Features of creating an automatically controlled system of detecting and identifying the seismic signal bulk waves from high potential events of technogenic and natural origin

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***Abstract*—In order to develop a scientific-technical basis for creating an automatically controlled seismic monitoring system, this paper studies angular characteristics peculiarities of the seismic signal components resulting from the events with foci in the regional zone. Based on the angular characteristics analysis, the approaches are proposed for detecting and identifying automatically of the seismic signal bulk waves arising as a result of high potential events of technogenic and natural origin with foci in the regional zone. The proposed approaches implementation makes it possible to reduce the time of seismic record processing with appropriate reliability.**

***Keywords*—automatically controlled monitoring system, earthquake, seismic waves, seismic signal, signal detection, signal identification, seismic monitoring, three-component seismic station**

I. Introduction

Many processes that occur during the natural-technogenic-social functioning of the Earth's system, as well as their mutual transformation, generate many emergency situations (emergencies, ES) of natural, technogenic and military origin. Among them, earthquakes, nuclear weapons tests, tsunami, volcanic eruption, floods, hurricanes, accidents at nuclear power facilities, warfare conducting and others, are the most dangerous for the Earth's biosphere.

Over the past few decades of human activity, a tendency has established to a sharp increase in the volume and destructive power of various emergencies. This leads to a worsening of socio-economic and ecological consequences, thereby indicating the need to develop effective measures for the prevention and managing emergencies of various nature on the Earth.

A promising direction for solving this problem is the effective development of a system for detecting hazardous factors at their inception stage, identifying the causes of their manifestation, as well as an impact on them in order to prevent emergencies. It can be implemented on the basis of the classical control loop, schematically presented in Fig. 1 [1–14].

This work is part of a planned scientific research set aimed at developing a security system that enables elimination or minimization to the maximum of losses during emergencies. It is focused on studying the processes of occurrence and propagation of seismic emergencies that constitute or may constitute a serious danger to the society life.

In order to create an automatically controlled system for the detection and identification of the seismic signal bulk waves resulting from high potential events of technogenic and natural origin, the angular characteristics peculiarities of the components of seismic signal from the events with foci in the regional zone are studied in the paper. Thus, one of the main stages of processing a seismic signal detected according to the seismic observation results using a three-component seismic station (TCSS) is the identification of the main seismic waves types.

Based on the results of the seismic waves types identification, it is possible to obtain the following information about the seismic source parameters: a) azimuth on the seismic event center – as the ratio of the first entry components of the seismic signal on horizontal channels; b) distance to the seismic event center – as the difference in the time of bulk seismic waves entry; c) identification of the seismic source nature – natural (earthquake) or technogenic (explosion) origin, by comparing the energy characteristics of the extensional and transverse seismic waves; d) seismic event intensity – is assessed based on data on the amplitude and period of soil vibration for each of the main seismic waves types, as well as by the distance to the seismic event source.

The task of detecting and identifying the main seismic waves types for an event in a regional zone (for distances $\Delta = 100 \div 500\, km$) is very difficult, since the entry of the next wave type of a seismic signal occurs against the background of the previous wave tail.

At present, the seismic waves types identification in the institutions of the Main Center for Special Control of the State Space Agency of Ukraine (SSAU) is performed by the operator according to the analysis results of the total seismic signal. The accuracy of determining the seismic signal components and their parameters depends on the operator qualification level. In addition, approaches to determine the types of waves in manual processing cannot be controlled automatically.

Thus, the issue of methodological approaches development for detecting and identifying the main seismic waves types in an automatic mode in order to increase the decision-making efficiency relative to a seismic event, as well as timely warning of relevant bodies and services is acute.

