УДК 550.34: 551.243: 550.835.2
DOI: 10.30838/J.BPSACEA.2312.260324.152.1054

POSSIBLE CONSTRUCTION FEATURES OF EQUIPMENT FOR RADONOMETRY OF BOTTOM SEDIMENTS ON THE SEA SHELF DURING RESEARCH AT SHORE NPP SITES

SEDIN V.L.[1] *Dr. Sc. (Tech.), Prof.,*
ULIANOV V.Yu.[2], *Ass.,*
ZAHILSKYI V.A.[3], *Ph. D., Assoc. Prof.,*
KOVBA V.V.[4*], *Ph. D., Assoc. Prof.,*
HORLACH S.M.[5], *Ph. D., Assoc. Prof.,*
LUHOVSKA Yev.V. [6], *Postgrad. Stud.*

[1.] Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 24-a, Architect Oleh Petrov Str., Dnipro, 49005, Ukraine, e-mail: sedin.volodymyr@pdaba.edu.ua, ORCID ID: 0000-0003-2293-7243
[2.] Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 24-a, Architect Oleh Petrov Str., Dnipro, 49005, Ukraine, e-mail: uluanovvu@gmail.com, ORCID ID: 0000-0002-9028-3408
[3.] Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 24-a, Architect Oleh Petrov Str., Dnipro, 49005, Ukraine, e-mail: zahilskyi.vitalii@pdaba.edu.ua, ORCID ID: 0000-0002-7853-565X
[4*]Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 24-a, Architect Oleh Petrov Str., Dnipro, 49005, Ukraine, +38 (096) 588-46-71, e-mail: kovba.vladyslav@pdaba.edu.ua, ORCID ID: 0000-0001-7888-4393
[5.] Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 24-a, Architect Oleh Petrov Str., Dnipro, 49005, Ukraine, e-mail: horlach.serhii@pdaba.edu.ua, ORCID ID: 0000-0001-6511-7574
[6.] Department of Engineering Geology and Geotechnics, Prydniprovska State Academy of Civil Engineering and Architecture, 24-a, Architect Oleh Petrov Str., Dnipro, 49005, Ukraine, e-mail: luhovska.yevheniia@pdaba.edu.ua, ORCID ID: 0009-0004-3643-3155

Abstract. ***Problem statement.*** Along with other natural gases that are freely discharged into the atmosphere in tectonic fault zones in Earth's crust, the best-known one is the radioactive gas Radon (^{222}Rn). The properties of this gas, namely inertness, short half-life period (up to 3.8 days) and availability of progeny distinguish it from other gases, such as methane, hydrogen, helium, etc. Another problem is determining the activity of tectonic faults identified by seismic exploration works in the waters near sites of future shore NPPs or those under construction. All the existing devices for offshore works were analyzed. Their advantages and disadvantages, as well as their suitability for radon research, have been revealed. ***Purpose of the article.*** In the paper, the need is substantiated to introduce radonometry for seismotectonic studies at shore NPP sites located in the sea and ocean shelf zones. ***Conclusions and results.*** As a result of analyzing the systems available for these purposes, it was deemed necessary to develop new types of devices different from the already existing ones and, for good measure, experimental prototypes. Moreover, there have been proposed their possible layout schemes. Layout schemes of specialized devices for radon research on the shelf, just as the need for such research, have been proposed and justified for the first time. Offshore radonometry conducted to identify the tectonic activity of revealed fault zones can become another additional factor that increases the operational reliability of future NPPs and, first of all, their hydraulic structures.

Keywords: *NPP; shelf; radon; engineering surveys; radonometry; underwater vehicle*

МОЖЛИВІ КОНСТРУКТИВНІ ОСОБЛИВОСТІ ОБЛАДНАННЯ ДЛЯ РАДОНОМЕТРІЇ ДОННИХ ОСАДІВ МОРСЬКОГО ШЕЛЬФУ ПРИ ВИШУКАННЯХ НА МАЙДАНЧИКАХ БЕРЕГОВИХ АЕС

СЄДІН В. Л.[1], *докт. техн. наук, проф.,*
УЛЬЯНОВ В. Ю.[2], *ас.,*
ЗАГІЛЬСЬКИЙ В. А.[3], *канд. техн. наук, доц.,*
КОВБА В. В.[4*], *канд. техн. наук, доц.,*
ГОРЛАЧ С. М.[5], *канд. техн. наук, доц.,*
ЛУГОВСЬКА Є. В.[6], *асп.*

