Application of Polarization-Time Model Seismic Signal for Remote Monitoring of Potential Sources Emergencies by Three-Component Seismic Station

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Abstract

The aim of the work is to develop theoretical foundations aimed at improving efficiency of detecting hazard factors related to natural and man-made disasters based on the results a seismic observation. An analysis of seismic monitoring equipment operated by the Main Center for Special Control of State Space Agency of Ukraine and methods of seismic data processing was carried out. Various components of seismic signals from events with epicenters in the regional zone was analyzed. A relationship was established between location of seismic event location relative to seismic observation station and angular characteristics of main seismic signal components for events with regional epicenters. In order to reduce the time of providing preliminary information to users about the fact of a seismic event and its seismic source parameters, it is proposed to move from a search task of determining focal point location to remote monitoring of potential sources of natural and man-made disasters. In order to realize continuous remote monitoring for potential sources of emergency events, a polarization-time model was proposed for expected seismic signal from an event with a focal point in a controlled area (object). Results of applying the proposed approach for detecting seismic signals from earthquakes with foci in the regional zone are presented. Relative simplicity of implementing our approach allows monitoring potential sources an emergency events in a time mode close to real time. Parameters of a polarization-time model of seismic signals for nuclear power plants in Ukraine and hydraulic structures of the Dnipro cascade are presented. At the same time, this work is included in a broader set of studies aimed at improving existing and creating new theoretical foundations for detecting seismic hazards of natural and man-made origin. In addition, this research covers processes of occurrence and propagation of seismic emergencies that may threaten society's vital activity.

Keywords [1]

Emergency events, Earthquake, seismic signal, three-component seismic station, signal detection, seismic waves, polarization-time model of seismic signal, seismic monitoring, automatically controlled monitoring system, source of emergency

1. Introduction

The interaction of natural, technological, and social systems on Earth leads to the emergence of numerous emergency situations that can have natural, technological, or military origins. Among these emergencies, the most dangerous for the Earth's biosphere are earthquakes, floods, hurricanes, accidents at nuclear power facilities, military actions, and others that can have a serious impact on human life and the ecological balance of the planet.

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Recently, disasters have become global in nature. Population growth increases the scale of consequences from natural disasters as more and more people are forced to live in dangerous places, which are located in areas of flooding, landslides, earthquakes, etc. Examples of this are catastrophic consequences of powerful earthquakes in recent decades – China (2008), Japan (1995, 2011), Haiti (2010), Indonesia (2004), Turkey (1999, 2023), and others.

Ukraine is no exception. In certain regions of Ukraine with a high population density, there are high-risk facilities, which dramatically increases risk of possible natural disasters, accidents and catastrophes. Every year, natural and technological ES occur in our country, leading to loss of life and significant material damage [1-4]. Hostilities as a result of Russia's armed aggression increase risks at potentially hazardous facilities, such as nuclear power plants, dams of the Dnipro cascade, and others. In addition, earthquakes are one of the hazardous natural phenomena that can occur on Ukrainian territory and lead to an emergency. Earthquakes cover large areas and are characterized by destruction of buildings and structures, massive fires and industrial accidents, as well as negative psychological impact.

Tendency of sharp increase in numbers and destructive force caused by disasters of different nature causes deterioration of social, economic and environmental consequences and points to the need to develop effective measures for prevention and elimination of disasters of different nature. Therefore, an urgent way to solve this problem is to develop an effective system for detecting hazards at stage of their inception, establishing causes of their manifestation and impact on them in order to prevent disasters and reduce their consequences.

In order to organize and ensure protection of citizens from the consequences of disasters, Civil Protection System (CPS) was created in Ukraine [1,2]. Tasks of the CPS are: prevention of emergencies and elimination their consequences; warning population about threat and occurrence of emergencies; protection of population from consequences thereof. A main component of qualitative fulfillment of tasks assigned to the CPS is timely receipt of information about disasters and their consequences, for which purpose a disaster monitoring system (DMNS) is created. At same time, the task of enhancing capabilities of the CPS by expanding monitoring methods becomes urgent.

One of these methods is seismic, its main advantages being high efficiency of establishing fact of a seismic event and ability to simultaneously monitor several potentially hazardous objects (areas) remotely, which reduces risk for technical means of observation and service personnel.

One of information segments of the DMNS is the Main Center for Special Monitoring (MCSM) of the State Space Agency (SSA) of Ukraine, which, through National Seismic Observation System and Governmental Information and Analytical System for Emergency Situations, provides information to the CPS on seismic situation in Ukraine and neighboring countries [5]. The seismic observation network (SON) of MCSM includes three-component seismic stations (TCSS), a seismic grouping system (SGS), which was included in the International Seismic Monitoring Network as PS45 station, and a National Data Center (Figure 1).

