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Geophysical technology for determining the ground parameters (methods and apparatus)

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At the Institute of Geophysics of the National Academy of Sciences of Ukraine a modern technology for ground investigation has been created for solution of the engineering geological problems, including seismic microzonation. Technology is based on the methods and apparatus of radioactive logging (RL), which involves neutron-neutron logging (NNL), gamma-gamma density logging (DL) and gamma-ray logging (GR).

The paper presents the results of the development of radioactive logging apparatus as an integral part of the new technology. Set of prototype dual-channel tools, namely 2NNL (dual-spacing NNL) and DL+GR, prototype three-component tool 2NNL+DL+GR, surface control and registration console were developed and produced on the basis of the modern elemental base.

The 2NNL tool makes it possible to determine neutron porosity in two ways: single-sonde method and compensation method. Compensation neutron logging, in particular, aims to determine the porosity in the presence of anomalous neutron absorbers in the rock, and also, in combination with the single-sonde method, to estimate the content of anomalous absorbers.

GR-channel of the DL+GR tool was equipped the same gamma-ray detector as the DL-channel. Here, the GR-detector performs a dual function: 1) integral registration of natural gamma-ray of ground, 2) account of natural background in the total readings of the DL-detector.

The three-component radioactive logging tool combines three RL-methods and includes all the advantages of dual-channel tools. The obtaining a results in one trip by this tool is particularly important for relatively deep boreholes.

According to the experimental results, the optimal intervals between sources and detectors of radiation in the created combined RL tools were established. The importance of adjustment and controlling the signals of sensors of the RL tools is shown; the new console allows to perform these procedures operational.

The created apparatus increases the productivity and efficiency of logging operations by reducing the number of trips, digital recording, storage and transmission of information, and by using of a computer programs for processing and interpreting the results of borehole measurements. The effectiveness of the developed apparatus, together with the appropriate metrological and interpretation-methodical support, has been demonstrated on specific examples of borehole investigations and confirmed by independent laboratory data.

The technology allows to determine the following engineering geophysical parameters: total density, dry ground density, content of shale, porosity, volume moisture, water saturation factor, groundwater level, etc.

Key words: ground, complex of neutron-neutron logging, gamma-gamma density logging and gamma-ray logging, apparatus, engineering geophysical parameter, geophysical technology.

Introduction. At the Institute of Geophysics of the National Academy of Sciences of Ukraine (IGPh), new geophysical technology for the investigation of grounds (near-surface rocks) to solve engineering geological problems, including seismic microzonation, was created.

By geophysical technology, we mean a set of methods, apparatus, equipment, metrological and interpretation-methodical support, algorithms, and software.

The technology includes the following components:

– a complex of radioactive methods of logging (RL), combining neutron-neutron logging (NNL), gamma-gamma density logging (DL), and gamma-ray logging (GR);

– technical means of making a dry cased borehole and other equipment [Zvolskiy, 1980];

– modern apparatus for borehole measurements [Ketov et al., 2009; Yevstakhevych et al., 2012; Kulyk et al., 2012, 2013c, 2017b];

– facilities and methods for the metrological support of logging apparatus [Zvolskyi et al., 2008; Bondarenko et al., 2021; Bondarenko, Kulyk, 2022];

– theoretical basis, novel methodical approaches, and ways for the complex determination of an extended set of engineering geophysical parameters with the help of radioactive logging [Kulyk et al., 2013a, b; 2015, 2017a; Kulyk, Bondarenko, 2014, 2019; Bondarenko, Kulyk, 2015, 2016, 2019, 2022];

– software to process and interpret logging data [Bondarenko et al., 2013].

Grounds are the near-surface rocks that are the object of construction engineering activities [Pyankov, Azizov, 2008]. Our geophysical technology allows determining the following parameters: total density, dry ground density, shale content, clay minerals content, porosity, volume moisture, water saturation factor, groundwater level, etc.

The effectiveness of the NNL+DL+GR complex has been time-tested by practice for many years. It was widely used to solve engineering geological problems in the Soviet times [Ferronskyi, Gryaznov, 1979; Zvolskiy, 1980; Grounds…, 1990; Kuznetsov, Polyachenko, 1990; Ogilvi, 1990]. Certain traditions have been kept in Ukraine in the post-Soviet period, too [Deineko, 2007; Grounds…, 2010; Zvolskyi et al., 2010]. However, the scope of works has been significantly reduced, the apparatus in use has grown obsolete, and the metrological and interpretation-methodical support needs to be updated and improved.

In other countries, the near-surface geology problems (engineering geology, hydrogeology, ecology, etc.), are mainly tackled by non-radioactive geophysical methods (e. g., seismic, electrical, magnetic, etc.) [Steeples, 2005; Everett, 2013; Persico et al., 2019; Bisvas, Sharma, 2020]. Even in highly specialized journals (such as *Near Surface Geophysics*), the papers on radioactive methods of grounds research are very rare. This is largely due to the tendency to avoid using radiation sources [Badruzzaman, 2020; Radioactive…, 2021].

The technology, created at IGPh, is based on low-strength sources of gamma-rays (^{137}Cs) and neutrons (^{238}PuBe), subject to strict observance of radiation safety standards and rules.

It will be noted that we also use the RL apparatus for near-surface investigations and the corresponding interpretation-methodical support to develop the apparatus and methodology for radioactive logging to determine the petrophysical parameters of rocks in sections of oil and gas boreholes. Also, we use the grounds as natural physical models of oil-gas-water-saturated reservoirs [Kulyk, Bondarenko, 2016].

This paper presents the results of developing novel radioactive logging (RL) apparatus as an integral part of the created technology of grounds investigation. The technology is a unique advanced development that serves to solve topical production problems. The paper continues a series of publications [Bondarenko et al., 2018; Bondarenko, Kulyk, 2022].

