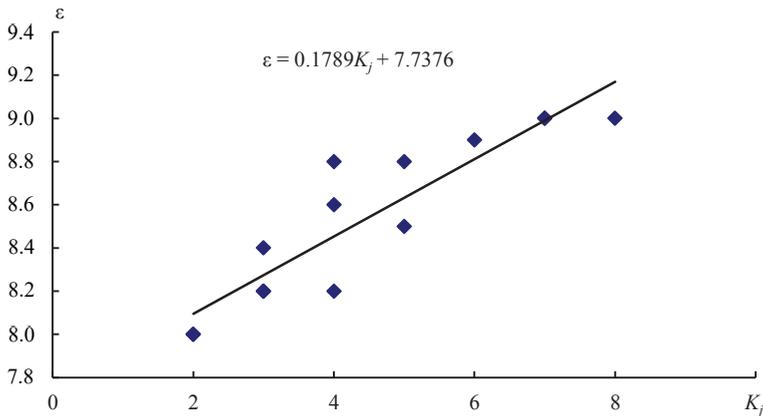


Fig. 2. Graph of behavior of the jointing intensity K_j and the permittivity ϵ in six boreholes

Рис. 2. График изменения интенсивности трещиноватости $K_{тр}$ и диэлектрической проницаемости ϵ по шести буровым скважинам

25–40 m it reaches maximum values of 12.5 units (dark blue palette); rock here is most disturbed. The detected zone of disturbance, according to the data of hard rock mass permittivity values analysis coincides with the detailed analysis of electromagnetic lines frequency response (fig. 1). At the depth of 10–12 m, where according to the geological section data the rest water level extends; the values of permittivity are also high and make up 11.5–12 units. However, only subjectively or based on some geological data it is possible to distinguish between water level and disturbed zone level. Lower than 15 m (red palette) permittivity values decrease reaching 7.5–8 units, which complies with undisturbed solid rock mass.

Permittivity increase is a sign of water saturation growth which results in electromagnetic wave velocity decrease and research depth reduction. A number of empirical expressions determining this connection is known today. For example, for sedimentary rock these expressions determine the medium with a wide range of water content change from 3 to 45% and the medium with high humidity correspondingly [11, 12]:

$$\epsilon = 3.03 + 9.3W_{vol} + 14W_{vol}^2 - 76.7W_{vol}^3;$$

$$\epsilon = \frac{720}{180 - W},$$

where ϵ is the real part of integrated relative medium permittivity, W_{vol} – volumetric water content, W – water content.

Thus, both the zone of structural disturbance and the water saturated area may correspond to the increased values of permittivity in the section; that may again result in the ambiguous interpretation of data, and that is what the interpretation complexity is associated with together with the disturbed zone and rest water level boundary division in fig. 3.

Considering the opportunity of wave field attribute analysis, a section constructed with the help of the quality factor of the backscattered fields can be distinguished (fig. 4), so called Q factor which characterizes electromagnetic losses in the medium and has correlational connection with strength [7].

