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Research paper

Impact of Seismic and Air-Blast Waves Caused by Civilian and Military Explosions on Critical Infrastructure Facilities

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Abstract: The parameters of seismic waves during a civilian explosion in the directed destruction of brick chimneys by detonation of explosive charges were determined using a seismic measuring complex consisting of standard one-component sensors (SM-3) for recording the parameters of vertical, longitudinal, tansverse (vert (Z), long (X) and tran (Y)) components of the oscillations, the electrical signals from which are transmitted to a personal computer (PC) through a 16-channel analogue-to-digital converter (ADC). Similarly the parameters of seismic and acoustic waves from a military explosion during the impact of shells on the Kyiv TV tower were determined using a MiniMatePlus seismic station (Canada), consisting of a MiniMatePlus seismograph, a 3-component sensor for recording the parameters of vertical, longitudinal, tansverse (vert (Z), long (X) and tran (Y)) components of the oscillations (seismic) and a microphone for measuring the air-blast waves (acoustic). The results from both seismometric measurements of the parameters of earth surface vibrations during the collapse by blasting of a high-rise chimney (60 m) in the village of Kalynivka, Vasylkiv district, Kyiv region, and the results of seismic and acoustic vibrations during the explosion on 01 March, 2022, in Kyiv, and the missile strike on the Kyiv TV tower, with their subsequent destructive effects, both on the ground and in the air, are presented. A comparison of the parameters for a civilian and a military explosion, with the available calculation methods for determining the seismic and acoustic effects of these explosions, is presented.

Keywords: explosion, detection, air-blast wave, ground displacement rate, seismicity coefficient, seismic safety

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1 Introduction

Civilian man-made explosions, as a method for the explosive destruction of buildings and facilities and large industrial stacks, are widely used, since, along with other methods, this method is the fastest and least labour-intensive among other methods for using explosive energy for peaceful purposes. These operations are mostly carried out in cramped conditions, and therefore, accounting for seismic safety and shock-air waves on the glazing of nearby buildings and structures, communication networks, *etc.* is very important. There are few publications on this topic [1-6], especially those that analyse the results of measuring the parameters of seismic blast waves and waves caused by the impact of chimneys and individual structures on buildings on the ground surface during their destruction.

Technogenic explosions of a military character, which were used to monitor seismic and acoustic waves during the destruction by the Russian army, using various types of missiles and rockets on critical infrastructures of military and civilian nature, both on the ground and in the air, are considered in our research as evidence of material damage to Ukraine, and are compared with the actual data obtained during direct measurement of the production of civilian explosions, their detection and assessment of a charge mass of 2,4,6-trinitrotoluene (TNT). These research results have the potential to be used by forensic experts involved in certain measures to counteract terrorist and extremist manifestations of an aggressor country, as well as for the Prosecutor General's Office, which is investigating crimes committed by the Russian occupiers in Ukraine, to confirm them and to use the calculation methodology being developed at the Hydromechanics Institute of the National Academy of Science of Ukraine regarding material damage to Ukraine.

The purpose of this study was to establish and compare the effects of seismic and air-blast waves caused by civilian explosions during the blasting of chimneys with explosive charges and military explosions during the missile attack on the Babyn Yar TV tower and a memorial complex, the burial place of thousands of people killed during World War II, in Kyiv, as well as to evaluate the existing methods for determining the seismic effects of technogenic explosions and to compare them with actual data obtained by direct measurement of the production process during the destruction of a high-rise building by explosive methods.

2 Experimental

2.1 Explosions of civilian character

2.1.1 Test site and destruction technique

In Figure 1, we show the photo-registration of technogenic explosions of civilian character, which were used to study the effect of seismic and air-blast waves caused by explosions. Seismic measurements were carried out during the explosive destruction of two brick chimneys of height 45 and 60 m, in Kalynivka village (Vasylykiv district, Kyiv region).

The directed destruction of the 45 and 60 m high brick chimneys was carried out by means of horizontally drilled holes filled with explosive charges and through cutting, which was not carried out along the entire horizontal section, but only from the direction of the intended collapse. This direction is the bisector of the sector directed to the south-west (a free area prepared for receiving the brick chimneys destroyed in the explosion). The explosive used in the blasting operations was Ammonite No. 6ZhV (cartridge), and the initiation was carried out with instantaneous electric detonators of the ED-8Zh type. Table 1 shows the characteristics of the brick chimneys that were subjected to destruction and the parameters of the explosives charges that created the through bore (cut).