[1.] Кафедра інженерної геології та геотехніки, Придніпровська державна академія будівництва та архітектури, вул. Архітектора Олега Петрова, 24а, 49005, Дніпро, Україна, e-mail: sedin.volodymyr@pdaba.edu.ua, ORCID ID: 0000-0003-2293-7243
[2.] Кафедра інженерної геології та геотехніки, Придніпровська державна академія будівництва та архітектури, вул. Архітектора Олега Петрова, 24а, 49005, Дніпро, Україна, e-mail: uluanovvu@gmail.com, ORCID ID: 0000-0002-9028-3408
[3.] Кафедра інженерної геології та геотехніки, Придніпровська державна академія будівництва та архітектури, вул. Архітектора Олега Петрова, 24-а, 49005, Дніпро, Україна, e-mail: zahilskyi.vitalii@pdaba.edu.ua, ORCID ID: 0000-0002-7853-565X
[4*.] Кафедра інженерної геології та геотехніки, Придніпровська державна академія будівництва та архітектури, вул. Архітектора Олега Петрова, 24-а, 49005, Дніпро, Україна, тел. +38 (096) 588-46-71, e-mail: kovba.vladyslav@pdaba.edu.ua, ORCID ID: 0000-0002-5140-8140
[5.] Кафедра інженерної геології та геотехніки, Придніпровська державна академія будівництва та архітектури, вул. Архітектора Олега Петрова, 24-а, 49005, Дніпро, Україна, e-mail: horlach.serhii@pdaba.edu.ua, ORCID ID: 0000-0001-6511-7574
[6.] Кафедра інженерної геології та геотехніки, Придніпровська державна академія будівництва та архітектури, вул. Архітектора Олега Петрова, 24-а, 49005, Дніпро, Україна, e-mail: luhovska.yevheniia@pdaba.edu.ua, ORCID ID: 0009-0004-3643-3155

Анотація. ***Постановка проблеми.*** Поряд з іншими природними газами, що вільно розвантажуються в атмосферу в зонах тектонічних розломів земної кори, найбільш відомий радіоактивний радон (^{222}Rn). Такі властивості цього газу як інертність, малий період піврозпаду (до 3,8 діб) та наявність дочірніх продуктів розпаду виділяють його серед інших газів, таких як метан, водень, гелій та ін. Іншою проблемою стало визначення активності виявлених сейсморозвідкою тектонічних розломів на акваторії поблизу майданчиків майбутніх або АЕС, що будуються (берегового типу). Проаналізовано всі існуючі пристрої для роботи в акваторіях. Виявлено їх переваги та недоліки, як і придатність для досліджень радону. ***Мета статті.*** Обґрунтовується необхідність запровадження радонометрії для сейсмотектонічних досліджень на майданчиках АЕС берегового типу, розташованих у шельфовій зоні морів та океанів. ***Висновки.*** В результаті аналізу існуючих систем для цих цілей визнано необхідним розробити пристрої нового типу, відмінні від існуючих і до того ж дослідних зразків. Також запропоновано можливі компонувальні схеми пристроїв нового типу. Вперше запропоновано компонувальні схеми спеціалізованих пристроїв для радонових досліджень на шельфі. Обґрунтовано необхідність подібних досліджень. Проведення радонометрії в акваторії з метою виявлення тектонічної активності виявлених розломних зон може стати ще одним додатковим фактором, що підвищує експлуатаційну надійність майбутніх АЕС, в першу чергу – їх гідротехнічних споруд.

Ключові слова: *АЕС; радон; інженерні вишукування; радонометрія; підводний апарат*

Formulation of the problem. Along with other natural gases that are freely discharged into the atmosphere in tectonic fault zones in Earth’s crust, the best-known one is the radioactive gas Radon (^{222}Rn). The properties of this gas, namely inertness, short half-life period (up to 3.8 days) and availability of progeny distinguish it from other gases, such as methane, hydrogen, helium, etc. These properties of radon served as the basis for its use as one of the available indicators in establishing the activity rate of tectonic fault zones, especially at nuclear power plant sites [1]. During numerous field studies in the 70−80s of the last century, a direct connection was established between the intensity of radon anomalies and geodynamic processes in tectonic fault zones. This phenomenon served as the basis to start up a fundamentally new direction of applied research in the field of engineering geology: − structural geodynamic mapping (SGM) [2]. A method being similar in objectives and tasks is a method of structural thermal-and-atmospheric and hydro-geochemical investigations developed and used by the Marine Research Department of the Institute of Geological Sciences (IGS) of the National Academy of Sciences of Ukraine (NASU) [9]. Nevertheless, despite numerous facts of quite successful application of this method, radon has so far received undeservedly little attention as a possible indicator of changes in the stressed state of subsoil at sites of nuclear power plants being designed, under construction and in operation. This was especially true for measurements of radon concentrations in groundwater, where the method of measuring radon in groundwater for the purposes of geodynamic and earthquake forecast has yet to prove its value, although individual studies in this area have still been carried out [3; 4].

