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Analysis of natural and technogenic factors on the seismicity of Kryvyi Rih

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Abstract. Information is provided on the number of earthquakes in Kryvyi Rih and their parameters for the period 2007–2018. The types of seismic phenomena, the criteria for their identification are considered. The most probable natural and technogenic factors of the epicenters of local earthquakes are established by analyzing their location and sequence in time from the point of view of the tectonic features of the territory and the nature of the technogenic interference in its structure. The necessity of creating a local seismological network in Kryvyi Rih is substantiated. With a view to predict hazardous seismic phenomena, there is a need to continue hydrogeodynamic monitoring of ground water, to introduce seismic gravity monitoring and to conduct microseismic monitoring at mining enterprises. The results of systematic monitoring shall serve as the basis for seismic microzoning of the city. It is emphasized that popularization and dissemination of knowledge about the seismicity of mining regions among the population shall play an important role in the implementation of this task. The research materials can be used in the master's degree programme within the framework of higher education system and in advanced training of specialists in the mining industry.

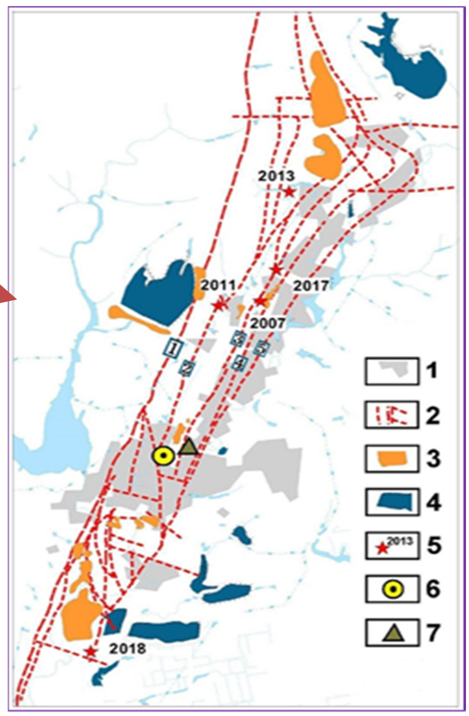
1. Introduction

For almost 140 years, the Kryvyi Rih structure has undergone an active anthropogenic impact – mining of ferruginous quartzites and rich iron ores by open and underground methods, accompanied by significant changes in the geological environment. Historically, both the residential quarters and the entire infrastructure of the city of Kryvyi Rih are in close proximity to the mining zones. The combination of the critical volume and duration of the mining in quarries and mines of Kryvyi Rih, with global seismotectonic activity, can increase the measure of seismic hazard for the city.

The world seismic activity for the period from 2010 to 2018, considering the number of earthquakes with a magnitude of 2.5–3.5, has grown almost by a factor of three. A significant part of the emerging elastic energy of earthquakes realized in recent mobile zones of the earth's crust, is transmitted to geological structures of relatively calm platforms in which dangerous local earthquakes can occur [7]. In general, the seismic hazard of Ukraine's territory is determined by the location of the south-eastern regions of the country near the powerful seismically active Mediterranean (Alpine-Himalayan) belt of the planet. About 10 % of Ukraine's territory is in the Vrancea zone. This is a seismically active zone at the junction of the Southern and Eastern Carpathians in Romania. Southwest Ukraine is directly influenced by it. Earthquakes from 6 to 9 points on a 12-point macroseismic scale (MSK-64) can occur here. Therefore, a significant territory in both southwestern and southern parts of Ukraine is classified as seismically dangerous.

Geologically Kryvyi Rih basin is located in the central part of the Ukrainian shield on the border of two megablocks of different ages – Ingulsky and Seredneprydniprovsky, separated by the Ingulets – Kryvorizhsky sature zone. The Kryvyi Rih structure is located in the eastern part of this zone and, according to the latest data, is represented by two large synclinal folds (Main and Saksagansky), which are substantially deformed by discontinuous faults that are part of the Kryvyi Rih – Kremenchuk deep fault system (Western, Tarapakivsky, Eastern, Saksagansky) (figure 1).