(a) (b)

Figure 1. Photographic recording of anthropogenic civilian destruction of two brick chimneys

Table 1. Main characteristics of the chimneys and the explosive charges

Name	Chimney height of	
	45 m	60 m
Chimney material	brick	brick
Outer diameter of the chimney (bottom) [mm]	5808	7010
Outer diameter of the chimney (top) [mm]	3110	4020
Chimney wall thickness [mm]	510	510
Chimney weight [tons]	750	1500
Diameter of hole [m]	0.04	0.04
Total number of charges	79	74
The mass of the hole charge [kg]	0.12	0.176
Total charge weight [kg]	7.9	11.1

2.1.2 Detection method

In this research, the detection of explosions of various technogenic accidents was carried out using two measuring complexes. The first complex was used to measure technogenic accidents of a civilian type, which during technological explosions excite seismic waves in the ground that are safe for different types of objects, and consisted of standard one-component SM-3 sensors for recording the parameters of vertical, longitudinal, transverse (vert (Z), long (X) and tran (Y)) components of the oscillations, the electrical signals of which are transmitted to a personal computer (PC) through a 16-channel analogue-to-digital converter (ADC). Based on the measured data, Excel digital files are downloaded from the PC's memory, and graphic files are obtained by processing in RDF.

The seismic equipment was installed on the surface of the territory of "Kalynivka Logistics Centre" LLC and "Kyivmetallloprom" OJSC, located at 5 and 7 Industrialna Street, respectively, in the Kalynivka, Kyiv region, Vasylkiv district, and along the profile towards the territory of "Kyivmetallloprom" OJSC from the base of the brick chimneys. Sensor installation points:

– points 1, 2, 3 and 4: on the surface of the ground base at a distance of 120, 170, 200 and 250 m from the exploded sector of the brick chimney (seismic receivers Nos 217, 188, 166 and 22, respectively),
– point 5: on the surface of the ground base near the concrete boundary between Kalynivka Logistics Centre LLC and "Kyivmetallloprom" OJSC at a distance of 292 m from the blown-up sector of the brick chimney (seismic receiver No. 31),
– point 6: on the surface of the ground base near the warehouse No. 1 of "Kyivmetallloprom" OJSC at a distance of 350 m from the blown up sector of the brick chimney (seismic receiver No. 32).

2.1.3 Main characteristics of the seismic surveys

Data registration and processing (analysis of the amplitude-frequency parameters of the seismic blast waves) according to the profile of the seismic receivers installed on the territories of "Logistics Centre Kalynivka" LLC and "Kyivmetallloprom" OJSC are reflected in the seismogram of the ground vibrations during the chimney collapse at distances of 120-292 m (see Figure 2), and the digital data from the seismograms are listed in Table 2.

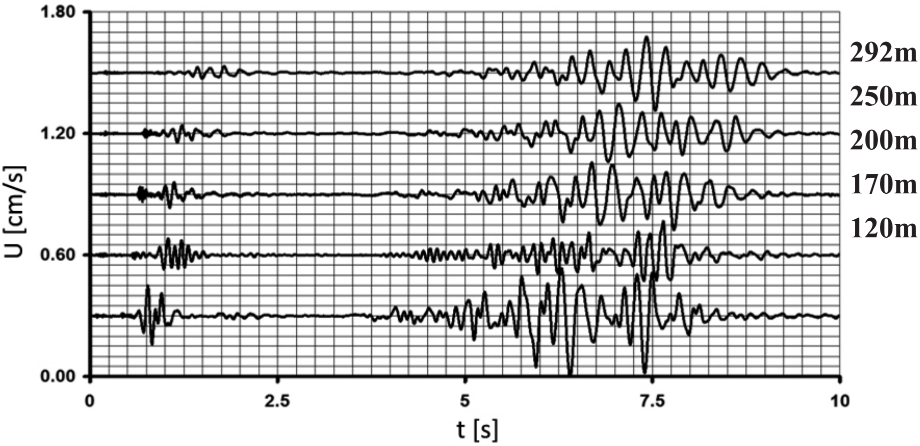

Figure 2. Seismogram of the ground vibrations from the blast (t < 2.5 s) and during the impact of crashing of the brick chimneys on the earth's surface (t > 3 s)