Another problem is determining the activity of tectonic faults identified by seismic exploration works in the waters near sites of future shore NPPs or those under construction. That is, the matter is radon measurements in bottom sediments in the sea and ocean shelf waters above fault zones, as well as large storage reservoirs and lakes. It should be noted that according to the number of publications, radon measurements in the marine environment were actively carried out in the 60−70s of the previous century, but after that period the interest in this area decreased significantly. The problem of measuring radon in bottom sediments on the shelf for the purposes of seismotectonics, when choosing sites for nuclear power plants, is generally quite new and associated, unlike determining radon on land, with a number of objective technical difficulties, given the depth of upcoming investigations. This paper is devoted to this topic.

The purpose of the article. In the paper, the need is substantiated to introduce radonometry for seismotectonic studies at shore NPP sites located in the sea and ocean shelf zones.

Materials and Methods. Methods used at shallow depths near the coastline are described in a number of papers [5; 7; 15]. In such studies, bottom sediments are collected using a bucket sampler or a tubular gravity column, with a subsequent complex process of determining the radon concentration in pore fluid or soil particles directly on the ship or in an onshore laboratory. Certainly, such determinations are discrete and such technology is far from optimal one existing for mass determinations during surveys.

A different way was chosen by a number of researchers, in particular that for the in-situ continuous determination of radon concentrations in the water of submarine sources [6]. For example, one such system consists of a submerged module using a commercial radon sensor with a pulsed ionization chamber and gas separation membrane module to provide high accuracy and high resolution. In operating mode, water is continuously pumped through a membrane contactor, in which radon dissolved in water is degassed and balanced by a closed air circuit. The membrane physically separates water and air. Further, after dehumidification, the balanced air is directed to an active radon detector. Two back valves and a water leakage detector prevent unexpected reverse flow. The detector monitors the temperature, humidity and pressure in the inner chamber. The submerged module can be powered by either a 12V-battery or an external AC power supply via an eight-wire waterproof cable. The maximum power consumption is ~33 W when the water and air pumps are running. Once communication is established between the underwater detection unit and shore-monitoring module, no additional intervention of the operator will be required. Data collection (no more than one minute) can be programmed for any user-desired integration interval, depending on the expected radon concentration in samples. For each time step, the user receives data on radon activity, temperature, humidity and pressure, which are automatically stored in a memory device inside the shore monitoring module. Data set transmission, as well as system management, can be controlled using the Wi-Fi-based remote terminals. This experimental setup uses proprietary software to visually monitor changes in radon activity on a real-time basis from a remote laboratory located 20 km away. During the tests, the installation operated continuously over 100 hours. However, this case also touched shallow depths (up to 2.5 m), although the creators of the system claimed that it could operate at depths of up to 40 m and even be part of an autonomous underwater vehicle. In addition, the described device is a purely experimental installation, consisting of commercially available components, and moreover, requiring the presence of a coastal stationary base, which limits the offshore survey area. As it was revealed when testing, the turbid water can clog the membrane relatively quickly and, therefore, contactors typically require the rather clean water with a low concentration of suspended solids, which in itself is unlikely in near-bottom conditions, and even more in the bottom environment. To reduce the likelihood of clogging the extraction module with suspended solids while in operation, a pre-filtration device with a 45 mm-microfilter was installed at the water inlet to the submerged module system. In some situations, it was found necessary to install a multi-stage filtration, which seriously complicates and increases the cost of a purely experimental design. Other devices of this kind were developed.

Some attempts have also been made to measure radon activity in situ using the underwater gamma counters based on Nal (TI) scintillators or HPGe (high-purity germanium) detectors. However, Nal (Tl) applications have high background and low resolution, and HPGe systems are too expensive. There is evidence of using KATERINA-type sensor devices in water areas, which take into account the activity of radon progeny (214Pb, 214Bi) [16]. Nevertheless, the significant dimensions of devices do not yet allow them to be deepened into bottom sediments by more than a few centimeters.

