UDC 550.34. + 551.24

Yuriy ANDRUSHCHENKO[1a], Oleksandr LIASHCHUK[1b]

Main Center for Special Control NSMC SSA of Ukraine, 1, Kosmichna Str., Gorodok, Radomyshl district, Zhytomyr region, 12265, Ukraine, tel. +38 (096) 2152823, e-mail: andruschenko_yuriy@ukr.net, [1a] https://orcid.org/0000-0001-8993-0113; [1b] https://orcid.org/ 0000-0002-8690-1808

https://doi.org/10.23939/jgd2021.02.084

LOCAL SEISMOLOGICAL NETWORKS OF NUCLEAR POWER PLANTS OF UKRAINE AS COMPONENTS OF THE NATIONAL SEISMOLOGICAL MONITORING SYSTEM

The aim of the work is to determine the possibility of using local seismological networks of nuclear power plants as elements of the seismological monitoring system of the territory of Ukraine. Estimation of local seismicity and specification of quantitative parameters of seismological influences is carried out on the basis of materials of seismological observations. Operational processing and analysis of seismic signals registered on the elements of local seismological networks of NPPs is carried out by the Main Center for Special Control of the State Space Agency of Ukraine (MCSC SSA of Ukraine). In the process of implementation of the “Seismic Hazard Assessment and Seismic Resistance Action Plan” of existing NPPs, seismic monitoring networks were deployed at Ukrainian NPPs. To date, the MCSC receives data from the local seismological networks of Rivne, Khmelnytsky and Zaporizhzhya NPPs in a continuous mode. The processing of geophysical information coming from the NPP to the FSC is carried out by the operational next shift of the center with the help of FSC hardware and software and provides reliable data on the parameters of seismic sources registered by stations, their location and energy characteristics. In total, in the period from 2017 to 2021, 36 local earthquakes were registered by NPP seismic networks in Ukraine. The epicenters of the vast majority of them are located within the Ivano-Frankivsk, Ternopil and Lviv regions. The experience of conducting instrumental observations at NPP seismic stations testifies to their high efficiency and possibility of use as full-fledged elements of the seismological monitoring system of the territory of Ukraine. According to the results of primary processing of seismic data of 2017–2021, a catalog of seismic events registered by NPP seismic stations was created. The system of interpretation of the obtained results was improved, which allowed to determine equally well local, regional and teleseismic events of different nature and energy level. The practical significance of the obtained results lies in their direct focus on solving a number of practical problems of processing and interpretation of seismological data. The use of NPP seismic stations as elements of the general system of seismological monitoring of Ukraine will increase the reliability of detection and localization of sources and the probability of correct identification of the nature of seismic phenomena, which in turn will improve the assessment of tectonic structures in Ukraine.

Key words: nuclear power plant; seismic event; seismological monitoring; seismic receiver; microseismics; epicenter.

Introduction

Nuclear energy has been and remains the most important element in ensuring a reliable and secure electricity supply in Ukraine and its development continues. Construction and operation of nuclear power plants requires compliance with modern requirements for seismic design and application of modern international approaches to assessing the seismic hazard of power units [Ryzhov, et al., 2012, 2013, 2017]. In accordance with the requirements for seismic design and seismic safety assessment of nuclear power units (NP 306.2.208–2016), in the area of the NPP location the operating organization creates a special local network of permanent highly sensitive seismic monitoring stations. The seismicity of the site of nuclear power plants and the parameters of seismic influences are determined on the basis of seismological studies taking into account specific geodynamic, seismotectonic, seismological, soil and hydrological conditions of the site location. To perform these studies, the operating organization involves specialized organizations that have the necessary experience and resources to conduct such work, as well as the authority to approve their results. Seismological monitoring networks were deployed at Ukrainian NPPs in the process of implementation of the “Plan of measures for seismic hazard assessment and seismic resistance testing of existing NPPs”, approved by the resolution of the Board of the State Nuclear Regulatory Committee of Ukraine dated 19.02.2009 No. 7.

Carrying out seismological monitoring on permanent networks of seismic stations in the NPP areas to ensure seismological safety involves solving the following tasks:

– observation of micro-earthquakes and their dynamics in space and time;

– registration of local and strong remote earthquakes;

– specification of quantitative parameters of seismic impacts during a project earthquake (PE) and maximum calculated earthquake (MCE) from local seismically active zones and the Vrancea zone, based on materials of seismological observations conducted directly at NPP sites and data on seismic energy attenuation with distance according to all system points;

– performance of early warning functions in case of a strong or catastrophic earthquake.