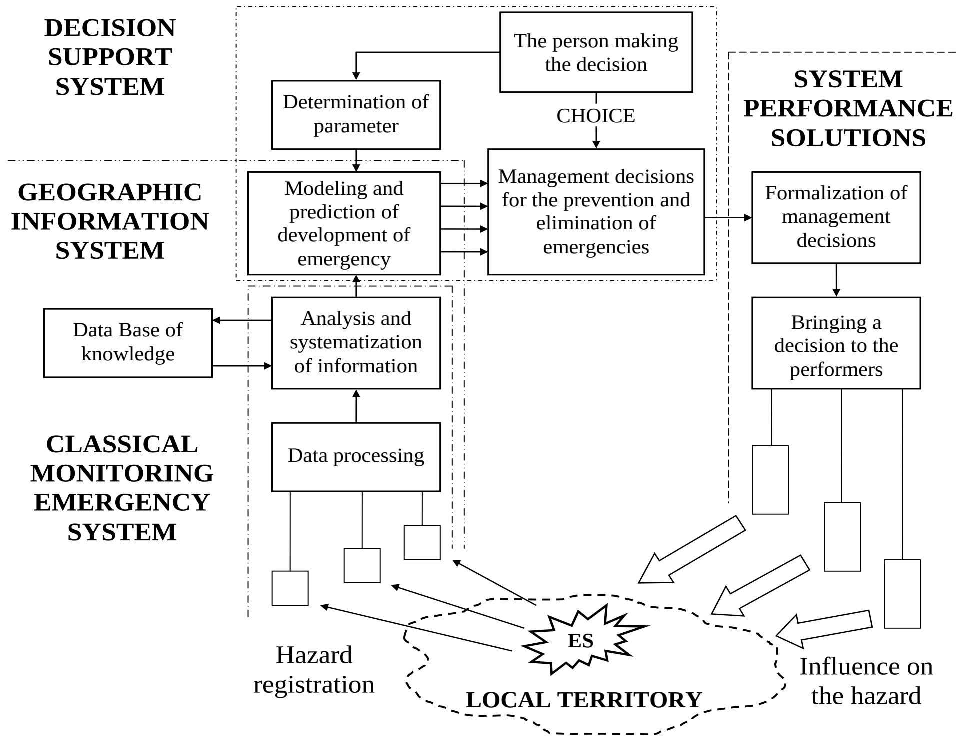

Fig. 1. Diagram of the emergencies monitoring structure as a means of control

II. Unresolved Issues

Currently, the automatic identification algorithms of the seismic signal components, which are based on the frequency characteristics of the main seismic waves types, are widely used for three-component seismic station [15–25]. However, seismic detectors with a wide frequency range are required for their implementation. For the currently existing network of seismic observations at the Main Center for Special Control of the State Space Agency of Ukraine, the seismic detectors of this type account for less than 25% of the total quantity.

Due to the seismic observation network peculiarities of the Main Center for Special Control of the State Space Agency of Ukraine, today there is an acute question of methodological approaches development for identifying the main seismic waves types resulting from hazardous events of technogenic and natural origin in the nearest zone on the basis of additional information criteria. As such criteria, the angular characteristics of the seismic signal components are promising.

III. Main Part

Currently, the angular characteristics are calculated only for the first seismic wave entry (P–waves) – the azimuth of the seismic wave entry α and the angle of the wave exit to the daylight surface γ, which are used to calculate the location of the seismic event source (SES).

To calculate the values of azimuth and the angle of the seismic wave exit according to the observation results of the three-component seismic station, the values of signal levels that arise on the P-wave in the channels oriented north-south A_x, east-west A_y, compression-rarefication A_z are used. The calculation is performed according to the expressions:

$$\alpha = arctg \frac{A_x}{A_y}, \tag{1}$$

where α – azimuth of the seismic wave entry;

$$\gamma = arctg \frac{A_z}{\sqrt{A_x^2 + A_y^2}}, \qquad (2)$$

where γ – angle of the seismic wave exit to the daylight surface.