It should be noted that individual elements of such modules were created in the Department of Geo-Ecology and Exploratory Research of the Institute of Geological Sciences of the National Academy of Sciences of Ukraine. An application no. a 201509394 dd. 30.09.2015 was submitted to obtain a patent of Ukraine for one of these devices: − a bathometer-degasser (see Fig. 1). Actually, it has undergone the formal examination No. 2064/38/16 dd. 28.01.2016 [8]. However, in addition to unsolved technical problems, the seawater samples were collected and degassed for various purposes by a device developed under the guidance of the Institute of Geological Sciences of the National Academy of Sciences of Ukraine (PDBK-2M), and this was only done from the bottom water, and not from the layer of sediments, i.e. the resulting values were initially subject to a number of disturbing factors and distortions. The device itself needed some correcting works. Notwithstanding, it is also possible to develop other design schemes (Fig. 1).

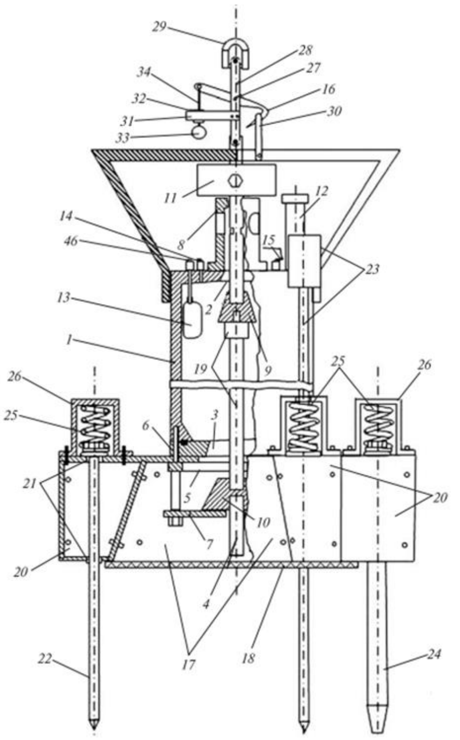


Fig. 1. Geological complex for studying water bottoms (including additional elements: 1 − sealed body, 2, 3 − upper and lower parts of the body, 4 − rod, 5 − platform, 6 − flange, 7, 8 − upper and lower parts of the guide bushing, 9, 10 – sampler-degasser valves,11 − cargo,12 − pressure compensator, 13 − device for changing the sample volume, 14 − gas tap, 15 − water tap,16 – hook kicker, 17 – water intake, 18 − filter, 19 − stock, 20 − plate rectangular-trapezoidal consoles, 21 – fixing holes, 22 − stabilizers, 23 – geological meter, 24 – bottom soil sampler, 25, 26 – shock absorber, 27 − axis, 28 − cheeks, 29 − bracket, 30 − loop, 31 – additional console, 32 – bushing, 33 – counterweight, 34 – flexible cable, 46 − tap. The photo is taken from publicly available sources

In particular, it is a known fact that there exist two patents for similar sampling systems based on the multi-chamber syringe-type boxes: the US patent 2006090894 МПК E21B 49/08, and the RU patent (11) 2 446 388(13) C1 (see Fig. 2, 3). However, the analysis of samples in all cases was carried out already on the surface.

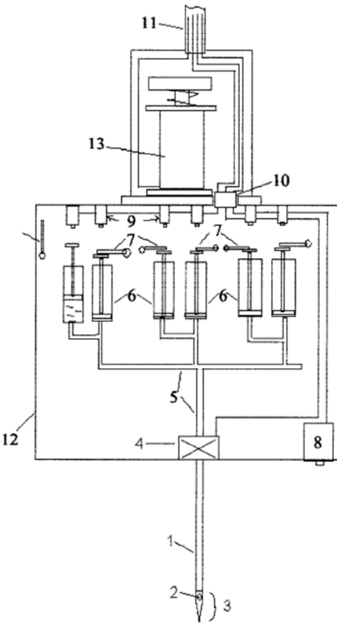
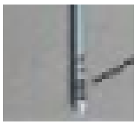


Fig. 2. Scheme of a probe for sampling pore fluid from bottom sediments:1 – sampling tube; 2 – water inlet; 3 − filter; 4 – solenoid valve; 5 – hose for connecting syringes; 6 − syringes; 7 – spring-loaded locks; 8 – pressure control device; 9 – stoppers for full travel of syringe stocks with limit switches; 10 – connector joining electrical components of the sealed container via the cable-cord 11 with the control unit (not shown in Figure); 12 – sealed container body; 13 – immersion mechanism. The photo is taken from publicly available sources

probe



probe tip

Fig. 3. Probe for sampling pore water from bottom sediments. (The photo is taken from publicly available sources)