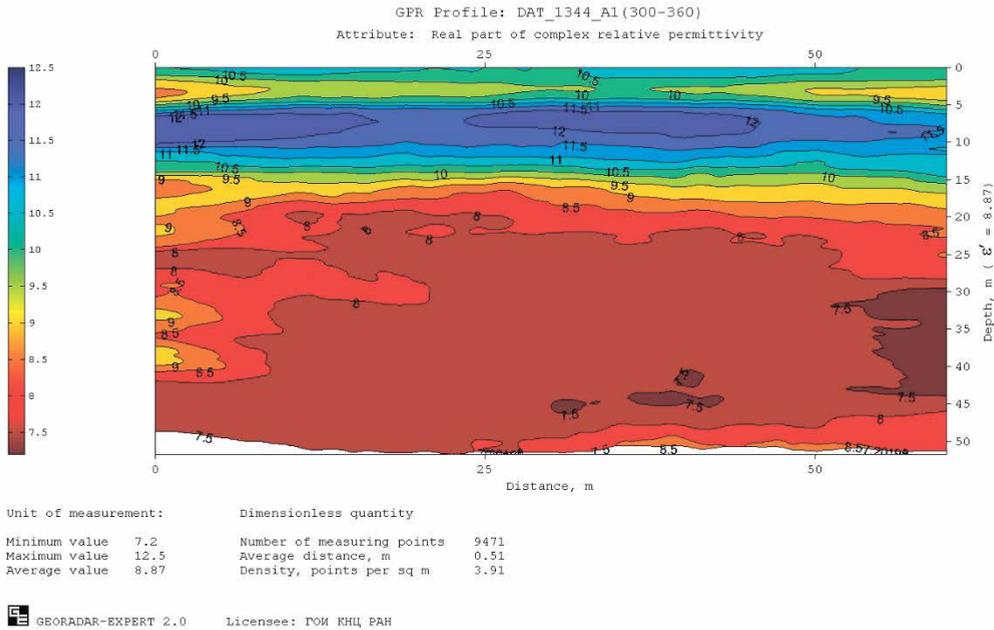


Fig. 3. Section constructed according to the permittivity values distribution data

Рис. 3. Разрез, построенный по данным распределения значений диэлектрической проницаемости

Q factor in this case is a correlation between the center frequency and the width of the signal spectrum in the level of -3 dB:

$$Q = \frac{\omega}{\Delta\omega},$$

where ω is the center frequency of the reflection response of a radar; $\Delta\omega$ is the width of the reflected signal spectrum at the level of -3 dB.

The spectrum is calculated for the neighborhood of the target reflection, the diffracted one, for instance; and the higher the quality value, the sharper the peak of the center frequency at the signal spectrum.

Based on the Q factor analysis of the initial radarogram the zone of higher values of 4.5 units contrasts (dark blue palette); it reflects the loss of rock mass continuity and interpreted as 4–10 m deep disturbed zone. The value of Q factor in the remaining part of the obtained section changes insignificantly and resides in the interval of 1.5 units.

Thus, judging from the experience of the research on hard rock disturbance estimation through Q factor it can be stated that it serves as an indicator of hard rock continuity and solidity; the lower its value, the more solid the medium, and vice versa.

Structural approach together with the GPR data geophysical signs analysis to detect hard rock disturbance makes it possible to greatly improve detection accuracy and localization according to the data of the nondestructive subsurface GPR research.

The author of the article would like to mention that this area was not taken at random, apart from a priori information in the form of the geological section to obtain the data, the measurements had been carried out shortly before this area of the bench collapsed along the detected weakness zone both according to the drilling data and the GPR data. This research has made it possible to convince of the correctness of the proposed approach which includes the analysis of the geophysical signs determining the zones of disturbance in hard rock mass.