The territory of Kryvyi Rih basin, as well as the Ukrainian shield as a whole, has traditionally been considered to be aseismic. The territory of the Kryvyi Rih district as well as the territory of Ukraine belongs to the zone where earthquakes with an intensity of up to 5 points on the MSK-64 scale can occur once every 500 years; once in 1000 years – 6 points and once in 5000 years – 7 points. Taking into account local engineering and geological conditions and the influence of technogenic factors, the intensity of seismic impacts can vary by 1–2 points [16]. With an increase in the degree of interference in the geological environment, the establishment of real seismicity of the territory becomes more and more relevant even for seismically weakly active regions. Since the establishment of the National Center for Seismological Data on the basis of the Institute of Geophysics by S. I. Subbotin name of the National Academy of Sciences of Ukraine, this Center has the opportunity to collect and analyze data on seismic events occurring in the Krivyi Rih region as recorded by various seismic stations of both the Ukrainian and international seismological networks. Table 1 shows the parameters of earthquakes that have been recorded in the Krivyi Rih area in recent years (since 2007), although similar phenomena have occurred in Kryvyi Rih basin before (09/12/2000; 01/27/2006, etc.) [16]. At the end of 2012, the UK15 seismic station was installed in Krivyi Rih (figure 1).



1 – residential areas of Kryvyi Rih-city, 2 – main faults of the Earth's crust, 3 – main industrial waste dumps and overburden rock, 4 – tailing ponds, 5 – some epicenters of the local earthquakes and the year, 6 – seismic station UK-15, 7 – mine "Artem-1" of Joint-Stock Company "ArselorMittal Kryvyi Rih".
Faults: Kryvyi Rih – Kremenchug deep fault – 1; Western – 2; Tarapakivsky – 3; Saksagansky – 4; Eastern – 5.

Figure 1. Local technogenic mining load on the territory of Kryvyi Rih [19], [3] with the authors additions (https://www.earthdoc.org/content/figure/10.3997/2214-4609.201902490.F1).

Table 1. The list of seismic events of various origin within the Krivyi Rih region for the period from 2007–2018.

No	Date	Latitude φ	Longitude λ	Magnitude M	Depth H, km
1	25-12-2007 04:09:31	47.79	33.38	3.3	-
2	13-06-2010 03:58:17	48.02	32.35	4.3	0.447-0.527
3	18-09-2010 04:00:35	47.84	33.30	3.3	0.447-0.527
4	14.01-2011 05:03:12	48.10	33.40	3.5	1.200-1.300
5	26-06-2011 04:04:30	48.02	32.99	2.5	0.447-0.527
6	22-10-2011 04:06:45	48.89	33.24	3.1	1.200-1.270
7	31-03-2012 04:00:42	48.20	32.50	3.0	1.200-1.270
8	17-06-2012 04:03:16	47.70	33.57	3.0	1.270-1.300
9	28-11-2012 20:47:43	48.10	33.50	3.1	-
10	23-06-2013 21:16:33	48.04	33.42	4.6	2.000
11	29-07-2017 03:31:00	48.03	33.46	4.3	3.000-3.500
12	19-02-2018 00:35:03	47.86	33.45	2.8	17.000

For the period from 2007 to 2018 inclusive, in the city of Kryvyi Rih and near it there were 12 earthquakes. For the territory located within the generally aseismic Ukrainian crystalline shield, this number of hazardous seismic phenomena is anomalous, therefore it is extremely important to identify the causes and origin of these phenomena, to anticipate the effects of seismic impacts on the city's population and infrastructure.

2. Literature review

Recently, the seismicity of the Kryvyi Rih basin has been repeatedly covered in various scientific publications.

Volodymyr M. Shmandii, Viktor I. Bredun and O. V. Kharlamova [17] investigated an earthquake near Kryvyi Rih on December 25, 2007, and looked into the mechanism and formation of the seismic component of environmental hazard emphasizing the limitations on the practical study of specific earthquakes. Soon, Olexander M. Sklyar et al. [18], Bella G. Pustovitenko et al. [12], [13], Valentina V. Kutas et al. [8] investigated further the parameters and origin of this earthquake. Petro G. Pihulevskyi [11], [16], [19] summarized information about the seismic activity of the Kryvyi Rih – Kremenchug and Orekhovo – Pavlograd suture zones.

Yuri A. Andrushchenko, Valentina V. Kutas, Olexander V. Kendzera and others [1], [5] considered the difference between weak earthquakes which had occurred on the East European platform in 2005–2010 from industrial explosions, as well as the difference between man-made and tectonic earthquakes, in particular, the earthquakes of 2007, 2010, 2011 were discussed. The necessity of identifying seismic events and determining their origin is noted.