Research results. Thus, based on the aforementioned with a view to solve problems of seismotectonics, one can talk about creating a submerged laboratory module with a sealed chamber, capable to operate at depths of up to 200 m. The module is lowered to a point either independently or from on board a research vessel (i. e., an instrument of the so-called inert type). Power supply sources are located on the platform. However, the option of supplying power via a cable from the surface cannot be ruled out. The operation of the module at the bottom can be controlled by autonomous small-sized submersible robotic platforms. The inert-type module can consist of the following basic components:

- a platform with a sealed instrument capsule and a sluice device for the forced overboard discharge (as an option) of an already studied portion of pore water at depth, and a system for pipeline purging from high-pressure air cylinders, and a system for stabilizing /reducing pressure in the capsule body, and membrane filters, and an energy supply system, and a radon-content analysis unit of selected configuration (with a pulse ionization chamber, or with the use of underwater gamma counters based on NaI (Tl) scintillators, or HPGe-detectors). In the latter case, the introduction of a gamma counter into the bottom soil is possible when it is placed in the lower part of the auger column modified for marine conditions of the so-called sound procedure installation. It is also possible to appropriately use the modified commercial radon detectors, such as RAD7 (https://durridge.com) or RTM-1688 (SARAD GmbH), although there is no information about the use of these devices on underwater vehicles at sea depths of up to 200 m;
- a sampling device for collecting water samples in the environment of bottom sediments (a press-in type probe with a cone tip, or a rotary auger type probe additionally equipped, if necessary, with a gamma counter). The submersible device can be either built into a sealed capsule or externally coupled with it. It must be structurally possible to collect and store the pore fluid samples at 2 horizons as a

minimum, in depth of submerging the probe at a specific point;

- a system for stabilizing and anchoring the platform (in the case of a lightweight structure), as well as preventing the overturn or lurch;
- a weighting load with the possibility of its separation in emergency cases (reinforced concrete structures, cast iron shot or ingots);
- lighting, video surveillance and communication systems.

In particular, a modified platform for the seabed cone penetration testing at depths of up to 300 m, for example ROSON 100 (see Fig. 4) manufactured by the Dutch company “A.P. van den Berg” [10], can be used as a basis. But the cone probe for CPT in this platform must be adapted to sample pore fluid when pressed-in exactly at the desired level, i.e. equipped with a solenoid valve. The diameter of the probe itself can be increased, since it is very difficult to create a similar system with valves and with a standard CTP-probe diameter of 36 mm. It is the pressed-in probe or otherwise submerged one, for example the drilled-in probe, that will presumably be the most complex part of this device.

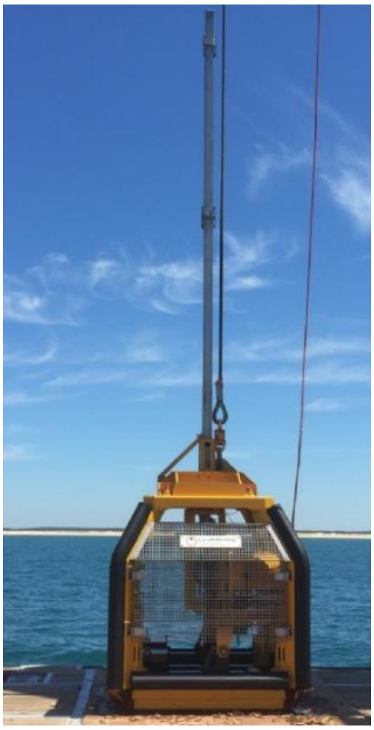


Fig. 4. Underwater CPT- penetrometer. The photo is taken from publicly available sources

In addition to the system for collecting and analyzing the pore water samples for radon, the platform itself can be equipped with auxiliary sensors (including a gas chromatography unit), which will significantly expand the list of recorded parameters, although it will lead to an inevitable increase in the cost of the entire system. However, a combined option is also possible, when the sampling system is installed on the platform in addition to the main CPT-equipment. A sampler for pore fluid from loose bottom sediments should initially ensure sampling from depths of at least 0.5−1 m below the reference seabed point. The converted bottom stations from LDEO and SIO Companies (USA), or ones similar to them, can also be considered as a basis.

For obvious reasons, the autonomous option will be much more complicated and expensive, because it must be additionally equipped with an ascent-submergence system, a point stabilization system, and a radar for determining the thickness of bottom sediments and their material composition, as well as an orientation system and drop weight. Moreover, there must be provided means to search for an emersed vehicle, made in the shape of a flashing beacon and/or an active radar reflector. Also, as in the inert version, it is possible to combine such a platform with other equipment-specific complexes for studying bottom sediments of marine areas [11]. The option of equipping submerged modules of both types with radon analyzers based on HPGe or other types cannot be ruled out, even despite its high cost. However, in a technical sense, this option will most likely be much easier to implement in practice.

