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Application of georadiological subsurface sensing for hydrogeological monitoring

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Abstract. This article presents the results of the application of the georadar area near-surface sounding and the possibility of using a georadar for hydrogeological monitoring in the zone of negative influence of the liquidated coal mines.

1. Introduction
Flooding of large volumes of water in goaf abandoned mines accompanied by change in the stress state of the rock mass, the activation of displays of seismic rock pressure. Seismic observations conducted in various coal regions of the country note the activation of seismic phenomena, periodically record technogenic earthquakes up to 3-4 points on the Richter scale. Continued, and in some cases intensified, there are processes of subsidence of the earth's surface with the formation of deflections, dips, funnels, cracks. The consequence of this is the flooding of underworked areas, where industrial buildings and structures, residential settlements, valuable agricultural lands and forest tracts are located. To prevent these phenomena, a timely forecast of the possibility of flooding of territories is important [1, 2]. To determine the level of groundwater and man-caused waters, it is proposed to use a set of equipment for georadar location near-surface sounding [3-5].

2. Materials and methods
For georadar surveys, the most commonly used method is called vertical time in seismic surveys. In this case, the georadar moves along the profile with a constant separation between the receiving and transmitting antennas, and at each point of the profile a signal consisting of a probe pulse and secondary waves is recorded (see Fig. 1). Any subsurface inhomogeneities associated with changes in the ground will give a response in the wave structure of the received signal.

Figure 1. A schematic diagram of the georadar movement along the selected route
3. The study of the propagation of electromagnetic waves

The most important parameters characterizing the possibility of using the georadiolocation method in various environments are the specific attenuation and propagation velocity of electromagnetic waves in the environment, which are determined by its electrical properties. Specific attenuation determines the depth of sounding. The value of the propagation velocity of radio waves is necessary for recalculating the time delay of the reflected pulse in the distance parameter to the reflecting boundary (Fig. 2).

Figure 2. A scheme of propagation of radio waves in different layers of soil.

The main parameters that are necessary to ensure the correct technology of surveying and interpretation of georadiolocation data:

- the dielectric constant: \( \varepsilon = \varepsilon' - j\varepsilon'' \);
- conduction: \( \sigma = \omega \varepsilon'' \varepsilon_0 \);
- dielectric loss tangent: \( \tan \delta = \varepsilon'/\varepsilon'' = \sigma/\omega \varepsilon'' \varepsilon_0 \);
- light speed in vacuum \( c \);
- dielectric permeability in vacuum: \( \varepsilon_0 \);
- magnetic permeability in vacuum: \( \mu_0 \);

For most rocks:
- phase velocity: \( V_p = c/R_{\varepsilon}/\sqrt{\varepsilon} \);
- the degree of attenuation of the wave at a distance \( z \) in dB (decibels): \( L = 20 \log_{10}[E_0/E_z] = 8.68\alpha z \), where \( \alpha = \omega/c/\ln\sqrt{\varepsilon} \);
- specific attenuation: \( \Gamma = 8.68\alpha = 54.6/\alpha/\ln\sqrt{\varepsilon} \).

Approximate values of the electrical characteristics of some soils and rocks at a field frequency of 100 MHz used to operate in the study area are given in Tables 1 and 2.
Table 1. Dielectric values of materials in the frequency range recommended for measurements