Olexander V. Kendzera [7], Sergii V. Scherbina, Petro G. Pihulevskyi, Iryna V. Gurova and Olha O. Kalinichenko [16], Oleg K. Tiapkin, Olexander V. Kendzera and Petro G. Pihulevskyi [19], Dmytro V. Malitsky, Sergii T. Verbytskyi, Lyudmila A. Shumlyanska, Volodymyr A. Il'yenko [14] and others studied the origin of individual earthquakes from 2011 to 2017.

An analysis of the geodynamic features of the natural – and technogenic seismicity of Kryvyi Rih basin on the interpretation of monitoring data on the hydrogeodynamic parameters of groundwater is given in the works by Petro G. Pihulevskyi, Volodymyr K. Svistun, Sergii V. Scherbina [11].

The need to create a subregional seismological and geophysical network of system monitoring to control the activation of non-tectonic processes (including natural and technogenic seismicity) in the territory of the Kryvyi Rih agglomeration, and the main steps to implement this task were discussed in the review article by Olexander V. Kendzera [7].

Lyudmila V. Feskova [5] examined the need for geodynamic monitoring, and methods of seismic protection, in order to increase the seismic resistance of the construction of industrial facilities relative to the safe operation of the Kryvyi Rih geotechnical system.

The aim of the study is to identify the influence of natural – and technogenic factors on the seismicity of Kryvyi Rih by analyzing the location of the epicenters of local earthquakes and their sequence in time in terms of the tectonic features of the territory and the nature of the technogenic interference in its structure which will minimize the impact of powerful explosions in mines and quarries on the city's infrastructure.

3. Results and discussion

Most researchers of the Kryvyi Rih earthquakes [7], [16], [19] share the view that these seismic phenomena are technogenic, directly related to technogenic impact, namely: explosive works in quarries and mines, naturally technogenic ones – associated with landslide processes in zones of shifts from iron ore mining or in other technogenic underground cavities, and tectonic, caused by the discharge of tectonic stress arising in the geological environment [16]. As a rule, the causes of such stress in the bowels are analyzed approximately, due to the complexity and insufficient knowledge of the geodynamic environmental conditions. The main attention is paid to the development of criteria and the identification of these types of seismic phenomena.

Another important criterion is the energy characteristics of earthquakes, which is closely related to the determination of the magnitude. In practice weak seismic events with Mb = 3.5–4.5, surface-waves of any magnitude are extremely rare. This is partly due to the fact that there are regional features in the attenuation of the surface-wave energy and specific ranges of frequencies for a Rayleigh wave, and partly due to a generally uncertain allocating a specific time interval for measuring amplitude. However, this magnitude is involved in the law of attenuation of macroseismic intensity. Therefore, in the unified catalogs involved in seismic zoning, all other energy and magnitude definitions are converted to macroseismic intensity. All recalculation formulas have inaccuracies and depend on the representativeness of the samples on which they are built. Therefore, obtaining instrumental magnitudes from a surface wave is extremely important.

Among the proposed methods for weak earthquakes, it turned out to be attractive to calculate the broadband surface-wave magnitude Ms (V_{max}) [5], where the assessment of surface-wave magnitude is carried out when measuring the amplitudes of a Rayleigh wave in 9 frequency intervals with periods from 8 to 25 seconds, instead of the usually used 17-23 second period. This method allowed increasing the number of Ms observations for small earthquakes at regional distances. The results obtained led to the development of a time-domain method for measuring surface waves [15] with minimal digital processing using a Butterworth zero-phase filter. This technique shows the stability of the result, both at regional and teleseismic distances. Under the conditions of a continental crust, the formula for calculating Ms (V_{max}) in an extended range of periods has the form 1:

$$M_{s(b)} = log_{(a_b)} + \frac{1}{2} log(sin(\Delta)) + 0{,}0031 \left(\frac{20}{T}\right)^{1.8} \cdot \Delta - 0{,}661 \log\left(\frac{20}{T}\right) - \log(f_c) - 0{,}43, \quad (1)$$

where a_b – the amplitude in nanometers at the maximum of the Rayleigh wave, Δ – the epicentral distance in degrees, T – the period at the maximum of the Rayleigh wave, f_c – the angular frequency that is used to find the frequency band f or the filters is calculated by the formula 2:

$$f = \frac{G_{min}}{T\sqrt{\Delta}} \quad (2)$$

For continental paths and Rayleigh wave periods between 8 and 25 s, the value of G_{min} = 0.6 (based on dispersion effects). An algorithm was compiled at the GS RAS, in which the recommendations of the authors of Ms (V_{max}) were taken into account [5], [15].