As an intermediate option, a battery-type submersible ampulized system can be proposed. In this case, after sampling at selected points in the shelf area, ampoules filled with pore fluid rise to the surface along with the platform, or float to the surface in the certain sequence, as they are filled, with the help of additional equipment. As soon as they are delivered on board the vessel, they will immediately be sent to the laboratory for analysis. As a matter of course, the floating part is equipped with a detection device (a flashing light and a radio signal for direction finding).

It is certain that when using devices of both types, there is a necessity to take into account not only the topography and structure of seabed, but also the composition and thickness of bottom sediments. The presence of the silt thick mass of soupy consistency will be an obstacle to the planned measurements. In such cases, an indirect additional option for solving this problem can be the use of modules for continuous registration of radon in the near-bottom part of the shelf, located on the so-called gliders [12−14]. In particular, determining the radon content in the near-bottom part of the shelf may allow roughly outlining the tectonic disturbance at the stage of preliminary searches, especially that in the active phase, certainly if the “picture” is not distorted by gas seeps, near-bottom flows or submarines sources. However, the disadvantage of this scheme is the revealed sharp difference in the radon content within the bottom sea waters and bottom sediments.

Scientific Novelty and Practical Significance. When conducting surveys at shore NPP sites, it is necessary, apart from radonometry on land, to carry out similar works in the water area, which, however, is associated with a number of difficulties of both technical and methodological nature.

It is recognized that for radonometry of the shelf zone conducted with the aim of seismotectonics during the construction of shore NPPs, equipment of a completely different type is required, alternatively to numerous existing installations used in oceanology and marine geology. Although, it is quite acceptable to use individual components of available devices that have been already tested. The possible schemes for such devices have been proposed.

Radonometry in the water area to identify the tectonic activity of discovered fault zones can become another additional factor that increases the operational reliability of future nuclear power plants.

Conclusion

When conducting surveys at shore NPP sites, it is necessary, apart from radonometry on land, to carry out works in the water area.

For radonometry of the shelf zone in the aims of seismotectonics, it is necessary to have equipment of a completely different type alternatively to numerous existing installations used in oceanology and marine geology. The platform of such a device can be of either active (self-propelled) or passive type (connected to the vessel). The instrumentation can be based both on existing commercial components that are already used, and on newly created overspecialized devices. The own schemes of such devices have been proposed.

For works in water areas, it also seems necessary to make adjustments to the methodology of such research, especially with regard to determining the activity of tectonic faults by radonometry methods, if they will be identified in the study area. It is not inconceivable that the version of the universal scale of tectonic fault activity in Earth’s crust developed for land can be adjusted for the conditions of water areas.

However, there is no doubt that radonometry in water areas to identify the tectonic activity of discovered fault zones can become another additional factor that increases the safety of sites and, as a consequence, the operational reliability of both nuclear power plants under construction and those already in operation. Moreover, such research is primarily required for sites located in highly seismic regions.