Stock-produced RL-apparatus and its disadvantages. The radioactive logging apparatus consists of a borehole tool and a surface control and registration console, connected by a wire line [Kuznetsov, Polyachenko, 1990]. The sensor and the electronic unit are the main elements of the logging tool.

The source of fast neutrons and the slow-neutron detector serve as the sensor of the NNL tool. The distance between the centers of the neutron source and detector is called sonde spacing. The sensor of the DL tool consists of a gamma-ray source and a gamma-ray detector which includes a scintillation crystal and a photomultiplier (PhMP). The interval between the centers of the gamma-ray source and the crystal is sonde spacing. The gamma-ray detector (a crystal and a PhMP) serves as the sensor of the GR tool.

Set of single-spacing tools VPGR-1 and PPGR-1. The stock-produced set of RL tools, developed as far back as the 1980s, is still used in Ukraine to study near-surface rocks [Deineko, 2007; Zvolskyi et al., 2010]. The set includes the single-spacing neutron-neutron moisture meter VPGR-1 [Surface…, 1982] and single-spacing gamma-gamma density meter PPGR-1 [Surface…, 1986].

The sensor of the VPGR-1 tool has a «zero» length of the NNL-sonde (when logging, the neutron source is located in the middle of the neutron counter). The tool includes a plutonium-beryllium (^{238}PuBe) neutron source with a strength of up to $5{\cdot}10^4$ neutrons per second and a ^{3}He-counter SNM-17.

The sensor of the PPGR-1 tool with DL sonde spacing of 30 cm has a gamma-ray source with ^{137}Cs ($E_0 = 0.66$ MeV) with an activity of up to $1.2{\cdot}10^7$ Bq and a NaI(Tl) crystal together with PhMP. The PPGR-1 tool without a gamma-ray source is also used for gamma-ray logging; at the same time, the GR data serve to take into account the contribution of natural gamma-radiation of rocks as a background in the readings of the DL detector.

Measurements are performed in a dry cased borehole up to ~30 m deep, made by the shock-and-vibration technique [Zvolskiy, 1980] using steel casing pipe with outer diameter of 51 mm and wall thickness of 5.5 mm. Logging is performed discretely when hoisting the RL tools, mainly every 0.5 m with 10 s exposure and three readings for each point. This technique of logging was selected due to the use of low-strength sources of neutrons and gamma-rays.

The first disadvantage of combining the VPGR-1 and PPGR-1 tools is the need to perform tripping operations three times (separate registration of NNL, DL, GR). This significantly reduces productivity and efficiency for boreholes deeper than 10—15 m.

The second disadvantage (a design flaw affecting both the physical essence of the methods and the determined parameters) is the lack of operational control over the level of discrimination of gamma-ray and neutron detectors. The discriminators of the VPGR-1 — PPGR-1 tools are «packed» in the borehole sonde and not available for operational control and correction if necessary.

The third disadvantage is the total deterioration of apparatus, outdated element base and the registration method (manual recording of the readings).

A distinct disadvantage of the VPGR-1 tool, which can lead to significant errors in determining porosity and moisture, is the uncontrolled effect of anomalous and strong absorbers of thermal neutrons (Li, B, Cl, K, Fe, rare-earth and other elements) on the detector readings [Kulyk et al., 2013b, 2017b]. These elements may be present in the investigated section, especially in technogenic grounds.

Combined RL tools. The combined tools, so-called density-and-moisture meters, are used to perform neutron and density logging in a single trip [Grounds..., 1990]. The sensor of a density-and-moisture meter contains both a neutron source and a source of gamma-rays and the corresponding detectors. The disadvantages of these tools are the absence of a GR sensor and the effect of neutron capture gamma-ray on the readings of the detector of density logging due to the small distance between this detector and the neutron source.

A complete complex of NNL+DL+GR methods is used in the multichannel apparatus of penetration logging MAK-5P [Ferronskiy, Gryaznov, 1979; Ferronskiy, 2015]. A design feature of the RL tool of this apparatus is the placement of the PuBe neutron source and ^{137}Cs gamma-ray source in the same chamber. Here the NNL is performed according to the «zero» sonde spacing scheme, the DL is performed with a sonde spacing of

40 cm, and the GR sensor is located 1 m from the source chamber.

The RL tool of MAK-5P has the following disadvantages.

1. Because of the gamma-rays originating during the radiation capture of thermal neutrons and other processes, the neutron source has a significant effect on the readings of the DL detector, since they are only 40 cm apart. This introduces systematic error, as the density becomes significantly underestimated.

2. The sensor of the gamma-ray logging is located too far (1 m) from the neutron source and the gamma-ray source, adding to the overall length of the tool.

3. Single-spacing neutron logging to determine porosity and moisture content leads to a systematic error in the presence of anomalous and strong absorbers of thermal neutrons in the borehole section.

Statement of the RL apparatus problem. Experiments and direct practical experience show that the serial radioactive logging apparatus needs modernization. Moreover, the task is to create a new RL apparatus to investigate natural and technogenic grounds.

The tool must be based on the current level of scientific developments, have a modern elemental base and the appropriate quality of recording, storage and transmission of data. Such apparatus is a necessary component of novel technology to determine engineering geophysical and other ground parameters. It must increase the efficiency and accuracy of measurements, depth interval of the boreholes, and labour productivity, and expand the range of the recorded parameters.

To implement the created technology, we developed, made, and tested prototypes of a new RL apparatus (borehole tools and surface console): a set of dual-channel tools, namely DL+GR and dual-spacing 2NNL, a three-component tool 2NNL+DL+GR, and a universal control and registration console.

Placement of sources and detectors in combined RL tools. The general requirements to the placement of neutron and gamma-ray sources and the NNL, DL, and GR detectors in the RL combined tool are:

– the grouping of the sondes must exclude their mutual influence;

– the spacing of the NNL and DL sondes must ensure the statistical accuracy of measurements and the required depth of investigation;

– sondes must be placed in a way to minimize the total length of the tool.