However, this approach can be used only for surface or near-surface ($H < 15\,km$) seismic sources. For sources with significant depth, such as, for example, earthquakes in the Vrancea region (Romanian part of the Carpathians) with depth of foci $H = 80 \div 170\,km$, the use of this approach, when processing measurement information in automatic mode, can lead to erroneous determination of the seismic event source location. This is conditioned by the fact that the information about the azimuth and the angle of the seismic signal exit to the daylight surface, obtained from the results of processing of the first seismic signal entry at the observation point (OP), determines the parameters of the seismic signal propagation path, but does not determine the seismic event source (SES) location on it (Fig. 2).

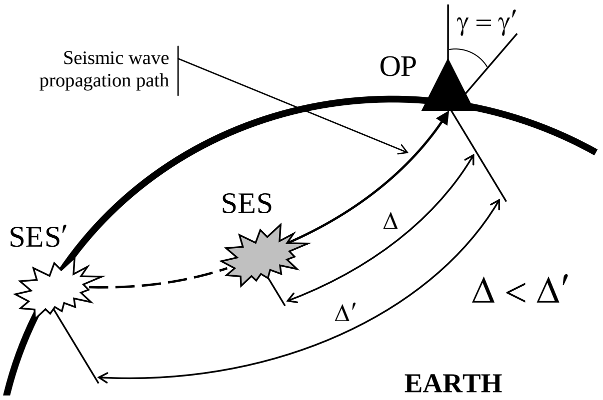

Fig. 2. The scheme of an error occurrence when determining the SES position based on the angular characteristics assessment result of the first seismic signal entry

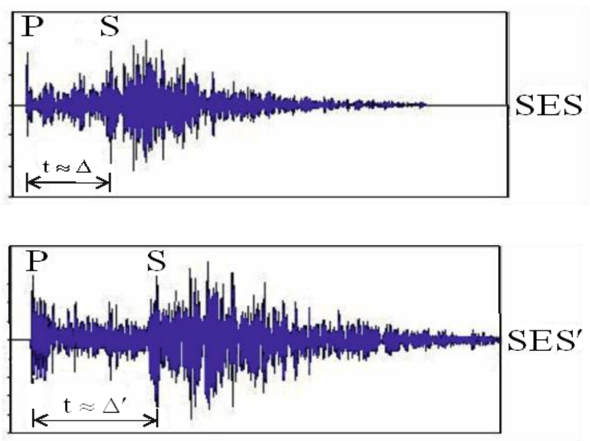

Fig. 3. Signalogram from seismic events with the same angular characteristics – $\alpha = \alpha'$, $\gamma = \gamma'$, and different distance from SES to OP – $\Delta < \Delta'$, which corresponds to the difference between the time of the bulk waves entry $t < t'$

Figure 3 shows the examples of recording seismic signals with the same angular characteristics for different seismic event sources ($\alpha = \alpha'$, $\gamma = \gamma'$). Wherein, the distances between the observation points and the epicenters of seismic events are different ($\Delta < \Delta'$), which corresponds to the difference between the time of bulk waves entry ($t < t'$).

To increase the accuracy of determining the seismic event source location according to the observation results of three-component seismic station, it is necessary to use additional information about the distance between the observation point and the event epicenter Δ. Such information can be obtained by detecting and identifying the main seismic signal components, with subsequent using a residual time curve.

From the seismic event epicenter (earthquake or explosion), the soil elastic vibrations are propagated in all directions. These vibrations are propagated over considerable distances from the epicenter and are an important source of information for identifying a seismic phenomenon and assessing its parameters.

According to the nature of the soil movement during the seismic waves propagation, they are divided into bulk – extensional (P), transverse (S) and surface – L_r - Rayleigh waves and L_q - Love waves.