REFERENCES

1. Sedin V.L., Uluanov V. and Bicus K.M. *Shkala otsenki aktivnosti tektonicheskix razlomov zemnoj kory po intensivnosti radonovydeleniya iz nedr na ploshhadkah stroyashhihsya i dejstvuyushhih AES* [Scale assessment of active tectonic faults of the crust on the Intensity of radon exhalation from the depths to the construction site and the existing energy facilities]. *Georysyk* [Heorisk]. 2015, no. 4, pp. 48–52. (in Ukrainian).
2. Gorbushina L.V. and Ryaboshtan Y.S. *Ehmanacionnyjj metod indikacii geodinamicheskikh processov pri inzhenerno-geologicheskikh izyskanijakh* [Emanation method indication of geodynamic processes in geotechnical investigations]. *Sovetskaya geologiya* [Soviet Geology]. 1975, no. 4, pp. 106–112. (in Ukrainian).
3. Shigeki Tasaka and Yoshimi Sasaki. Observations of Underground Water Radon Concentration at the Kamioka Mine, Gifu Prefecture. Faculty of Education, Gifu University, Yanagido 1-1. Gifu 501-11, 2‒45, Japan, 1992, 9 p.
4. Maho Matsumoto, Yumi Yasuoka, Yui Takakaze, Masahiro Hosoda, Shinji Tokonami, Kazuki Iwaoka and Takahiro Mukai. Evaluation of radon concentration measurements in water using the radon degassing method. Journal of Radioanalytical and Nuclear Chemistry. 2022, 6 p.
5. Munaf Qasim Jaber, Abdul. R.H. Subber and Noori H.N. Al-Hashimi. Radon Concentrations in the Marine Sediments of Khor-Abdulla Northern West of the Arabian Gulf. International Journal of Physics. 2015, vol. 3, no. 6, pp. 239–243.
6. Zhao S., Li M., Burnett W.C., Cheng K., Li C., Guo J., Yu S., Liu W., Yang T., Dimova N.T., Chen G,. Yu Z. and Xu B. In-situ radon-in-water detection for high resolution submarine groundwater discharge assessment. Front. Mar. Sci. Vol. 9, 2022, p. 1001554.
7. *Heolohichni, heoekolohichni, hidroakustychni, hidroekolohichni doslidzhennya shel'fu ta kontynental'noho skhylu ukrayins'koho sektora Chornoho morya* [Geological, geoecological, hydroacoustic, hydroecological studies of the shelf and continental slope of the Ukrainian sector of the Black Sea]. Ed. By A.Yu. Mitropolsky, Kyiv, 2013, 150 p. (in Ukrainian).
8. Bagriy I.D. and Kiryushchenko I.G. *Modul'no-blochnyy kompleks dlya issledovaniya morskogo dna i pridonnykh vod* [Modular-block complex for studying the seabed and bottom waters]. *Geologiya i poleznyye iskopayemyye Mirovogo okeana* [Geology and Minerals of the World Ocean]. 2016, no. 4, pp. 128–134. (in Russian).
9. Bagriy I.D., Dubosarsky V.R. and Zhalovsky V.P. *Primeneniye metodiki strukturno-termo-atmogidrogeokhimicheskikh issledovaniy (STAGI) s tsel'yu poiskov zalezhey uglevodorodov i otsenki ekologicheskogo sostoyaniya okruzhayushchey sredy* [Application of the methodology of structural-thermo-atmohydrogeochemical research (STAGI) for the purpose of searching for hydrocarbon deposits and assessing the ecological state of the environment]. *Materialy Mezhdunarodnoy nauchnoy konferentsii, posvyashchennoy 215-letiyu so dnya rozhdeniya I. Domeyko* [Materials of the International Scientific Conference dedicated to the 215th anniversary of the birth of I. Domeiko]. Minsk, 2017, pp. 93–95. (in Russian).
10. Deep Water ROSON 100 the versatile seabed CPT system for ultra-deep water. URL: https://OffR3_0615_Deep_Water_ROSON_100_seabed_CPT_system%20(4).pdf
11. Gonchar A.I., Fedoseyenkov S.G., Shlychek L.I. and Shundel A.I. *Bahatotsil'ovyy avtomatyzovanyy modul'no-blochnyy informatsiyno-vymiryuval'nyy kompleks dlya monitorynhu akvatoriyi* [Multipurpose automated modular-block information and measurement complex for water area monitoring]. *Hidroakustychnyy zhurnal (Problemy, metody ta zasoby doslidzhen' Svitovoho okeanu)* [Hydroacoustic Journal (Problems, Methods and Means of Ocean Research)]. 2012, no. 9, pp. 97–102. (in Ukrainian).
12. Brückmann W., Leibold P., Schmidt M., Al Balushi H. and Al Abri O. In Using an Autonomous Wave Glider to Detect Seawater Anomalies Related to Submarine Groundwater Discharge − Engineering Challenge. AGU Fall Meeting, GEOMAR, 2017.
13. Thomas Müller, Jonas Gros, Patrick Leibol, Hajar Al-Balushi, Eric Petermann, Mark Schmidt, Warner Brückmann, Mohammed Al Kindi and Omar S. Al-Abri Autonomous Large-Scale Radon Mapping and Buoyant Plume Modeling Quantify Deep Submarine Groundwater Discharge : a Novel Approach Based on a Self-Sufficient Open Ocean Vehicle. Environ. Sci. Technol. 2023, no. 57, pp. 6540–6549.
14. Al Balushi H. Detecting Submarine Groundwater Plumes in the Salalah Area : a Radon Tracer and Numerical Integral Plume Model. Master Thesis, GEOMAR, 2019, 70 p.
15. Collection and preparation of bottom sediment samples for analysis of radionuclides and trace elements. IAEA. Vienna, 2003, 130 p.
16. Tsabaris C., Androulakaki E.G. and Alexakis S. An Optimized Quantification Method for Marine Radioactivity Measurements : Application in the Southern Caspian Sea Using the KATERINA Underwater γ-Spectrometer. Journal of Marine Science and Engineering. 2023, no. 11 (4), p. 725.