The last requirement arises from the need to obtain data over as large part of a section as possible when one performs complex logging, especially for shallow boreholes.

The intervals between sources and detectors of radiation in the RL tools were found experimentally. In the physical model, the ground was represented by water-saturated sand. The model parameters were as follows: ~ 40 % porosity, 90 cm diameter, 85 cm height; the borehole was simulated by a steel pipe with a diameter of 51 mm and a wall thickness of 5.5 mm. ^{238}PuBe neutron source with a strength of $4.1 \cdot 10^4$ neutrons/s and ^{137}Cs gamma-ray source with an activity of $6.6 \cdot 10^6$ Bq were used.

Measurement results are shown in Fig. 1 showing the dependences of the readings of gamma-ray detector (counts per second, cps) on the distances to:

– gamma-ray source (*1*), that is, the dependence of DL readings on the sonde spacing;

– neutron source (*2*), that is, the dependence of neutron-gamma logging (NGL) readings on the sonde spacing;

– both the gamma-ray and neutron sources

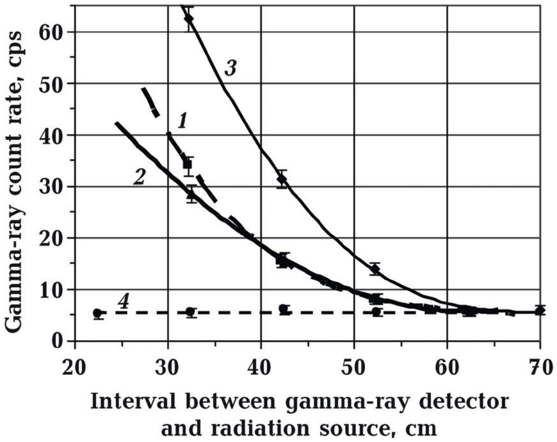

Fig. 1. Readings of the gamma-ray detector vs distance to: *1* — gamma-ray source, *2* — neutron source, *3* — gamma-ray and neutron sources together, *4* — empty source chamber (gamma background).

together (*3*), that is, the dependence of the sum readings of DL+NGL on the sonde spacing.

Also in Fig. 1 is shown the background level of the gamma-ray (*4*).

As follows from Fig. 1, spatial closeness of the neutron and gamma-ray sources leads to a significant increase in the readings of the DL detector (curves *3* and *1*) due to neutron capture gamma-ray and, consequently, to a significant underestimate of the density of the investigated ground. In order for the neutron source (of such strength) to not affect the DL detector, they should be over 60 cm apart.

Fig. 1 also shows that to prevent the influence of the gamma-ray source on the GR detector, the distance between them also must exceed 60 cm. The same holds for the interval between the neutron source and the GR detector.

These values should be adjusted for grounds of different porosity and for the aeration zone (see Fig. 3).

Note that the gamma-ray source, like the natural background gamma-ray, practically does not affect the readings of the ^{3}He-counter of neutrons.

Set of dual-channel radioactive logging tools. Dual-channel tools 2NNL and DL+GR [Kulyk et al., 2017b] were developed based on stock-produced tools (VPGR-1 and PPGR-1). The design of the basic sondes was left unchanged so that both the traditional approach and the new technology could be used at the transitional stage. A photo of the prototypes of dual-channel tools is shown in Fig. 2.

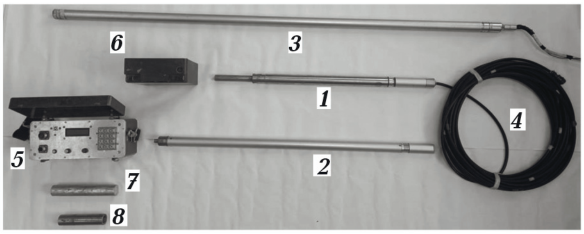

Fig. 2. Prototypes of new radioactive logging tools and support equipment: *1* — 2NNL tool, *2* — DL+GR tool, *3* — TRL tool, *4* — logging cable, *5* — surface console, *6* — accumulator, *7* — chamber of γ-ray source, *8* — chamber of neutron source.

Dual-channel (dual-spacing) tool 2NNL. The 2NNL tool was developed on the basis of the stock-produced tool VPGR-1, to which is added a far-spacing sonde with the same neutron counter as the near-spacing sonde. The counters are located at a minimum interval one by one (see Fig. 3, *a*).

The addition of the second sonde to the neutron logging tool makes it possible to determine neutron porosity in two ways: the single-sonde method and the compensation method (by a ratio of the readings of two sondes). Compensation neutron logging (CNL) [Kuznetsov, Polyachenko, 1990], in particular, aims to determine the porosity in the presence of anomalous neutron absorbers in the rock and, in combination with the single-sonde method, to estimate the content of anomalous absorbers [Zvolskiy et al., 2003, 2007; Ketov et al., 2009].

Dual-channel tool DL+GR. The DL+GR tool was developed based on the tool PPGR-1, to which is added a GR channel with the same gamma-ray detector (NaI(Tl) crystal+PhMP) as the DL channel (Fig. 3, *b*). The interval between the gamma-ray source and the crystal of GR detector, chosen on the basis of the study, is 75 cm.

The addition of the GR channel to the DL tool makes it possible to increase productivity, namely to reduce the number of trip operations when performing the RL measurement complex (from three to two). At the same time, the GR detector performs a dual function: 1) integral registration of natural gamma-ray of the ground, 2) correction for natural background in the total readings of the DL-detector.

Three-component tool 2NNL+DL+GR. The three-component radioactive logging tool (TRL tool) combines three RL methods: neutron-neutron logging (a dual-spacing version), density logging, and gamma-ray logging [Kulyk et al., 2012, 2013c], and includes all the advantages of the dual-channel tools.