Purpose

The aim of the work is to determine the possibility of using local seismological networks of nuclear power plants as elements of the seismological monitoring system of Ukraine. The study also focuses on conducting regime seismological observations of local and regional seismic events, improving the method of processing records. In addition, the study conducts comprehensive processing of registered events assessing local earthquakes to estimate current activity of tectonic structures of Ukraine.

To achieve this goal, the following tasks were set:

1. To provide data collection of seismological observations and to form on their basis the corresponding databases of digital seismological data.
2. To analyze the possibility of using local seismological networks of nuclear power plants as elements of the seismological monitoring system of the territory of Ukraine.
3. Using the data obtained at NPP seismic stations, to investigate the manifestations of modern activity of tectonic structures of Ukraine.

Method

Estimation of local seismicity and specification of quantitative parameters of seismological influences is carried out on the basis of materials of seismological observations. Specialists of the Main Center for Special Control of the State Space Agency of Ukraine detected and recognized seismic signals using seismic monitoring systems of NPPs. They also formed relevant catalogs of seismic events. In accordance with the "Regulations on the National System of Seismic Observations and Improving the Safety of Living in Seismically Dangerous Regions" (Resolution of the Cabinet of Ministers of June 28, 1997 No. 699) [Regulations …., 1997], the State Space Agency of Ukraine organizes and provides continuous surveillance of geodynamic and seismic conditions objects in order to assess the real seismic resistance of these objects and their response to seismic and other geodynamic effects. The Agency creates a database of seismic and other geodynamic effects on radiation-hazardous objects. In accordance with the Decision of NNEGC "Energoatom" on the approval of the supplier No. РШ-П 0.22.159-18, MCSM processes and analyzes records of local and regional seismic events registered by seismological networks installed in the areas of NPP location.

Hierarchical multilevel construction of automated systems of data collection, processing and storage was adopted during the processing of digital data received by the MCSC processing center from NPP seismological networks. This greatly simplifies the final result, as full processing is carried out in the NDC without additional computing resources. The processing of geophysical information coming from the NPP to the MCSC is carried out by the operational next shift of the center with the help of MCSC hardware and software. It provides reliable data on the parameters of seismic sources registered by stations, their location and energy characteristics.

To date, the MCSC receives data from the local seismological networks of Rivne, Khmelnytsky and Zaporizhzhya NPPs in a continuous mode. The seismological networks of each of the nuclear power plants consist of six observation points located within a radius of 25 km around the technical sites of the NPP. Points of seismic monitoring networks are the basic elements of information collection networks as part of seismic monitoring systems. The elements of seismic monitoring systems are integrated into a single telemetry system, which performs the functions of collecting information simultaneously with all elements of the group, and centralized control of elements from the technical site. The main functions of the points are the collection of information from seismometers, the accumulation and transmission of digital seismic information to the data center in real time.

Soil vibrations are recorded by seismic receivers manufactured by Güralp System Limited and Nanometrics, located in specially equipped instrument wells. Signals from downhole seismic receivers CMG-40TB and CMG-SPB. are converted to digital form by means of the DM24 analog-to-digital converter. The Güralp DM24 digitizer is implemented in the form of a downhole probe and can be installed directly in the well together with the seismic receiver. This design feature of the analog-to-digital converter has a number of advantages over the traditional installation in the head of the downhole structure, namely:

– digital signals are not attenuated during transmission from the seismic receiver to the surface;

– digitization of data at the point of registration allows to guarantee reliable identification of the nature of the registered seismic signal;

– DM24 digitizer can also be combined with the authentication module in the wellbore.

In addition, each element of the group is equipped with a receiver of satellite navigation signals such as GPS Palisade to provide temporal and spatial data binding.

Seismic receivers contain three sensors in a sealed housing, capable of measuring the displacement of the soil in the directions north/south, east/west and vertical direction simultaneously.