Man-made earthquakes, like powerful explosions, are characterized by low energy, confined epicenters to the zones of mining, occurring simultaneously with the explosive operations. Any man-made explosions are clearly established by recordings on seismograms where there are no *S* waves and surface waves *LQ* (Love waves) (Figure 2).

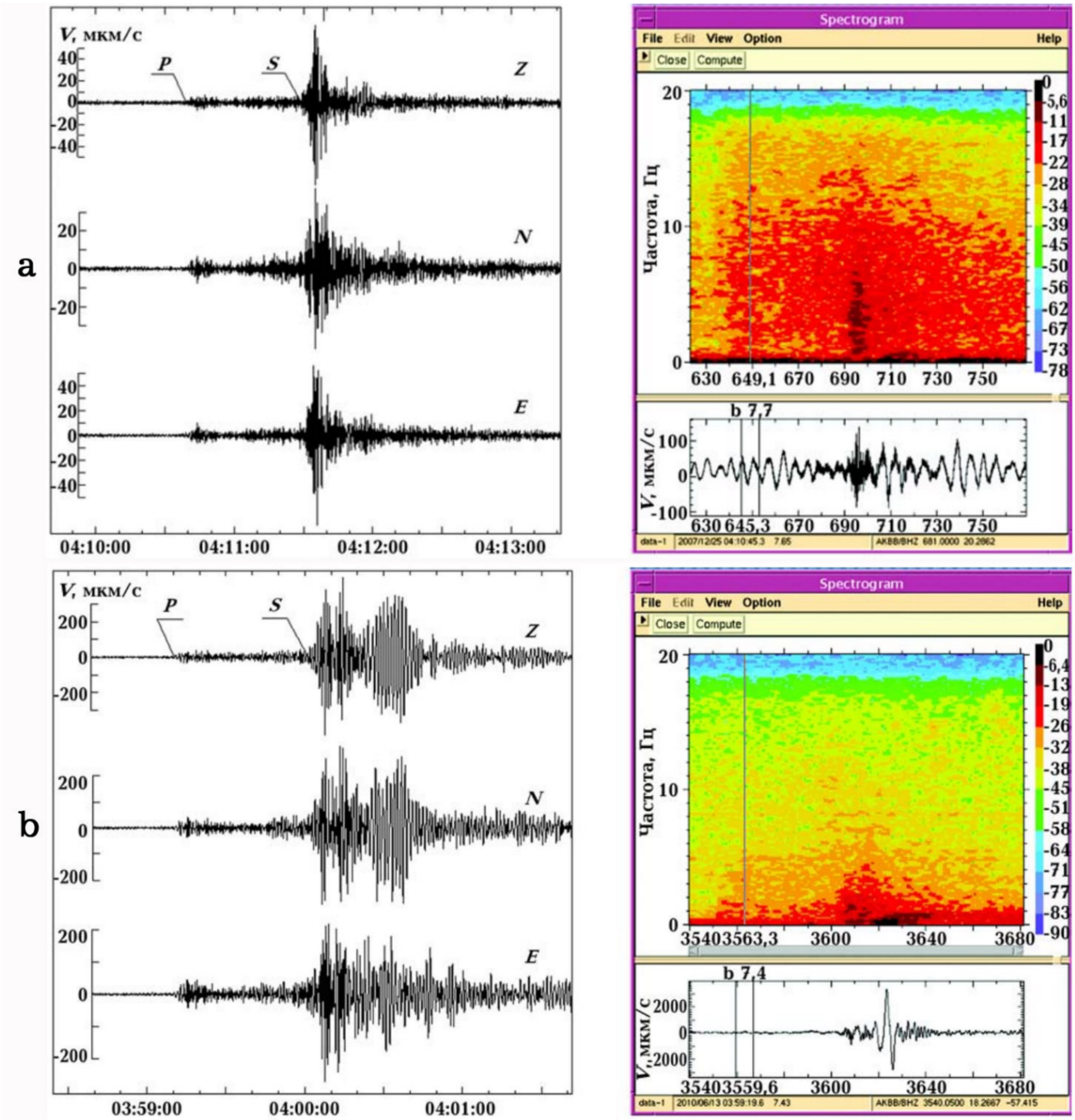


Figure 2. The records and spectrograms (screen shots) of the local Kryvbas seismic events (seismic station "Malin" PS-35, distance from Kryvyi Rih-city – 430 km, 0.5-2.0 Hz): a – the earthquake 25/12/2007, 4:09:31 UTC, *Mb* =3.3; b – explosion in mine 22/10/2011, 03:58:45 UTC, *Mb* = 3.1 (depth – 1200–1300 m, 60 tons of explosives).