This multisonde RL tool can be implemented in several ways [Kulyk et al., 2013c] meeting the requirements for the relative position of radiation sources and detectors. The scheme of the variant selected for implemen-

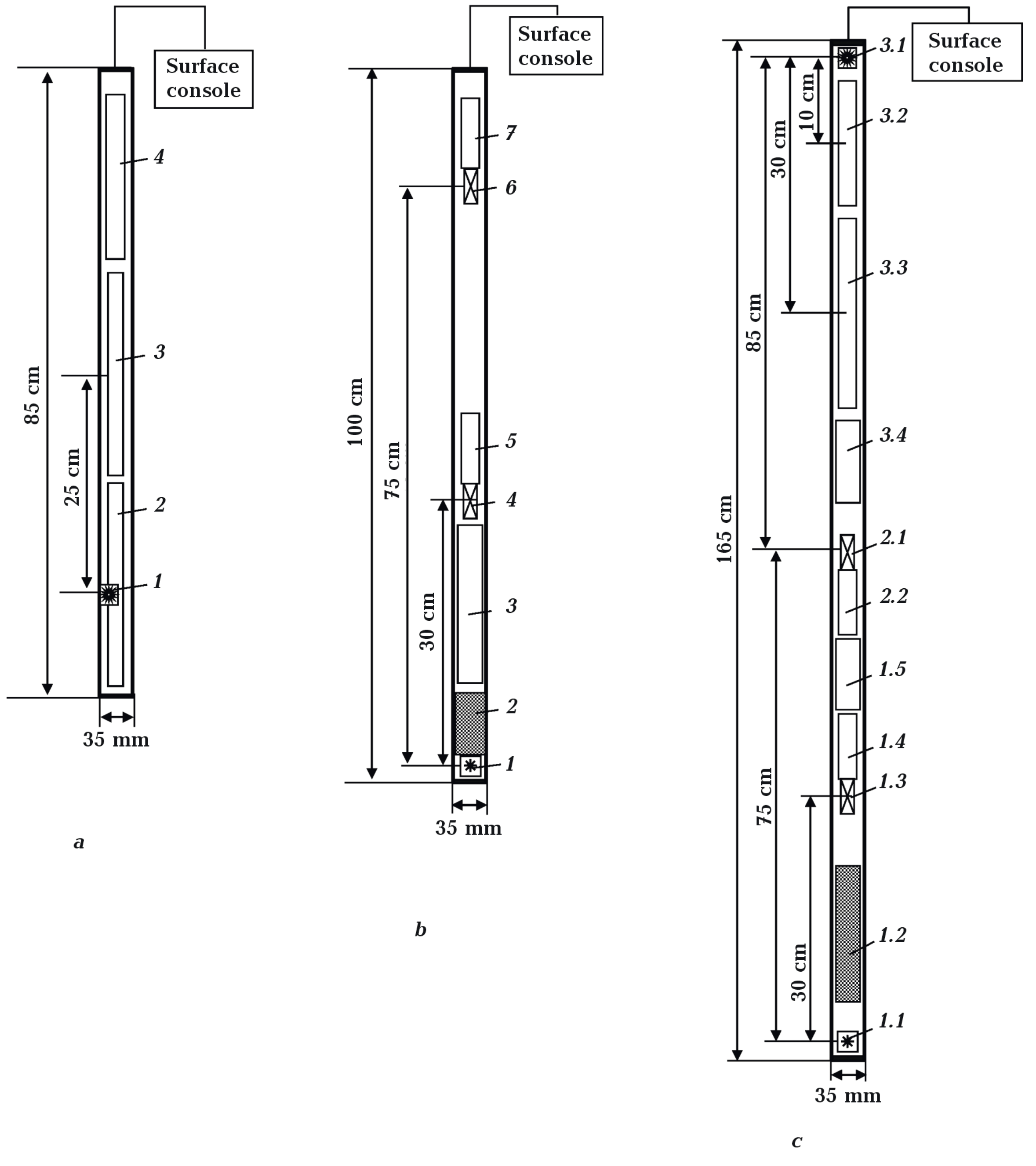

Fig. 3. Schemes of prototypes of RL-tools: *a* — 2NNL tool (*1* — neutron source, *2*, *3* — near and far neutron counters SNM-17, *4* — electronic unit); *b* — DL+GR tool (*1* — gamma-ray source, *2* — lead shield, *3* — electronic unit, *4*, *5* — crystal NaI and PhMP of DL-channel, *6*, *7* — crystal NaI and PhMP of GR-channel); *c* — TRL tool (*1.1* — gamma-ray source, *1.2* — lead shield, *1.3*, *1.4* — crystal NaI and PhMP of DL-sonde, *1.5* — electronic unit of DL and GR, *2.1*, *2.2* — crystal NaI and PhMP of GR-sonde, *3.1* — neutron source, *3.2* — near neutron counter SNM-16, *3.3* — far neutron counter SNM-17, *3.4* — electronic unit of NNL).

tation [Bondarenko et al., 2023] is presented in Fig. 3, *c*. Its particular features are:

– the neutron component of the tool contains two sondes equipped with ^{3}He-detectors of slow neutrons: the near detector SNM-16 is located at the minimum distance from the source, and the far detector SNM-17 is at the minimum distance from the near detector;

– the order of the principal tool components (bottom to top when the instrument is placed in the borehole): gamma-ray source, DL detector, GR detector, far NNL detector, near NNL detector, neutron source.

A photo of a prototype of the TRL tool is shown in Fig. 2.

The main advantage of the TRL tool is getting results in one trip, which is important for relatively deep boreholes. The tool increases the informativeness and accuracy of research, productivity, and efficiency of the logging. At the same time, the disadvantages of the TRL tool are the increased length and the need to bring into coherence the readings relative to each recording point in the borehole section.

