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IDENTIFICATION OF NATURAL AND TECHNOGENIC SEISMIC EVENTS BY ENERGY CHARACTERISTICS

One of the key problems of seismic monitoring is the identification of earthquakes and signals from technogenic sources detected by a network of seismic stations. In peacetime, technogenic events are mainly associated with industrial mining developments, however, with the beginning of russia's full-scale aggression against sovereign Ukraine, thousands of seismic signals from explosions as a result of missile, aircraft, artillery strikes were registered by the seismological network of the Main Center of Special Monitoring of the State Space Agency of Ukraine. This significantly complicates the process of assessing seismicity and makes the question of determining the nature of registered events extremely relevant. The analysis of seismic signals established the relationships between energy classes (K), magnitudes (mb), maximum amplitudes of longitudinal volumetric phases (A^P_{max}), and yields (Y) of explosions in TNT equivalent in Kyiv, Zhytomyr, Vinnytsia, Khmelnytsky, Chernihiv regions. Energy characteristics can be used to identify the nature of seismic events Additionally, the results of the analysis of the ratios $K = f(Y), mb = f(Y), \lg(Y) = f(lgA^P_{max})$ make it possible to yield estimate of explosions in TNT equivalent and determine the probable types of ammunition based on the received data. The energy from the signal source in the case of an explosive event can be determined additionally by infrasound data The presence of an acoustic wave serves as an additional criterion for identifying the event. At the same time, energy characteristics make it possible to identify natural sources, an example of which is the tectonic earthquake of May 26, 2023 in the Poltava region.

Key words: seismic station, seismic signal, seismic wave, explosion, ammunition, power in TNT equivalent, magnitude, energy class, maximum amplitude, earthquake, infrasound, identification.

Introduction

Among the tasks of the Main Center of Special Monitoring (MCSM), in addition to detecting the facts of nuclear tests, is the monitoring of seismicity on the territory of Ukraine and throughout the world. For this purpose, an extensive network of seismometers connected by a single National Data Center is located on the territory of the state [Seismic Network Main Center of Special Monitoring, 2010, Mărmureanu et al., 2021, Andruschenko et al., 2021]. Based on the results of processing registration materials, users are provided with spatial and energy parameters of events.

One of the key problems of seismic monitoring is the identification of earthquakes and signals from technogenic sources detected by a network of seismic stations.

Right-bank Ukraine, especially its central and northwestern parts, is densely covered by a network of mining enterprises that actively generate seismic signals in the course of their activities. The yield of industrial explosions is usually from units to hundreds of tons, which makes it possible to detect them in the entire range of regional distances. In addition, the dynamic characteristics of seismic recordings from explosions are highly dependent on the geological and tectonic conditions in the place where they were conducted, which complicates identification.

There are a number of criteria by which the source of a seismic signal can be identified [Kedrov, 2005; Andrushchenko, Gordienko, 2009a]. The ability to distinguish a seismic record of a chemical explosion from an earthquake record is based on such characteristics of these sources as the mechanism, magnitude, time of action, location of the source, and depth.

The Main Center of Special Monitoring developed additional criteria based on the spectral-temporal analysis of oscillations and showed their effectiveness (Andrushchenko, Gordienko, 2009b). However, they are not absolute, and for many seismic events it is impossible to determine their nature based only on the results of the analysis of seismic records.

One of the additional criteria for identifying the signal source was the use of information about acoustic waves [Liashchuk, 2015, Liashchuk et al., 2015].

With the beginning of Russia's full-scale aggression against sovereign Ukraine, thousands of seismic signals from explosions as a result of missile, aircraft, and artillery strikes were registered, which greatly complicated the process of assessing seismicity and actualizing the question of determining the nature of the registered events. In addition, information about registered events is extremely important for providing a complete and objective documentary of the aggressor country's crimes. The possibility of registering war crimes to provide information on violations of international law by a separate seismic group using the PS-45 seismic station as an example is given in [Dando et al., 2023].

