УДК 550.832.5+624.131.32 DOI: https://doi.org/10.24028/gzh.v44i1.253708

Determination of engineering geophysical parameters of grounds on building sites and for seismic microzonation (methodical and metrological components of technology)

M.S. Bondarenko, V.V. Kulyk, 2022

S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
Received 30 August 2021

To ensure the reliability and long-term usage of high housing buildings, important industrial, infrastructural and other objects, it is necessary to carry out engineering geological investigations of grounds (near-surface rocks) as the basis of these structures. To prevent the potential danger of destruction of the objects, it is also necessary to perform microseismic investigations of the near-surface geological environment and to agree the obtained results with the engineering geological parameters in the section of the test boreholes. Engineering geological parameters, determined by geophysical methods, are named engineering geophysical parameters.

To solve the geophysical engineering problems, including seismic microzonation, at the Institute of Geophysics of the National Academy of Sciences of Ukraine a modern investigation technology has been created. The technology is based on apparatus and methodical complex of radioactive logging, which involves gamma-ray logging (GL), density logging (DL) and neutron logging (NL). This paper presents the results of developing adequate methodical and metrological assurance of the radioactive logging complex as a key technology element.

Complexation of methods GL, DL and NL (taking into account a priori data) and the use of the proposed approaches allow determining a wide set of engineering geophysical parameters: density, porosity, volume moisture, groundwater level, the content of shale, the content of clay minerals, water saturation, dry ground density, etc. The features of obtaining parameters by the radioactive logging complex in the zone of aeration and the zone of saturation are shown, as well as taking into account the influence of the shaliness on the determined parameters. The effectiveness of the technology has been demonstrated by specific examples and confirmed by independent laboratory measurements.

Key words: grounds (near-surface rocks), zone of aeration, zone of saturation, groundwater level, complex of gamma-ray, density and neutron loggings, methodical and metrological assurance, engineering geophysical parameters, seismic microzonation, geophysical technology.

Introduction. The heightened interest in engineering geophysical investigation is connected with the increase in Ukraine of the volume of high-rise housing construction, with the building of important industrial and infrastructure objects, etc. Assurance of reliability and long-term usage of buildings and structures requires investigations of grounds (near-surface rocks) as the basis of these constructions. In many cases, monitoring changes in ground properties under the influence of natural and anthropogenic factors is also required. Such works imply a detailed and express investigation of the geological structure and the determination of engineering geological and other ground parameters of the near-surface geological section to a depth from several meters to tens of meters.

Another important direction, which makes necessary the investigation of the features of the near-surface section, is the estimation of the seismic hazard of a particular territory when designing new and for existing potentially hazardous industrial facilities, buildings for various purposes, dams, oil-and-gas pipelines, etc. Microseismic characteristics of particular localities are related to the properties of grounds and changes in these properties under the influence of various factors. When preparing sites for the construction of important objects, it is necessary to carry out the seismic investigations of the near-surface multilayer geological environment and compare obtained results with the engineering geological parameters of the appropriate layers in the section of test boreholes.

The investigation of the near-surface section based on ample sampling of grounds (monoliths) for laboratory determination of engineering geological parameters presents significant difficulties and is possible only selectively. This technology is costly, time-consuming (especially with increasing depth), insufficiently detailed, not always accurate and informative due to changes of ground properties during sample procession, and some degree of randomness of local sampling.

Geophysical technologies allow for expeditious obtaining, with sufficient accuracy, a set of engineering geological parameters of near-surface rocks in real conditions of their natural occurrence.

Engineering geological parameters, determined by geophysical methods, will be termed engineering geophysical parameters [Ogilvi, 1990].

At the Institute of Geophysics of the National Academy of Sciences of Ukraine (IGPh), systematic work has been carried out to create a new technology for the ground investigation. The technology is based on the apparatus and methodical complex of radioactive logging (RL) for solving geophysical engineering problems, including seismic microzonation [Zvolskyi et al., 2010; Kulyk et al., 2012, 2013, 2015, 2017a-c; Bondarenko et al., 2013, 2018, 2019, 2021; Bondarenko, Kulyk, 2015; Kendzera et al., 2016].

We also use the near-surface rocks as natural models of gas-water-saturated reservoirs to develop the apparatus and methodical complexes of radioactive logging for determining petrophysical parameters of rocks in the section of oil-and-gas boreholes [Bondarenko, Kulyk, 2016, 2017; Kulyk, Bondarenko, 2016].

This paper presents the results of the development of adequate methodical and metrological assurance as a key element of modern technology for investigating near-surface rocks by the complex RL.

1. Subject of investigations, a complex of logging methods and the borehole conditions. The subject of investigation is the engineering geophysical parameters of near-surface sand shale and carbonate rocks in the aeration zone and the saturation zone. It should be noted that the near-surface rocks of the greater part (~ 70 %) of the territory of Ukraine are sand shale grounds [Shutenko et al., 2017].

For geophysical engineering problems, including seismic microzonation, important parameters are the ground density, content of shale and content of clay minerals, porosity, dry ground density, groundwater level, volume moisture, water saturation. For example, in seismic microzonation of territories, the groundwater level and the ground density are used in calculating the increase in seismic magnitude by the seismic rigidity method [Kendzera et al., 2016; Kurbatskiy, Kosaurov, 2016; Trifonov et al., 2019], and the full set of engineering geophysical parameters is used to identify individual layers and interlayers.

The borehole nuclear geophysical methods occupy the leading position among the geophysics engineering methods. It has been proven in practice that complex of radioactive logging involving gamma-ray logging (GL), density logging (DL) and neutron logging (NL) is effective [Osipov, 1968; Ferronskiy et al., 1977; Ferronskiy, Gryaznov, 1979; Zvolskiy, 1980; Kuznetsov, Polyachenko, 1990]. The complex provides fast and detailed determination of a number of geophysical engineering parameters of the grounds of the near-surface layer. In addition, laboratory methods are used selectively for control and comparison and, if necessary, to determine additional parameters.

Radioactive logging is performed in a dry cased borehole. The optimal technique for making such boreholes is the shock-and-vibration technique (SVT) [Zvolskiy, 1980]. SVT uses a steel casing pipe of 2 in (51 mm) diameter and 5.5 mm wall thickness; the casing pipe is adjacent to the ground. The boreholes range from several meters to ~20 m in depth (in this case, depth is limited by the power of the SVT equipment). Thermobaric conditions of occurrence correspond to normal PT conditions and, within the considered depths, have no affects on the determined parameters.

2. Shortcomings of the traditional technology of using the complex RL. The GL+DL+NL complex has been used for solving geophysical engineering problems for more than half a century [Osipov, 1968; Ferronskiy et al., 1977; Ferronskiy, Gryaznov, 1979; Zvolskiy, 1980; Kuznetsov, Polyachenko, 1990; Ogilvi, 1990]. Existing in Ukraine technology of engineering geophysical investigations using radioactive logging [Grounds…, 1990, 2010; Deineko, 2007] is based on a serial set of single-spacing tools. The set involves the neutron moisture meter VPGR-1 [Surface…, 1982] and the gamma-gamma density meter PPGR-1 [Surface…, 1986]. The methodical and metrological basis of tools was developed as far back as the 1980s and has a number of shortcomings when performing borehole measurements and obtaining geophysical engineering parameters.

The main shortcomings are as follows.

1. The gamma-ray logging is used qualitatively as an indicator of lithological properties (first of all, as an indicator of shaliness of grounds). It is used quantitatively as the natural background value, which must be taken into account in the density logging tool readings. The density and the neutron loggings are used to determine the density and moisture of the ground, respectively. That is, in fact, in traditional technology [Grounds…, 1990, 2010], only individual methods (DL and NL) are used for quantitative (but not always accurate enough) parameter determinations, rather than full agreed complex (GL+DL+NL). That can be considered as *fundamental shortcomings* of traditional technology.

2. The set of aluminium-plexiglass simulators of density and moisture is an integral part of traditional technology. This set is used to obtain the calibration functions of density and neutron logging tools. Standard calibration functions are used on all investigation objects without considering the features of these objects. However, these simulators do not always represent the investigated section's real properties, particularly in the case of natural sand shale grounds. Besides shaliness in such grounds, there are almost always a zone of aeration and a zone of saturation. This leads to systematic errors in the quantitative determination of both density and moisture and other parameters.

Along with calibration procedure of density and neutron logging tools using aluminum-plexiglass simulators, full-scale physical models of grounds with different porosity and moisture and, respectively, the water saturation can be used for this purpose [Grounds…, 1990, 2010]. However, it is practically impossible to implement the latter approach by constructing a sufficient set of physical models that would cover the required range of changes in porosity, clay content, moisture, and water saturation.

3. *The next shortcomings* of traditional technology are the impossibility of taking into account the effect of chemically bound water in clay minerals when determining moisture along the borehole section and the neglect of features of the moisture determination in the aeration zone (variable porosity and variable filling of pores with water).

4. Other *methodical shortcomings*:

– obtaining the calibration functions of the tools (PPGR-1 and VPGR-1) for readings in the form of an absolute count rate leads to increases the systematic error in determining the desired parameters; it is as a result of an uncontrolled change in the efficiency of detecting systems and a decrease in the activity of sources with time, etc.

– the absence of a procedure for determining clay minerals content, chemically bound water in clay minerals, the density of the solid phase, etc.

5. The set of tools PPGR-1 and VPGR-1 is characterized by several *technical and tech-*

nological shortcomings [Kulyk et al., 2017c].

Thus, in use since Soviet times, the technology strongly needs renewal. In world practice, there are also no sufficiently advanced technologies in this direction [Keys, 1990; Coe et al., 2018].

3. Petrophysical model. We have taken the following petrophysical model for investigation of fundamental aspects of determining the ground parameters.

The near-surface sandshale rock consists of the matrix (quartz skeleton), shale component, and pores. The pores are filled with air and fresh water in various proportions (zone of aeration and zone of saturation, respectively).

The shale component includes hydrogen-containing clay minerals (mainly hydromica, kaolinite, and montmorillonite), quartz particles, feldspar, etc. In many cases, the density of the shale component of the ground is not much different from the density of quartz. On this basis, it is often convenient to consider the matrix together with the shale component as an integral solid phase of the ground with a density of ≈2.65 g/cm^3.