Control and registration console. The set of 2NNL and DL+GR tools and the TRL tool are equipped with a new surface control and registration console [Yevstakhevych et al., 2012; Kulyk et al., 2017b]. The main differences between the new console and serial analog are the following:

– the discriminator of pulses is moved from the electronic unit of the logging tool to the surface console; this allows, if necessary, quickly adjusting and monitoring the sensor signals using an oscillograph in the laboratory;

– for registration and processing of informative pulses, a modern microprocessor is used, located in the console;

– the console is equipped with flash memory for storing, reproducing, and transmitting information to a laptop for immediate interpretation of measurements (directly at the research site).

The control and registration console of the new apparatus is developed and produced on the basis of modern electronic components. A photo of the console is shown in Fig. 2. The block scheme in Fig. 4 shows the relationship of the main components of the surface console.

Discrimination levels. A necessary element of the methodical support of radioactive logging apparatus is the adjustability of the registering system of informative pulses. The key step in the adjustment is the choice of the discrimination level.

In the developed tools, the gamma-ray detectors consist of a NaI(Tl) crystal and PhMP, whereas the ^{3}He-counters are used as neutron detectors. The procedure of adjustment includes the following main steps:

– adjusting the operating range of supply voltage of the detector according to the technical certificate; this provides the best agreement between the count rate and the number of gamma-photons or neutrons entering the corresponding detector and also ensures independence of the count rate from voltage changes;

– ascertaining the self-noise amplitude of each specific detector is performed in the absence of radiation sources and background;

– for gamma-ray detectors, the setting of an agreement between the amplitude of pulses (volts) and the energy of gamma-photons (E_γ, electron-volts); adjusting the discrimination level to eliminate noise and to register Compton gamma-rays with energy above ~ 150 keV;

– for neutron detectors, additional adjustment of the discrimination level up to approximately triple the noise amplitude.

Fig. 5 shows the results of measurements for full-scale physical models of rocks at different discrimination levels:

– dependencies of readings of DL (I_{DL}, cps) on the ground density (Fig. 5, *a*);

– dependencies of near detector readings of the 2NNL-tool (I_{NNL}, cps) on the water-saturated porosity of the rock (Fig. 5, *b*).

Fig. 5 demonstrates the importance of controlling and regulating the discrimination level:

1) highest sensitivity to ground density is provided by relatively low levels of discrimination for the DL tool (the better level for the

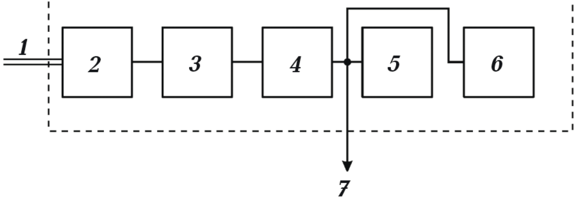

Fig. 4. Block scheme of console: *1* — connection of logging cable with console, *2* — amplifier, *3* — discriminator, *4* — microprocessor, *5* — flash memory, *6* — numeric display, *7* — output to computer.

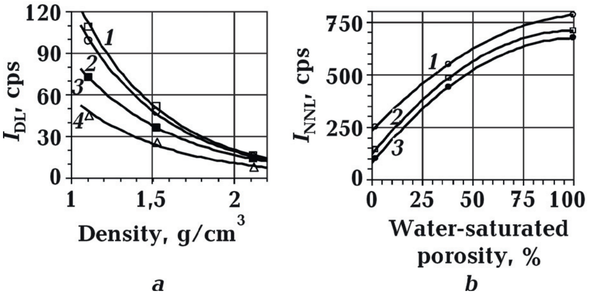

Fig. 5. Dependencies of readings on discrimination level (millivolt): *a* — for DL-channel (*1* — 100, *2* — 300, *3* — 400, *4* — 500); *b* — for near detector of 2NNL-tool (*1* — 35, *2* — 55, *3* — 70).

developed tools is ~ 100 mV; it is equivalent to E_γ~ 150 keV);

2) sensitivity of the neutron detector readings to the hydrogen content almost does not depend on the discrimination level;

3) count rate of neutrons and gamma photons decreases significantly with increasing discrimination level.

Examples of using the new apparatus. The created RL apparatus was tested by solving practical problems on real geological objects in partnership with Kyiv Institute «Energoproject». Fig. 6—8 show examples of its operation [Bondarenko, Kulyk, 2022].

Based on the logging results, the following parameters were determined: 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 NNL+GR (*7*) and porosity by method DL (*8*); true porosity according to the RL complex (*9*); volume moisture (*10*); water saturation factor (*11*).

The investigated near-surface sections in all cases included an aeration zone and a zone of water saturation, and the boundaries between them corresponded to the groundwater levels. It should be noted that neutron porosity (7) and density porosity (8) are apparent