It is known from many years of experience studying underground and surface chemical explosions that a certain insignificant part of the energy (less than 5 %) is transferred to the zone of elastic deformations, including the formation of seismic oscillations [Rodionov et al., 1971]. The scale of a seismic phenomenon by recording seismic waves at some distance from the source (munition explosion) can be estimated by calculating the magnitude M or energy E.

Magnitude M - the relative energy characteristic of an earthquake - is the logarithm of the maximum speed of vibrations of the Earth's surface or the logarithm of the maximum displacements in seismic waves of various types, calculated from some conditional level corresponding to a weak shock, the magnitude of which is taken as 0. The value of the magnitude of the energy class of the earthquake K is defined as a logarithm expressed in joules of the energy E of seismic waves that cross a reference sphere with a radius of 10 km [Kedrov, 2005].

The value of magnitude and energy class also depends on the explosive power of the ammunition in the TNT equivalent.

In the work [Andrushchenko et al., 2018], on the basis of statistical data on mass explosions within the Ukrainian shield, the ratio of the magnitudes and powers of explosions for granite industrial mines in Kyiv, Zhytomyr, Vinnytsia, Rivne, Khmelnytskyi, and Cherkasy regions was determined. Based on the results of the $M = f(Y)$ dependence analysis, the average ratio between the magnitudes and yield of the explosions was calculated for each of the studied mines. This ratio can be considered fair for the conditions of the Ukrainian shield and will be used in the future when assessing the consequences of blasting.

However, the analysis of the possibility of applying the obtained ratios revealed significant deficits in the magnitudes of the investigated industrial explosions compared to the data of experimental explosions with the same amount of explosive substance.

Objective

The purpose of the work is to determine the possibility of using energy criteria to identify the nature of seismic events and to combine several geophysical methods for a comprehensive assessment of the obtained characteristics and identification.

Signal detection and identification methodology

Collection, processing and analysis of seismic data is carried out using specialized software SeisComP3, which supports both automatic and manual data processing and interactive viewing of processing results.

The epicenter and source depth of the seismic event were determined using the *LocSAT* method, which uses a one-dimensional model of the Earth's crust (Bratt & Nagy, 1991). The operator can change, add, or remove the arrival time of the signal phases at the station, thereby achieving minimal errors.

To determine the magnitude, the values of the local ML magnitude ("Richter magnitude") were used [Hutton et al., 1987]:

$$ML = \log A_{max} - \log A_0 \quad (1)$$

where A_{max} – is the maximum amplitude of the transverse wave in mm, A_0 – is the amplitude of the reference event.

For bulk waves, the magnitude value mb is used, which is intended for teleseismic distances, but its use is permissible from a distance of 5 degrees, when there is already a clear direct phase of the P-wave:

$$mb = \log(A/T) + Q(h, \Delta) \quad (2)$$

where A –is displacement amplitude in micrometers, T is the dominant period in seconds, Q is the correction factor for distance (Δ) and depth (h).

In the conditions of the platform part of the territory of Ukraine, the most effective identification criteria are the evaluation of changes in spectra over time and the peculiarities of the waveforms of seismic signals. However, they do not have an absolute character, and for many seismic events it is impossible to reliably say what the event was: an explosion or an earthquake, based only on the results of the analysis of seismic records [Andrushchenko, Gordienko, 2009]. In such conditions, there is a need to involve additional criteria, including the energy characteristics of events, as well as the use of other geophysical methods for identification.

The method of detecting infrasound signals is based on the principle that the useful signal is a certain sequence of discrete readings on each of the elements of the infrasound array, while the noise is random and incoherent for each element of the infrasound array. Single microbarographs record the signal at different points in time as it propagates through the array. Assuming that the signal is coherent, the cross-correlations between pairs of sensors can be used to determine the time delays between individual sensors, which, in turn, depend on the geometry of the array and the characteristics of the wave front.

Such parameters as azimuth and speed of infrasound wave propagation are obtained from the analysis of time delays. The technique [Cansi, 1995] called *Progressive Multi Channel Correlation* (PMCC) is used to detect and calculate parameters.