The water content in the ground is characterized by a volume moisture W_V (the ratio of the volume of water to the volume of the ground), which is determined as $W_V=S_w\phi$. In this formula, ϕ is the porosity (the ratio of the pore volume to the ground volume), S_w is the water saturation (the ratio of the water volume in the pores to the volume of pores), which can vary from 0 (dry ground) to 1 (water-filled ground).

As an aeration zone, we shall understand a part of the near-surface section, which is located above the groundwater level. Below this level, in the zone of saturation, the grounds are fully saturated with fresh water. The relative volume of air in the pores is characterized by the air saturation factor $S_{air}=1–S_w$.

Such a petrophysical model adequately represents the main components and characteristic features (aeration zone, zone of saturation, shaliness) of near-surface rocks and is effective for determining parameters and interpreting the radioactive logging complex results.

4. Metrological assurance. ***4.1. Graduation characteristics and calibration functions.*** When developing metrological assurance for radioactive logging tools, we will adhere to the terminology based on monograph [Lobankov, 2016].

Tool *graduation* is a set of metrological operations on full-scale physical models of rocks. The purpose of the operation is to establish a correspondence between the readings of a logging tool (under given borehole conditions) and some values of the measured engineering geophysical parameter (in accepted units).

Graduation establishes a certain functional dependence between the argument (engineering geophysical parameter) and the values of the function (tool readings at each value of the parameter). This functional dependence is called the *graduation characteristic*.

To obtain the required engineering geophysical parameter in the borehole section, a *calibration function* is used. Calibration function is a functional dependence of the measured parameter on the tool readings. In essence, the calibration function is the inverse function of the graduation characteristic. At that, the technical conditions of the «tool—borehole» system for physical models and the investigated borehole section must be appropriate.

One of the requirements for calibration function is the choice of an adequate approximate formula that provides minimum errors in the operating range of variation of the determined parameter. The simplest approximation is linear, and polynomial, exponential and logarithmic approximations are also commonly used.

Nowadays, when a series of radioactive logging tools of the same type is relatively small (there may even be several exemplars), graduation characteristics and calibration functions are construct for each tool exemplar. Such individual dependences can have different constants of the approximation formulas.

In case of incomplete correspondence between the model and real parameters of the «tool—borehole» system, the appropriate correction is made to the calibration function. If the rocks of the investigated section and the model are different, then the correction is made directly to the required parameter.

4.2. Tool readings. The quantities directly recorded by the detectors when carrying out the radioactive logging complex in near-surface wells are *the count rate of gamma rays of natural radiation* along the borehole section (I_γ, counts per second (cps)); *the count rate of Compton gamma rays* arising from the interaction of the gamma rays from source ^{137}Cs with the ground ($I_{\gamma\gamma}$, cps) (for a given sonde spacing of the density logging tool);*the count rate of slow neutrons* arising from the slowing-down and diffusion of neutrons from the ^{238}PuBe source (I_n, cps) by one or two sonde spacing of the neutron logging tool.

When interpreting, it is conventional to present the readings of gamma-ray logging in the form of index ΔI_γ [Golovatskaia et al., 1984; Kuznetsov, Polyachenko, 1990; Ellis, Singer, 2008]:

$$\Delta I_\gamma = \left(I_\gamma - I_{\min}\right) / \left(I_{\max} - I_{\min}\right), \qquad (1)$$

where I_γ is the directly measured count rate of gamma-rays; $I_{\max}$, $I_{\min}$ are the reference values of the count rate of gamma-rays (commonly these values are determined in shale and the slightly radioactive ground, respectively).

The index ΔI_γ allows users to convert the results of gamma-ray logging to a unified scale, compare the data obtained by different tools and recorded in different units, and use universal relationships for quantitative estimating the shaliness the shaliness of sandshale rocks. The index ΔI_γ is also characterized by significant compensation properties that allow it to be used with sufficient accuracy in practice without applying the corrections.

Representing the density and neutron logging readings in relative units (r.u.) makes it possible to obtain correct results when measuring with the same type of tools using the corresponding sources with different strengths. The application of r.u. also compensates for the change with time in the efficiency of detectors. As an r.u., it is convenient to take the readings of the corresponding tool in a tank with fresh water in the presence of a casing pipe, simulating a borehole («water» unit).

4.3. Graduation characteristics of gamma-ray logging. Mass content of shale, C_{sh}, and mass content of clay minerals, C_{cl}, are parameters of grounds, measured with the help of gamma-ray logging. Using the correlation between these parameters of shaliness, which are determined by laboratory investigations of core material, and the corresponding well-logging data in the form of index ΔI_γ [Golovatskaia et al., 1984; Bhuyan, Passey, 1994], we shall obtain the graduation characteristics of gamma-ray logging [Kulyk et al., 2015]:

$$\Delta I_\gamma = f_{sh}\left(C_{cs}\right), \ \Delta I_\gamma = f_{cl}\left(C_{cl}\right). \qquad (2)$$

Fig. 1, *a* shows the graduation characteristics of the method GL and their approximation in the form of polynomials. Parameters C_{sh} and C_{cl} we determine in the borehole section directly from calibration functions of gamma-ray logging.

4.4. Graduation characteristics of density and neutron loggings. According to our approach [Kulyk et al., 2017b], when investigating the near-surface sandshale rocks, neutron logging tools should be graduated on physical models based on the clean (clay-free) quartz material, with different water-filled porosities (S_w=1, ϕ=W_V). It is reasonable to graduate density logging tools on the same models. Moreover, to increase the number of graduation points in density, the parameter S_w of the models can have three values: S_w=1 (water-filled ground), S_w=0 (dry ground), S_w<<1 (moist ground). Such models were constructed at the IGPh [Bondarenko et al., 2021]. From measurements on physical models, we obtain the graduation characteristics of density and neutron logging tools:

$$B_{\gamma\gamma} = f_{DL}\left(\delta\right), \qquad (3)$$

where $B_{\gamma\gamma}$ is the readings of the density logging tool in r.u.;

$$B_n = f_{NL}\left(\phi\right), \qquad (4)$$

where B_n is the readings of the neutron logging tool in r.u.

Thus, the density ($\delta_{\gamma\gamma}$) and water-filled

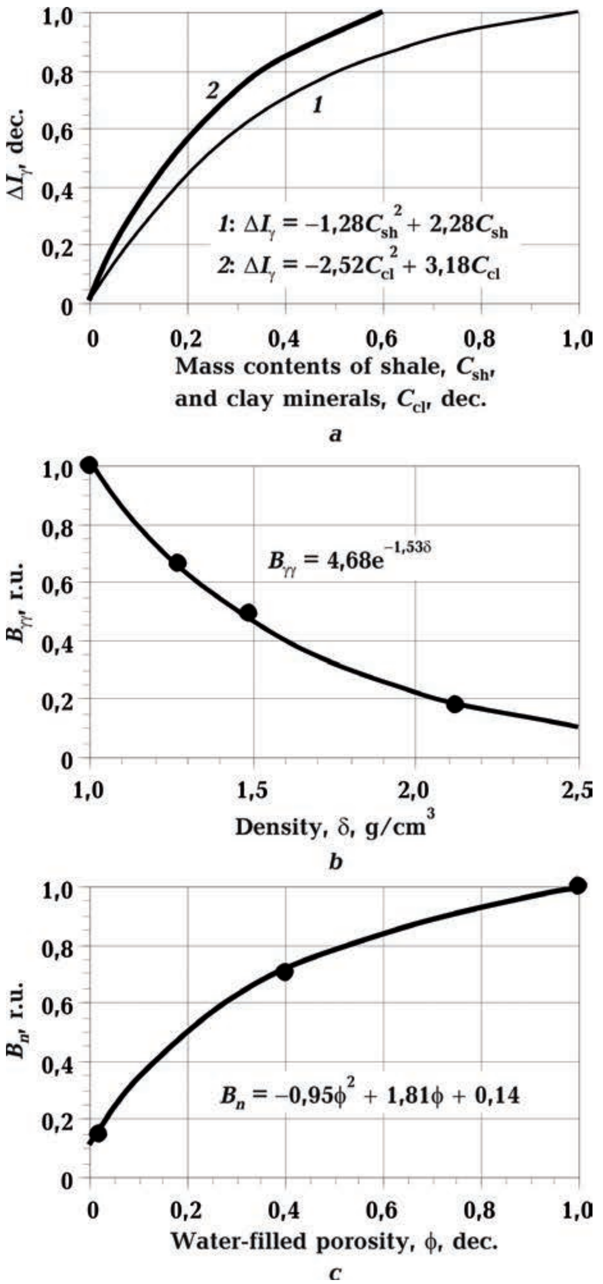

Fig. 1. Graduation characteristics of: *a* — gamma-ray logging for mass contents of shale (*1*) and clay minerals (*2*); *b* — density logging for dual-channel tool DL+GL; *c* — neutron logging for near detector of tool 2NL. ● — measurements in physical models at IGPh; r.u. — relative units, dec. — decimal fraction.

neutron porosity (ϕ_n) are the parameters of grounds, measured by density and neutron loggings, respectively. Density, $\delta_{\gamma\gamma}$, and porosity, ϕ_n, we directly obtain by well-logging data from corresponding calibration functions. The calibration functions of density and neutron logging tools are inverse functions for graduation characteristics (3) and (4), respectively.

There are developed and created dual-channel density and gamma-ray logging tool (DL+GL) and the dual-spacing neutron logging tool (2NL) at the IGPh [Kulyk et al., 2017c]. Fig. 1, *b*, *c* show the graduation characteristics of the density gauge of the dual-channel logging tool and near detector of the neutron logging tool, respectively. The graduation characteristics were obtained on full-scale physical models constructed at the IGPh [Bondarenko et al., 2021].

5. Parameters of shaliness. ***5.1. The contents of shale and clay minerals.*** Shaliness is an important lithological characteristic of near-surface rocks. There are distinguished the shale content and the clay minerals content in ground [Bhuyan, Passey, 1994; Ellis, Singer, 2008]. The latter is associated only with clay minerals in the shale component of the ground.

The content of shale is determined by the presence of pelitic material. The pelitic material is small particles (by convention, less than 0.01 mm), regardless of their mineral composition (clay minerals proper, quartz, feldspar, etc.) [Dobrynin et al., 2004].