Table 2. Parameters of the measurements of seismic vibrations during the destruction of the brick chimneys of height 45 and 60 m

No. of sensor	Seismic data from oscillograms V_{max} [cm/s] (f [Hz])		Intensity of seismic oscillations on the MSK-64 scale, in points	Distance from the explosion location [m]
	explosion of two chimney sections	chimney collapse		
217	0.161	0.3 (4)	2	120
188	0.054	0.17 (6)	1	170
166	0.048	0.18 (3.5;4)	1	200
22	0.360	0.15 (4)	1	250
31	0.0343	0.187 (4)	1	290
32	0.0430	–	1	350

The intensity of the oscillations from the explosion of the two chimneys was 1 point, and oscillations of 1 to 2 points were recorded when the 60-metre chimney collapsed, which is 2.5 times less than in the analytical calculations. The analytical calculations failed to predict the score, since simultaneous collapse of the chimneys did not occur, and the recorded oscillations from the crash of the 60-metre chimney did not occur along its entire length, but only in parts. Thus, the blasting operations to destroy the brick chimneys were carried out in full compliance with the necessary safety requirements for the adjacent territories, including the industrial site of "Kyivmetallloprom" OJSC.

Following the proposals of the Presidium of the National Academy of Sciences of Ukraine in connection with the military aggression of the Russian federation of 24 February, 2022, regarding the reorientation of budgetary projects, research on this topic related to the assessment of the environmental impact of seismic and air-blast waves from technogenic civilian explosions, was reoriented and applied in the military field with the involvement of employees of the Research Laboratory for Seismic Safety of Technological Explosions of the Institute of Hydromechanics of the National Academy of Sciences of Ukraine, and measuring equipment complexes (Mini Mate Plus seismic stations) tested in industrial explosions, to study technogenic explosions of a military character, to monitor the parameters of the movement of seismic and air-shock waves generated both in the ground and in air during missile attacks on the city of Kyiv, to calculate the material damage and to confirm the crimes committed by the Russian occupiers in Ukraine. Consequently, the experience gained in the civilian sector was applied to the registration of military explosions by the air-blast waves.

2.2 Explosions of military character

2.2.1 Test sites and destruction technique

As an example of technogenic explosions of a military character, which was monitored for seismic and acoustic waves during the bombardment by Russian troops, the bombardment that took place on 01 March, 2022 on the:

– Kyiv TV tower at 17:07 (Figure 2),
– Babyn Yar memorial complex in Kyiv,

was chosen.

Three Russian missiles hit the TV tower in Kyiv near the Dorohozhychi metro station. The TV tower in Kyiv was one of the first objects to be hit by Russian missiles. One of the missiles hit the base of the TV tower, the second hit the technical building, and the third fell near the tower, on Illyenko Street, destroying a Sport Complex and a vehicle. As a result of these explosions, the electricity transformer substation supplying the TV tower was damaged, as well as the technical room on the TV tower itself. Ukraine's 385-metre high TV tower is the world's first all-welded structure of its kind. The tower is the tallest structure in Ukraine and the tallest all-metal and all-grid free standing structure in the world. Overall, staff of the TV tower were not killed during the attack, but civilians who happened to be passing the TV tower in Kyiv died. Five people were burned alive. Another five people were wounded.

(a) (b)

Figure 2. Photographic recording of anthropogenic explosions of a military character: explosion (a) and structural deformation (b)

2.2.2 Detection method

The seismic station was a Mini Mate Plus seismograph (made in Canada), consisting of a Mini Mate Plus seismograph, a 3-component sensor for recording the parameters of vertical, longitudinal, transverse (vert (Z), long (X) and tran (Y)) components of vibrations (seismic), and a microphone for measuring air-shock waves (acoustic). With the software THOR, the measured data obtained from the Mini Mate Plus seismograph memory were transferred to a personal computer (PC) and, after processing, the results were obtained in the form of Instantel Event Report protocols in PDF graphic and Excel digital files. Registration of the air-blast waves was carried out at a distance of 4500 m from the explosion (Figure 3).