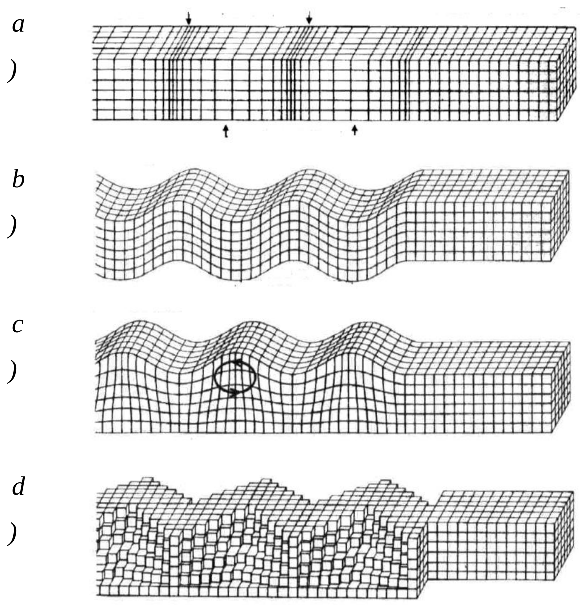

Fig. 4. The nature of the soil displacement for different seismic waves types

In P-waves, compression and rarefication of soil particles occurs in the direction of wave propagation (Fig. 4, a). In Fig. 4, the areas of compression and rarefication are indicated by arrows. For S-waves, the soil displacement occurs perpendicular to the direction of wave propagation (Fig. 4, b). Along with bulk waves, surface waves can also propagate over the Earth. These waves are of two types: Rayleigh waves (L_r) and Love waves (L_q). In a Rayleigh wave, the soil particles are displaced in a vertical plane oriented along the direction of wave propagation, and their trajectories are ellipses (Fig. 4, c). In a Love wave, particles move in a horizontal plane, transversely to the direction of wave propagation (Fig. 4, d).

After the seismic waves types are determined and the time of their entry is estimated, the distance from the observation point to the seismic event focus is assessed using a residual time curve. Fig. 5 demonstrates a residual time curve – a dependency graph of the wave propagation time from the source to the seismic detector on the epicentral distance for the nearest zone.

A slight difference in propagation time, as a result of small distances, leads to the fact that each subsequent phase of the seismic signal occurs against the background of the previous wave tail, which makes it difficult to identify the seismic signal components in automatic mode.

Given the peculiarities of the soil particles displacement for each of the main seismic waves types for the event with foci in the regional zone, the angular characteristics of these waves will depend on the seismic source position relative to the observation point as follows: P-wave – since the soil particles vibration occurs along the propagation direction, so the azimuth of the seismic wave entry coincides with the azimuth on the seismic source; S-wave – due to the fact that soil vibration during this phase occurs perpendicular to the direction of wave propagation, therefore, the calculated azimuth of the wave entry will differ from the actual one by 90°; L_r-wave – a surface wave with elliptical polarization, oriented perpendicular to the propagation direction, therefore, the calculated azimuth will also differ from the actual one by 90°; L_q-wave - a surface wave with elliptical polarization in the propagation direction, therefore, the calculated azimuth will coincide with the actual azimuth on the seismic source.

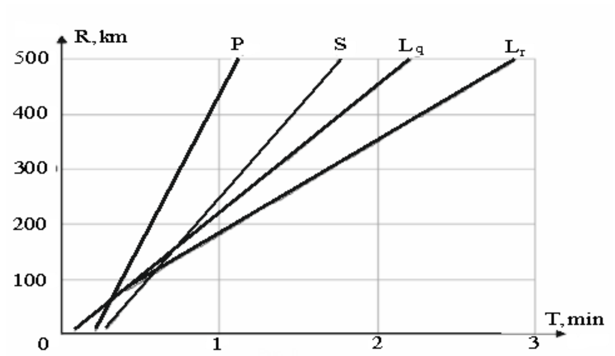

Fig. 5. Residual time curve of different seismic waves types for a regional zone

Thus, the identification of the seismic signal components can be implemented using the peculiarities of their angular characteristics, such as searching for areas of a seismic signal recording, for which the conditions are satisfied $(\alpha_P \cap \gamma_P) \cup (\alpha_P + 90^\circ \cap \gamma_P)$, where α_P and γ_P – are angular characteristics of P-wave.