The shale component has an influence, in particular, on the ground's filtration properties (permeability). Shales are characterized by increased radioactivity due to the large specific surface area of pelitic particles, which adsorb salts of radioactive elements (mainly isotopes of the uranium-radium and thorium series), and the presence of potassium, which contain radioactive isotope ^{40}K, in some clay minerals and feldspar. This allows distinguishing grounds by the shale content and evaluating it quantitatively applying data of gamma-ray logging [Ferronskiy, Gryaznov, 1979; Golovatskaia et al., 1984].

The content of clay minerals [Bhuyan, Passey, 1994; Ellis, Singer, 2008] and their type affect the physical and mechanical properties of grounds. Chemically bound water, which is contained in clay minerals, significantly affects the readings of neutron logging tools. This water should be taken into account when determining the porosity and moisture content of the investigated grounds. The hydrogen index and density of individual clay minerals are their characteristic properties.

5.2. Parameters of mass shaliness. *The mass content of shale*, C_{sh}, and *the mass content of clay minerals*, C_{cl}, are determined by means of calibration functions of the gamma-ray logging, which are inverse functions for the graduation characteristics (2). For the graduation characteristics of the gamma-ray logging in Fig. 1, *a*, the corresponding calibration functions can be represented [Kulyk et al., 2015] as:

$$C_{sh}^{\gamma} = 2.60\Delta I_{\gamma}^{4} - 3.55\Delta I_{\gamma}^{3} + 1.78\Delta I_{\gamma}^{2} + 0.15\Delta I_{\gamma}, \quad (5)$$

$$C_{cl}^{\gamma} = 0.74\Delta I_{\gamma}^{4} - 0.84\Delta I_{\gamma}^{3} + 0.51\Delta I_{\gamma}^{2} + 0.20\Delta I_{\gamma}. \quad (6)$$

According to functions (5) and (6), the parameters C_{sh} and C_{cl} are determined in decimal fractions (dec.).

When solving practical problems and in the absence of laboratory determinations of the content of clay minerals, it is sufficient to take the average value of parameter C_{cl} in the total relative mass of shaly material C_{sh}. In most cases, based on the analysis of measurements, it is assumed that clay minerals amount to about 60 % of the mass of shaly material, namely, $C_{cl} \approx 0.6C_{sh}$ [Bhuyan, Passey, 1994; Kulyk et al., 2015].

The mass content of shale and the mass content of clay minerals are essentially independent of the zone in which they are determined (zone of aeration or zone of saturation).

5.3. Parameters of volume shaliness. When analyzing and interpreting well-logging data, the parameters of *volume content of shale*, K_{sh}, and *volume content of clay minerals*, K_{cl}, are used [Dobrynin et al., 2004]:

$$K_{sh} = C_{sh}(1-\phi), \; K_{cl} = C_{cl}(1-\phi), \quad (7)$$

where ϕ is the porosity.

5.4. Parameters of clay minerals. To solve some geological engineering problems, it is important to obtain information about the type of clay minerals contained in sandshale grounds. These minerals can affect the properties of the ground as the basis of building structures. For example, montmorillonite is characterized by strong swelling and plasticity, while hydromica weakly absorbs water [Alexander et al., 2011]. The identification of clay minerals is performed using laboratory methods, including sampling of grounds and carrying out of laborious and costly laboratory investigations [Logvinenko, Sergeeva, 1986].

The volume content of chemically bound water in clay minerals, $K_{cl.w.}$, is determined as

$$K_{cl.w.} = \omega_{cl} C_{cl} (1-\phi), \quad (8)$$

where ω_{cl} is the hydrogen index of clay minerals; C_{cl} is the mass content of clay minerals.

At the full water saturation, the parameter $K_{cl.w.}$ is the difference between neutron porosity, ϕ_n, (see subsection 8.2) and porosity by methods DL+GL, $\phi_{\delta+\gamma}$, (see subsection 8.1):

$$K_{cl.w.} = \phi_n - \phi_{\delta+\gamma}. \quad (9)$$

The difference between ϕ_n (porosity by method NL without taking into account the content of clay minerals) and $\phi_{\delta+\gamma}$ (true porosity by methods DL+GL) means the apparent porosity of the ground on account of chemically bound water in clay minerals.

In Fig. 2, the interdependence of the volume content of chemically bound water, $K_{cl.w.}$, and the index of gamma-ray logging, ΔI_{γ}, is constructed. The relationis based on the borehole measurements in the zone of saturation of near-surface sandshale rocks. There can be seen a sufficiently close correlation between clay minerals (due to the content of chemically bound water) and the index of gamma-ray logging ΔI_{γ}.

The hydrogen index of clay minerals, ω_{cl}, can be obtained by knowing the parameters ϕ_n, $\phi_{\delta+\gamma}$, and C_{cl}:

$$\omega_{cl} = \frac{1}{C_{cl}} \frac{(\phi_n - \phi_{\delta+\gamma})}{(1-\phi)}, \quad (10)$$

where ϕ_n is the neutron porosity; $\phi_{\delta+\gamma}$ is the porosity by methods DL+GL.

The density of clay minerals of sandshale ground, δ_{cl}, in the zone of saturation can be estimated using the complex of radioactive logging [Bondarenko, Kulyk, 2015]:

$$\delta_{cl} = \frac{\delta_{\gamma\gamma} - \delta_w \phi}{C_{cl}(1-\phi)} - \delta_q \left(\frac{1}{C_{cl}} - 1 \right), \quad (11)$$

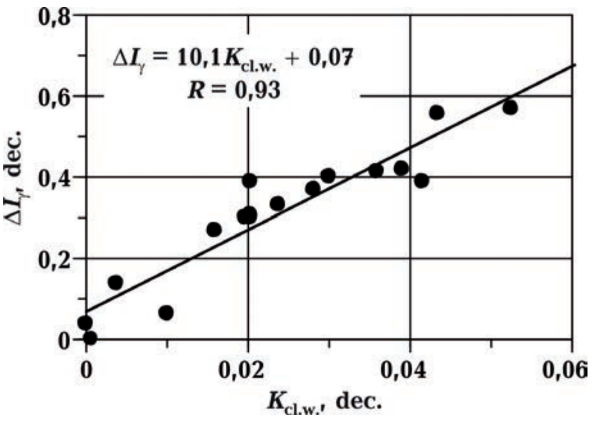

Fig. 2. Relationship between the volume content of chemically bound water in clay minerals and the index of the gamma-ray logging based on well-logging data. dec. — decimal fraction.

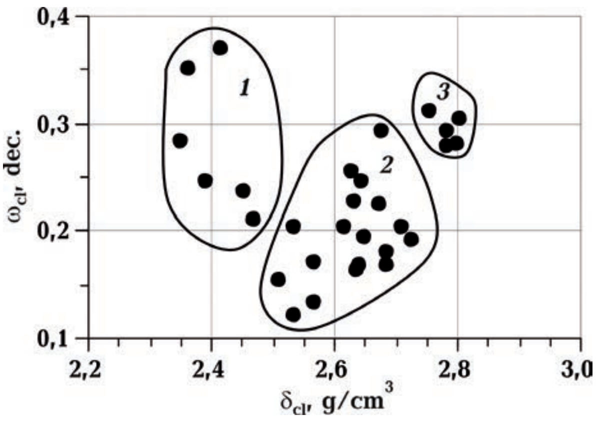

Fig. 3. Crossplot of hydrogen index vs density for determination of the type of clay minerals: *1* — montmorillonites, *2* — mixture of minerals, *3* — chlorites.

where $\delta_{\gamma\gamma}$ is the ground density by method DL; δ_q is the density of quartz, assumed equal to 2.65 g/cm^3; δ_w is the density of water, which is taken as 1.00 g/cm^3.

The hydrogen index ω_{cl} (10) and the density δ_{cl} (11) of clay minerals are related to their type. By layer-by-layer comparison of the parameters δ_{cl} and ω_{cl}, obtained from the results of complex RL, in favourable cases, it is possible to estimate the type of clay mineral (or its predominant content in the mineral mixture) in the layer. In Fig. 3 based on the well-logging data in near-surface sandshale rocks, a crossplot $\delta_{cl}\Leftrightarrow\omega_{cl}$ was constructed, and the results of this approach are demonstrated. It can be seen that montmorillonite and chlorite are predominant in some layers, and a mixture of clay minerals are predominant in most layers.

6. Density of near-surface rocks. Under the chosen petrophysical model, the density of near-surface sandshale rock, δ, is determined by the density of its components and their relative content:

$$\delta = \delta_q\left(1-\phi-K_{sh}\right)+\delta_{sh}K_{sh}+\delta_w W_V\ , \quad (12)$$

where δ_{sh} is the density of shaly material; K_{sh} is the volume content of shale; ϕ is the porosity; W_V is the volume moisture.

The result of the density logging, $\delta_{\gamma\gamma}$, is determined by the electron density of the ground, which, in turn, is closely related to the density, δ. Graduation of density logging tools on physical models of grounds with various porosity and different water saturation allows at once taking into account the anomalous properties of hydrogen [Lobankov, 2016]. Therefore, for sandshale grounds in the aeration zone and below the groundwater level, the equality $\delta_{\gamma\gamma}$=δ is fulfilled in practice with a satisfactory accuracy (with an error of no more than ~0.01 g/cm^3) [Ferronskiy, Gryaznov, 1979; Golovatskaia et al., 1984].

The density of the near-surface rock from density logging, $\delta_{\gamma\gamma}$, is determined through calibration function, which is the inverse function of the graduation characteristic (3).

For the dual-channel tool DL+GL, which is created in IGPh [Kulyk et al., 2017c], the calibration function of density logging is given by

$$\delta_{\gamma\gamma} = -0.65\ln\left(B_{\gamma\gamma}\right)+1.00\,. \quad (13)$$

The dry ground density, δ_d, is determined with the help of Eq. (13) and the moisture W_V according to the complex of methods GL+DL+NL (see section 11):

$$\delta_d = \delta_{\gamma\gamma}-\delta_w W_V\ . \quad (14)$$

7. Groundwater level. The groundwater level is the boundary between the zone of aeration and the zone of saturation. To find the groundwater level, it is necessary complex use of methods DL+GL and methods NL+GL [Kulyk et al., 2017b].