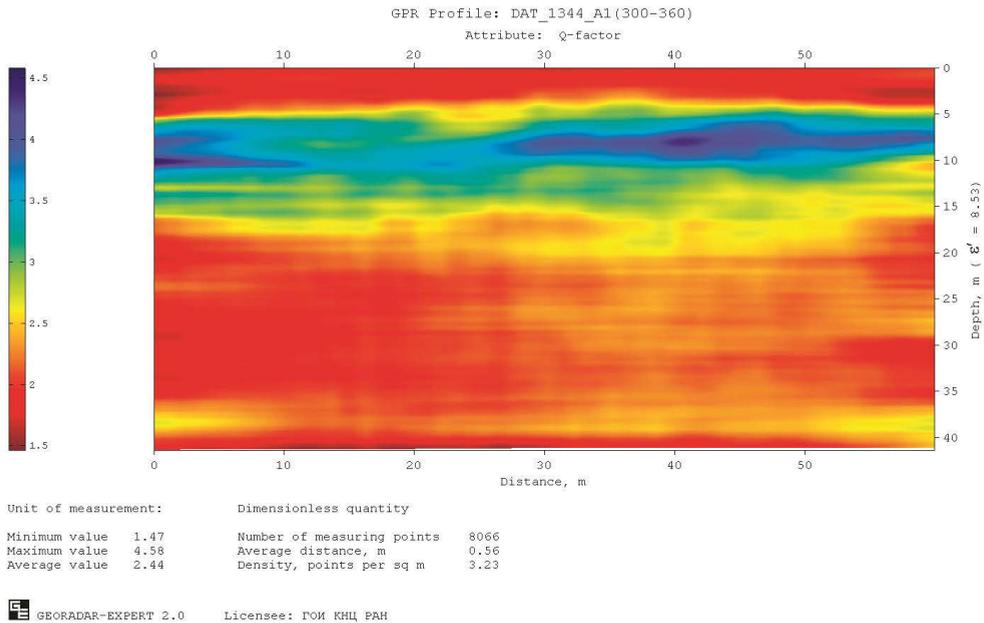


Fig. 4. Section constructed according to Q factor distribution data
Рис. 4. Разрез, построенный по данным распределения Q -фактора

Summary. Based on GPR measurements, the author has studied geophysical principles of disturbed rock zones identification at the open pit benches which consist in a quantitative estimation of change in reflection response amplitude characteristic, permittivity of a section and Q factor attribute.

The correlation has been determined between the frequency response of the reflected/distorted signal, the values of open cast permittivity, and the attribute of the Q factor and the disturbance of the rock at the bench which makes it possible to quickly determine and estimate the state of hard rock.

The state of the marginal rock mass of the sites of Zhelezny open pit of JSC Kovdorsky GOK has been estimated with the proposed analysis of the geophysical signs; it can contribute to the adoption of differentiated and providing greater stability parameters of benches and mining operations.

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Received 14 May 2020

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УДК 622.271.332:550.837.76(470.21)

DOI: 10.21440/0536-1028-2020-6-58-65

Геофизические признаки нарушения скальных пород

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Реферат

Введение. При разработке горизонтов глубоких карьеров месторождений полезных ископаемых необходимы достоверные знания о состоянии пород скального массива для локализации потенциально опасных участков, которые существенно влияют на эффективность и рациональность освоения месторождения. Выявление нарушенных зон на уступах карьера является актуальной научно-практической задачей в части обеспечения в первую очередь устойчивости и функциональности сооружений такого типа.

Цель работы. Исследование геофизических признаков нарушения скальных пород по данным неразрушающего георадиолокационного обследования законтурного массива пород участков рабочих уступов карьера для оценки их геолого-структурного строения и дифференцирования по степени нарушения.

Методология. В настоящее время в подавляющем большинстве случаев интерпретация георадиолокационных данных производится на основе детального анализа амплитудных, частотных и фазовых характеристик электромагнитного сигнала без использования атрибутного анализа волнового поля. При использовании структурного подхода на основе анализа динамических и кинематических характеристик волнового поля для выявления зон нарушения скальных пород появляется возможность существенно повысить точность их определения и локализации по данным неразрушающего подповерхностного георадиолокационного исследования.

Результаты. На основе георадиолокационных определений исследованы геофизические признаки идентификации зон нарушения скальных пород уступов карьера, заключающиеся в количественной оценке изменения амплитудной характеристики отраженного сигнала, диэлектрической проницаемости разреза и атрибута Q -фактор.

Выводы. При использовании установленных взаимосвязей с предложенным подходом анализа геофизических признаков данные георадиолокационного исследования могут стать основой для принятия дифференцированных, обеспечивающих большую устойчивость параметров уступов и ведения горных работ.

Ключевые слова: карьер; уступ; скальный массив; георадиолокация; радарограмма; нарушенность.

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Поступила в редакцию 14 мая 2020 года

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Для цитирования: Дьяков А. Ю. Геофизические признаки нарушенности скальных пород // Известия вузов. Горный журнал. 2020. № 6. С. 58–65 (In Eng.). DOI: 10.21440/0536-1028-2020-6-58-65
For citation: Diakov A. Yu. Geophysical signs of hard rock disturbance. *Izvestiya vysshikh uchebnykh zavedenii. Gornyi zhurnal = News of the Higher Institutions. Mining Journal.* 2020; 6: 58–65. DOI: 10.21440/0536-1028-2020-6-58-65