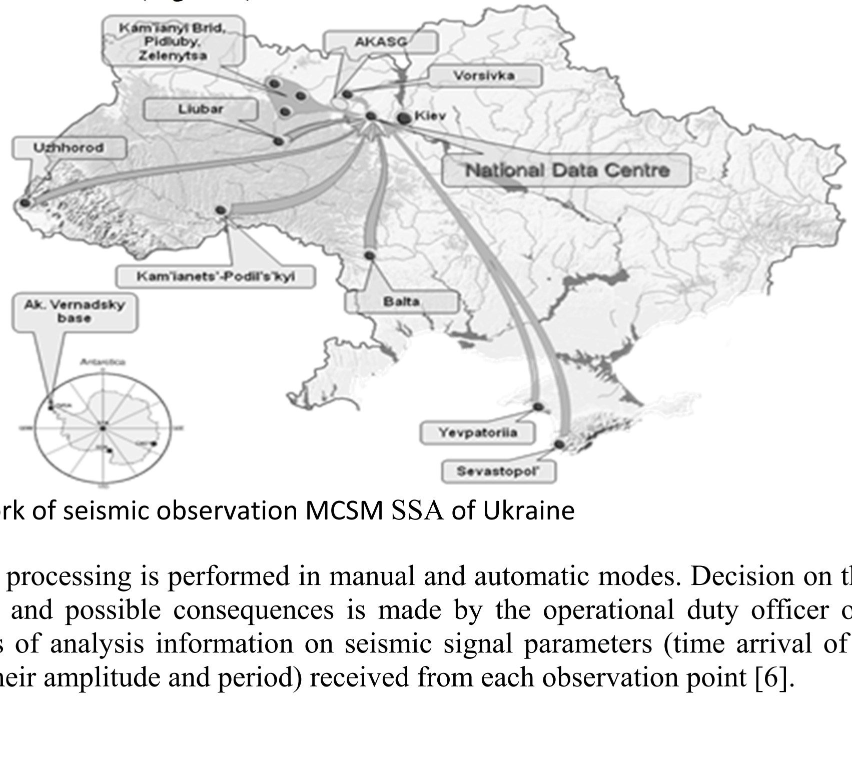


Figure 1: Network of seismic observation MCSM SSA of Ukraine

Seismic data processing is performed in manual and automatic modes. Decision on the parameters a seismic event and possible consequences is made by the operational duty officer of the MCSM based on results of analysis information on seismic signal parameters (time arrival of main types a seismic wave, their amplitude and period) received from each observation point [6].

Methods of seismic data processing currently implemented in the MCSM allow providing preliminary information to users about seismic event parameters and possible consequences in 15 minutes, and final information in 40 minutes after event occurrence [6,7].

Modernization of seismic observation equipment, transmission and processing of measurement data, transition to digital information processing, which is carried out at the MCSM within the framework of national and international programs, allows to move to a qualitatively new level of seismic monitoring. However, these capabilities are currently used to a limited extent, since seismic data processing methods implemented in the MCSM are based on algorithms for "manual" processing of seismograms by operators. At the same time, time limits for providing information to users are caused primarily by capabilities of existing approaches to processing seismic detection data.

2. Review of the literature

At present, in international and national data centers other countries, the main trend in detecting a seismic event in automatic mode is to use relatively simple measurement data processing procedures (such as STA/LTA), which allow for rapid data analysis and detection of seismic signals, but at the same time increase the density of the seismic observation network [6,8]. Territorial limitations of the seismic observation network of the MCSM, especially after temporary loss of observation stations "Sevastopol" and "Yevpatoriya" due to the occupation of the Crimea by the Russian Federation, necessitates development of methodological principles for solving seismic monitoring tasks by individual observation stations (OS) and TCSS.

Polarization analysis apparatus is used to process TCSS measurement data, but usually to determine angular characteristics of seismic wave exit to ground surface of seismic recording sections, which are defined as a signal based on preliminary detection results [6]. Another approach to applying the polarization analysis apparatus is polarization filtering, which consists in increasing signal to noise ratio of seismic vibrations from a certain direction [9]. Application of this approach makes it possible to detect seismic signals from sources with cells along a propagation path (beam), which is determined by angular characteristics – azimuth α and angle of arrival at daylight surface γ, but does not determine position of source within beam [10].

For analyzing data from seismic grouping system measurements, a method of controlled directional reception is used [6]. However, its application allows detecting signals over entire area covered by a generated beam (maximum of the seismic grouping system radiation pattern formed by time delays for each element of a seismic group for a corresponding area of Eart's surface), and also doesn't allow determining position of a seismic source within a beam.

Development of theoretical foundations for continuous remote monitoring potential sources of emergencies (PSE) natural and man-made disasters based on observations by a separate TCSS is one possible way to overcome this problem. In addition, such a need is caused by problem of ensuring the functional stability of seismic observation network as a whole, especially in cases when it is impossible to use seismic data from several stations (equipment failure, communication interruption, maintenance, etc.). Another prerequisite for improving seismic data processing methods is modernization of the MCSM seismic observation network, which is being carried out within international and national projects. Therefore, development as well as improvement of the existing theoretical foundations for automated processing of seismic signals recorded by a separate TCSS is a relevant issue.

Aim of the work is development of methodological principles for implementing continuous remote monitoring a potential source on natural and man-made emergencies based on results of observations by a three-component seismic station, taking into account kinematic and dynamic features, seismic component of signal from events centered in regional area.

3. Research methods

Reducing time for providing preliminary information to users about a seismic event and its parameters can be realized by moving from a search task of determining location a seismic source in absence of a priori information to remote monitoring potential sources by natural and man-made hazards.

PSE include potentially dangerous objects (civilian and military) and seismically active zones, earthquakes with centers in which pose a real potential threat to territory of Ukraine. Therefore, consideration of developing appropriate methodological principles for implementing continuous remote monitoring of PSE is important.

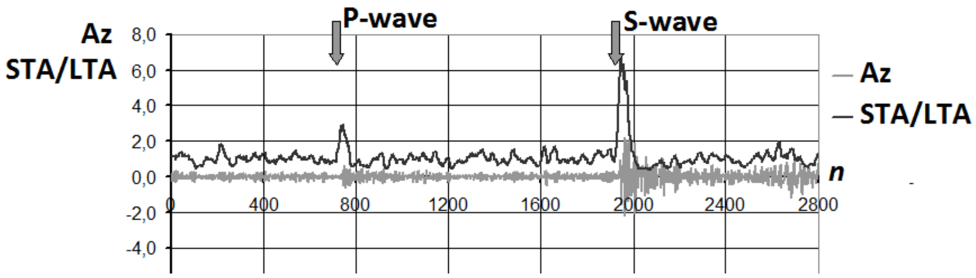
Problem of PSE monitoring by seismic means consists in detecting seismic signal, identifying main types of seismic waves, determining parameters a seismic signal components and making a decision on whether the detected signal belongs to a source from controlled area (facility).

Nowadays, the main direction for solving problems of PSE monitoring based on the results on seismic observations is to determine compliance of adopted implementation with previously registered seismic signals from events in controlled area [6]. Main problem in applying existing approaches is lack of reference signals for each of monitoring objects. So, to implement continuous remote monitoring of PSE, it is necessary to use additional information criteria due to seismic signals peculiarities. Such criteria can be used as dynamic (polarization of soil particle oscillations) and kinematic (propagation time) properties of seismic signal components.