The difference Δ_{RL} between the porosity according to method DL taking into account the content of shale with the help of method GL, $\phi_{\delta+\gamma}$, (see subsection 8.1) and porosity according to method NL taking into account the content of clay minerals with the help of method GL, $\phi_{n+\gamma}$, (see subsection 8.2) along the borehole section can serve as a criterion for the discrimination of aeration zone and zone of saturation:

$$\Delta_{RL} = \phi_{\delta+\gamma} - \phi_{n+\gamma}\,. \qquad (15)$$

In the aeration zone, where the porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$ are apparent porosities, parameter Δ_{RL} takes on a positive value (Δ_{RL}>0). In the zone of saturation, where the porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$ are approaching true porosity, the parameter Δ_{RL} is close to zero ($\Delta_{RL}\approx0$). On the borehole logs the depth point of transition from value Δ_{RL}>0 to value $\Delta_{RL}\approx0$ represents the groundwater level. Above this level, that is, in the aeration zone, the parameter Δ_{RL} grows the higher true porosity and the lower water saturation. In so doing, the parameter Δ_{RL} does not depend on the shaliness.

For reliable identification of the groundwater level, the difference Δ_{RL} shall exceed the total error of the porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$. In our estimation, the absolute total error of the value Δ_{RL} in practice is less than about ±2 %, which corresponds to the error in determining the groundwater level of about ±0.1 m.

Fig. 4 shows the calculated dependences of the parameter Δ_{RL} on the water saturation for sandshale ground with porosity of 20 %, 30 %, and 40 %. As may be seen from Fig. 4, the complex of methods GL+DL+NL makes it possible to identify the aeration zone practically over the whole real range of true porosity and water saturation of near-surface rocks.

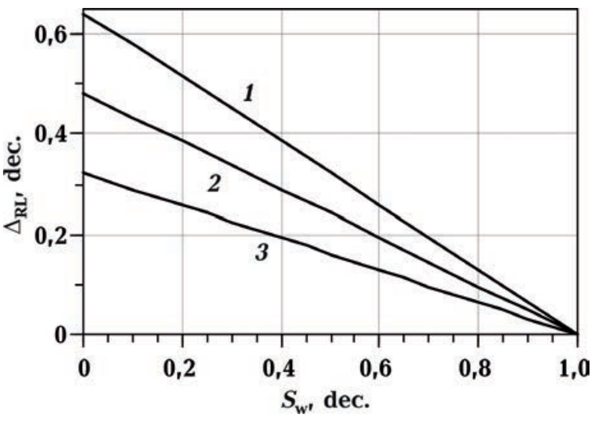

Fig. 4. Parameter Δ_{RL} vs water saturation for sandshale ground with porosity 0,4 (*1*), 0,3 (*2*) and 0,2 (*3*).

8. Porosity of shaly grounds in the zone of saturation. ***8.1. Porosity by methods DL+GL.*** Seeing that $\delta_{\gamma\gamma}=\delta$, the *porosity by methods DL+GL* of water-filled sandshale grounds ($W_V=\phi$), taking into account the content of shale with the help of method GL, is expressed from Eq. (12) in terms of the density $\delta_{\gamma\gamma}$ as

$$\phi_{\delta+\gamma} = \frac{\delta_q - \delta_{\gamma\gamma}}{\delta_q - \delta_w} - \frac{\delta_q - \delta_{sh}}{\delta_q - \delta_w} K_{sh}^{\gamma}\,, \qquad (16)$$

where $\phi_{\delta+\gamma}$ is the porosity by methods DL+GL; $\delta_{\gamma\gamma}$ is the density by method DL; K_{sh}^{γ} is the volume content of shale based on method GL.

On the right-hand side of Eq. (16), the first summand is the porosity from density logging (ϕ_δ) and the second summand is the apparent porosity of the shaly material.

Taking into account relationship (7), it is possible to obtain the porosity by methods DL+GL in the following form:

$$\phi_{\delta+\gamma} = \frac{\left(\delta_q - \delta_{\gamma\gamma}\right) - \left(\delta_q - \delta_{sh}\right) C_{sh}^{\gamma}}{\left(\delta_q - \delta_w\right) - \left(\delta_q - \delta_{sh}\right) C_{sh}^{\gamma}}\,, \qquad (17)$$

where C_{sh}^{γ} is the mass content of shale by means of calibration function of gamma-ray logging (5).

Since Eq. (17) contains only directly measured parameters ($\delta_{\gamma\gamma}$ and C_{sh}^{γ}) and constants (densities δ_q, δ_{sh}, and δ_w), it is this equation is used in practice for determination of the porosity of shaly grounds by methods DL+GL.

In many cases, the density of the shaly material is close to the density of the quartz skeleton ($\delta_{sh}\approx\delta_q$). The shalinessh as a small effect on the determination of porosity by method DL [Gulin, 1975]:

$$\phi_\delta = \frac{\delta_s - \delta_{\gamma\gamma}}{\delta_s - \delta_w}\,, \qquad (18)$$

where ϕ_δ is the density porosity [Ellis, Singer, 2008]; δ_s is the density of the solid phase of the ground.

8.2. Porosity by methods NL+GL. The porosity by method NL (neutron porosity [Ellis, Singer, 2008]) is closely related to the hydrogen content of the rock. *The neutron porosity*, ϕ_n, is determined according to the calibration function, which is inverse to the graduation characteristic obtained on physical models of water-filled grounds. In clay-free water-filled grounds, when interpreting the readings of the neutron logging tool by such a calibration function, the true value of water-filled porosity is determined (ϕ_n=ϕ). For example, for a near detector of a dual-spacing tool 2NL [Kulyk et al., 2017c], the calibration function, corresponding to the graduation characteristic (4), for f<50 % has the form

$$\phi_n = 0.73 B_n^2 + 0,06 B_n - 0,01 , \qquad (19)$$

where B_n is the readings of the near detector of a dual-spacing tool 2NL in r.u. According to Eq. (19), the neutron porosity is determined in decimal fraction.

To determine the porosity of shaly grounds, it is necessary to consider the hydrogen content in clay minerals. The relative hydrogen content (hydrogen index, ω) of porous shaly ground in the zone of saturation is expressed through the hydrogen indices of water and a mixture of clay minerals:

$$\omega = \omega_w \phi + \omega_{cl} K_{cl} , \qquad (20)$$

where ω_w is the hydrogen index of water (for the fresh water ω_w=1); ω_{cl} is the hydrogen index of clay minerals [Golovatskaia et al., 1984]; K_{cl} is the volume content of clay minerals; ϕ is the water-filled porosity.

The hydrogen index ω is considered as neutron porosity, that is, $\omega \approx \phi_n$ [Dobrynin, 1988].

The water-filled porosity by methods NL+GL taking into account the content of clay minerals with the help of method GL is determined from Eq. (20) as

$$\phi_{n+\gamma} = \phi_n - \omega_{cl} K_{cl}^{\gamma} , \ \omega_w = 1 , \qquad (21)$$

where $\phi_{n+\gamma}$ is the porosity by methods NL+GL; K_{cl}^{γ} is the volume content of clay minerals based on method GL. The hydrogen index of clay minerals is determined from apriori data. As practice shows, in the absence of laboratory determinations, it is reasonable to take $\omega_{cl} \approx 0.2$.

On the right-hand side of Eq. (21), the first summand is the neutron porosity, and the second summand is the apparent porosity of clay minerals.

Taking into account Eq. (7), the porosity by methods NL+GL can be obtained in the following form:

$$\phi_{n+\gamma} = \frac{\phi_n - \omega_{cl} C_{cl}^{\gamma}}{\omega_w - \omega_{cl} C_{cl}^{\gamma}} , \qquad (22)$$

where C_{cl}^{γ} is the mass content of clay minerals by means of calibration function of method GL (6).

Since Eq. (22) contains only directly measured parameters (ϕ_n and C_{cl}^{γ}) and constants (hydrogen indices ω_{cl} and ω_w), it is this equation is used in practice for determining the porosity of shaly grounds by methods NL+GL.

9. Apparent porosity of shaly grounds in the aeration zone. ***9.1. Apparent porosity by methods DL+GL.*** In the aeration zone, the density of grounds is less than in water-filled grounds. Therefore, we will obtain an apparent porosity in the aeration zone by methods DL+GL, which is higher than the true porosity.

Substituting Eq. (12) into Eq. (16), taking into account that $\delta_{\gamma\gamma}$=δ and moisture in the aeration zone is determined as $W_V = \phi(1 - S_{air})$, we obtain the expression for *the apparent porosity by methods DL+GL* for grounds in the aeration zone:

$$\phi_{\delta+\gamma}^{air} = \phi + \Delta\phi_{\delta} , \qquad (23)$$

where

$$\Delta\phi_{\delta} = \frac{\delta_w}{\delta_q - \delta_w} \phi S_{air} . \qquad (24)$$

For given δ_q and δ_w, the value of $\Delta\phi_\delta$ is determined by the true porosity ϕ and the air saturation factor S_{air}=1–S_w, where S_w is the water saturation.

The apparent porosity of shaly grounds in the aeration zone by methods DL+GL according to Eq. (23) is higher than the true porosity on the value of $\Delta\phi_\delta$. In the case of water-filled ground (S_{air}=0), the apparent porosity by methods DL+GL becomes true: $\phi_{\delta+\gamma}^{air} = \phi$. In dry ground ($S_{air}$=1), the apparent porosity by methods DL+GL takes the maximum value:

$$\phi_{\delta+\gamma}^{\text{air}} = \frac{\delta_q}{\delta_q - \delta_w}\phi .$$

9.2. Apparent porosity by methods NL+GL. The number of hydrogen nuclei per unit volume of ground in the aeration zone is less than in the water-filled ground. Therefore, we will obtain an apparent porosity ϕ_n, when interpreting the neutron logging tool readings by the «water-filled» calibration function. This apparent porosity ϕ_n is lower than the true porosity.

Since $\omega \approx \phi_n$, the neutron porosity of the porous shaly ground in the aeration zone is expressed through the hydrogen indices of water, ω_w, which fills part of the pores, and a mixture of clay minerals, ω_{cl}:

$$\phi_n = \omega_w \phi (1 - S_{\text{air}}) + \omega_{cl} K_{cl}^{\gamma} , \qquad (25)$$

where ϕ is the true porosity of ground; S_{air} is the air saturation factor. The hydrogen index of air is zero ($\omega_{\text{air}}=0$).