| Material       | Dielectric constant | Conduction | Specific attenuation | Phase velocity |
|----------------|---------------------|------------|----------------------|----------------|
| Air            | 1                   | 0          | 0                    | 300            |
| Fresh water    | 81                  | 10⁻³       | 0.18                 | 33             |
| Sea water      | 81                  | 4          | 330                  | 15             |
| Sandy soil is dry | 2.6                | 1.4×10⁻⁴   | 0.14                 | 190            |
| Sandy soil moist | 25                | 6.9×10⁻³   | 2.3                  | 60             |
| Dry loam       | 2.5                 | 1.1×10⁻⁴   | 0.11                 | 190            |
| Wet loam       | 19                  | 2.1×10⁻²   | 7.9                  | 69             |
| Clay soil is dry | 2.4              | 2.7×10⁻⁴   | 0.28                 | 190            |
| Clay soil moist | 15                | 5×10⁻²     | 20                   | 74             |
| Basalt wet     | 8                   | 10⁻²       | 5.6                  | 110            |
| Granite wet    | 7                   | 10⁻¹       | 0.62                 | 110            |
| Clay slate moist | 7                | 10⁻¹       | 45                   | 83             |
| Sandstone wet  | 6                   | 4×10⁻²     | 24                   | 110            |
| Limestone moist | 8                  | 2.5×10⁻²   | 14                   | 110            |
| Iron           | 1                   | 10⁶        | 1.7×10⁻⁷             | -              |

As the moisture content of the soil increases, the specific dielectric constant also increases. The electrical conductivity of the soil increases.

Table 2. Dependence of the basic electromagnetic parameters of soils on humidity

| Material       | Dielectric constant | Conduction |
|----------------|---------------------|------------|
| Road construction | 5…10          | 0,0002…0,00002 |
| Rock           | 4…10               | 0,01…0,0000 |
| Clay           | 4…16               | 0,05…0,0002 |
| Loam           | 2,5…19             | 0,021…0,00011 |
| Sand           | 3…25               | 0,007…0,00002 |
| Peat wet       | 50…78              | 0,002…0,001 |
| Moraine        | 9…25               | 0,01…0,0001 |
| II             | 9…23               | 0,001…0,0001 |
| Metal          | 1…2                | 10000000 |
| Ice            | 3…4                | 0,001 |
| Water          | 80…81              | 0,002…0,001 |
| Air            | 1                   | 0 |
| Road construction | 5…10          | 0,0002…0,00002 |
| Rock           | 4…10               | 0,01…0,0000 |

The minimum values of the dielectric constant refer to dry the material, the maximum - to water-saturated.

The difference in the phase velocity for different frequencies determines the variance. The probe pulse in a dispersion medium changes its shape due to phase distortion of the shape.
4. Results
The method of georadar location near-surface sounding has been tested with the purpose of remote
determination of the following parameters: groundwater level (hydrogeological monitoring), depth
parameters of the source of ignition of coal dumps (monitoring of land resources), failure-dangerous
zones around the old abandoned mine workings (geodynamic monitoring).

Allocation of the groundwater level (GWL) using the georadiolocation method is much easier if the
study area or in the immediate vicinity are located in some ponds (ponds, rivers, lakes, etc.), i.e., it is
possible to trace the groundwater level directly from the water's edge on the work site, especially for the
laying of at least one profile. If necessary, it is possible to conduct regular observations on fluctuations
of the GWL, which can be of great importance in engineering geological and geocological studies [6 -
8].

The scheme of the profiles examined by the georadar in the immediate vicinity of the hydro-
observation well is shown in Fig. 3.

Interpreted results of georadar surveying in the determination of GWL are shown in Fig. 4.
Figure 4. Interpretation of georadar survey data: a) the waveform of the reflected signal and the radarogram with the deposited groundwater level on track 1; b) a radarogram with a well-traced reflection from the wet boundary before processing

5. Conclusion
As can be seen, the value of the ground water level correlates well with the appearance of the "tail" on the wave form, that is, the departure of the signal from the centerline on the waveform chart. Emerging intermediate layers introduce additional losses; nevertheless, GWL is fixed quite confidently, especially in a uniform palette [9, 10].

Based on the data obtained, it can be concluded that the method is valid for the constant monitoring of the dynamics of groundwater, especially in the area of the liquidated mines.

The main advantage of this method in hydrogeological monitoring is remote sensing of the groundwater level without the need to drill expensive observation wells. This method makes the process of hydromonitoring much more cost-effective.

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