3.1. Polarization properties of seismic signal components

Solving seismic monitoring tasks by a single observation point (OP) consists of following stages: seismic signal detection, identification, a seismic signal component (seismic wave types identification), seismic event center location, seismic source parameters estimation. In case a single-position observation is used, the last three stages are solved if the problem of determining the main components a seismic record is confidently solved. So, when analyzing existing methods of seismic data detection and processing, the main attention will be paid to possibility of solving this problem. Another criterion should be simplicity of software and algorithmic implementation for processing methods, which in turn will ensure possibility real-time processing a measurement data.

Currently, most of implemented approaches to detecting seismic signals based on TCSS observations use a criterion for exceeding amplitude thresholds (such as STA/LTA) [11], which is quite effective at an energy signal-to-noise ratio of at least 2÷3. However, using this approach leads to a limitation of magnitude sensitivity of a seismic station. In addition, this method doesn't allow to accurately determine components of seismic signal, since the arrival of next seismic wave occurs against a background of tail part of previous one. On the Figure 2 shows results of processing seismic signals from earthquakes in Ukraine using STA/LTA detection method. An example of numbered list is as following.



a)

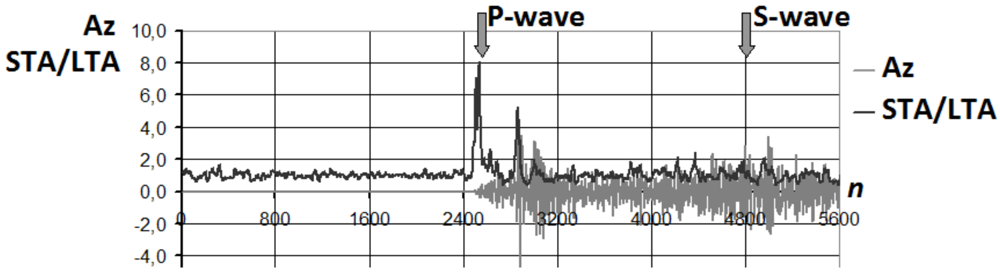


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Figure 2: Results processing of seismic signals from earthquakes on territory of Ukraine, using STA/LTA detection method: a – earthquake with center in Chernivtsi region (January 16, 2020, M=2.4); b – earthquake with center in Poltava region (February 3, 2015, M=4.6)

Applying a detection method based on amplitude criterion doesn't always allow to determine seismic signal components, since the arrival of a next seismic wave occurs against a background of a tail part from the previous one (Figure 2b, several sections a seismic record after seismic signal arrival for which the STA/LTA ratio exceeds threshold).

After a seismic event, such as an earthquake or explosion, elastic ground vibrations begin to spread in all directions from the epicenter. These vibrations can travel significant distances from epicenter and provide an important source for determining parameters of a seismic event. Depending on ground motion during seismic wave propagation, seismic waves can be classified into volumetric (longitudinal P-waves and transverse S-waves) and surface (Rayleigh waves and Love waves).

P-waves cause compression and rarefaction of soil particles along a direction of wave propagation, as shown in Figure 3. Arrows in this figure show areas of compression and rarefaction. In case of S-waves, soil displacement occurs perpendicular to direction of wave propagation. In addition to bulk waves, surface waves can also propagate across the Earth's surface. These waves are divided into two types: Rayleigh (L_r) and Love (L_q). In a Rayleigh wave, soil particles move in a vertical plane that is directed along a wave propagation direction, and their trajectories form ellipses. In a Lova wave, particles move in a horizontal plane perpendicular to the wave propagation direction.

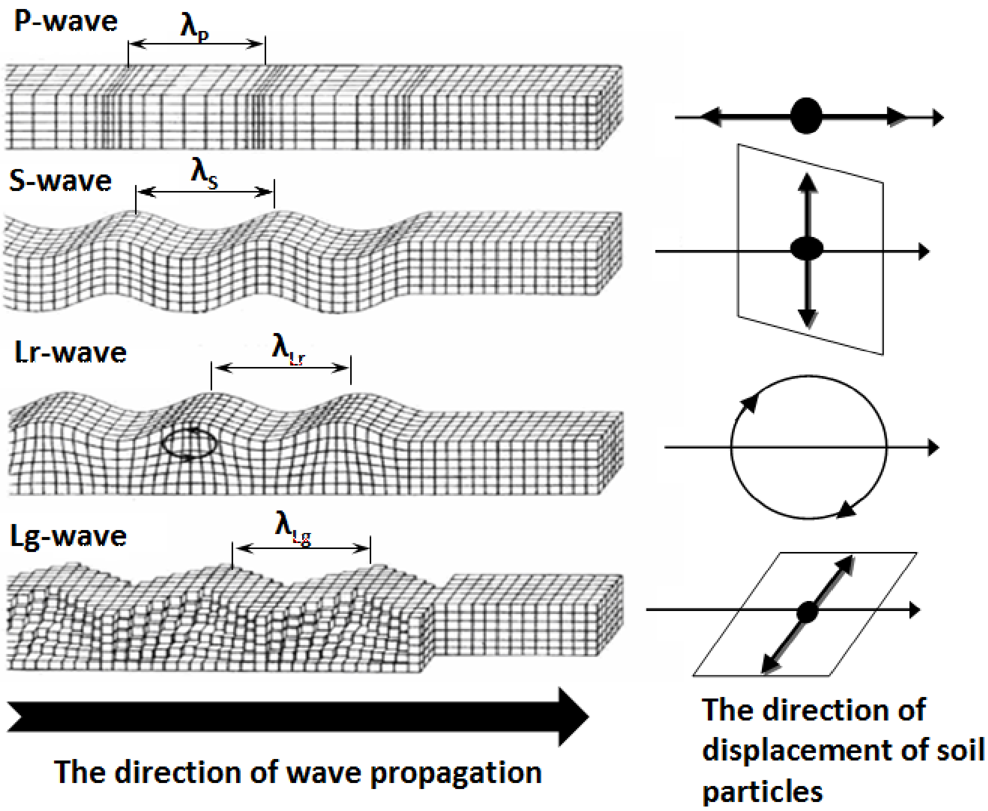


Figure 3: The nature of soil displacement for different types of seismic waves

Taking into account specific features of soil particle displacement for each main type of seismic waves in an event with centers in regional areas, angle characteristics of such waves will be related to the position of the seismic source relative to the OP as follows [10]:

– *P*-wave – since oscillation of particles in soil occurs along seismic wave propagation direction, the calculated angular characteristics coincide with position of seismic event center relative to the OP *(*$\alpha_P=\alpha_{sec},\gamma_P=\gamma_{sec}$*);*

– *S*-wave – due to soil oscillation occurs perpendicular to direction of wave propagation at this phase, angular characteristics are calculated (α_S, γ_S) will be different from direction to seismic event center relative to OP at 90°;

– *Lr*-wave – a superficial wave with elliptical polarization focused perpendicular to propagation direction, so its calculated azimuth will be different from input azimuth one on 90°,that is $\alpha_{Lr} \perp \alpha_P$;

– *Lq*-wave is a surface wave with an elliptical polarization in direction of propagation, so the calculated azimuth will coincide with actual azimuth to seismic source *(*$\alpha_{Lq}=\alpha_P$*)*.

After determining types of seismic waves and estimating their arrival time, distance from OP to seismic event center is estimated using a difference hodograph. In Figure 4, hodograph – shows a graph of dependence of time of propagation from source to seismic wave receiver on epicentral distance for regional zone [6,10].

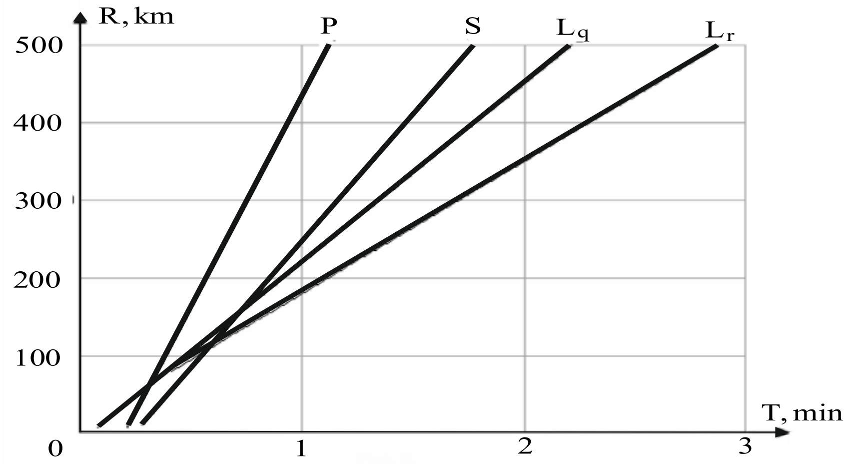


Figure 4: Hodograph of different types of seismic waves for regional zone

Slight differences occurring over short distances can cause each subsequent phase of a seismic signal to overlap the previous one, making it difficult for automatic identification of individual seismic signal components. Therefore, to determine a seismic event center in a regional area, it is sufficient to limit detection and identification to only the volume waves – P- and S-waves. At the same time, the time of obtaining measurement data necessary for detecting a seismic event and determining its parameters is limited by time of arrival second component a seismic signal (S-wave) for a separate TCSS, or time of arrival of one component (P-wave) to the observation points of SON.

Based on soil particle displacement features for bulk waves (Figure 3), S-wave detection can be realized as a result of using (taking into account) peculiarities of their angular characteristics, as a search for seismic signal recording areas for which the following conditions are met $(\alpha_P, \gamma_P) \perp (\alpha_S, \gamma_S)$.

On Figure 5 shows a seismic vertical component of recording from earthquake signal with center in Chernivtsi region (16.01.2020, M=2.4), registered by seismic station “Malyn” (Zhytomyr region), and results obtained from calculations on angular characteristics for recording sections corresponding to background, P- and S-waves. As shown previously, volume waves, in contrast to background waves, have grouping of their angular characteristics around a certain azimuth and angle of exit (direction).

As value of the angular characteristics of P- and S-waves, arithmetic mean seismic wave azimuth and exit angle to day surface $\bar{\gamma}$ is used, which is defined as [7,10].

$$\bar{\alpha} = \sum_{i=1}^{N} arctg \frac{A_{xi}}{A_{yi}} \cdot \quad (1)$$

$$\bar{\gamma} = \sum_{i=1}^{N} arctg \frac{A_{zi}}{\sqrt{A_{xi}^2 + A_{yi}^2}} \cdot \quad (2)$$

where N – is a sample size, N = 40, which corresponds to 1 s, at a sampling rate of f_D = 40 Hz;

A_{zi}, A_{xi}, A_{yi} – a displacements of soil particles in the vertical and horizontal (north-south and east-west) channels, respectively.

An angle between position of P- and S-wave angular characteristics is defined as [8].

$$\cos\Omega = x_p \cdot x_s + y_p \cdot y_s + z_p \cdot z_s \cdot \quad (3)$$

where $\{x_p, y_p, z_p\}$ and $\{x_s, y_s, z_s\}$ coordinates of single vectors for P- and S-wave angular characteristics.