For the seismic events with foci in the regional zone, it is expedient to be limited to detection and identification of only bulk waves, since for a group of surface waves, due to relatively small distances, the difference in the time of surface waves entry between themselves and the S-wave is insignificant, which leads to a complex wave pattern.

Fig. 6a shows the vertical component of the signal seismic recording from an earthquake at the territory of Romania with the focus in the Vrancea region (09/03/2019, $M = 4.5$), which was recorded by the Malin seismic station (Zhytomyr region), as well as the calculation results of the second interval azimuth distribution for areas of recording, corresponding to P and S-waves.

As can be seen from the seismic recordings, for the background (Fig. 6 b) the azimuth distribution does not have a clearly expressed maximum. As for bulk waves, there are clearly expressed maxima, and the difference between the maxima is ≈ 90° (Figs. 6 c, d).

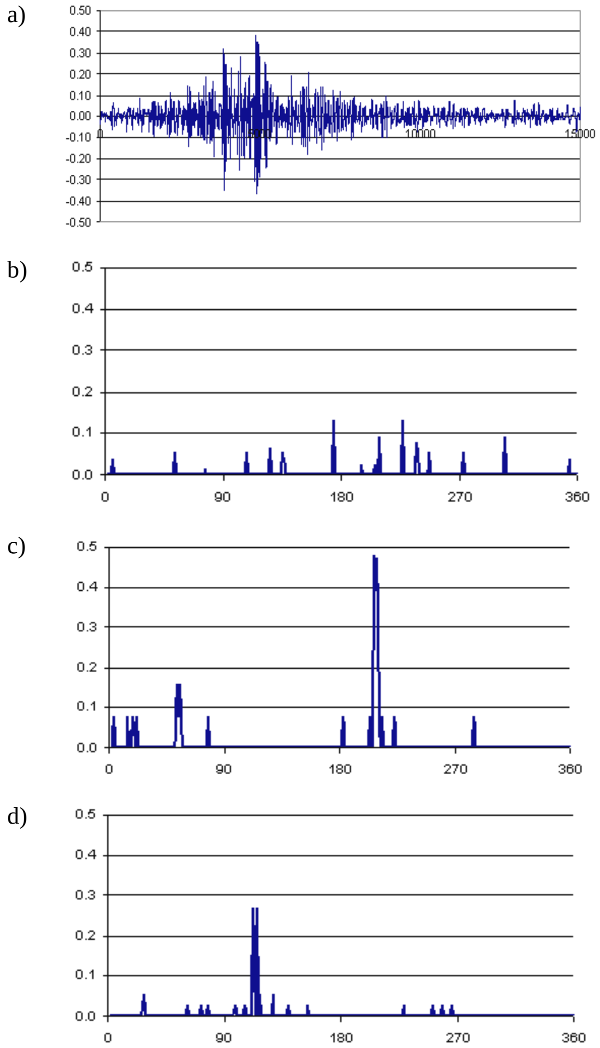

Fig. 6. The vertical component of the seismic signal from an earthquake in the Vrancea region (a) and normalized values of azimuth distribution for areas of recording: b – background; c – P-wave; d – S-wave

The difference error between the calculated azimuths is conditioned by the fact that the S-wave enters in the tail part of the P-waves. Similar differences in the azimuths of the P and S-waves entry were observed for other seismic sources of both natural and technogenic origin.

The orthogonality peculiarities of the calculated azimuths for bulk waves can be the basis for the seismic signals automatic identification algorithm.

Given the foregoing, the algorithm for the automatic processing of measurement information at the three-component seismic station output, using the angular characteristics peculiarities, will include the following stages: 1 stage – signal detection; 2 stage – assessing the first entry angular characteristics (P-waves) – α_p and γ_p; 3 stage – search for areas of a seismic signal recording with angular characteristics, corresponding to the S-wave – $\alpha_p + 90°$ and γ_p; 4 stage – assessing the distance to a seismic source using a residual time curve; 5 stage – assessing the seismic source coordinates; 6 stage – assessing the seismic source parameters – time, magnitude and seismic event type.