Determination of the coordinates of the epicenters of the registered seismic events is carried out by network processing, which involves the data of seismological networks of NPPs and stations MCSC. For hypocentria the LocSat program [Bratt, & Bache, 1988] is used, which is a part of the Geotool software package [Coyne, et al., 2003]. This program takes into account not only the first entries of longitudinal waves, but also the selected secondary phases (Sn, Lg, LR) considering their model errors (possible statistical deviations). This allows you to get stable solutions even with a small number of stations that registered the event. In addition, this program can use azimuth and slowness data calculated for each of these phases, which is especially important when participating in the location of seismic group data.

Results

One of the main difficulties in detecting weak seismic signals is that it is performed against the background of constantly operating microseismic oscillations of different intensity and frequency composition. To increase the efficiency of signal detection, a large number of new means of registration and methods of processing digital seismic information in real time have been developed [Zhigalin, & Lokshin, 1987; Antonova, & Aptikaev, 2004]. In order to study the noise situation in the locations of elements of local seismological networks of NPPs in the process of instrumental observations, we conducted constant analysis of the noise situation and the impact of microseisms of different order on the possibility of isolating useful signals at checkpoints. It should be noted that broadband devices, which are equipped with seismic networks of NPPs, simultaneously register microseismics of different types [Gutenberg, 1958; Vinnik, 1968; Savarensky, 1955], and therefore such intensive and various in frequency structure noises are registered on the primary seismogram. So, it is necessary to carry out band frequency filtering for allocating weak signals. The average values of the microseismic background at the registration points were calculated according to the records obtained using seismic sensors installed in observation wells and on the day surface. As an example, the results of calculations for stations of the seismic network of RNPP are presented (Table 1).

As can be seen from Table 1, the amplitudes of the seismic background calculated from the seismic records obtained from instrumental observations on the day surface (industrial site of RNPP) are quite high due to the surface layer of sedimentary rocks and, as a consequence, high intensity of second-order microseismics.

Table 1

Values of microseismic amplitudes at RNPP seismological network registration points

Observation point	Location of the observation point	Amplitude of seismic background, μm
RNPP 1	Kostyukhnivka village	0.004
RNPP 2	RNPP industrial site	0.424
RNPP 5	Stary Chortoryisk village	0.005
RNPP 6	Polytsi village	0.004
RNPP 8	city Varash	0.004
RNPP 9	Sopachiv village	0.003

In turn, the installation of a seismic sensor in the instrument well has the effect of reducing the level of the microseismic background by about one order of magnitude. A striking illustration of this effect is the comparison of the level of microseismic noise at the point of seismic observations RNPP 9 (Fig. 1) in the well at a depth of 33 m in dense rocks and on the surface at the point of seismic observations RNPP 2 (Fig. 2).

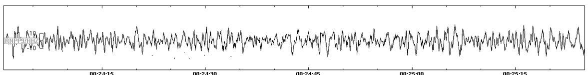

Fig. 1. Example of recording the microseismic background obtained at the point of seismic observations RNPP 9

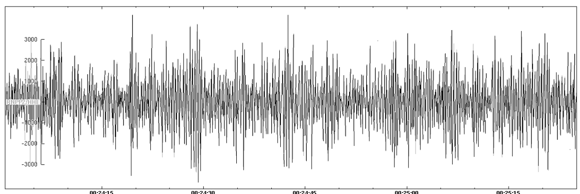

Fig. 2. Example of recording the microseismic background obtained at the point of seismic observations RNPP 2

The spectrum is the most objective characteristic of microseismic noise at a station. It is necessary to analyze a representative recording interval to obtain a stable estimate of the mean spectrum that characterizes the conditions for recording seismic oscillations. This interval should be greater, the longer the period of the microseisms under study [Harjes, 1990, GSE/US/79, 1992] is. Thus, an objective characteristic of the spectral properties of noise was obtained, which is a very important efficiency indicator of seismic network stations of RNPP in detecting useful signals.

Fig. 3 and Fig. 4 show the normalized noise spectra obtained from the records of the broadband seismometer CMG-SPB at the point of seismic observations RNPP 9 in the well at a depth of 33 m in dense rocks and on the surface at the point of seismic observations RNPP 2 in loose sedimentary rocks. It is clear that in contrast to surface seismic receivers when registering in a well at frequencies above 1 Hz there is a decrease in the density of the spectral power of noise by more than one order. This result shows that weak high-frequency signals can be detected only when registering in wells.