Coordinates of single vectors of angular characteristics of P- and S-waves are related to arithmetic mean azimuth index $\bar{\alpha}$ and exit angle $\bar{\gamma}$ of corresponding seismic wave types as:

$$x_P = \cos(\overline{\gamma}_P)\cdot\cos(\overline{\alpha}_P)\,,\, y_P = \cos(\overline{\gamma}_P)\cdot\sin(\overline{\alpha}_P)\,,\, z_P = \sin(\overline{\gamma}_P)\,; \quad (4)$$

$$x_S = \cos(\overline{\gamma}_S)\cdot\cos(\overline{\alpha}_S)\,,\, y_S = \cos(\overline{\gamma}_S)\cdot\sin(\overline{\alpha}_S)\,,\, z_S = \sin(\overline{\gamma}_S)\,. \quad (5)$$

Values of determined angular characteristics for seismic recording of a signal from an earthquake with a center in Chernivtsi region (Figure 5c-b) are respectively for P-wave $\overline{\alpha}_P$= 217° and $\overline{\gamma}_P$= 37°, for S-wave $\overline{\alpha}_S$= 293° and $\overline{\gamma}_S$= 4°. Values of angular characteristics of seismic signal components were determined at levels of 76°.

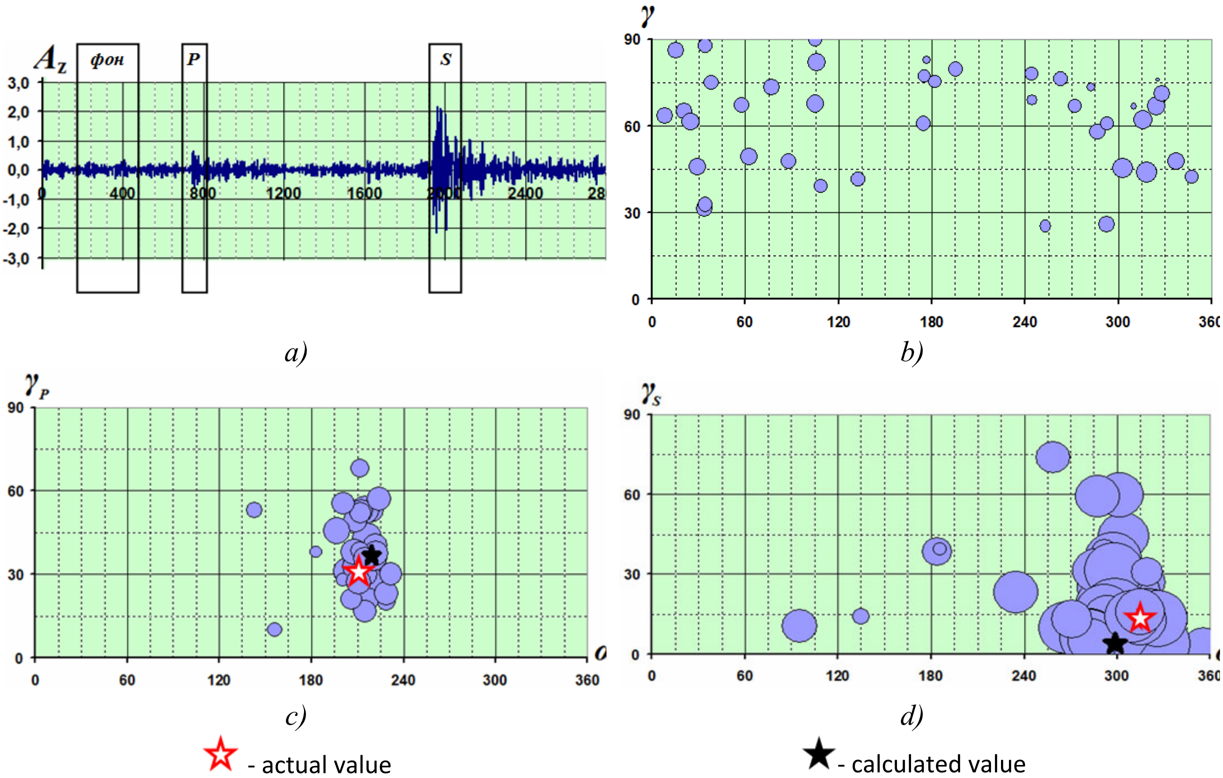


Figure 5: Seismic signal vertical component from an earthquake with center in Chernivtsi region (a) and angular characteristics for background (b), P-wave (c) and S-wave (d) recording sites

Difference obtained between the angles between the directions of the bulk wave exit from the normal (from 90°) is due to the fact that expressions (1,2) use only angular indicators, while not taking into account amplitude features.

3.2. Polarization analysis of a three-component seismic record

Another approach to determining angular characteristics is polarization analysis apparatus (PA) [8]. Trajectory of soil particles during seismic wave propagation has a shape of a strongly elongated ellipsoid, and for background it is close to a sphere. Main purpose of existing approaches to polarization analysis, regardless of implementation of solving function, is to assess degree of linearity in oscillations and determine angular position of large ellipsoidal axis.

In [6], a degree of linearity of a three-component seismic record $\{z_i, n_i, e_i\}$ is determined by a calculation of covariance matrix K

$$K = \begin{vmatrix} \mathrm{cov}(n,n) & \mathrm{cov}(n,e) & \mathrm{cov}(n,z) \\ \mathrm{cov}(e,n) & \mathrm{cov}(e,e) & \mathrm{cov}(e,z) \\ \mathrm{cov}(z,n) & \mathrm{cov}(z,e) & \mathrm{cov}(z,z) \end{vmatrix}. \quad (6)$$

A quadratic shape (ellipsoid) defined by this matrix is reduced to the major axes. Major axis of ellipsoid characterizes orientation in space of full seismic wave displacement vector by angles – azimuth α and angle of exit to bottom surface γ.

Linearity coefficient G (0< G <1) adopted implementation three-component recording is defined as:

$$G = 1 - \frac{b}{c}\,. \qquad (7)$$

where, b and c are values of smallest and largest semi-axis of ellipsoid, respectively.

Other approaches to determining a degree of linearity of a three-component seismic record are approximation of trajectory for soil particles by an ellipsoid, sequential polarization filtering, etc. [12].

Despite different methodological foundations, main goal of known (existing) approaches to polarization analysis is to determine how close oscillations of current (recorded) sample in three-component seismic record are to a certain direction (direction is determined by azimuth and angle of seismic signal component output).