СПИСОК ВИКОРИСТАНИХ ДЖЕРЕЛ

1. Сєдін В. Л. Ульянов В. Ю., Бікус К. М. Шкала оцінювання активності тектонічних розломів земної кори за інтенсивністю радоновиділення застосування для об'єктів АЕС. *Георизик*. 2015. № 4. С. 48–52.

2. Горбушина Л. В., Рябоштан Ю. С. Еманаційний метод індикації геодинамічних процесів при інженерно-геологічних дослідженнях. *Советская геология*. 1975. № 4. С. 106–112.

3. Shigeki Tasaka, Yoshimi Sasaki. Observations of Underground Water Radon Concentration at the Kamioka Mine, Gifu Prefecture. Faculty of Education, Gifu University, Yanagido 1-1. Gifu 501-11, 2−45, Japan, 1992. 9 p.

4. Maho Matsumoto, Yumi Yasuoka, Yui Takakaze, Masahiro Hosoda, Shinji Tokonami, Kazuki Iwaoka, Takahiro Mukai. Evaluation of radon concentration measurements in water using the radon degassing method. *Journal of Radioanalytical and Nuclear Chemistry*. 2022. 6 p.

5. Munaf Qasim Jaber, Abdul. R. H. Subber, Noori H.N. Al-Hashimi. Radon Concentrations in the Marine Sediments of Khor-Abdulla Northern West of the Arabian Gulf. *International Journal of Physics*. 2015. Vol. 3, № 6. Pp. 239–243.

6. Zhao S., Li M., Burnett W. C., Cheng K., Li C., Guo J., Yu S., Liu W., Yang T., Dimova N.T., Chen G., Yu Z., Xu B. In-situ radon-in-water detection for high resolution submarine groundwater discharge assessment. *Front. Mar. Sci.* 9. 2022. P. 1001554.

7. Геологічні, геоекологічні, гідроакустичні, гідроекологічні дослідження шельфу та континентального схилу українського сектора Чорного моря. Під ред. А. Ю. Митропольського. Київ, 2013. 150 с.

8. Багрий И. Д., Кирющенко И. Г. Модульно-блочный комплекс для исследования морского дна и придонных вод. *Геология и полезные ископаемые Мирового океана*. 2016. № 4. С. 128–134.

9. Багрий И. Д., Дубосарский В. Р., Жаловский В. П. Применение методики структурно-термо-атмогидрогеохимических исследований (СТАГИ) с целью поисков залежей углеводородов и оценки экологического состояния окружающей среды. *Материалы Международной научной конференции, посвященной 215-летию со дня рождения И. Домейко*. Минск, 2017. С. 93–95.

10. Deep Water ROSON 100 the versatile seabed CPT system for ultra-deep water. URL: https://OffR3_0615_Deep_Water_ROSON_100_seabed_CPT_system%20(4).pdf

11. Гончар А. І., Федосеєнков С. Г., Шличек Л. І., Шундель А. І. Багатоцільовий автоматизований модульно-блочний інформаційно-вимірювальний комплекс для моніторингу акваторії. *Гідроакустичний журнал (Проблеми, методи та засоби досліджень Світового океану)*. 2012. № 9. С. 97–102.

12. BrückmannW., Leibold P., Schmidt M., Al Balushi H., Al Abri O. In Using an Autonomous Wave Glider to Detect Seawater Anomalies Related to Submarine Groundwater Discharge − Engineering Challenge. AGU Fall Meeting. *GEOMAR*. 2017.

13. Thomas Müller, Jonas Gros, Patrick Leibol, Hajar Al-Balushi, Eric Petermann, Mark Schmidt, Warner Brückmann, Mohammed Al Kindi, Omar S. Al-Abri Autonomous Large-Scale Radon Mapping and Buoyant Plume Modeling Quantify Deep Submarine Groundwater Discharge : a Novel Approach Based on a Self-Sufficient Open Ocean Vehicle. *Environ. Sci. Technol*. 2023. № 57. Pp. 6540–6549.

14. Al Balushi H. Detecting Submarine Groundwater Plumes in the Salalah Area : a Radon Tracer and Numerical Integral Plume Model, Master Thesis. *GEOMAR.* 2019, 70 p.

15. Collection and preparation of bottom sediment samples for analysis of radionuclides and trace elements. *IAEA.* Vienna, 2003. 130 p.

16. Tsabaris C., Androulakaki E. G., Alexakis S. An Optimized Quantification Method for Marine Radioactivity Measurements : Application in the Southern Caspian Sea Using the KATERINA Underwater γ-Spectrometer. *Journal of Marine Science and Engineering*. 2023. № 11 (4). P. 725.

Надійшла до редакції: 21.02.2024.