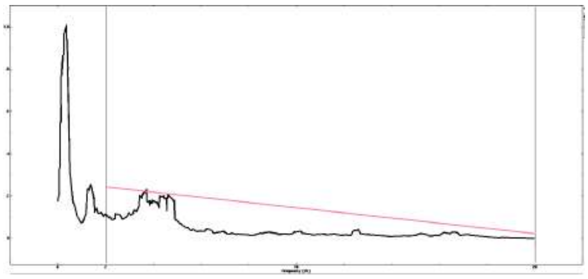

Fig. 3. Normalized noise spectrum obtained by recording the broadband seismometer CMG-SPB in the well at the point of seismic observations RNPP 9

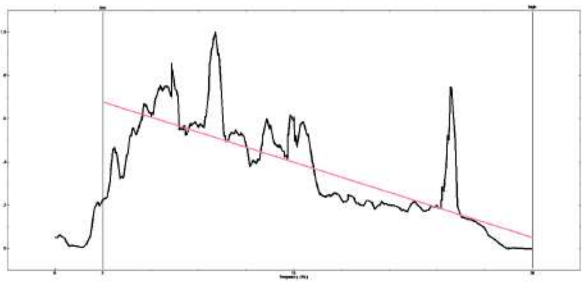

Fig. 4. Normalized noise spectrum obtained by recording the broadband seismometer CMG-SPB on the surface at the point of seismic observationsRNPP 2

Thus, it is possible to state the low efficiency of terrestrial geophysical observations in the registration of high-frequency signals from local seismic events in comparison with observations in wells. This is due to the fact that downhole observations are less dependent on the influence of geophysical noise associated with the influence of the earth's surface, namely: seismic, acoustic, deformation, electrical, magnetic and gravitational influence. Most of them are sensitive to variations in groundwater levels and weather conditions. Measurements in wells reveal subtle variations in geophysical fields associated with both local and global geodynamic processes.

At the same time, seismological observations on the day surface are necessary for the registration of "surface" noise, primarily man-made. In addition, the separation of signals from local and global geodynamic processes requires comparison of data obtained both in the well and on the surface with the results of observations of natural and man-made impacts on the earth's crust. This allows us to identify the effects of individual factors and to monitor the state of the earth's crust, to more accurately assess the background level of the microseismic field, and to quantify the energy parameters of registered seismic events.

In total, in the period from 2017 to 2021, 36 local earthquakes were registered by NPP seismic networks in Ukraine. The epicenters of the vast majority of them are located within the Ivano-Frankivsk, Ternopil and Lviv regions. The values of the magnitudes of seismic events are in the range from 1.9 to 4.3. The maximum epicentral distances, at which seismic networks of NPPs record local seismic events, are about 300 km [Andrushchenko et al., 2020].

During the instrumental observations at the seismic stations of the NPP, the most powerful earthquake was registered on September 23, 2021. Seismic recordings and spectrograms of the event, obtained using stations of the seismic network of the NPP, are presented in Fig. 5. The epicenter was located in the Ternopil region near Chortkiv, at a depth of 6 km. The intensity of shaking in the epicenter was 5 points on the MSK-64 scale. The largest number of reports of concussions came from the town of Chortkiv and nearby villages. This earthquake was also felt in the settlements of Kamyanets-Podilsky and Dunaivtsi at distances from the epicenter of 65–80 km.

Analyzing the parameters of this earthquake, we can also conclude that there is no need to change the source data to assess the seismic resistance of NPP sites. After all, the estimated intensity of shaking in the areas of Rivne, Khmelnytsky and Zaporizhzhya NPPs was 2.7, 2.5 and 0.9 points on the MSK-64 scale, respectively. There are requirements for seismic design and seismic safety assessment of nuclear power units [Requirements…, 2016]. They determine that for NPP units, regardless of the seismicity of the site, the peak value of the acceleration of the horizontal component of soil movement during an earthquake, corresponding to the maximum calculated earthquake, should be not less than 0.1*g*. That corresponds to the intensity of seismic oscillations of 7 points. Based on this, today there is no need to change the initial data to assess the seismic resistance of NPP sites.