The basis of the algorithm is the signal coherence measure (r_{ijk}), which is calculated in the subnet of the three nearest elements of the array (i, j, k), which is determined by the relation

$$r_{ijk} = \Delta t_{ij} + \Delta t_{ik} + \Delta t_{ki} \quad (3)$$

where Δt_{ij} – is the delay time between the arrival of the signal at sensors i and j, calculated for each pair of traces using the cross-correlation function. The maximum coherence threshold is defined to detect the coherence of waveforms on all elements of the array.

After the location of the seismic source, knowing the distance R from the epicenter of the seismic event to the observation point, we can determine the time interval [t_1:t_2] during which the infrasound wave can arrive:

$$t_1 = R/16{,}5;\ t_2 = R/20{,}4 \qquad (4)$$

where 16.5 and 20.4 are, respectively, the lower and upper limits of infrasonic wave propagation speeds (in km/min).

If an infrasound wave is present in the specified time interval, the azimuth of its arrival coincides with the specified direction and the signal has a characteristic shape, then it is considered that the explosive nature of the signal source has been confirmed. In the presence of an infrasound signal simultaneously on several arrays, it is possible to locate the source of the signal using the angular method and compare the obtained spatio-temporal characteristics with the data of the seismic method.

Thus, the results of infrasound observations can be used as an additional criterion for identifying the nature of seismic events with certain limitations regarding the power of the charge and the distance to the signal source.

Methodology for estimating the energy of a seismic event

From the law of conservation of energy:

$$E = Edr + Es + Ed \qquad (5)$$

where E – is the summary potential energy of the explosive charge, which is:

$$E = QC \qquad (6)$$

where Q – is the heat of the explosion in J/kg, C – is the mass of the explosive in kg [Shagov, 1976]; ***Edr*** – is the share of energy that is used for useless work during the explosion (heating of rock and water, occurrence of shock and sound waves, flying of rock, etc.); ***Es*** is the share of energy used for the formation of seismic waves; ***Ed*** is the fraction of energy used for rock crushing.

The amount of elastic energy involved in the formation of seismic vibrations in the surrounding massif, that is, the amount of radiated seismic energy, depends on the geological structure of the environment, the depth of the explosion and, first of all, on the type of rock around the explosive charge, its physical, mechanical and strength properties [Haskell, 1967]. Studies have shown that the share of energy that goes to the formation of seismic waves from ammunition explosions is less than 0.1 %.

In the practice of processing seismic data, the classification of events from energy classes K, introduced by T. G. Rautyan, has become widespread. [Rautian, 1964]. This classification can also be used for chemical explosions, including weak ones, as it allows determination at distances starting from 10 km.

When determining the energy class of the event, the maximum amplitude in the P- and S(Lg)-phases of seismic waves on short-period channels was used. Then the calculation was carried out according to the formula [Rautian, 1964]:

$$K = 1{,}8\, lg(Ap + As) + \sigma(\Delta), \qquad (7)$$

where: ***Ap*** and ***As*** – are the maximum amplitude of ***P*** and ***S*** – is waves in microns; *σ(Δ)* is the calibration function for ***Ap*** + ***As*** in the range of distances from 10 to 3000 km.

$$K = lg(E) \qquad (8)$$

where ***E*** – is energy that is emitted during a seismic event in J.

Statistical data on explosions in the Kyiv, Zhytomyr, Vinnytsia, Khmelnytskyi, and Chernihiv regions were used to determine the relationship between the energy class and yield estimates of explosions in TNT equivalent. The power of the explosions ranged from several dozen to several thousand kilograms in TNT equivalent.

The resulting relationship between the energy class ***K*** and the power of explosions ***Y*** is as follows:

$$K = 1{,}5511\, lg(Y) + 1{,}2653 \qquad (9)$$

Coefficient of determination $R^2 = 0.97$.

Fig. 1 shows the relationship between the energy class and the power of explosions calculated according to the ratio (9).