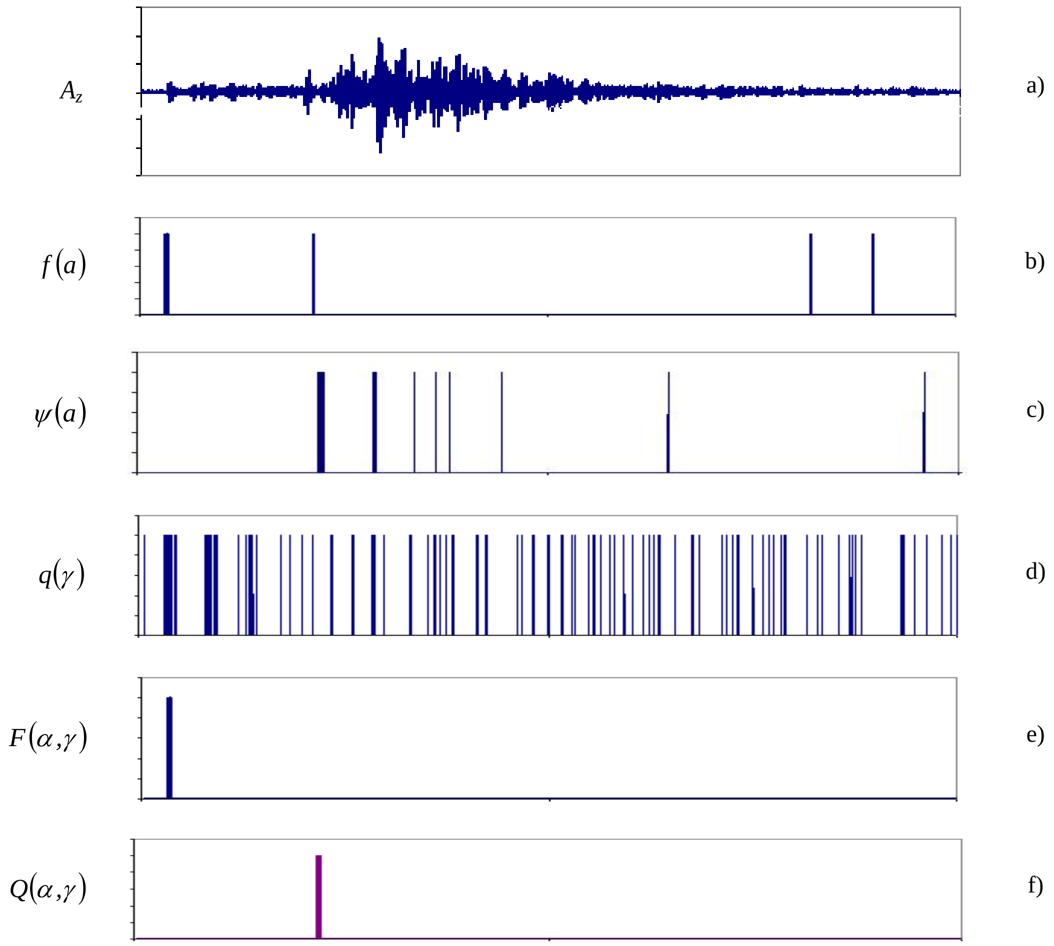

Fig. 7. The results of determining bulk waves for a seismic signal from an earthquake in the Vrancea region: a – vertical component A_z; b – $f(a)$; c – $\psi(a)$; d – q(γ); e – $F(\alpha,\gamma)$; f – $Q(\alpha,\gamma)$

Fig. 7 shows the results of determining bulk waves based on the angular characteristics analysis for a signal from an earthquake in the Vrancea region that occurred on January 31, 2020 with a magnitude of $M = 5.1$, the focus depth is 145 km.