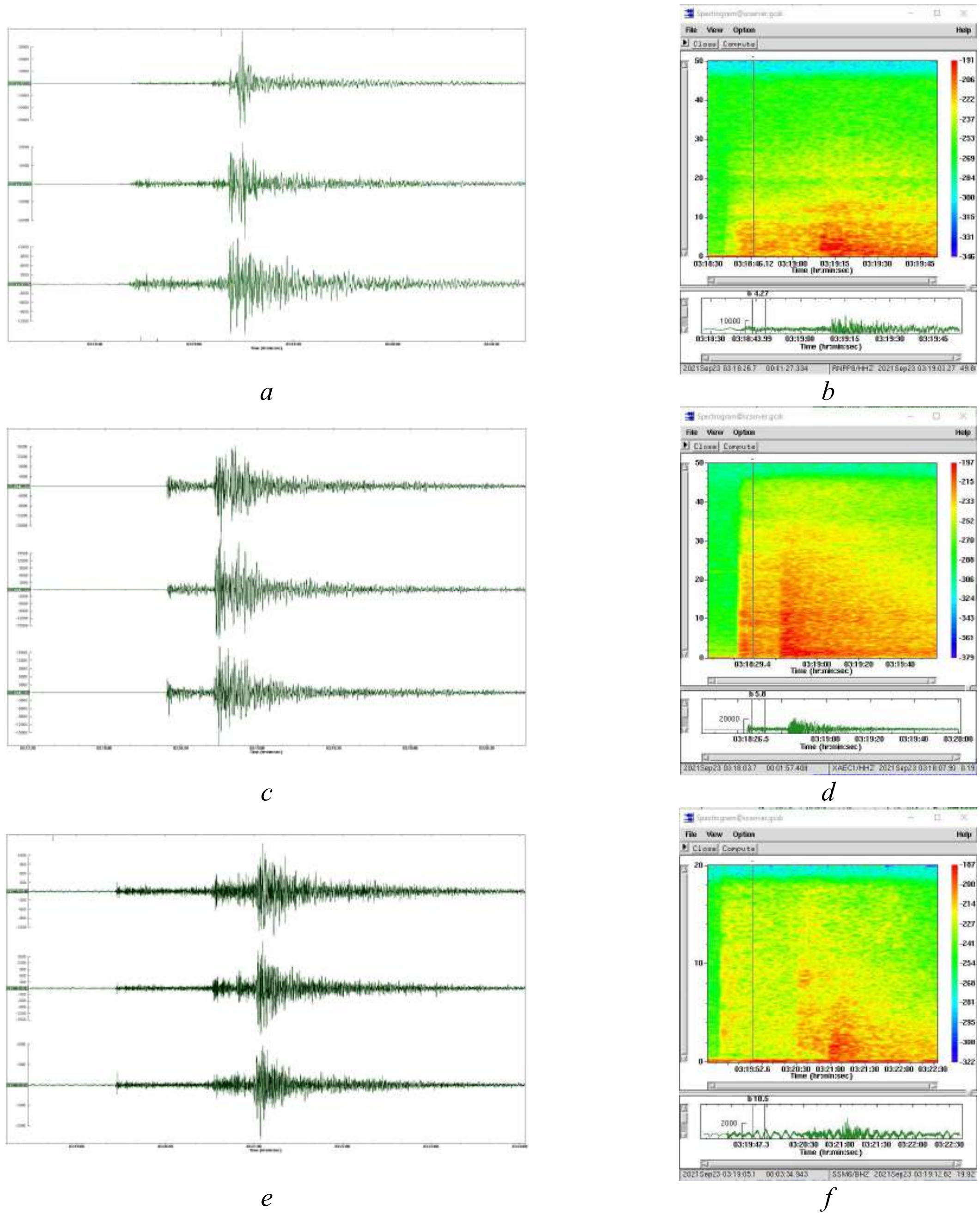

Fig. 5. Seismic records and spectrograms of the event on September 23, 2021, obtained using the stations of the seismic network of Rivne NPP (a, b), Khmelnitsky NPP (c, d) and Zaporizhzhya NPP (e, f)

The earthquake that occurred on February 19, 2021 is another seismic event that characterizes the capabilities of stations of the NPP seismological network. Fig. 6 presents seismic records and spectrograms of this event, obtained using stations of the NPP seismological network. The source of the earthquake was in the Donetsk region, at a depth of 12 km. The intensity of shaking in the epicenter was 1–2 points on the MSK-64 scale. Despite the small magnitude (M = 3.3) and the depth of the hypocenter, the earthquake was confidently registered by all stations of the NPP seismological network.