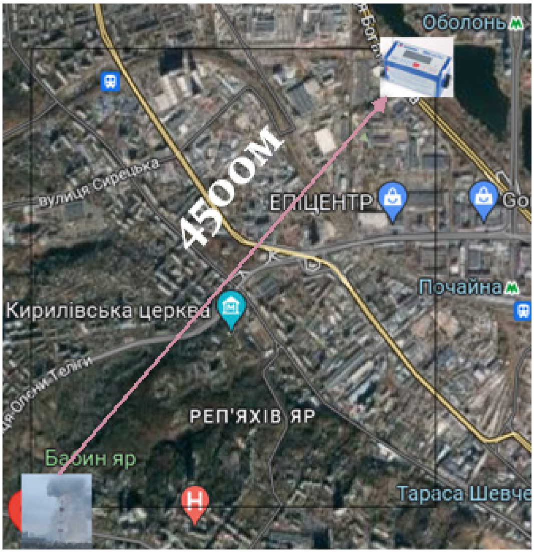

Figure 3. Regional map for the apartment building (Obolon) showing the scheme of measurements of air-blast waves excited by the explosion of the Kyiv TV tower (in Ukrainian)

2.2.3 Main characteristics of the seismic surveys

The protocols of the rocket attacks on 01 March, 2022, on the Kyiv TV tower, obtained by the Mini Mate Plus seismic station, with the display of vertical, longitudinal, transverse (vert (Z), long (X) and tran (Y)) types of seismic waves and acoustic vibrations on RDF graphic files, are presented in Figures 4 and 5.

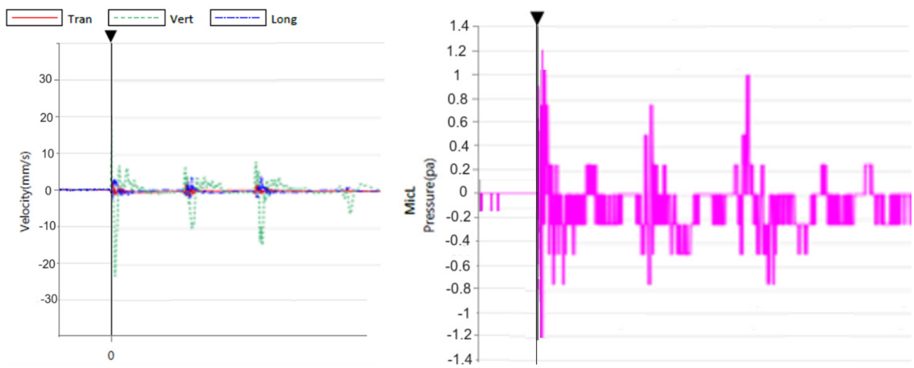

Figure 4. Monitoring record, received by the Mini Mate Plus seismic station, of the missile attacks on 01 March, 2022, at 17:07 on the TV tower in Kyiv

In the graphs of Figure 4 for the period from 0 to 0.5 s, 3 signals were registered, where 3 maximum amplitudes of oscillations can be distinguished: seismic (mm/s), for all components (vert (Z), long (X) and tran (Y)), and 3 acoustic (air wave pressure in Pa), which correspond to the following explosions: the first maximum is the 1st rocket hitting the base of the TV tower (the broadcaster's control room); the second is the 2nd rocket hitting the technical building; the third maximum is the 3rd rocket that fell on Illyenko Street, damaging the Sports Complex, and a fourth seismic signal from the impact of its fragments on the ground.

As a result of the strike on 01 March, 2022, (17:08), the Babyn Yar memorial complex was also destroyed. The graphs in Figure 5 show one seismic (mm/s) signal for all 3 components (vert (Z), long (X) and tran (Y)), where one can see the maximum amplitude of oscillations in the Z component and the acoustic signal (air wave pressure in Pa), which correspond to the missile striking the ground – the building of the Babyn Yar memorial complex.