Substituting (25) into (21), we obtain the expression for *the apparent porosity by methods NL+GL* for grounds in the aeration zone:

$$\phi_{n+\gamma}^{\text{air}} = \phi - \Delta\phi_n , \qquad (26)$$

where

$$\Delta\phi_n = \phi S_{\text{air}} . \qquad (27)$$

The apparent porosity of grounds in the aeration zone by methods NL+GL, $\phi_{n+\gamma}$, according to (26) is less than the true porosity ϕ on the value $\Delta\phi_n$. In the case of water-filled ground (S_{air}=0, $\Delta\phi_n$=0), the apparent porosity by methods NL+GL becomes true porosity. In dry ground (S_{air}=1, K_{cl} is any), the apparent porosity by methods NL+GL is equal to zero.

10. True porosity in the near-surface section. The porosity by methods DL+GL in the aeration zone is increased compared to the true one due to a diminution in the total density of the ground. The porosity by methods NL+GL in the aeration zone decreases due to the lower hydrogen content and, to some extent, lower density. Thus, the porosities by methods DL+GL and by methods NL+GL in the aeration zone are apparent ones. It is impossible to determine the true porosity in this zone separately by methods DL+GL and by methods NL+GL. It is necessary to use a complex of these methods to obtain true porosity in the aeration zone.The porosity by the radioactive logging complex GL+DL+NL, ϕ_{RL}, can be represented in general form as the weighted arithmetic mean

$$\phi_{RL} = \alpha\phi_{\delta+\gamma} + \alpha_2\phi_{n+\gamma} , \; \alpha_1 + \alpha_2 = 1 , \qquad (28)$$

where α_1 and α_2 is weight factors; $\phi_{\delta+\gamma}$ is the porosity by methods DL+GL according to Eq. (17); $\phi_{n+\gamma}$ is the porosity by methods NL+GL according to Eq. (22).

In the aeration zone, we obtained numerical estimates of the weight factors at first empirically and then confirmed them with the help of theoretical calculations [Bondarenko, Kulyk, 2016; Kulyk, Bondarenko, 2016; Kulyk et al., 2017b].

Within the framework of the used approximations for sandshale grounds, it is easy to obtain the following values of the weight factors for the aeration zone:

$$\alpha_1 = \frac{\delta_q - \delta_w}{\delta_q} , \; \alpha_2 = \frac{\delta_w}{\delta_q} . \qquad (29)$$

As follows from Eq. (29), in the approximation under consideration, the weight factors α_i have the following properties:

– α_i depend on lithology (through the density of the skeleton, in this case, δ_q);

– α_i do not depend on the porosity and water saturation of the ground;

– α_i do not depend on the specifications and metrological characteristics of specific logging tools and on the borehole characteristics (diameter, casing, etc.).

For near-surface sandshale rocks, the values of the weight factors are as follows: $\alpha_1 \approx 0{,}65$ and $\alpha_2 \approx 0{,}35$.

In the zone of saturation, the weight factors are equal to 0.5 ($\alpha_1=\alpha_2=1/2$). That is, in this case, the porosity by the radioactive logging complex GL+DL+NL is reasonable to take as the arithmetic mean of the porosities by methods DL+GL and by methods NL+GL [Kulyk et al., 2017b]:

$$\phi_{RL} = \frac{\phi_{\delta+\gamma} + \phi_{n+\gamma}}{2} . \qquad (30)$$

11. Volume moisture. Volume moisture, W_V, is determined as the ratio of the volume of water in the pores of the ground to its volume.

In the zone of saturation, the volume moisture and porosity coincide, that is, $W_V=\phi$.

In the aeration zone, volume moisture can be determined through the apparent porosities by methods DL+GL and by methods NL+GL as their arithmetic mean weighted value [Kulyk et al., 2017b]

$$W_V^{RL} = \beta_1\phi_{\delta+\gamma} + \beta_2\phi_{n+\gamma}\,,\;\; \beta_1+\beta_2=1\,, \qquad (31)$$

where the weighting factors are obtained empirically based on the analysis and comparison of laboratory and well-logging data: $\beta_1 \approx 0.10$ i $\beta_2 \approx 0.90$.

12. Water saturation. Water saturation, S_w, is determined as the ratio of volume moisture to porosity: $S_w=W_V/\phi$.

In the zone of saturation, where volume moisture and porosity have the same value, water saturationis equal to 1.

In the aeration zone, the water saturation by radioactive logging complex GL+DL+NL [Kulyk et al., 2017b] is equal to:

$$S_w^{RL} = \frac{\beta_1\phi_{\delta+\gamma} + \beta_2\phi_{n+\gamma}}{\alpha_1\phi_{\delta+\gamma} + \alpha_2\phi_{n+\gamma}}\,. \qquad (32)$$

13. Procedure of determination of engineering geophysical parameters. The sequence of determination of engineering geophysical parameters by the radioactive logging complex according to our proposed approaches [Bondarenko, Kulyk, 2015; Kulyk et al., 2015, 2017b] is as follows.

1. Based on the registered count rates I_γ, $I_{\gamma\gamma}$ and I_n, the corresponding relative readings of methods GL, DL and NL are formed: ΔI_γ, $B_{\gamma\gamma}$ and B_n.

2. The mass content of shale, C_{sh}^{γ}, and the mass content of clay minerals, C_{cl}^{γ}, are determined by the calibration functions of the gamma-ray logging (5) and (6).

3. The total ground density, $\delta_{\gamma\gamma}$, is determined by the calibration function of the density logging tool (13).

4. The neutron porosity, ϕ_n, is determined by the means of calibration function of neutron logging tool (19). The porosity by methods NL+GL, $\phi_{n+\gamma}$, taking into account the mass content of clay minerals is determined according to Eq. (22).

5. In the case of a significant difference in the density of the shaly material, δ_{sh}, from the density of the quartz skeleton, δ_q, the density porosity of sandshale grounds, $\phi_{\delta+\gamma}$, is obtained on the basis Eq. (17). In the case $\delta_{sh} \approx \delta_q$, the density porosity is obtained with the help of Eq. (18).

6. Based on the results of determining the porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$, the parameter Δ_{RL}, which permits to identify aeration zone and zone of saturation as well as to install the groundwater level, is calculated by Eq. (15).

Two porosities, $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$, which are plotted together on the same diagram, disagree in the aeration zone ($\phi_{\delta+\gamma} > \phi_{n+\gamma}$). This divergence will be the larger the greater true porosity and the smaller water saturation. In the intervals of full water saturation, the porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$ practically coincide (within the limits of errors).

The groundwater level is determined by the transition point from $\Delta_{RL}>0$ to $\Delta_{RL}\approx 0$ in depth.

7. The true porosity ϕ_{RL} in the aeration zone is determined by the complex RL as the weighted arithmetic mean of the apparent porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$. In the zone of saturation (below the groundwater level) the true porosity is determined as the arithmetic mean of porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$.

8. The volume content of shale, K_{sh}^{γ}, and the volume content of clay minerals, K_{cl}^{γ}, are determined by Eq. (7) through the corresponding values C_{sh}^{γ} and C_{cl}^{γ} taking into account the true porosity ϕ_{RL}.

9. The volume moisture, W_V^{RL}, in the aeration zone is determined by the complex RL as the weighted arithmetic mean of the apparent porosities $\phi_{\delta+\gamma}$ and $\phi_{n+\gamma}$ according to Eq. (31). In the zone of saturation the volume moisture is equal to the porosity.

10. The radioactive logging complex determines the density of dry ground according to Eq. (14) through the total ground density and volume moisture.

11. Complex RL determines the water saturation in the aeration zone according to Eq.

(32). Below the groundwater level, the water saturation is equal to 1.

12. According to the results of determining the parameters of shaliness and to a priori data, a lithological column is imaged.

13. Analysis of the full set of engineering geophysical parameters and lithological column allows layer identification and marking local features.

14. Within the identified homogeneous layers or determined lithotypes, under favourable conditions, the hydrogen index of clay ω_{cl} and the density of clay minerals δ_{cl} are determined, as well as the type of clay mineral is estimated.

Based on the previous methodical approaches and the described procedure of determining the geophysical engineering parameters by the complex GL+DL+NL, the appropriate algorithms have been developed, and a computer program «NSL-complex» has been created [Bondarenko et al., 2013].

14. Examples of determination of engineering geophysical parameters. Well-logging examples of the geophysical engineering parameters determination are shown in Fig. 5—8. The results were obtained with the help of tools DL+GL and 2NL, which have been created and produced at the IGPh [Kulyk et al., 2017c].Interpretation of well-logging data has been performed based on developed apparatus and methodical complexes, and metrological approaches.

Borehole № 1 (Fig. 5) is located on the territory of the IGPh on the site of natural modelling. The site serves to test the apparatus and methodical complexes of the radioactive logging and to test the portable resonance seismic source, developed at the IGPh [Roman et al., 2018; Gryn et al., 2019]. Boreholes № 2 (Fig. 6) and № 3 (Fig. 7) are placed on high-rise housing construction sites in Kyiv. Borehole № 4 (Fig. 8) is located on the construction site of a new dam of the Northern Mining and Concentration Enterprises (the city of Kryvyi Rih).

In all cases the investigated near-surface section is represented by sandshale grounds and includes a zone of aeration and a zone of saturation. Based on the logging results, the following parameters are determined in boreholes № 1—4:

– mass content of clay minerals (curve *1*);
– mass content of shale (*2*);
– volume content of clay minerals (*3*);
– volume content of shale (*4*);
– dry ground density (*5*);
– total density (*6*);
– porosity by methods NL+GL (*7*) and density porosity (*8*), which are apparent in the aeration zone;
– true porosity according to the complex RL (*9*);
– volume moisture (*10*);
– water saturation (*11*).

Lithological identification of the near-surface section has been performed according to diagrams of shaliness.

<u>In the borehole № 1 (Fig. 5)</u>, the following layers have been identified:

– loam (in the intervals 1.0—2.2 m, 4.5—6.6 m, 8.2—9.2 m, deeper than 11.2 m);
– sand (2.2—4.5 m);
– loamy sand (6.6—8.2 m);
– shale (9.2—11.2 m).

The groundwater level in the borehole № 1 is determined at a depth of 9.7 m. Two thick layers are identified in the borehole section according to the density: 1.0—8.0 m (density ~1.9—2.1 g/cm^3) and deeper than 8.0 m (density ~2.4 g/cm^3). The layers also correlate with porosity.

<u>In the borehole № 2 (Fig. 6)</u>, the following lithotypes have been identified:

– loam (in the intervals of 0.5—1.7 m, 9.2—9.8 m, deeper than 11.3 m);
– sand (1.7—5.0 m, 8.3—9.2 m);
– loamy sand (5.0—8.3 m);
– shale (9.8—11.3 m).