Originality

For the first time, the functional capabilities of seismic monitoring systems of Ukrainian NPPs were analyzed. A catalog of seismic events registered by NPP seismic stations was created according to the results of primary processing of seismic data in 2017–2021. The system of interpretation of the obtained results was improved. That allowed us to detect equally well local, regional and teleseismic events of different nature and energy levels.

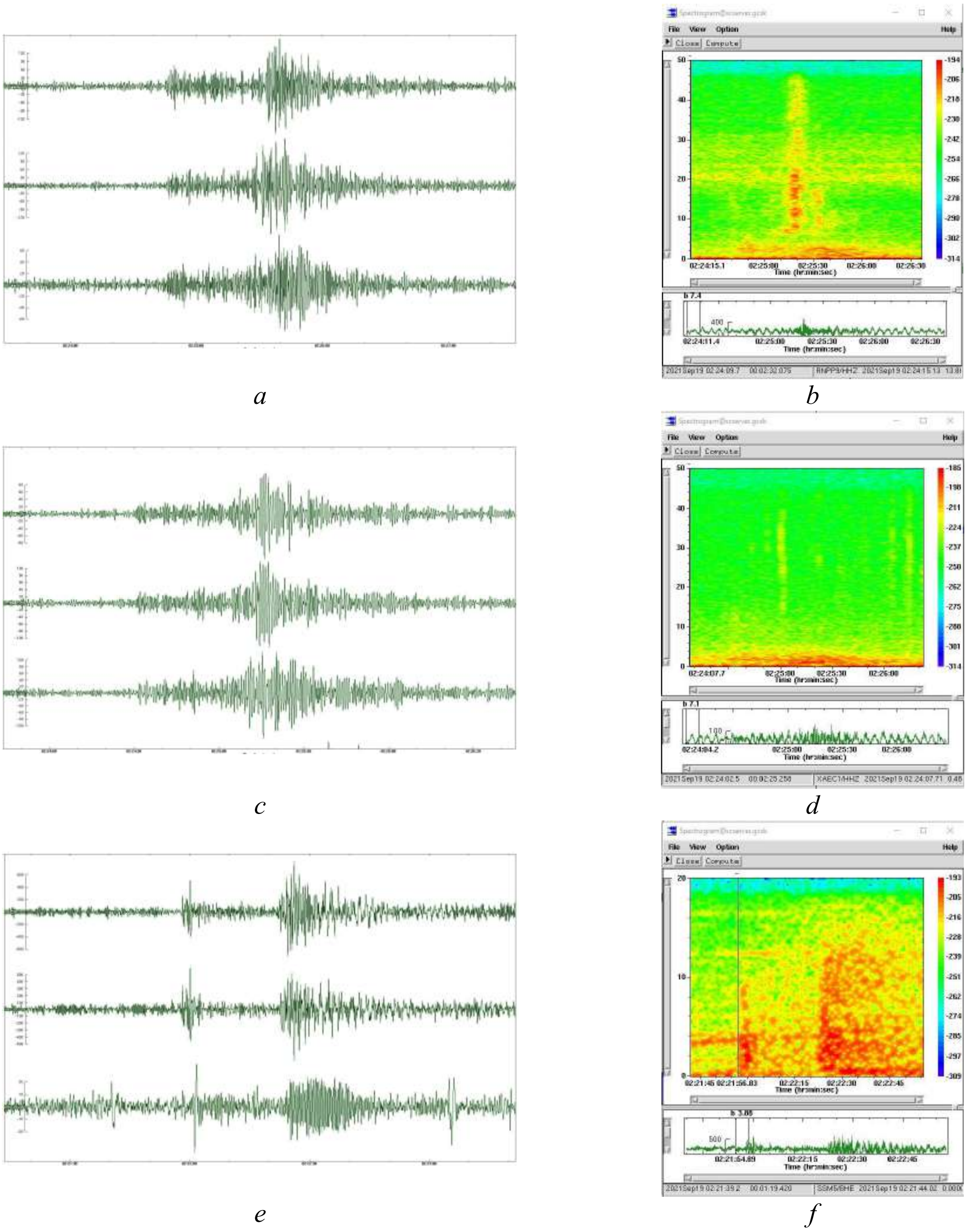

Fig. 6. Seismic records and spectrograms of the event on February 19, 2021, obtained using the stations of the seismic network of Rivne NPP (a, b), Khmelnitsky NPP (c, d) and Zaporizhzhya NPP (e, f)

Practical significance

The practical significance of the obtained results lies in their direct focus on solving a number of practical problems of processing and interpretation of seismological data. The use of NPP seismic stations as elements of the general system of seismological monitoring of Ukraine will improve the quality of detection and localization of sources and the probability of correct identification of the nature of seismic phenomena, which in turn will clarify the assessment of tectonic structures in Ukraine.