Values of determined angular characteristics for seismic recording of a signal from an earthquake with a center in Chernivtsi region (Figure 5a) using the APA (6) are, respectively, for the P-wave $\boldsymbol{\alpha_P}$ = 210º and $\boldsymbol{\gamma_P}$ = 34º, for the S-wave $\boldsymbol{\alpha_S}$ = 313º and $\boldsymbol{\gamma_S}$ = 14º. According to determined angular characteristics of seismic signal components, angle value is 92º, which corresponds to conditions on orthogonality of oscillation by soil particles for bulk waves, in contrast to case on using arithmetic mean azimuth and angle on seismic wave exit to the day surface. However, using polarization analysis apparatus requires significant computational costs and is usually used in post-processing of measurement data of three-component seismic recordings.

3.3. S-wave detection and focal point determination

For implementation of remote monitoring by seismic means in real time, it is necessary to use additional criteria that take into account particularities of seismic signal components from sources in regional area.

Monitoring potential sources of emergencies requires availability of a priori information - position of monitoring object relative to observation point where TCSS is located. Availability of such input data makes it possible to determine angles of seismic wave arrival at surface from an event at a monitored object (object for which continuous remote monitoring by seismic means is implemented) and difference of arrival time between seismic signal components.

Taking into account above-mentioned dynamic (polarization of soil particle oscillations) and kinematic (seismic wave propagation time) features of the main components in seismic signals from sources with foci in regional area, continuous remote monitoring of the PSE based on observations of a TCSS is proposed to be realized by applying coordinated polarization-time filtering, for which a polarization-time model of expected seismic signal from an event with a center in a controlled area (object) is used.

Input data for forming the polarization-time model of expected seismic signal are: expected angular characteristics of first arrival of seismic signal (P-wave) on day surface and distance between observation point and monitored object (area).

Polarization-time model of seismic signal from events with a center in a controlled potential source of emergencies for a three-component seismic station has following general form:

$$F(t) = \Omega(\alpha_P, \gamma_P, \tau_{PS}, t) = \Omega_P(\alpha_P, \gamma_P, t) \cdot \Omega_S(\alpha_S, \gamma_S, t + \tau_{PS}), \qquad (8)$$

where, α_P, γ_P – expected azimuth and angle of first component seismic signal (P-wave) exit to daily surface, which are determined by position of the PSE relative to OP;

α_S, γ_S – expected azimuth and angle of S-wave exit to the daytime surface, which are determined by condition of orthogonality to expected direction of P-wave exit to daytime surface;

τ_{PS} – time difference between the arrivals of seismic signal components (volume waves), which is determined from information on distance between PSE and OP using a hodograph (Figure 4);

$\Omega_P(\alpha_P, \gamma_P, t)$ and $\Omega_S(\alpha_P, \gamma_P, t + \tau_{PS})$ – estimation of degree a linearity of sections in the three-component seismic record corresponding to P- and S-waves, respectively.

In order to assess degree of linearity and their compliance with controlled directions of seismic signal components exit to ground surface, it is proposed to define as the ratio between projection of ground vibrations to selected direction and total value of soil particles displacement for accepted realization.

To detect the first arrival of seismic signal (P-wave), decisive function has following form:

$$\Omega_P(\alpha_P,\gamma_P,i)=\frac{\sum_{i=1}^{N}|R_i|\cdot\cos\phi_i}{\sum_{i=1}^{N}|R_i|}, \qquad (9)$$

where, R_i is modulus of soil particle displacement vector

$$R_i=\sqrt{z_i^2+n_i^2+e_i^2}\ ; \qquad (10)$$

z_i, n_i, e_i – displacement of soil particles in vertical and horizontal (north-south and east-west) channels, respectively;

ϕ_i – angle between expected direction of seismic wave exit and current position of ground displacement vector.

Detection of a seismic record section corresponding to an S-wave is carried out under condition of orthogonal oscillations by soil particles relative a direction towards first arrival of seismic signal on day surface $(\alpha_P,\gamma_P)\perp(\alpha_S,\gamma_S)$. For S-wave detection, a decisive function is defined as:

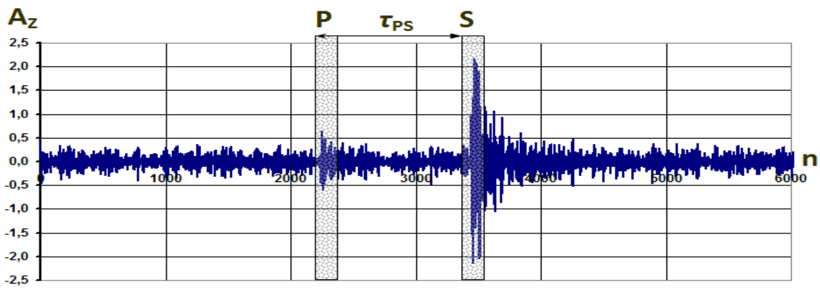
$$\Omega_S(\alpha_P,\gamma_P,\tau_{PS},i)=\frac{\sum_{i=1+\tau_{PS}}^{N}|R_i|\cdot\sin\phi_i}{\sum_{i=1+\tau_{PS}}^{N}|R_i|}. \qquad (11)$$

On Figure 6 shows results of applying proposed approach by detecting seismic signal from earthquake with center in Chernivtsi region (16.01.2020, M=2.4).

Input data for formation of polarization-time model a seismic signal are:

– distance to seismic event center 281 km, which, in accordance with seismic wave hodograph for regional zone (Figure 4), corresponds to 30 seconds difference in arrival time between P- and S-waves

– angles of seismic wave exit on the daily surface are respectively α_P = 210º та γ_P = 34º.