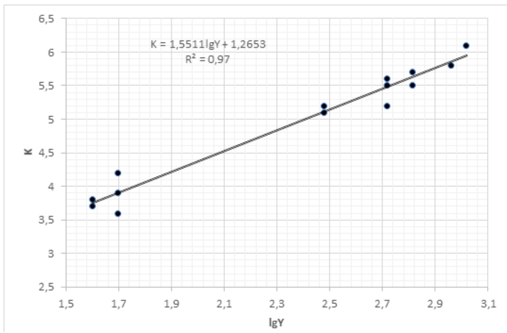


Fig. 1. The relationship between the energy class and the power of explosions, which is calculated according to the ratio (9)

Taking into account formula (9), we estimate the yield of the explosion Y:

$$Y = 10^{(K-1{,}2653)/1{,}5511} \qquad (10)$$

In the works [Khalturin, 1998; Sharov, 2007] shows the relationship between the magnitude ***mb*** and the energy class ***K***:

$$mb = 0{,}46K - 0{,}64 \qquad (11)$$

Taking into account formulas (9) and (11), we determine the relationship between the magnitude mb and the power of explosions ***Y***:

$$mb = 0{,}7143\, lg(Y) - 0{,}05746 \qquad (12)$$

Given formula (12), we determine the power Y:

$$Y = 10^{(mb+0{,}05746)/0{,}7143} \qquad (13)$$

For explosions registered by the network of seismic stations, we estimate the yield of explosions at epicentral distances of 7–220 km as follows:

$$lg(Y) = 1.076lg(A^P_{max}) + 1.4082lg(\Delta) + 2.9358 \quad (14)$$

where: A^P_{max} – is the maximum amplitude of the longitudinal wave in μm; Δ – is the epicentral distance in km.

Considering expression (14), we determine Y by the ratio:

$$Y = 10^{1,076lg(A^P_{max})+1,4082lg(\Delta)+2.9358} \quad (15)$$

Constant coefficients were determined using statistical data on explosions in Kyiv, Zhytomyr, Vinnytsia, Khmelnytskyi, and Chernihiv regions using multiple linear regression.

Multiple linear regression is expressed as a direct dependence of the average value of Y on two or more values X_1, X_2, ..., X_n. It is customary to call the quantity *Y* the dependent or resulting variable, and the quantities X_1, X_2, ..., X_n – are independent or explanatory variables.

The multiple linear regression equation looks like this:

$$Y = b_0 + b_1X_1 + b_2X_2 + \dots + b_nX_n \quad (16)$$

If there are *n* observations, the multiple linear regression model is written as:

$$y_i = \beta_0 x_{i0} + \beta_1 x_{i1} + \dots + \beta_{k-1} x_{i,k-1} + \varepsilon_i, i = \overline{1,n} \quad (17)$$

where x_{ij} is the value of the jth independent variable x_j in the ith observation, ε_i – is the error.

Regression parameters are determined using the method of least squares [Komashko, 2004].

Energy parameters are estimated from acoustic data using an empirical formula proposed by AFTAC (Air Force Technical Applications Center) [ReVelle, 1997, Golden et al, 2012]:

$$E_{(TNT)} = 2 * \left(\frac{T}{5.92}\right)^{3.34} \quad (18)$$

where E – yield in kilotons of TNT, T - is the period of the infrasound signal measured at the site of maximum amplitude.