The groundwater level in the borehole № 2 is located at a depth of 6.6 m. In the borehole section following layers are identified according to the density: 1.5—4.0 m (density ~1.8 g/cm^3), 4.0—10.0 m (density ~2.0 g/cm^3 with a local increase up to ~2.3 g/cm^3) and deeper than 10,0 m (density ~2.15 g/cm^3). Changes in density correlate with changes in porosity.

<u>In the borehole № 3 (Fig. 7)</u>, the following lithological layers have been identified:

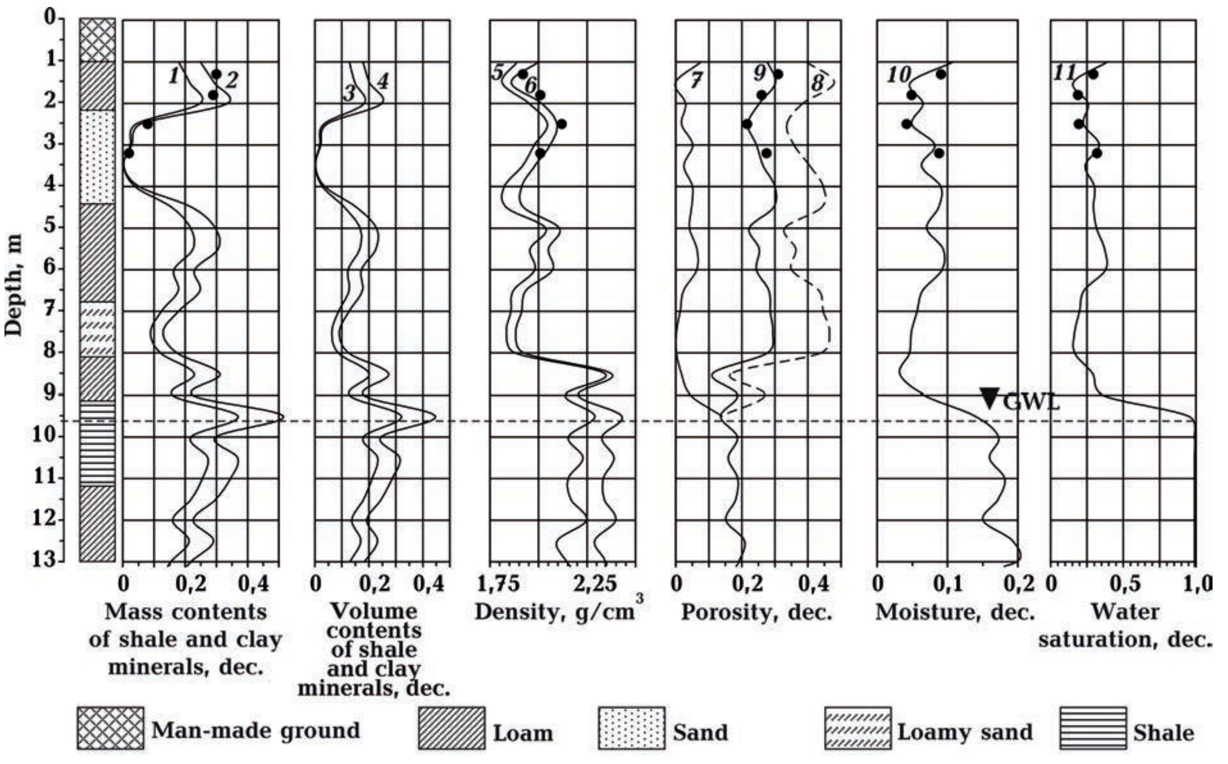

Fig. 5. Engineering petrophysical parameters in the section of borehole № 1 (the site of natural modelling, IGPh) according to well logging by tools DL+GL and 2NL: *1* — mass content of clay minerals, *2* — mass content of shale; *3* — volume content of clay minerals; *4* — volume content of shale; *5* — density of dry ground, *6* — total density, *7* — porosity by methods NL+GL, *8* — density porosity; *9* — true porosity, *10* — volume moisture; *11* — water saturation; dec. — decimal fraction; ● — laboratory determinations; GWL — groundwater level.

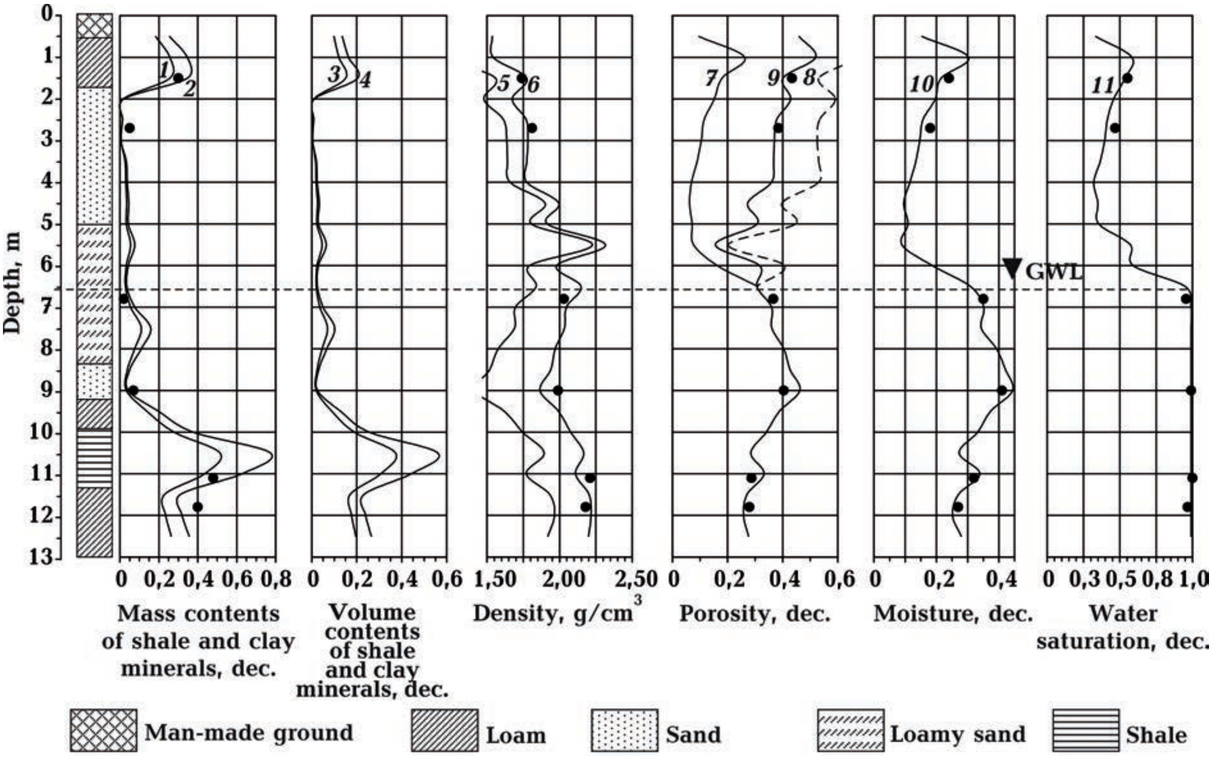

Fig. 6. Engineering petrophysical parameters in the section of borehole № 2 (the construction site, Kyiv) according to well logging by tools DL+GL and 2NL. Symbols see in Fig. 5.

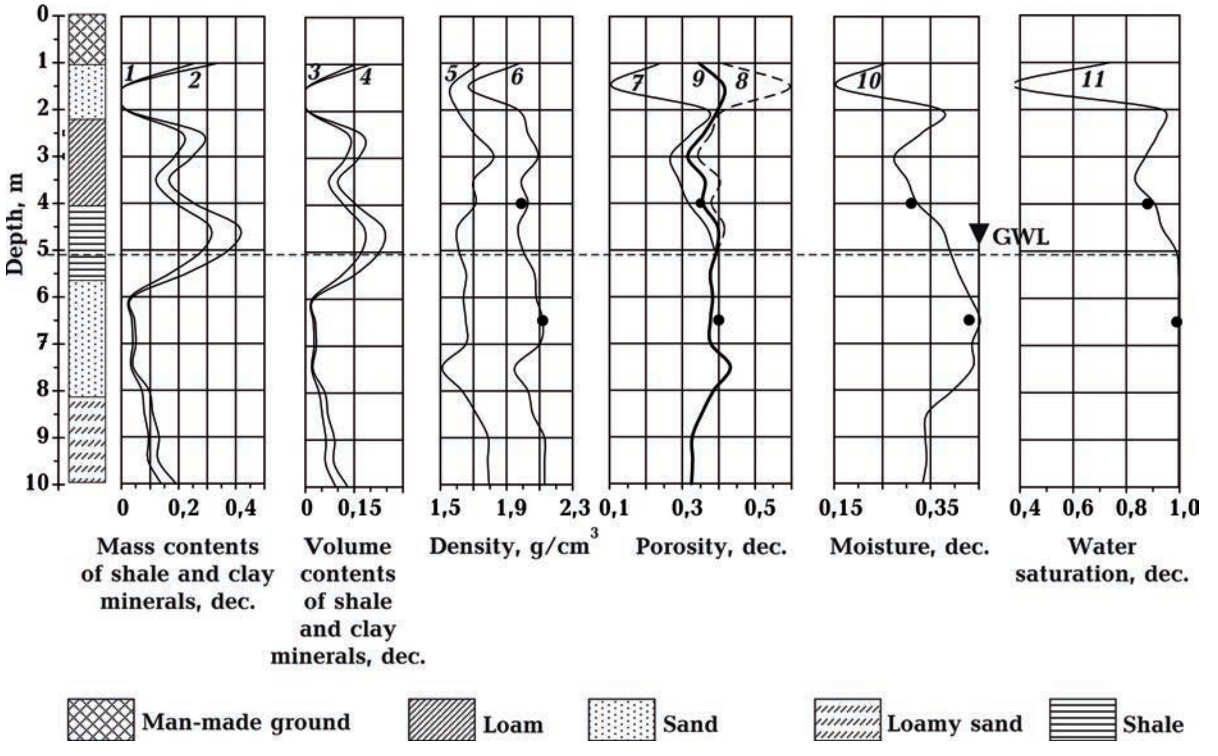

Fig. 7. Engineering petrophysical parameters in the section of borehole № 3 (the construction site, Kyiv) according to well logging by tools DL+GL and 2NL. Symbols see in Fig. 5.