Natural technogenic earthquakes occur under the influence of natural factors, which are quantitatively and qualitatively altered by technogenesis processes. The natural process of collapse occurs within the cavities of artificially created mining operations. These processes are not controlled by humans and occur as a result of a voltage discharge that has accumulated as a result of disturbance of the natural equilibrium by technogenesis. The energy of such earthquakes can be both low and significantly exceed the energy of any explosions in mines, their places and times do not coincide either. But their direct relationship with the places of treatment works can be traced. The depths of these earthquakes do not go beyond the depths of the development of rich iron ores. The seismograms do not have a clear structure of wave entry and there are no *S* waves.

Tectonic earthquakes have all the signs of natural tectonic processes and they are therefore the most potentially dangerous. Their energy can fluctuate significantly and often exceed the energy of earthquakes of the second group. The depths are most often, much more than the depths of mining. The seismograms always show a clear structure of wave arrival. For Love surface waves *LQ*, which is not typical when recording explosions, the ratio of the wave amplitude *P* to the wave amplitude *S* is less than 1 [19].

Despite the fact that the causes of these earthquakes are of natural origin, it is possible that the proximity of the mining industry with a disrupted technogenesis, unstable zone of the Kryvyi Rih – Kremenchuk deep fault helps increase the intensity of natural tectonic deformations to a critical level at which the total stresses can exceed the rock strength and cause their destruction. An external manifestation of the influence of technogenesis on the seismicity of Kryvyi Rih basin is an increase in the number of seismic events (table 1). According to 2004 seismic zoning, tectonic earthquakes with an intensity of up to 5 points should only take place on the average once every 500 years within Kryvyi Rih basin. In reality, they happened more often in a shorter period of time. The origin of at least three earthquakes from this table, which was investigated in detail, are determined as tectonic. For two of them, their landslide origin has been proved and for two of them caused by explosives, with an explosive mass of up to 60 tons (figure 2). The rest of the earthquakes are in one way or another connected with the sites of the workings and at the same time they are caused by a significant release of energy, comparable to a small nuclear explosion if one perform a in a comparative analysis of their energy magnitudes. The energy of Kryvyi Rih earthquakes is often significantly more than the energy of any explosions in mines, their places and times do not coincide either. That is, this is a manifestation of the anomalous seismicity of a complex geological structure on the surface of which the city of Kryvyi Rih is located.

Determination of the parameters of Kryvyi Rih earthquakes with minimal errors is possible if there are records of at least three nearby seismic stations. Kryvyi Rih earthquakes, the parameters of which are listed in the table, were recorded by seismic stations around the world and in Ukrainian seismological networks. However, due to the lack of stations located directly in Kryvyi Rih, in the center and in the east of Ukraine, the accuracy of determining earthquake parameters is insufficient. Errors in determining coordinates are thus up to 0.03 degrees. This was the reason for the disagreement in the interpretation of the origin and the mechanisms of earthquakes.

The situation improved somewhat after the installation of a seismic station in Kryvyi Rih in late 2012. This made it possible to increase the accuracy of determining the parameters of earthquakes using records of the Crimean seismic network, and to establish the landslide nature of the earthquake on November 28, 2012 [16].

It is well known that the accuracy of determining the mechanism and origin of earthquake organization depends on the accuracy of determining the parameters of the earthquake. To get an unambiguous solution, one nearby station is not enough. With the expansion of the seismic network in central Ukraine, the start of seismic stations in the Dnipro, Zaporizhia, Kremenchuk, Poltava, it became possible to accurately determine the parameters of the earthquake 07/29/2017 (from records of 8 stations) and, accordingly, unambiguously establish the nature of the earthquake as a tectonic related to displacement blocks along the fault [19].

A more reliable determination of the parameters of earthquakes and, accordingly, their identification allows a more accurate analysis of both natural and technogenic factors of these phenomena, taking into account local conditions for their localization. For example, for the seismic events of June 23, 2013 and July 29, 2017, the establishment of close coordinates of the epicenters located in the central part of Kryvyi Rih between the sludge dumps of the Central Iron Ore Enrichment Works (CGOK) and the zones of shift from mining of rich iron ores (figure 1). The first earthquake was identified as a landslide (natural-technogenic). Its magnitude – 4.6 was high, as for such phenomena and may indicate the displacement of a significant amount of rocks, although this was not reflected in the relief of the earth's surface. The next earthquake occurred after 4 years and had all the signs of a tectonic process. It was accompanied by acoustic phenomena, not typical for Kryvyi Rih earthquakes. It may indicate the activation of fault structures in the complex zone of the Kryvyi Rih – Kremenchuk deep fault. Despite the precise localization of these seismic events, it is possible to conclude that the first of these earthquakes, which had a natural-technogenic character, accelerated or started the release of their own reserves of elastic energy, which accumulated in the Precambrian crystalline rock mass.