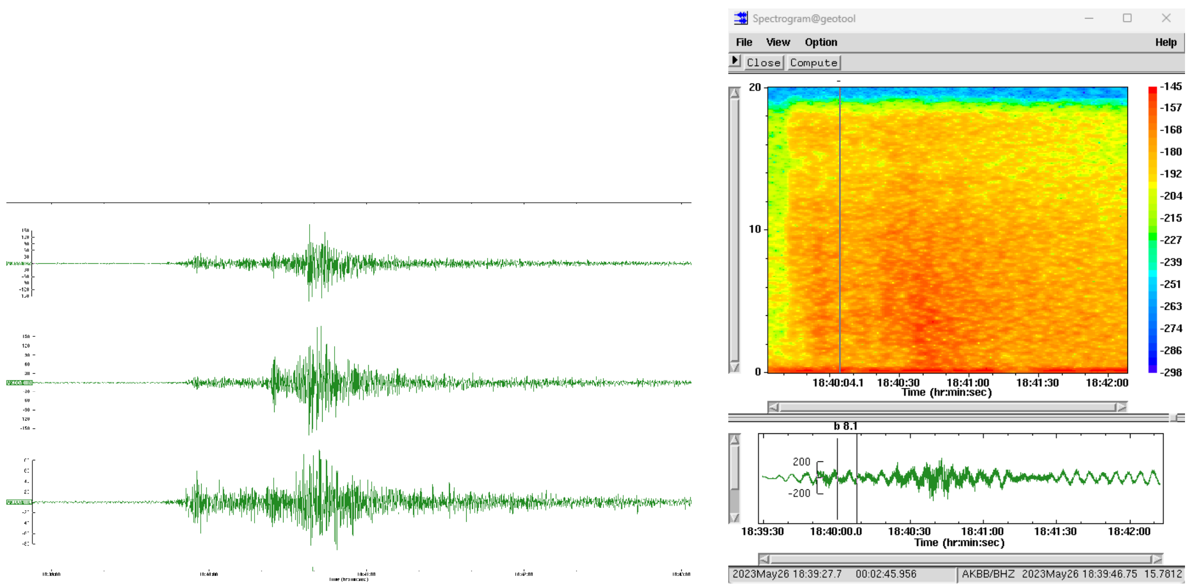
The expression showed a good correlation with energy values determined by seismic methods for powerful chemical explosions [Pilger, 2021, Kim, 2022] and high-energy natural phenomena [Vergoz et al, 2022].

Results

For analyzing the differences between seismic records and energy characteristics of events of natural and technogenic origin, we taken seismograms of the tectonic earthquake of 05/26/2023 in Poltava region and seismograms of explosions that occurred as a result of missile attacks and kamikaze drone attacks in Khmelnytskyi and Kyiv regions were considered.

According to calculations, the seismic event of 05/26/2023 had the following parameters: origin time t0 = 18:38:49 (UTC), depth 5 km, magnitude ML=3.5, energy class Kr=9.0. The record and the spectral-temporal diagram of a seismic event have a number of specific features characteristic of tectonic earthquakes [Kutas, Andrushchenko, 2015]. The spectrogram is very saturated, without obvious attenuations. The maximum spectral density in the S-wave recording interval is in the frequency band up to 7 Hz, which is a characteristic feature of tectonic earthquakes (Fig. 2). If expressions (6) and (9) are applied to the obtained parameters, we will get an energy of about 95 tons of TNT. The infrasound wave from the specified event was not registered.

Figs. 3 and 4 show the seismograms of the missile attack on the Khmelnytsky region on February 18, 2023 and the attack by kamikaze drones on an infrastructure object in the Kyiv region on October 10, 2022.



a b

Fig. 2. Record (a) and spectral-temporal diagram (b) of the earthquake on May 26, 2023 in the Poltava region.

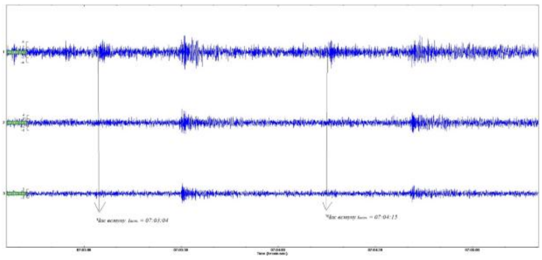


Fig. 3. Seismogram of the missile attack of the Khmelnytsky region on February 18, 2023 (2 missile strikes) on the elements of the PS-45 station.

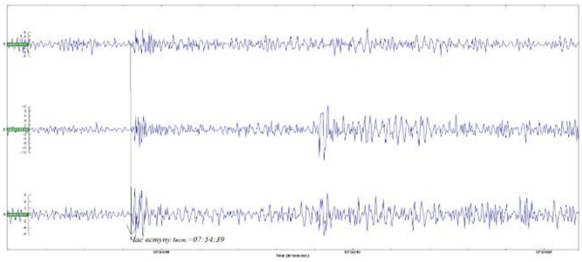


Fig. 4. Seismogram of the attack by kamikaze drones on an infrastructure object in the Kyiv region on October 10, 2022 at the elements of the PS-45 station

First strike: arrival time *– 07:03:04 (UTC + 0)*, energy class K = *5.5* (Y = $10^{\frac{5.5-1.2653}{1,5511}} = 537\,kg$), magnitude mb = *1.9* $\left(\text{Y} = 10^{\frac{1.9+0.05746}{0,7143}} = 550\,kg\right)$, maximum amplitude P – waves A^{P}_{max} = 0,00056 μm (Y = $10^{1.076\lg(0,56)+1.4082lg(213)+2.9358}$ = 520 *kg*), power in TNT equivalent (yield estimation) Y = 520–550 kg of TNT. The period of the registered infrasound wave was 0.5s, which apparently (18) corresponds to the power of 520 kg of TNT.