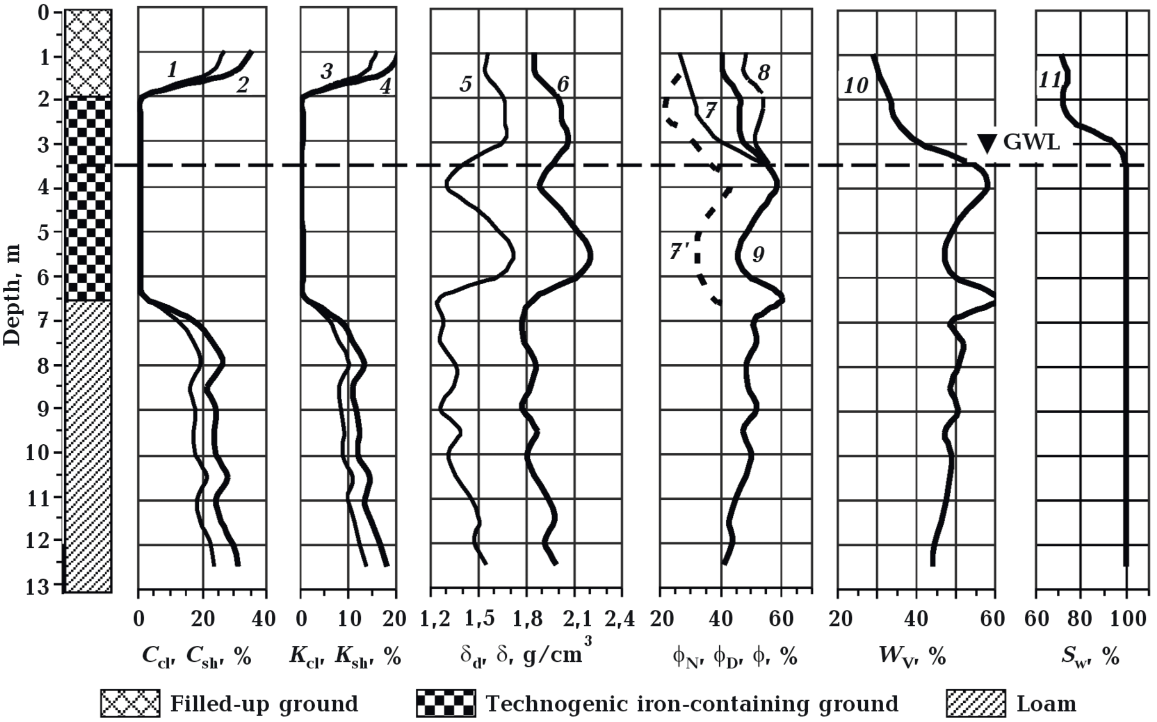

Fig. 6. Engineering geophysical parameters on the tailing dump of Northern mining and processing plant, borehole № 3016: *1* — mass content of clay minerals (C_{cl}), *2* — mass content of shale (C_{sh}), *3* — volume content of clay minerals (K_{cl}), *4* — volume content of shale(K_{sh}), *5* — dry ground density (δ_d), *6* — total density (δ), *7* — porosity by methods 2NNL+GR (ϕ_N) with the help of dual-spacing neutron tool (*7′* — porosity by methods 1NNL+GR with the help of small neutron sonde), *8* — density porosity (ϕ_D), *9* — true porosity (ϕ), *10* — volume moisture (W_V), *11* — water saturation factor (S_w), GWL — groundwater level.

ones in the aeration zone; true porosity is determined by their averaging [Bondarenko, Kulyk, 2022].

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

Tailing dump of the Northern mining and processing plant. Fig. 6 shows an example of using the set of dual-channel tools 2NNL and DL+GR for investigating the tailing dump of the Northern mining and processing plant. The presence of technogenic ground is a feature of the investigated section of borehole № 3016. This ground contains iron up to ~ 20 wt% [Hubina et al., 2009]. Iron is a strong absorber of thermal neutrons, and this creates a need for using a dual-spacing 2NNL tool in the RL complex. The near-to-far count rate ratio of this tool (compensation neutron logging, CNL) practically does not depend on the presence of iron; it is used to determine the neutron porosity and moisture.

In borehole № 3016 (see Fig. 6), the following layers were identified:

– filled-up ground (to a depth of 2.0 m);

– technogenic ground (2.0—6.5 m) with total density ~ 1.9—2.1 g/cm^3;

– loam (below 6.5 m)with total density ~ 1.8—1.9 g/cm^3.

The technogenic iron-containing ground is identified by the lowest GR readings (see Fig. 6) since it contains almost no radioactive elements and has increased total density. The groundwater level in borehole № 3016 is located at a depth of 3.5 m. The density of ground layers correlates with porosity and moisture content.

Porosity (taking into account the content of clay minerals according to GR-data) was determined by the 2NNL tool in two ways: by the ratio of the readings of two sondes (curve *7*) and according to the readings of the small sonde (curve *7*′). The single-spacing method in the iron-containing ground significantly