The technogenic factor that contributed to the disruption of natural balance in this region leading to the implementation of this chain of events, is the localization to the west of the Kryvyi Rih – Kremenchuk deep fault zone (which has a north-western fall) of the slime storage of the CGOK bordered by dumps, which holds much more than 300 million m^3 liquid waste enrichment. Filtration of water from the slag storage facility is carried out both to the west towards the Karachunivka reservoir and to the southeast – into fault zones and a zone of shear from mining of rich iron ores and, accordingly, towards a depression funnel created by mine drainage. Numerous underground cavities are located within the depression funnel, which create a redistribution of masses and disturbances of the natural balance. The role of these technogenic factors in the seismic activation of fault structures must be studied in the future.

Despite the fact that in the determination of the coordinates of earthquakes for that period, there was some uncertainty due to the lack of nearby seismic stations (error 0.2–0.30° in latitude 0.15–0.4° in longitude), a similar causal relationship can be traced in the seismic events of 2010 and 2011. First, a powerful landslide (natural-technogenic) earthquake occurred on June 13, 2010, which manifested itself on the earth's surface by the formation of a huge dip in the shear zone and partially beyond it and was triggered by an underground massive explosion at a neighboring mine. A year later an earthquake occurred on January 14, 2011 in the same area, which had signs of a natural tectonic process. It was also preceded by an underground explosion at the mine and the moment of neotectonic activation by the water level in the observation well, where on January 7, 2011. A decrease in groundwater level of 7–8 cm was recorded. This was due to the disclosure of a network of small faults and cracks [16]. In turn, this earthquake provoked the release of a funnel in the shear zone of the CGOK on January 18, 2011.

Thus, the assumption that technogenesis has qualitatively and quantitatively changed the nature of natural processes and is quite acceptable. The tectonic earthquakes that occur in the Kryvyi Rih region should also be attributed to natural-technogenic, since their factors were changed by technogenesis, as suggested [17]. The authors classified such earthquakes in the category of discharge ones, suggesting that the discharge of technogenic stresses occurs along zones of active neotectonic faults, and collapses in underground cavities. This is not their main cause, but only provoking and reinforcing factors [4], [9].

The classification of technogenic seismicity [5], available in geodynamics, to a certain extent more clearly reflects these patterns. According to this classification, seismic vibrations that occur immediately at the time of anthropogenic impact, are defined as primary seismicity.

All seismic phenomena that occur in a mountain massif for various reasons after or during anthropogenic impact are commonly called reduced seismicity. In turn, induced seismicity is divided into two categories: induced (excited) seismicity and trigger (initiated) seismicity.

The source of primary seismicity is technogenic factors, in particular such as demolition work in mines, quarries, and the like. It manifests itself in the form of a certain time interval of seismic waves, the duration of which is determined by the conditions of the explosive process, and the amplitude of the oscillations is determined by the energy of the explosion and the distance from where it takes place.

Any forms of technogenic seismicity that is formed after primary seismicity, are reduced seismicity. Induced seismicity is the result of various human influences on the earth's crust taking place dynamically, slowly growing, static or periodically. The main characteristic feature of induced seismicity is that the source of its manifestation is both its own reserves of elastic energy in the medium and the energy transferred to the medium during exposure.

Induced seismicity usually manifests itself in the form of relatively weak shocks during technogenic impacts both in tectonically active rock masses and in rocks with a low level of stress state. Due to the influence of stored energy in the medium, a certain level of stress state triggers the activation of the deformation processes. Hypocenters of induced seismicity are usually located within the influence area of a technogenic source. The oscillation energy during induced seismicity is usually not large and is limited by magnitudes < 3.0–3.5.