For the first entry (P-wave), the angular characteristics α_p and γ_p were assessed. Based on the these assessments results, a search was made for areas of recording, for which the angular characteristics correspond to the conditions:

$$f(a) = \begin{cases} 1, \alpha = \alpha_p \\ 0, \alpha \neq \alpha_p \end{cases} \quad (3)$$

$$\psi(a) = \begin{cases} 1, \alpha = \alpha_p + 90° \\ 0, \alpha \neq \alpha_p + 90° \end{cases} \quad (4)$$

$$q(\gamma) = \begin{cases} 1, \gamma = \gamma_p \\ 0, \gamma \neq \gamma_p \end{cases} \quad (5)$$

Azimuth and exit angle is calculated by the formulas (1, 2). The decisions on the appropriate seismic signal phases are made in accordance with:

for P-wave

$$F(\alpha,\gamma) = f(\alpha) \cdot q(\gamma), \quad (6)$$

for S-wave

$$Q(\alpha,\gamma) = \psi(\alpha) \cdot q(\gamma). \quad (7)$$

As it can be seen from Fig. 7, based on the angular characteristics estimation of the first entry (P-wave), the signal phase has been determined that corresponds to the S-wave. The time difference between the P and S-waves entry, calculated by this algorithm, is 1 minute 6 seconds, which coincides with the results obtained using a residual time curve.

Thus, the methodology presented in the work for processing the seismic signal from emergencies sources of various origins allows, within the framework of the proposed algorithm, to diagnose the seismic phenomenon in automatic mode based on a comprehensive analysis of the geographic coordinates of the seismic wave source, its nature and type, amplitude-frequency characteristics and other parameters. It is performed with an increased degree of reliability and a significant time reduction in the processing information on hazard and making managerial decisions aimed at minimizing the emergency consequences.

IV. Conclusion

A relation has been established between the characteristics of the seismic signal main components depending on the events with the foci in the regional zone, as well as between the angular characteristics of the seismic event focus relative to the observation point.

The bases are formed and an approach is proposed for detecting and identifying the seismic signal components in an automatic mode, depending on the angular characteristics peculiarities of the seismic signal components.

An algorithm has been developed for the automatically controlled processing of measurement information at the three-component seismic station output using the angular characteristics peculiarities of the seismic event focus determined in the work.

Implementation of the proposed approaches makes it possible with appropriate reliability to significantly reduce the time of processing a seismic record as compared to manual processing.

References

[1] The Code of Civil Protection of Ukraine dated October 2, 2012, No.5403-VI. (*in Ukrainian*)

[2] I. Petriv, “Constitutional and legal concept of national security,” *The law of Ukraine*, 2005, vol. 5, pp. 105–107. (*in Ukrainian*)

[3] V.P. Ghorbulin, and A.B. Kachynsjkyj, “Strategic Planning: Solving National Security Issues: A Monograph,” National Institute for Strategic Studies, 2011. (*in Ukrainian*)

[4] A.B. Kachynsjkyj, “National Security Indicators: Definition of their Limit Values: Monograph,” National Institute for Strategic Studies, 2013. (*in Ukrainian*)

[5] V.V. Cyghanov, “National Security: Problems in Defining and Evaluating Effectiveness,” *Strategic priorities*, 2013, vol. 3, pp. 122–127. (*in Ukrainian*)

[6] On Approval of the Regulations on the Uniform State Civil Protection System. Resolution of the Cabinet of Ministers of Ukraine dated January 9, 2014, No.11. (*in Ukrainian*)

[7] V. Tiutiunyk, V. Kalugin, O. Pysklakova, A. Levterov, and Ju. Zakharchenko, “Development of Civil Defense Systems and Ecological Safety”, *IEEE Problems of Infocommunications. Science and Technology*, October, 2019, pp. 295–299.