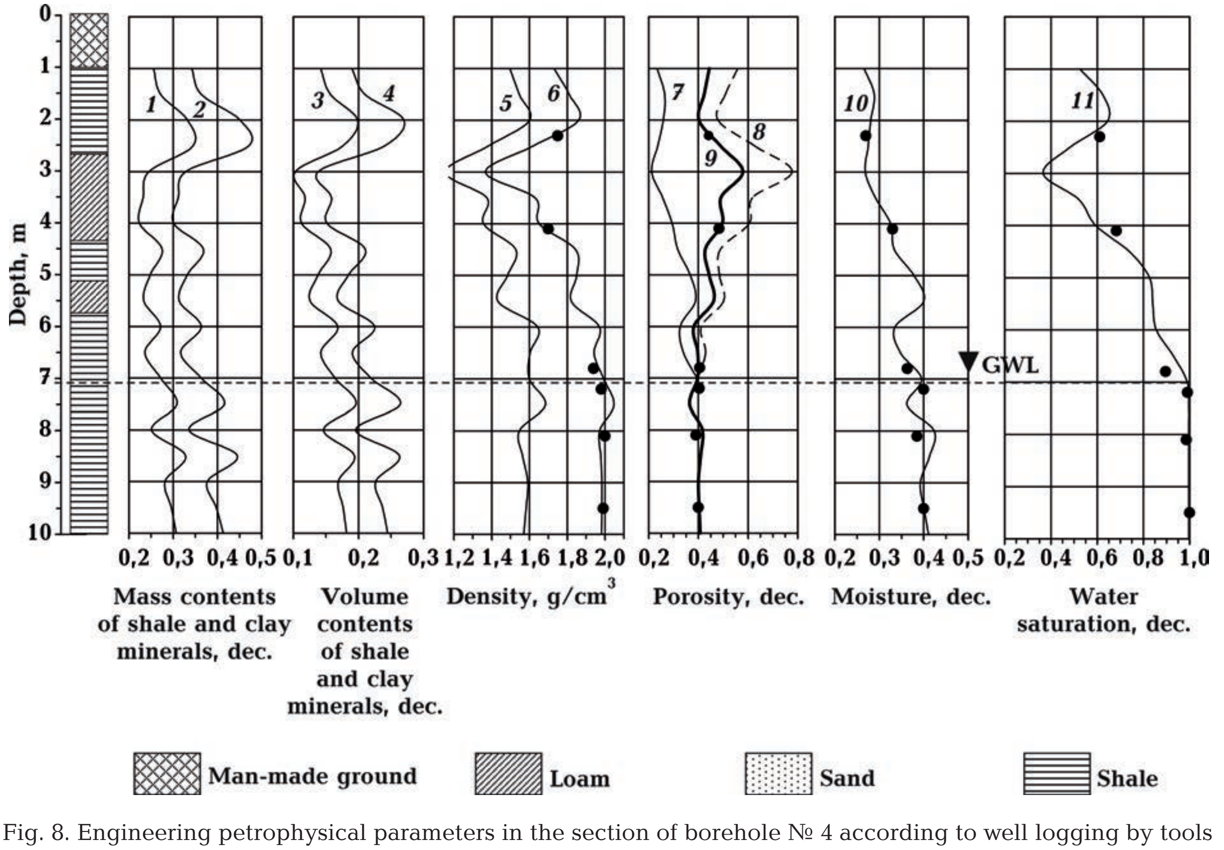

Fig. 8. Engineering petrophysical parameters in the section of borehole № 4 according to well logging by tools DL+GL and 2NL (the territory of the construction of a new dam of the Northern Mining and Concentration Enterprises, Kryvyi Rih). Symbols see in Fig. 5.

– sand (in the intervals of 1.0—2.2 m and 5.7—8.1 m);

– loam (2.2—4.0 m);

– shale (4.0—5.7 m);

– loamy sand (deeper than 8.1 m).

The groundwater level in the borehole № 3 is located at a depth of 5.1 m. The density in the section changes little: it is mainly ~ 2.0—2.1 g/cm^3, a local minimum is determined (up to ~ 1.7 g/cm^3) in the upper part of the section (1.0—2.0 m). The porosity in the borehole № 3 is practically unchanged (~ 35—40 %). The minimum density in the sand in the upper section is associated with a sharp decrease in moisture (up to 15 %) and, accordingly, water saturation (up to 40 %).

The layers in the section of borehole № 4 (Fig. 8) are represented by shale (in the intervals of 1.0—2.7 m, 4.3—5.1 m, deeper than 5.7 m) and loam (2.7—4.3 m, 5.1—5.7 m).

The groundwater level in the borehole № 4 is determined at a depth of 7.1 m. The following layers are identified according to the density: 1.0—2.5 m (density ~1.8 g/cm^3), 2.5—4.5 m (density varies from ~1.8 g/cm^3 to a minimum value ~1.4 g/cm^3) and deeper than 4.5 m (density ~1.9—2.0 g/cm^3). Changes in the density correlate with changes in the porosity. The minimum density at a depth of 3.0 m is associated with a sharp increase in porosity (up to 55 %) and a drastic decrease in water saturation (up to 40 %).

Fig. 5—8 also show the experimental points obtained from the data of laboratory investigations of ground samples along the borehole section. As can be seen from the Figures, the logging results of determining the engineering geophysical parameters agree with the laboratory data.

Conclusions. 1. Metrological and methodical assurance of the radioactive logging complex (GL+DL+NL) for determining the set of engineering geophysical parameters of near-surface rocks at building sites and for the solution of seismic microzonation problem is developed. The assurance is a key component of the modern geophysical technology for investigating grounds, which has been created at the IGPh.

2. Complexation of methods GL, DL, and NL (together with a priori data), using the proposed approaches, allows determining a wide set of engineering geophysical parameters (density, porosity, moisture, groundwater level, content of shale, content of clay minerals, water saturation, etc.).

3. The procedure of determining geophysical engineering parameters used to solve geological engineering problems and for seismic data correlation in seismic microzonation is developed.

4. The features of obtaining the engineering geophysical parameters by the complex GL+DL+NL in the aeration zone and the zone of saturation are shown; approaches to take into account the effect of the shaliness on the determined parameters are proposed.

5. The effectiveness of the proposed approaches is demonstrated on specific examples and confirmed by independent laboratory measurements.

Acknowledgments. The authors are grateful to the officials of «Kyiv institute «Energoproject» H.F. Nesterenko, S.I. Deineko and S.O. Ivaschenko, who, under terms of the Agreement on scientific cooperation between IGPh and «Energoproject», supported the borehole investigations and supplied the results of laboratory measurements of ground parameters.

The authors appreciate to corresponding member of NAS of Ukraine O.V. Kendzera and Cand. Phys.-Math. Sc. D.M. Gryn for the scientific cooperation and useful discussion of a set of the broached questions.

The authors also express gratitude to Z.M. Yevstakhevych, O.V. Dmytrenko, S.I. Diachenko, A.T. Novikov, O.V. Kamilova, A.Yu. Ketov, who participated in the creation and production of new radioactive logging tools, in carrying out experimental modelling work and in the borehole measurements.

References

Alexander, T., Baihly, J., Boyer, C., Clark, B., Waters, G., Jochen, V., Le Calvez, J., Lewis, R., Miller, C.K., Thaeler, J., & Toelle, B.E. (2011). Shale Gas Revolution. *Oilfield Review, 23*(3), 40—55.

Bhuyan, K. & Passey, Q.R. (1994). Clay estimation from GR and neutron-density porosity logs. *Transactions of SPWLA 35th Annual Logging Symposium*. June 19—22, 1994, Tulsa, USA.

Bondarenko, M.S., Dokuka, O.M., Karpenko, A.V. & Kulyk, V.V. (2013). Computer program «Complex interpretation of borehole investigations of near-surface rocks». Ukraine. *Certificate of registration № 52432* (in Ukrainian).

Bondarenko, M. & Kulyk, V. (2015). Method for determining density parameters of sandshale rocks by the radioactive logging complex. *Ukrainian useful model patent № 95931* (in Ukrainian).

Bondarenko, M.S. & Kulyk, V.V. (2016). Method for determining porosity of gas reservoirs by the radioactive logging complex. *Ukrainian useful model patent № 109946* (in Ukrainian).

Bondarenko, M. & Kulyk, V. (2017). Determination of basic gas reservoir parameters from radioactive logging taking into account PT-conditions. *Nafta-Gaz,* (3), 11—17. http://doi.org/10.18668/NG.2017.03.

Bondarenko, M., Kulyk, V., Dmytrenko, O., Danyliv, S., Stasiv. O. & Karmazenko, V. (2021). Physical modelling for density measurement of near-surface rocks, by wireline logging and logging while drilling. *Visnyk of Taras Shevchenko National University of Kyiv: Geology,* (1), 35—41. http://doi.org/10.17721/1728-2713.92.05 (in Ukrainian).

Bondarenko, M., Kulyk, V. & Yevstakhevych, Z. (2018). Petrophysical parameters of near-surface sandshale rocks based on radioactive loggings. *Visnyk of Taras Shevchenko National University of Kyiv: Geology,* (1), 46—52. http://doi.org/10.17721/1728-2713.80.06.

Bondarenko, M.S., Kulyk, V.V. & Yevstakhevych, Z.M. (2019). Geophysical methods for determining the parameters of the ground mass under the projectible and existing structures. *Section of report on departmental project «Development of investigation methods of the seismicity of the Ukraine territory and estimating the parameters of seismic hazard of sites of important and environmentally hazardous objects» № 0118U001918*. Kyiv, Institute of Geophysics of the National Academy of Sciences of Ukraine, 35 p. (in Ukrainian).

Coe, J.T., Brandenberg, S.J., Ahdi, S. & Kordaji, A. (2018). *Geophysical methods for determining the geotechnical engineering properties of earth materials*. Philadelphia: Temple University, 327 p. Retrieved from https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/final-reports/ca17-2111-finalreport-a11y.pdf.

Deineko, S.I. (2007). System monitoring of the state of hazardous geological processes on the territory of operating power facilities (on the example of the Rivne NPP). *Extended abstract of candidate's thesis.* Kyiv, 20 p. (in Ukrainian).