Trigger seismicity arises due to the release of its own energy reserves in the geological environment under the influence of external technogenic sources. The energy of vibrations generated in this case will be determined by the level of tectonic stresses and the size of the region with this level of stresses. The energy of trigger seismicity can exceed the energy of anthropogenic impact. Trigger seismicity can sometimes occur during industrial impacts in non-seismic or weakly seismic regions. Man-made impact only triggers and accelerates the process of releasing own reserves of elastic energy in the array. Thus, the manifestations of tectonic seismicity indicate that the technogenic changes in the geological environment in Kryvyi Rih have reached a certain critical point, and if landslide earthquakes are localized in the fault zones and their energy depends on the size of these zones, then the energy of tectonic triggers earthquakes. Itis thus difficult to predict and to what extent they constitute a significantly greater seismic hazard.

The almost 140-year-old mining of iron ore in Kryvyi Rih has created enough conditions for disturbing the balance of the geological environment and the appearance of tectonic stresses in the bowels of Kryvyi Rih basin, the discharge of which causes earthquakes [5].

Among the technogenic factors that upset the balance of the geological environment are the following:

- redistribution of masses in the bowels of the Earth and on its surface significantly changes the distribution of local fields of tectonic stresses (the creation of huge quarries, dumps, sludges, underground cavities, shear zones);
- changes in hydrogeological conditions (the creation of a depression funnel of ground waters as a result of water reduction in iron ore mining sites, causes a large gradient in the velocities of these waters in the surrounding massifs and, as a result, changes in the stress state and rock properties that affect the nature of groundwater movement);
- constant exposure to working mechanisms and periodic explosions in mines and quarries, which affects the physical properties of rocks;
- continuous growth of depths and scale of mining operations [10].

An example of the fact that earthquakes do not always occur in underground mining of iron ore, as well as in other areas transformed by technogenesis, is an earthquake that occurred 2018-02-19 00.35.03. The parameters of this earthquake were determined from the records of three stations located in Kiev (Kiev IRIC) (USGS) and Zaporizhia (PDUO and ZAES) (Local seismic network). The stations are distant, that is, some errors in determining the parameters are likely. The coordinates of the epicenter 47.86 950; 33.45 300, indicate that it was in the industrial zone in the south of Kryvyi Rih and was felt by residents mainly in the southern part of the city. The magnitude of the earthquake is 2.8, and the depth is 17 km. If we take into account the nature of the recording on the seismogram, the obtained depth of the hypocenter, it may be concluded that the earthquake was tectonic. The location of the epicenter in the south of Kryvyi Rih basin indicates that stress in the geological environment can also occur outside the Kryvyi Rih – Kremenchuk deep fault zone in areas transformed by technogenesis. The largest quarries are concentrated in the south of Kryvyi Rih basin (PGZK, Novokryvorizhsky GOK) where systematic explosions occur, quarries are surrounded by dumps, as well as sludge dumps from which filtration occurs and groundwater penetrates into the fault zones through cracks. It is likely that the earthquake was the result of a discharge of stress in the neotectonic fault zone.

Thus, one cannot deny the influence of technogenesis on the anomalous seismicity of Kryvyi Rih basin and also associate it with one kind of anthropogenic impact. Natural balance is disturbed by a complex situation of triggering technogenic factors.

Given the power and scale of the modern technogenic impact on the geological environment, its instantaneousness compared to geological time, the violation of natural equilibrium and the activation of seismogenic processes can be expected not only in Kryvyi Rih basin, but also in other mining regions of Ukraine. It is therefore necessary to create and expand the existing seismological networks in the future [19].

For the territory of the East European platform, the potential maximum magnitudes of earthquakes are possible (Mb = 5 – 5.5 – 6.6), determined from data on the bending of the earth's crust, the intensity of modern tectonic deformations, heat flux, the depth of the Precambrian basement and the Moho border [6]. Now, the energy of the Kryvyi Rih earthquakes did not exceed these values – max Mb = 4.3–4.6. But if earthquakes with potentially maximum magnitudes, take place in Kryvyi Rih basin, it can have significant negative consequences.

For example, the area of intense shaking of the 2017.07.29 earthquake was within the urban area. In order to determine the intensity (strength) of the earthquake, a survey of the residents of Kryvyi Rih was conducted (figure 3).