Second strike: arrival time - 07:04:15 (UTC + 0), energy class K = *5,6* $\left(\text{Y} = 10^{\frac{5.6-1.2653}{1,5511}} = 623\,kg\right)$, magnitude mb = *1.94* $\left(\text{Y} = 10^{\frac{1.94+0.05746}{0,7143}} = 626\,kg\right)$, maximum amplitude P – wave A^{P}_{max} = 0.69 nm (Y = $10^{1.076\lg(0,69)+1.4082lg(213)+2.9358} = 650\,kg$), power in TNT equivalent (yield estimation) Y = 620–650 *kg THT.* The period of the registered infrasound wave was 0.54 s, which corresponds to the power of 670 kg of TNT.

Arrival time *– 07:54:39 (UTC + 0)*, epicentral distance *Δ = 40 km* energy class К = 4.0 $\left(\text{Y} = 10^{\frac{4.0-1.2653}{1,5511}} = 58\,kg\right)$, magnitude mb = 1.2 $\left(\text{Y} = 10^{\frac{1.2+0.05746}{0,7143}} = 58\,kg\right)$, maximum amplitude P – waves A^{P}_{max} = 0.00065 μm (Y = $10^{1.076\lg(0.00065)+1.4082lg(40)+2.9358}$ = 58 kg), power in TNT equivalent (yield estimation) Y = 50–60 *kg.* The period of the registered infrasound wave was 0.28s, which corresponds to the power of 75 kg of TNT.

The amount of explosive substance or its mass C during calculations is expressed through power in TNT equivalent Y. TNT equivalent is the mass of TNT, the explosion of which emits the same amount of energy as will be emitted during the explosion of a given amount of a specific explosive substance. The power value in TNT equivalent is determined by the ratio [Vasylchenko et al., 2015]:

$$\text{Y} = K_{ef} \times \text{C} \tag{19}$$

where: C – the mass of the explosive, kg; K_{ef} – coefficient of explosive conversion to TNT. The mass of the explosive substance from the ratio:

$$\text{C} = Y/K_{ef} \tag{20}$$

Expression (19) is formulated for an explosion in which the shock wave propagates in the form of a sphere. When an explosion occurs on some surface, the shock wave spreads in the air in the form of a hemisphere. For explosions on a completely solid surface, all the energy released during the explosion is distributed within the hemisphere and, therefore, the value of the mass of the explosive substance is almost doubled. For an explosion on a not completely solid surface, for example, on the ground, part of the energy is spent on the formation of a funnel. Accounting for this flow is performed using the coefficient η (for example, for soil η = 0.6; for concrete η = 0.95). Y is generally determined by the formula [Vasylchenko et al., 2015]:

$$\text{Y} = 2\eta K_{ef} C \tag{21}$$

The mass of the explosive from the ratio (21):

$$\text{C} = Y/2\eta K_{ef} \tag{22}$$

Ammunition, depending on the amount of explosive substance in them and its type, has different power in TNT equivalent, therefore, by estimating the quantitative value of the explosion power in TNT equivalent (yield), it is possible to determine the probable type of ammunition (aviation bombs, guided (unguided) missiles, artillery ammunition). The presence of an infrasound wave in the acoustic channel is additional confirmation of the technogenic nature of the event.

In the considered examples, a significant excess of the energy of the earthquake in comparison with the energy of the explosion is visible. However, such high energy characteristics, as in the considered earthquake, are also possible under certain circumstances for chemical explosions. In this case, additional identification criteria should be applied, including cell depth and spectral characteristics.