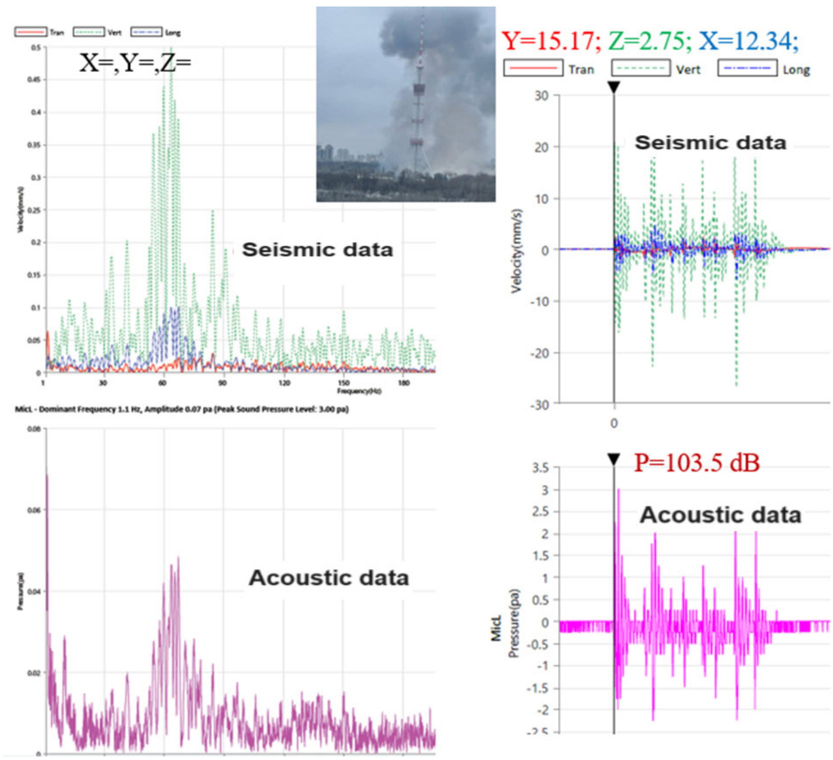

Figure 5. Monitoring record, received by the Mini Mate Plus seismic station, of the rocket attacks on 01 March, 2022 at 17:08

2.3 Determination of the seismic and acoustic wave parameters for military and civilian explosions

The results of studies on the effects of seismic and shock-air waves excited by civilian explosions caused by the detonation of cumulative explosive charges on chimneys and by military explosions during the missile attack on the TV tower and the Babyn Yar memorial complex in Kyiv will be used as a method of hardware determination of seismic and acoustic wave parameters based on the data obtained for the intensity of seismic vibrations of the earth's surface and residual air pressure in future detection of civilian and military explosions.

The civilian seismic effect of the explosive collapse of a chimney has two sources: the actual hole explosion of the explosive charges, followed by the formation of a blast as the chimney body impacts the ground surface.

As for the seismic effect of a military nature, as when tall buildings and structures are attacked by a missile, their collapse, the fall of the debris from a downed missile, *etc.,* there are three types of sources: two types are the actual explosion of the charge in the missile on the ground, with the formation of debris and the subsequent impact of the mass of collapsed debris on the ground, and the formation of blast wave from the airborne explosion in the part of the missile that did not go deep into the ground. These processes will be considered in sequence.

In turn, the intensity of seismic waves during the detonation of hole explosive charges to obtain weakening of the chimney base was determined by two methods. The first method was hardware measurements of the seismic blast wave parameters (ground displacement rate (in cm/s) and period of its oscillations (in s)) and, based on the above data, determination of the intensity of earth surface oscillations (Table 2). The second method was the analytical method of a rigid stamp on an elastic base.

Generally, depending on the purpose of the missiles and their destructive effect, different types of explosives are used, but their warhead mass is given in TNT equivalents, so further analysis of the seismic waves will be carried out for two types of explosives (Table 3), *i.e.* ammonite 6ZhV and TNT.

Table 3. Main characteristics of the explosives researched

Parameter	Unit	Type of explosive	
		Ammonite 6ZhV	TNT
Explosive density	[g/cm^3]	0.8-1.2	1.5-1.65
Detonation velocity	[m/s]	3700	6950
Heat of explosion	[kJ/kg] ([kcal/kg])	4312 (1030)	4184 (1000)
Breeziness	[mm]	–	by Hesse– 16 by Cast– 3.9
Explosiveness	[mL]	–	285
Volume of gases	[l/kg]	895	730
Temperature of explosion	[°C]	2960	–
Critical diameter:	[mm]		
– open charge		10-13	6-10
– charge within shell		4-6	6
TNT equivalent by heat of explosion	–	1.03	–