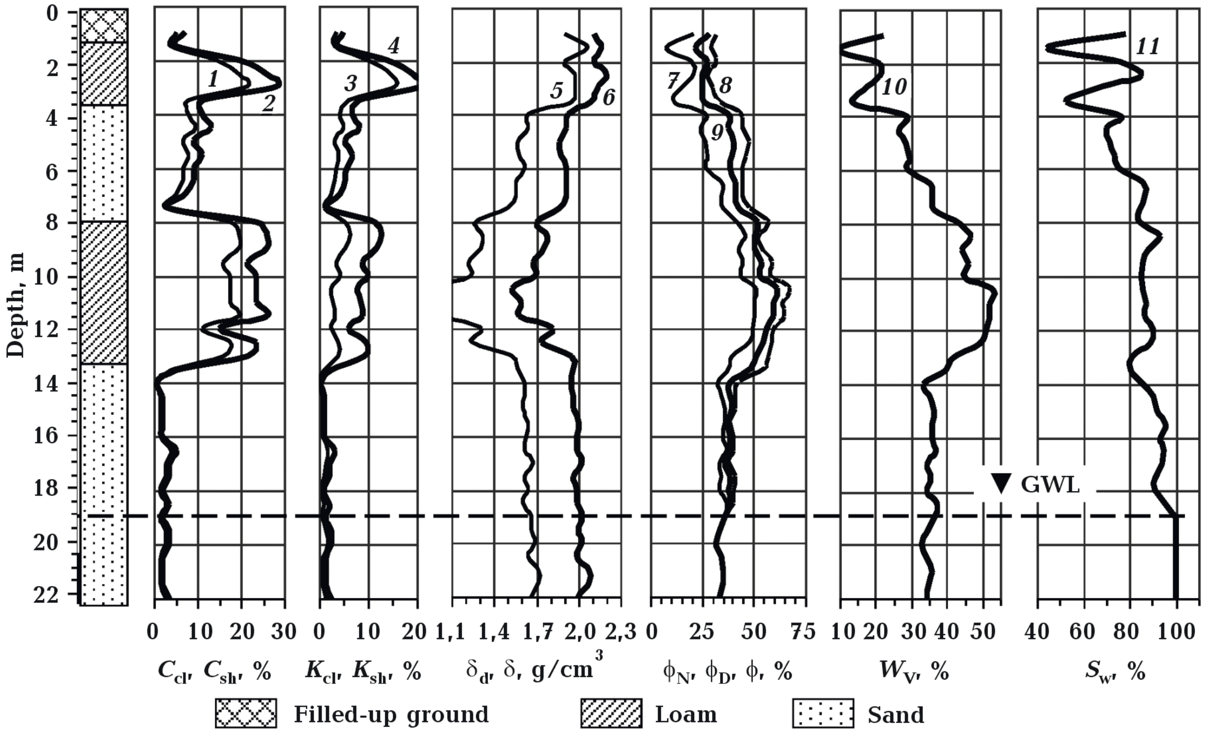

Fig. 7. Engineering geophysical parameters on the dam of Kyiv water-storage reservoir, borehole № 33: *1* — mass content of clay minerals (C_{cl}), *2* — mass content of shale (C_{sh}), *3* — volume content of clay minerals (K_{cl}), *4* — volume content of shale(K_{sh}), *5* — density of dry ground (δ_d), *6* — total density (δ), *7* — porosity by methods NNL+GR (ϕ_N), *8* — density porosity (ϕ_D), *9* — true porosity (ϕ), *10* — volume moisture (W_V), *11* — water saturation factor (S_w), GWL — groundwater level.

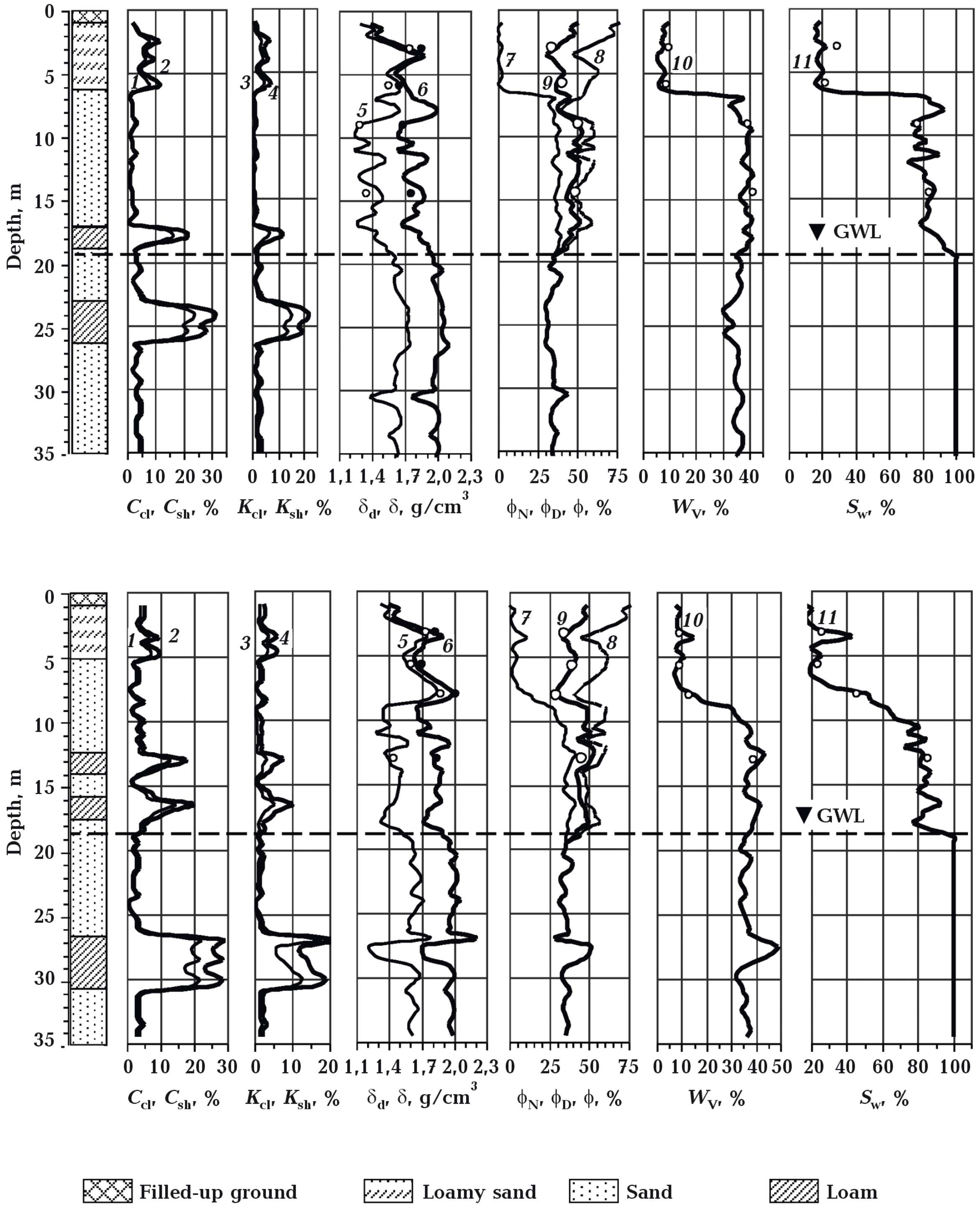

Fig. 8. Engineering geophysical parameters on the dam of Kakhovka water-storage reservoir: *a* — borehole № 28, *b* — borehole № 30, *1* — mass content of clay minerals (C_{cl}), *2* — mass content of shale (C_{sh}), *3* — volume content of clay minerals (K_{cl}), *4* — volume content of shale(K_{sh}), *5* — density of dry ground (δ_d), *6* — total density (δ), *7* — porosity by methods NNL+GR (ϕ_N), *8* — density porosity (ϕ_D), *9* — true porosity (ϕ), *10* — volume moisture (W_V), *11* — water saturation factor (S_w), GWL — groundwater level, ○, ● — laboratory data.