Scientific novelty

For the first time, the study analyzed and evaluated the possibility of using additional criteria for identifying the nature of seismic events, including their energy characteristics, as well as the use of a complex of geophysical methods for identification.

Based on the analysis of statistical data on explosions in the Kyiv, Zhytomyr, Vinnytsia, Khmelnytskyi, Chernihiv regions, an assessment of the power of explosions from missile, air, and artillery strikes was conducted to determine the likely type of ammunition.

Conclusions

Based on the analysis of seismic records of the tectonic earthquake of 05/26/2023 in Poltava region and explosions that occurred as a result of missile attacks and kamikaze drone attacks in Khmelnytskyi and Kyiv regions, the possibility of identifying the nature of seismic events by their energy characteristics was assessed. Using seismograms of ammunition explosions obtained at the seismic stations of the Main Center of Special Monitoring , based on the analysis of statistical data on explosions in the Kyiv, Zhytomyr, Vinnytsia, Khmelnytskyi, Chernihiv regions, the power of which explosions ranged from several dozen to several thousand kilograms, obtained functional dependences: explosion power in TNT equivalent Y from energy class K ($Y = 10^{(K-1.2653)/1.5511}$); power of explosions in TNT equivalent Y from magnitude mb ($Y = 10^{\frac{b+0.05746}{0,7143}}$); explosion power in the TNT equivalent of Y from the maximum value of the amplitude of the longitudinal phase of the seismic waveA^P_{max} ($Y = 10^{1,076lg(A^P_{max})+1.4082lg(\Delta)+2.9358}$).

The obtained empirical dependencies make it possible to determine the origin of the event (natural or technogenic) and to estimate the type of ammunition in the case of a technogenic event. The energy from the signal source in the case of an explosive event can be additionally determined by infrasound data, the presence of an acoustic wave serves as an additional criterion for identifying the event.

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ІДЕНТИФІКАЦІЯ ПРИРОДНИХ ТА ТЕХНОГЕННИХ СЕЙСМІЧНИХ ПОДІЙ ЗА ЕНЕРГЕТИЧНИМИ ХАРАКТЕРИСТИКАМИ

Однією з ключових проблем сейсмічного моніторингу є ідентифікація землетрусів і сигналів від джерел техногенного походження, виявлених мережею сейсмічних станцій. У мирний час техногенні події пов'язані в основному із промисловими гірничими розробками, однак з початком повномасштабної агресії росії проти суверенної України сейсмологічною мережею Головного центру спеціального контролю Державного космічного агентства України зареєстровано тисячі сейсмічних сигналів від вибухів у результаті ракетних, авіаційних, артилерійських ударів, що значно ускладнює процес оцінки сейсмічності та робить надзвичайно актуальним питання визначення природи зареєстрованих подій. На основі аналізу сейсмічних сигналів визначені співвідношення між енергетичними класами (K), магнітудами (mb), максимальними амплітудами поздовжніх об'ємних фаз (A_{max}^{P}), і потужностями (Y) вибухів в тротиловому еквіваленті у Київській, Житомирській, Вінницькій, Хмельницькій, Чернігівській областях. Енергетичні характеристики можуть бути використані для ідентифікації природи сейсмічних подій, а результати аналізу співвідношень $K = f(Y)$, $mb = f(Y)$, $\lg(Y) = f(lgA_{max}^{P})$ дозволяють здійснювати оцінки потужностей вибухів в тротиловому еквіваленті і визначати за отриманими даними ймовірні типи боєприпасів. Енергія від джерела сигналу у випадку вибухової події може бути визначена додатково за інфразвуковими даними, наявність акустичної хвилі слугує додатковим критерієм для ідентифікації події. Разом з тим енергетичні характеристики дозволяють ідентифікувати і природні джерела, прикладом якого є тектонічний землетрус 26.05.2023 року в Полтавській області.

Ключові слова: сейсмічна станція, сейсмічний сигнал, сейсмічна хвиля, вибух, боєприпас, потужність в тротиловому еквіваленті, магнітуда, енергетичний клас, максимальна амплітуда, землетрус, інфразвук, ідентифікація.

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