Conclusions

Specialists of the Main Center for Special Control of the SSA of Ukraine carried out detection and recognition of seismic signals using seismic monitoring systems of NPPs, as well as the formation of appropriate catalogs of seismic events. Hierarchical multilevel construction of automated systems of data collection, processing and storage was adopted during the processing of digital data received by the MCSC processing center from NPP seismological networks. This greatly simplifies the final result, as full processing is carried out in the NCD without additional computing resources. At the same time, NPP seismological networks are complete self-sufficient data collection and processing systems, and can act as elements in the system of the National Data Center of the National Seismic Observation System of Ukraine. The results of instrumental observations at the stations of the NPP seismological network testify to their high efficiency in the registration of seismic events of different nature and energy level on the territory of Ukraine. NPP seismic stations confidently register local earthquakes, the epicenters of which are located on both the right-bank and left-bank parts of Ukraine. Thus, the considered seismic stations can be used not only to clarify the quantitative parameters of seismological influences on the industrial sites of nuclear power plants, but also to be full-fledged components of the seismological monitoring system of Ukraine.

References

Andrushchenko, Y. A., Osadchy, V. I., Liashchuk, A. I., & Kornienko, I. V. (2020). Instrumental observations at the Rivne NPP permanent seismic monitoring network. *Geofizicheskiy Zhurnal*, *42*(4), 133–141. https://doi.org/10.24028/gzh.0203-3100.v42i4.2020.210677

Antonova, L., & Aptikaev, F. (2004). The level of short-period microseismics in Russia and neighboring countries. Research in the field of geophysics. *Jubilee collection of OIFZ RAS*, 43–53 (in Russian).

Bratt, S. R., & Bache, T. C. (1988). Locating events with a sparse network of regional arrays. *Bulletin of the Seismological Society of America*, *78*(2), 780–798. https://doi.org/10.1785/BSSA0780020780

Coyne, J., Clark, K., & Lloyd, S. (2003). IDC Documentations Geotool Software User Tutorial/J. *Coyne, K. Clark, S. Lloyd.–16 July*, *59*.

GSE/US/79. High-frequency noise characteristics of stations participating in the Group of scientific experts Second technical test April 22 – June 2, 1991 (Committee on Disarmament), 1992. 130 p.

Gutenberg, B. (1958). Microseisms. In *Advances in geophysics* (Vol. 5, pp. 53–92). Elsevier.

Harjes, H. P. (1990). Design and siting of a new regional array in Central Europe. *Bulletin of the Seismological Society of America*, *80*(6B), 1801–1817.

Requirements for seismic design and seismic safety assessment of nuclear power units: NP 306.2.2082016. Official Gazette of Ukraine. 2016. No. 92, p. 3013 (in Ukrainian).

Regulations on the national system of seismic surveys to improve the safety of the population in seismically dangerous regions. (1997). *Official Gazette of Ukraine,* 28, p. 68 (in Ukrainian).

Ryzhov, D., Shugailo, O., Shugailo, O-y, Buryak, R., Khamrovska, L., & Krytska, N. (2012). Review of modern international approaches to seismic design and assessment of seismic hazard of NPP power units. *Nuclear and radiation safety*, 4 (56), 23–26 (in Ukrainian).

Ryzhov, D., Shugailo, O-y, Kendzera, O., Inyushev, V., Shugailo, O-y, & Buryak, R. (2013). Application of modern international approaches to seismic hazard assessment of Ukrainian NPP sites. *Nuclear and radiation safety*, 3 (59), 16–20 (ISSN 2073-6237). (in Russian).