[8] M.M. Kuleshov, V.P. Sadkovyi, and V.V. Tiutiunyk, “State system of civil protection”, National University of Civil Defence of Ukraine, 2020. (*in Ukrainian*)

[9] V.A. Andronov, M.M. Diviziniuk, V.D. Kalugin, and V.V. Tiutiunyk, “Scientific and design basis for the creation of a comprehensive system for monitoring emergencies in Ukraine: Monograph,” National University of Civil Defense of Ukraine, 2016. (*in Ukrainian*)

[10] R. Bojanc, and B. Jerman-Blažic, “An Economic Modelling Approach to Information Security Risk Management,” *International Journal of Information Management*, 2008, pp. 413–422.

[11] B. Fahimnia, C.S. Tang, H. Davarzani, and J. Sarkis, "Quantitative models for managing supply chain risks: A review", *European Journal of Operational Research*, 2015, No.247, pp. 1–15.

[12] S. Haugen, J.E. Vinnem, "Perspectives on risk and the unforeseen", *Reliability Engineering and System Safety*, 2015, No.137, pp. 1–5.

[13] F. Khan, S. Rathnayaka, and S. Ahmed, "Methods and models in process safety and risk management: Past, present and future", *Process Safety and Environmental Protection*, 2015, No.98 , pp. 116–147.

[14] V.N. Burkov, D.A. Novikov, and A.V. Shchepkin, "Simulation models for control mechanisms in ecologicaleconomic systems", *Studies in Systems, Decision and Control*, 2015, Vol.10, pp. 117-154.

[15] L. Boschi, C. Weemstra, "Stationary-phase integrals in the cross correlation of ambient noise", *Reviews of Geophysics*, 2015, No.53, pp. 411–451.

[16] H.H. Huang, F.C. Lin, V.C. Tsai, and K.D. Koper, "High-resolution probing of inner core structure with seismic interferometry", *Geophysical Research Letters*, 2015, No.42, pp. 10622–10630.

[17] T. Wang, X. Song, and H.H. Xia, "Equatorial anisotropy in the inner part of Earth's inner core from autocorrelation of earthquake coda", *Nat. Geosci*., 2015, No.8, pp. 1–4.

[18] P. Poli, M. Campillo, and M. Hoop, "Analysis of intermediate period correlations of coda from deep earthquakes. Earth Planet", *Sc. Lett*., 2017, No.477, pp. 147–155.

[19] T.S. Phạm, H. Tkalčić, M. Sambridge, and B. Kennett, "Earth's Correlation Wavefield: Late Coda Correlation. Geophys", *Res. Lett*., 2018, No.45, pp. 3035–3042.

[20] J. Santos, A.N. Catapang, and E.D. Reyta, "Understanding the Fundamentals of Earthquake Signal Sensing Networks", *Analog Devices*, 2019, Vol.53, No.3. https://www.analog.com/en/analog-dialogue/articles/understanding-the-fundamentals-of-earthquake-signal-sensing-networks.html

[21] V. Tkachov, M. Hunko, "Quest Method for Organizing Cloud Processing of Airborne Laser Scanning Data", *IEEE 8th International Conference on Advanced Optoelectronics and Lasers (CAOL)*, Sozopol, Bulgaria, 2019, pp. 565–569.

[22] V. Tiutiunyk, V. Kalugin, O. Pysklakova, O. Yaschenko, and T. Agazade, "Hierarchical clustering of seismic activity local territories Globe", *EUREKA: Physics and Engineering*, 2019, No.4, pp. 41–53.

[23] Lei Li, Pierre Boué, and Michel Campillo, "Observation and explanation of spurious seismic signals emerging in teleseismic noise correlations", *Solid Earth*, 2020, No.11, pp. 173–184.

[24] Zheng-Yi Feng, Chia-Ming Hsu, and Shi-Hao Chen, "Discussion on the Characteristics of Seismic Signals Due to Riverbank Landslides from Laboratory Tests", *Water*, 2020, Vol.12, No.83, pp. 1–19.

[25] V. Tiutiunyk, L. Chernogor, O. Tiutiunyk, and T. Agazade, "Neural network forecasting of earth globe seismic activity level", *CEUR Workshop Proceedings*, 2020, No.2608, pp. 886–899.