(up to ~ 15 %) underestimates the neutron porosity compared with the CNL method.

Dam of Kyiv water-storage reservoir. Fig. 7 shows an example of using the three-component TRL tool while investigating the dam of the Kyiv water-storage reservoir.

Borehole depth here reached 22 m; therefore, implementing the RL complex in one-trip operation significantly reduced the total measurement time.

The investigated section of borehole № 33 in Fig. 7 was represented by sandshale grounds. Here loam (1.0—3.5 m; 7.8—13.4 m) and sand (3.5—7.8 m; deeper than 13.4 m) were identified. The groundwater level lied at a depth of 19.0 m. The total density of grounds in the borehole section varied from 1.6 to 2.2 g/cm^3 and correlated with porosity and lithology.

Dam of Kakhovka water-storage reservoir. Fig. 8 demonstrates the results of testing the TRL tool while investigating the dam of the Kakhovka water-storage reservoir. Here, the depth of the boreholes № 28 and 30 was 35 m. Increasing labor productivity for boreholes of such depth is especially important, particularly by performing the RL complex in one trip.

In the borehole № 28 (Fig. 8, *a*), loamy sand (1.0—6.3 m), sand (6.3—17.0 m; 18.7—22.6 m; deeper than 26.1 m), and loam (17.0—18.7 m; 22.6—26.1 m) were identified. The groundwater level was located at 19.2 m. The total density (1.5—2.1 g/cm^3) correlated with porosity.

Section of borehole № 30 (Fig. 8, *b*) was similar to the previous one. There were loamy sand (1.0—5.0 m), sand (5.0—12.1 m; 14.0—15.8 m; 17.2—26.2 m; deeper than 30.3 m) and loam (12.1—14.0 m; 15.8—17.2 m; 26.2—30.3 m) in this borehole section. The groundwater level was determined at 18.8 m. The total density (1.5—2.1 g/cm^3) correlated with porosity.

In Fig. 8, experimental points are shown, obtained from the data of laboratory investigations of ground samples along the borehole sections. The logging results agree with the laboratory measurements.

Conclusions. 1. The combined apparatus for investigating near-surface rocks was developed and produced based on a modern element base. The apparatus performs a complex of radioactive logging methods and is an integral part of the geophysical technology for solving engineering geological problems.

2. The new apparatus increases the productivity and efficiency of logging operations by reducing the number of trips, digital recording, storage, and transmission of information, and using software to process and interpret the results of borehole measurements.

3. The developed apparatus being used together with the appropriate metrological and interpretation-methodical support, increases the overall informativity of logging and the accuracy of results, eliminates systematic errors, and takes into account the features of the investigated objects.

4. The effectiveness of the apparatus has been demonstrated on specific examples of borehole determination of engineering geophysical parameters and confirmed by independent laboratory measurements taking a priori data into account.

5. An important factor is the production of prototype tools at the Institute of Geophysics itself; in so doing, the authors possess a number of know-how and can commercially apply the created technology.

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Геофізична технологія визначення параметрів ґрунтів (методи і апаратура)

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В Інституті геофізики НАН України для розв'язання інженерно-геологічних задач, зокрема сейсмічного мікрорайонування, створено сучасну технологію дослідження ґрунтів на основі методів і апаратури радіоактивного каротажу (РК) у складі нейтрон-нейтронного каротажу (ННК), гамма-гамма густинного каротажу (ГГК) і гамма-каротажу (ГК).

У статті наведено результати розробки апаратури РК як невід'ємної складової нової технології. На основі сучасних електронних комплектуючих розроблено і виготовлено: комплект експериментальних двоканальних приладів 2ННК (двозондовий ННК) та ГГК+ГК, експериментальний трикомпонентний прилад 2ННК+ГГК+ГК, наземний пульт керування і реєстрації.

Прилад 2ННК дає змогу визначати нейтронну пористість двома способами: однозондовим і компенсаційним. Компенсаційний нейтронний каротаж, зокрема, має на меті визначення пористості за наявності в породі аномальних поглиначів нейтронів, а також, у комплексі з однозондовим способом, оцінювання вмісту аномальних поглиначів.

Канал ГК приладу ГГК+ГК оснащено таким же детектором гамма-квантів, що і канал ГГК. Тут детектор ГК виконує подвійну функцію: 1) інтегральна реєстрація природного гамма-випромінювання; 2) врахування природного фону в сумарних показаннях детектора ГГК.

Трикомпонентний прилад радіоактивного каротажу поєднує три методи РК і включає всі переваги двоканальних приладів. Отримання результатів за одну спуско-підіймальну операцію таким приладом є особливо важливим для відносно глибоких свердловин.

За результатами експериментальних досліджень встановлено оптимальні відстані між джерелами і детекторами випромінювання у створених комбінованих приладах РК. Показано важливість настройки і контролю сигналів датчиків апаратури РК; новий наземний пульт дає можливість оперативно виконувати ці процедури.

Створена апаратура підвищує продуктивність і оперативність каротажних робіт за рахунок зменшення кількості спуско-підіймальних операцій, цифрового запису інформації, її збереження та передачі, використання комп'ютерних програм обробки та інтерпретації результатів свердловинних вимірювань. Ефективність розробленої апаратури разом з відповідним метрологічним та інтерпретаційно-методичним забезпеченням продемонстрована на конкретних прикладах свердловинних досліджень та підтверджена незалежними лабораторними даними.

Технологія дозволяє визначати такі інженерно-геофізичні параметри: загальна густина, густина сухого ґрунту, загальна глинистість, пористість, об'ємна вологість, водонасиченість, рівень ґрунтових вод та ін.

Ключові слова: ґрунт, комплекс нейтрон-нейтронного каротажу, гамма-гамма густинного каротажу і гамма-каротажу, апаратура, інженерно-геофізичний параметр; геофізична технологія.