Ryzhov, D., Shugailo, O., Shugailo, O-y, Kendzera, O., Maryenkov, M., Shenderovich, V., & Buryak, R. (2017). On modern requirements for seismic design and assessment of seismic safety of power units of nuclear power plants of Ukraine. *Nuclear and radiation safety,* 2 (74), 9–13. ISSN 2073-6231 (in Ukrainian). http://dspace.nbuv.gov.ua/handle/123456789/97255

Savarensky, E., & Kirnos, D. Elements of seismology and seismometry M.: GITL. 1955. 543 p. (in Russian).

Vinnik, L. (1968). The structure of microseismics and some questions of grouping methods in seismology. M.: Science. 104 p. (in Russian).

Zhigalin, A., & Lokshin, G. (1987). Technogenic vibrational impact on the geological environment. *Engineering technology*, 3, 86–92.

Юрій АНДРУЩЕНКО[1a], Олександр ЛЯЩУК[1b]

[1] Головний центр спеціального контролю НЦУВКЗ ДКА України, вул. Космічна, 1, смт Городок, Радомишльський р-н, Житомирська обл., 12265, Україна, тел. +38(096)2152823, ел. пошта: andruschenko_yuriy@ukr.net, [1a] https://orcid.org/0000-0001-8993-0113, [1b] https://orcid.org/ 0000-0002-8690-1808

ЛОКАЛЬНІ СЕЙСМОЛОГІЧНІ МЕРЕЖІ АТОМНИХ ЕЛЕКТРОСТАНЦІЙ УКРАЇНИ ЯК СКЛАДОВІ ЧАСТИНИ НАЦІОНАЛЬНОЇ СИСТЕМИ СЕЙСМОЛОГІЧНОГО МОНІТОРИНГУ

Мета роботи – визначити можливість використання локальних сейсмологічних мереж атомних електростанцій як елементів системи сейсмологічного моніторингу території України. Оцінювання місцевої сейсмічності та уточнення кількісних параметрів сейсмологічних впливів здійснено на основі матеріалів сейсмологічних спостережень. Оперативне опрацювання та аналіз сейсмічних сигналів, зареєстрованих на елементах локальних сейсмологічних мереж АЕС, здійснює Головний центр спеціального контролю Державного космічного агентства України (ГЦСК ДКА України). У ході виконання “Плану заходів з оцінки сейсмічної небезпеки і перевірки сейсмостійкості діючих АЕС” на АЕС України розгорнуто мережі сейсмологічного моніторингу. Сьогодні до ГЦСК у безперервному режимі надходять дані із локальних сейсмологічних мереж Рівненської, Хмельницької та Запорізької АЕС. Геофізичну інформацію, яка надходить з АЕС до ГЦСК, опрацьовує оперативна чергова зміна центру за допомогою технічних та програмних засобів ГЦСК, що забезпечує отримання достовірних даних про параметри, зареєстровані станціями сейсмічних джерел, їх локалізацію та енергетичні характеристики. Загалом, у 2017–2021 рр. станції сейсмологічних мереж АЕС зареєстрували 36 локальних землетрусів на території України. Епіцентри п ереважної більшості з них містяться у межах Івано-Франківської, Тернопільської та Львівської областей. Досвід проведення інструментальних спостережень на сейсмічних станціях АЕС свідчить про їх високу ефективність та можливість використання як повноцінних елементів системи сейсмологічного моніторингу території України. Вперше проаналізовано функціональні можливості систем сейсмічного моніторингу АЕС України. За результатами первинної обробки сейсмічних даних 2017–2021 рр. створено каталог сейсмічних подій, зареєстрованих сейсмічними станціями АЕС. Удосконалено систему інтерпретації отриманих результатів, що дало змогу однаково добре визначати локальні, регіональні та телесейсмічні події різної природи та енергетичного рівня. Практичне значення одержаних результатів полягає в їх безпосередній спрямованості на розв’язання низки практичних задач обробки та інтерпретації сейсмологічних даних. Використання сейсмічних станцій АЕС як елементів загальної системи сейсмологічного моніторингу України дасть змогу підвищити надійність виявлення та локалізації джерел та імовірність правильної ідентифікації природи сейсмічних явищ, що, своєю чергою, покращить оцінку активності тектонічних структур України.

Ключові слова: атомна електростанція; сейсмічна подія; сейсмологічний моніторинг; сейсмоприймач; мікросейсми; епіцентр.

Received 22.10.2021