Dobrynin, V.M. (Ed.). (1988). *Interpretation of oil and gas well logging results*. Moscow: Nedra, 476 p. (in Russian).

Dobrynin, V.M., Vendelshteyn, B.Yu. & Kozhevnikov, D.A. (2004). *Petrophysics (rock physics)*. (2nd ed.). Moscow: Oil and gas, 368 p. (in Russian).

Ellis, D.V. & Singer, J.M. (2008). *Well Logging for Earth Scientists*. (2nd ed.). Dordrecht: Springer, 692 p.

Ferronskiy, V.I., Danilin, A.N., Dubinchuk, V.T., Goncharov, V.S. & Seletskiy, Yu.B. (1977). *Radioisotope methods of investigations in engineering geology and hydrogeology* (2nd ed.). Moscow: Atomizdat, 204 p. (in Russian).

Ferronskiy, V.I. & Gryaznov, T.A. (1979). *Penetration logging*. Moscow: Nedra, 335 p. (in Russian).

Golovatskaia, I.V., Gulin, Yu. A., Enikeeva, F.Kh., Velizhanin, V.A., Zhuravlev, B.K., Koziar, V.F., Ruchkin, A.V. & Rezvanov, R.A. (1984). *The determination of reservoir properties and lithology of rocks in section of oil-and-gas boreholes by data of radioactive and acoustic loggings*. Kalinin: Publishing house of VNIGIK, 112 p. (in Russian).

Grounds: the methods of radioisotope measurements of density and moisture. (1990). *USSR State Standard 23061-90*. Moscow: Publishing house of Gosstroy of the USSR (in Russian).

Grounds: the methods of radioisotope measurements of density and moisture. (2010). *Ukraine State Standard B V.2.1-26:2009*. Kyiv: Publishing house of Minrehionbud of the Ukraine (in Ukrainian).

Gulin, Yu.A. (1975). *Gamma-gamma method of investigation of the oil boreholes*. Moscow: Nedra, 160 p. (in Russian).

Gryn, D.M., Verbytskyi, S.T. & Dmytrenko, O.V. (2019). Adaptive seismic complex for engineering geophysics. *Geoinformatika*, (4), 10—19 (in Ukrainian).

Kendzera, O.V., Kulyk, V.V., Gryn, D.M., Bondarenko, M.S., Roman, V.I. & Yevstakhevych, Z.M. (2016). Development of an apparatus and methodological complex for seismic microzonation of sites of important structures. *Report on scientific and technical project № 0116U003999*. Kyiv, Institute of Geophysics of the National Academy of Sciences of Ukraine, 150 p. (in Ukrainian).

Keys, W.S. (1990). *Borehole geophysics applied to ground-water investigations*. (5th ed.). Washington: US government printing office, 165 p. Retrieved from https://pubs.usgs.gov/twri/twri2-e2/pdf/TWRI_2-E2.pdf.

Kulyk, V.V. & Bondarenko, M.S. (2016). Identification of gas reservoirs and determination of their parameters by combination of radioactive logging methods. *Geofizicheskiy Zhurnal, 38*(2), 106—119. https://doi.org/10.24028/gzh.0203-3100.v38i2.2016.107770.

Kulyk, V., Bondarenko, M. & Deineko, S.I. (2015). Method for determining shaliness parameters of rocks by the radioactive logging complex. *Ukrainian patent № 109230* (in Ukrainian).

Kulyk, V., Bondarenko, M. & Dmytrenko, O. (2017a). Parameters of near-surface rocks by combination of radioactive logging in section of key wells for seismic microzoning. *Proceding of XI International Scientific Conference «Monitoring of Geological Processes and Ecological Condition of the Environment»*. October 11—14, 2017, Kyiv. Retrieved from http://earthdoc.org/publication/publicationdetails/?publication=91330.

Kulyk, V., Bondarenko, M. & Dokuka, O.M. (2017b). Method for determining parameters of near-surface rocks in the aeration zone and zone of saturation by the radioactive logging complex. *Ukrainian useful model patent № 114871* (in Ukrainian).

Kulyk, V.V., Bondarenko, M.S., Ketov, A.Yu., Yevstakhevych, Z.M., Deineko, S.I. & Kamilova, O.V. (2012). Fundamental backgrounds of a new technology of investigation of the natural and technogenic grounds with the help of radioisotope logging complex. *Science and Innovation, 8*(6), 26—39. https://doi.org/10.15407/scin8.06.026 (in Ukrainian).

Kulyk, V.V., Bondarenko, M.S., Ketov, A.Yu., Yevstakhevych, Z.M. & Kamilova, O.V. (2013). Creation of a new technology for geophysical investigation of near-surface technogenic and natural rocks. *Report on scientific and technical project № 0113U002462*. Kyiv, Institute of Geophysics of the National Academy of Sciences of Ukraine, 167 p. (in Ukrainian).

Kulyk, V., Yevstakhevych, Z., Bondarenko, M. & Dmytrenko, O. (2017c). Radioactive logging tools for the investigation of near-surface rocks. *Ukrainian useful model patent № 114892* (in Ukrainian).Kurbatskiy, E.N. & Kosaurov, A.P. (2016). On the issue of recalculating seismic intensity points into ground-motion accelerations. *Inzhenernyie izyiskaniya, 14*, 50—60 (in Russian).

Kuznetsov, O.L. & Polyachenko, A.L. (Eds.). (1990). *Borehole nuclear geophysics. Geophysicist's handbook.* (2nd ed.). Moscow: Nedra, 318 p. (in Russian).

Lobankov, V.M. (2016). *Metrological assurance in well logging*. Ufa: Publishing house of Ufa State Petroleum Technological University, 218 p. (in Russian).

Logvinenko, N.V. & Sergeeva, E.I. (1986). *Methods for determining sedimentary rocks*. Leningrad: Nedra, 240 p. (in Russian).

Ogilvi, A.A. (1990). *Fundamentals of Engineering Geophysics*. Moscow: Nedra, 502 p. (in Russian).

Osipov, V.I. (1968). *Determination of the density and moisture content of grounds by scattering of gamma rays and neutrons*. Moscow: Moscow University Press, 158 p. (in Russian).

Roman, V.I., Popkov, V.S., Bohaienko, M.V., Yevstakhevych, Z.M., Dmytrenko, O.V., Gryn, D.M. & Mukoied, N.I. (2018). Method of excitation of seismic waves. *Ukrainian patent № 116423* (in Ukrainian).

Shutenko, L.M., Rud, O.H., Kichaieva, O.V. Samorodov, O.V. & Havryliuk, O.V. (2017). *Soil mechanics, footings and foundations*. Kharkiv: Publishing house of O.M. Beketov National University of Urban Economy of Kharkiv, 563 p. (in Ukrainian).

Surface and borehole radioisotope density meter PPGR-1. (1986). *The technical specifications and operation manual.* Poltava, 60 p. (in Russian).

Surface and borehole radioisotope moisture meter VPGR-1. (1982). *The technical specifications and operation manual.* Poltava, 43 p. (in Russian).

Trifonov, B.A., Sevostyanov, V.V., Milanovskiy, S. Yu. & Nesyinov, V.V. (2019). Estimation of the seismic properties of water-filled dispersed grounds when solving problems of seismic microzonation. *Geoecology, engineering geology, hydrogeology, geocryology, 5*, 74—81. https://doi.org/10.31857/S0869-78092019574-81 (in Russian).

Zvolskiy, S.T. (1980). *Gamma methods for measuring the volume mass of dispersed grounds and bottom sediments.* Moscow: Atomizdat. 112 p. (in Russian).

Zvolskyi, S.T., Ketov, A.Yu., Kulyk, V.V., Bondarenko, M.S., Deineko, S.I., Ivashchenko, S.O., Kamilova, O.V. & Yevstakhevych Z.M. (2010). Borehole nuclear geophysical investigations of near-surface rocks 1. *Geofizicheskiy Zhurnal, 32*(6), 215—230. https://doi.org/10.24028/gzh.0203-3100.v32i6.2010.117465 (in Ukrainian).

Визначення інженерно-геофізичних параметрів ґрунтів на будівельних майданчиках і для сейсмічного мікрорайонування (методична і метрологічна складові технології)

М.С. Бондаренко, В.В. Кулик, 2022

Інститут геофізики ім. С.І. Субботіна НАН України, Київ, Україна

Для забезпечення надійної та довгострокової служби висотних житлових будинків, важливих промислових, інфраструктурних та інших об'єктів необхідні інженерно-геологічні дослідження ґрунтів (приповерхневих гірських порід) як основи споруд. Для запобігання потенційній небезпеці руйнації вказаних об'єктів потрібно також проводити мікросейсмічні дослідження приповерхневого геологічного середовища, узгодивши отримані результати з інженерно-геологічними параметрами в розрізі опорних свердловин. Інженерно-геологічні параметри, визначені за допомогою геофізичних методів, називають інженерно-геофізичними параметрами.

В Інституті геофізики НАН України для розв'язання інженерно-геофізичних задач, у тому числі сейсмічного мікрорайонування, створено сучасну технологію дослідження ґрунтів на основі апаратурно-методичного комплексу радіоактивного каротажу у складі гамма-каротажу (ГК), гамма-гамма каротажу (ГГК) і нейтрон-нейтронного каротажу (ННК). У статті наведено результати розробки адекватного методичного і метрологічного забезпечення комплексу РК як ключової складової технології.

Комплексування ГК, ГГК і ННК (з урахуванням апріорних даних) і використання запропонованих підходів дає можливість визначати широкий набір інженерно-геофізичних параметрів: густину, пористість, вологість, рівень ґрунтових вод, вміст глини, вміст глинистих мінералів, коефіцієнт водонасиченості, густину сухої породи та ін. Показано особливості отримання параметрів за комплексом радіоактивного каротажу в зоні аерації та в зоні повного водонасичення з урахуванням впливу на визначувані параметри глинистого компонента. Ефективність технології продемонстрована на конкретних прикладах і підтверджена незалежними лабораторними вимірюваннями.

Ключові слова: ґрунти (приповерхневі гірські породи), зона аерації; зона повного водонасичення, рівень ґрунтових вод, комплекс гамма-каротажу, гамма-гамма-каротажу і нейтрон-нейтронного каротажу, методичне і метрологічне забезпечення, інженерно-геофізичні параметри, сейсмічне мікрорайонування, геофізична технологія.