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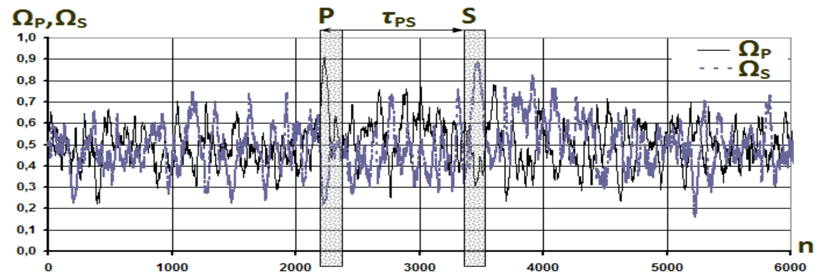

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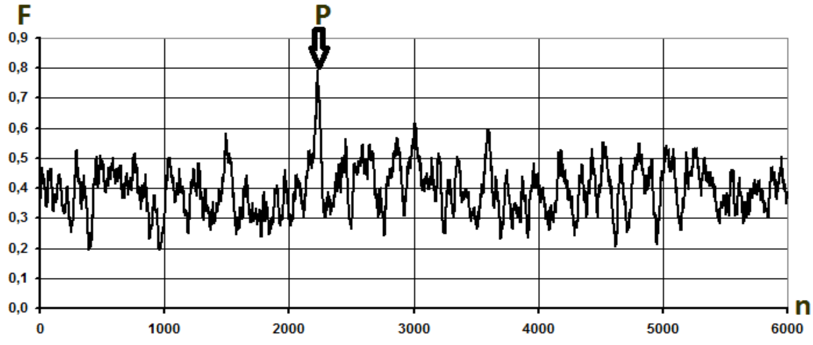

c)

Figure 6: Results application of polarization-time model of the picked seismic signal from earthquake with a center in controlled area: a – seismic signal vertical component from an earthquake with center in Chernivtsi region; b – values of decisive functions for detecting volume waves; c – values of decisive function for detecting seismic event from controlled area

As can be seen from above results, maximums of solving functions for seismic signal components Ω_P and Ω_S correspond to arrivals of P- and S-waves, respectively. Maximum of solving function F(t) corresponds to first arrival of seismic signal P-wave.

On Figure 7 shows a histogram of distribution values for the solving functions proposed by the method p(F) and to the first arrival a seismic signal from the direction corresponding to a monitored object p(Ω_P). Due to small sampling of earthquake signals from monitoring area, it is proposed to assess signal presence at a probability of false signal detection error at level α=0.001:

$$\alpha_F = \int_{h_F}^{\infty} f(F / H_0) dF = 0{,}001\, , \alpha_{\Omega_P} = \int_{h_{\Omega P}}^{\infty} f(\Omega_P / H_0) d\Omega_P = 0{,}001 \, . \qquad (12)$$

Under these conditions, threshold for detecting a signal from a seismic event with a center in monitoring area using polarization-time model of expected signal is h_F=0,64. At first arrival of seismic signal coming from direction corresponding to monitoring object $h_{\Omega p}$=0,81.

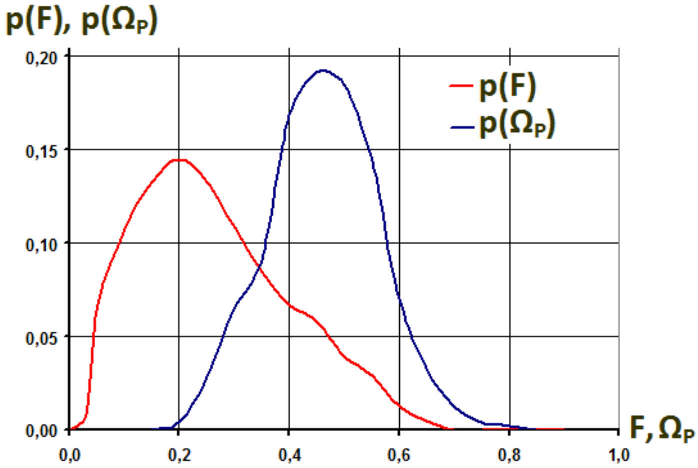

Figure 7: Histogram of distribution values using decision function for polarization-time model application of peaked seismic signal p(F), and for first seismic signal arrival corresponding to direction of monitoring object p(Ω_P)

In Figure 8 shows results of applying polarization-time model with parameters for the earthquake with a center in Chernivtsi region relative to Malyn observation point for processing a three-component seismic signal record from earthquake with a center in Vrancea seismically active zone (Romanian part of the Carpathian Mountains).

A special feature of seismic signals from these areas is proximity in values for the first seismic signal arrival at the daytime surface. Figure 8a, shows arrival of S*-wave for signal from earthquake with a center in Vrancea zone. Values of solving functions for seismic signal components Ω_P and Ω_S correspond to arrival only for the P-wave arrival (Figure 8b). At the same time, values of decision function for the first arrival of ΩP in some areas exceed the threshold value (Figure 8b). A value of decision function F(t) at the time of P-wave arrival is 0.53 (Figure 8c), which doesn't exceed threshold value according to condition (12).

In summary, this approach to processing measured data from a separate three-component seismic station allows detecting seismic signals from events with centers in controlled potentially hazardous objects (areas) by implementing their continuous remote monitoring.

At the same time, time for establishing a fact of an event in the controlled area (at the controlled facility) based on TCSS observations is limited by the propagation time of the S*-wave (Figure 4). For MCSM observation network, using polarization-time model of the detected signal will reduce time for establishing a fact of an emergency event within Ukraine from 15 to 3 minutes.

In order to form a polarization-time model of expected seismic signal from a possible event with a center in a controlled area (object), information on azimuth on the monitoring object relative an observation point where three-component seismic station is deployed, distance between observation point and remote monitoring station is required.

Table 1 shows parameters of polarization-time model seismic signals from the most hazardous facilities (nuclear power plants and hydroelectric facilities of Dnipro cascade) for Malyn observation point (Vorsovka village, Malyn district, Zhytomyr region).