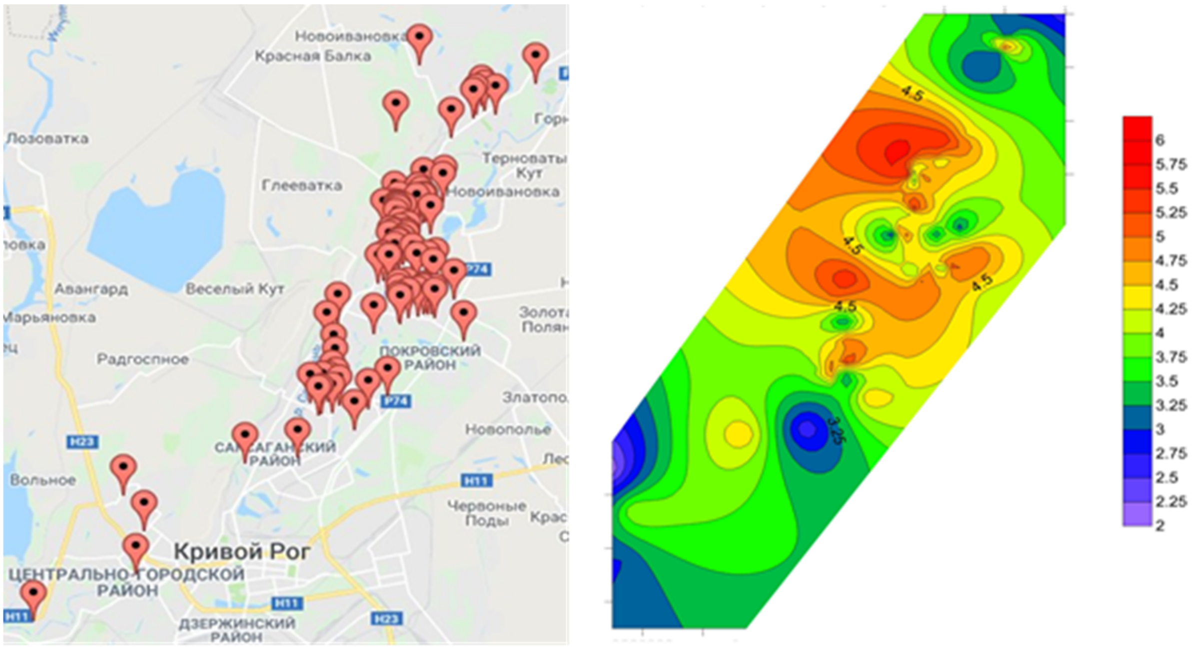


Figure 3. Map of the survey of city residents (1), map of the earthquake isoseismists of 07/29/17 based on the results of the survey (2).

With the number of polls 96, it was determined: the maximum value of the score 5.5; the minimum is 2.5; the average value is 4.2. The magnitude of the earthquake is 4.3, and the maximum divinity, as we see more and it is not determined at the epicenter itself. The distribution of pestilence on several floors of multi-story buildings was also examined and it was found that there is a tendency to increase the magnitude on each floor by 0.1 points on average [16], [19].Thus, in the event of the occurrence of earthquakes in Kryvyi Rih basin with the highest possible magnitudes, at small depths of hypocenters, the magnitude can increase to critical values of 7–7.5 and even 8 on the upper floors of high-rise buildings, and this will be accompanied by the destruction of these floors and possibly some brick houses [2].

4. Conclusions

Considering the unique nature of the Kryvyi Rih iron-ore basin – its location in the Kryvyi Rih – Kremenchug deep fault, the significant duration and the scale of man-caused interference with its subsoil, it is necessary to continue comprehensive studies of present-day geodynamic processes occurring in the geological environment in order to provide detailed assessment of the effect of particular man-caused and natural factors on abnormal seismicity of the territory. The introduction of systematic seismic monitoring shall play a leading role in the said research. For this, as has been repeatedly noted, it is necessary to:

- create a local seismic network from at least 3 seismic stations and seismic data processing service;
- continue to study the geodynamic conditions of the territory of Kryvyi Rih basin by monitoring the hydrogeodynamic parameters of groundwater and by introducing seismic gravity monitoring as promising methods for predicting local earthquakes.
- to implement online general microseismic monitoring on the premises of all mining enterprises.
- compile a map of active neotectonic disturbances based on a generalization of geological, geophysical, seismic and geodynamic studies of the Kryvyi Rih region.

The next step should be microseismic zoning of the city based on the results of systematic monitoring and studies of active fault zones the use of scientifically based stabilizing measures and increase the seismic resistance of buildings and structures. Funding for these studies is needed, both at the state and local levels.

The conscious response of the population to any seismic events, irrespective of their magnitude, shall play an important role in microseismic zoning. This applies to the assessment of seismic impact on objects, houses, human consequences, objective recording of this impact and active participation in the survey. Raising the awareness among city residents is possible by means of popularizing knowledge about the seismicity of Kryvyi Rih basin among the population making an emphasis on the most active part of employees at mining enterprises, as well as on the students.

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