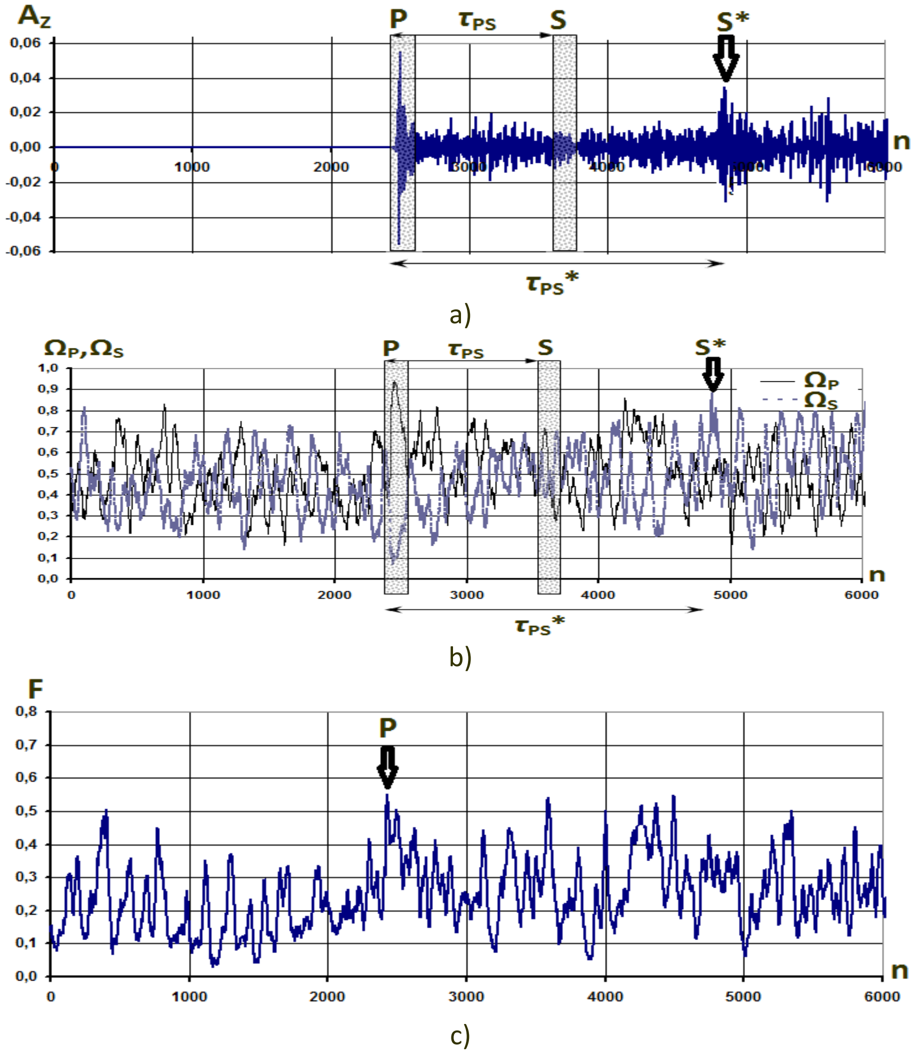

Figure 8: Results of applying polarization-time model of picked seismic signal from an earthquake with a source outside controlled area: a – seismic signal vertical component from an earthquake in the Wrench zone; b – values of decisive functions for detecting bulk waves; c – values of decisive function for detecting seismic

Table 1.
Parameters of polarization-time model seismic signals for nuclear power plants and hydroelectric facilities in Dnipro cascade for Malyn observation station

Monitoring object	Azimuth of the arrival α_P, °	Angle of access daylight surface γ_P, °	Difference in arrival time of bulk waves τ_{PS}, s

South Ukraine Nuclear Power Plant	153,5	37	42
Khmelnytsky Nuclear Power Plant	256,1	30	23
Rivne Nuclear Power Plant	286,2	32	28
Zaporizhzhya Nuclear Power Plant	130,4	44	47
Chernobyl Nuclear Power Plant	39,4	25	14
Kyivska Hydroelectric Power Plant	101,3	25	13
Kanivska Hydroelectric Power Plant	124,8	30	24
Kremenchuk Hydroelectric Power Plant	121,4	35	38
Kamianska Hydroelectric Power Plant	120,7	40	53
Dniprovska Hydroelectric Power Plant	123,9	46	60
Kakhovka Hydroelectric Power Plant	142,4	46	62

4. Conclusion

Prospects for seismic monitoring, as part of fulfilling tasks of information support within civil protection system (CPS) on seismic situation, are development and improvement of methodological and algorithmic approaches for complex processing seismic measurement data in order to promptly provide information on possibility, fact and consequences of a hazardous event.

One of approaches to solving this problem is implementation a continuous remote monitoring by seismic means potential sources of emergency events.

The present study analyzed components of seismic signals of events with centers in the regional area. A relationship is revealed between angular features of main components a seismic signal for events with centers in a regional zone and position of seismic source relative to observation point. Basics are formed and an approach is proposed for implementing remote monitoring using a three-component seismic station for potential sources by natural and man-made disasters. Monitoring potential sources of emergency events by a three-component seismic station is proposed to be realized by applying coordinated polarization-time filtering, for which a polarization-time model of the expected seismic signal from an event with a center in a controlled area (object) is proposed.

Results of applying proposed approach for detecting seismic signals from earthquakes with focal points in a regional area are presented. Relative simplicity of proposed approach allows to realize monitoring of PSE in real time. Application of this approach to the MCSM seismic observation network allows to reduce time to establish a fact of an emergency event within the territory of Ukraine from 15 to 3 minutes.

Parameters of polarization-time model of seismic signals for the most hazardous objects – nuclear power plants and hydroelectric facilities of the Dnipro cascade – are presented.

Main directions of further research are development and improvement a theoretical basis for processing seismic data, which will allow:

1. To identify the nature of a seismic source based on seismic data processing results in an automatic mode, taking into account amplitude-frequency differences in signals with different nature and seismic background features in a region where monitoring equipment is located;
2. Form databases of polarization-time models for potential sources of emergency events on the territory on Ukraine and neighboring countries;
3. Investigate variations of seismicity modes in seismically active zones (areas) for the purpose a timely detection a change in their state and prompt establishment a fact of an emergency.

Identified directions will allow solving the scientific and practical problem of detecting hazards factors related to man-made and natural emergencies by seismic means.

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