Let us consider the first method. According to the blasting project, the blasting was carried out with ammonite 6ZhV, placed in a blasthole with a diameter of 36 mm. At a height of one metre from the ground surface, 28 blasthole explosives were detonated, the grid of the blastholes was 0.5×0.5 m (double-row). In a single blasthole, the mass of the explosive charge was 0.147 kg, and the total mass of the charges was Q = 4.12 kg. The seismic receivers were installed on a profile of 120-290 m from the chimney base. Figure 2 shows a seismogram of the ground vibrations at different distances (r = 120-290 m) from the chimney base when the weakening charge explosion impacts the ground surface (the time of impact was in the range from 1.0 to 2400 ms) and when the chimney collapses (3300-1000 ms). The rock mass along the profile of the sensor installation consisted of sandy soil in the higher layers (up to 3-4 m deep), loam (up to 10 m), a 1 m deep water bearing layer of sand at the level of 11 m and then clay.

Let us now analyse the intensity of the impact of the weakening charge explosion on the earth's surface based on the results of seismometric measurements of the blast wave parameters. The dependence of the main criterion of the seismic safety of explosives (ground velocity, cm/s) on the distance in the surface wave is expressed by a static regression, which has the following form:

$$U^z = K_1 \cdot r^{-n} \quad (1)$$

where K_1 is the seismicity coefficient; r is the distance from the explosion location to the observation point, (in m); n is the attenuation coefficient of the wave process. As a result of the actual measurements, it was found that: $K_1 = 500$, $n = 1.7$.

In order to predict the seismic effect of the same operations under other conditions (e.g., a hit by a missile on the television tower foundations), as well as to calculate the seismic safe distance or permissible charge mass, Equation 1 can be written as:

$$U^z = K_2 \left({}^{r}\!/_{Q^{1/3}} \right)^{-1.7} \quad (2)$$

where $K_2 = K_1 \cdot (Q^{(1/3)})^{-1.7} = 500 \cdot (4.12^{(1/3)})^{-1.7} = 225$.

The distance (r_{SAW}) for the impact of shock-air waves (SAW) is determined by Equation 3:

$$r_{SAW} = 63\sqrt[3]{Q^2} = 63\sqrt[3]{4.12^2} = 147 \text{ m} \quad (3)$$

The results of processing the obtained seismometric data show that the ground displacement rate during the explosion of the charge varies from 0.15 to 0.032 cm/s at distances of 120 to 290 m from the explosion site, with a period of oscillation in the surface wave from 0.11 to 0.15 s.

The next stage is the analysis of the effect of the second type of oscillation of the earth's ground layer – the impact of the collapsed chimney on the ground and the formation of wave oscillations similar to the surface wave.

The dependence of the ground displacement rate on distance is expressed by the following static regression (Equation 4).

$$U^z = 45 \cdot r^{-1.05}, \quad R = -0.988 \quad (4)$$

The collapse of the chimney occured in two stages: firstly, its lowest part (2/3 of the height) dropped, followed by the highest part (1/3 of the height). The process of chimney collapse was recorded on channel 1 ($r = 120$ m) of the oscillogram (Figure 2), but in later channels (2-5) the wave processes combine into one, possibly reinforcing each other. Therefore, the impact of the chimney on the earth's ground was calculated as a single process. The equivalent mass of charge Q_{equ} is then determined by Equation 5.

$$Q_{equ} = {}^{E_k}/_{C} \tag{5}$$

where E_k is the kinetic energy of the load (in J) and C is the energy per unit mass of charge (in J/kg). For the explosive Ammonite 6ZhV, $C = 4.2 \cdot 10^6$ J/kg. In the case of the chimney crash:

$$E_k = M \cdot g \cdot H$$

where M is the mass of the chimney, and is $1.25 \cdot 10^6$ kg, g is the standard acceleration of gravity and H is the vertical displacement of the centre of gravity of the chimney at the moment of contact with the ground (25 m).

$$Q_{equ} = \frac{M \cdot g \cdot H}{C} = 70.45 \text{ kg}$$

To be able to predict the seismic safety of explosives associated with the collapse of smoke stacks and other tall structures, it is necessary to have a dependence of the rate of soil removal on the distance given to the mass of the explosive. Having the seismicity coefficient $K_3 = 45$ in Equation 4 and the equivalent charge mass, the rate of ground removal is determined by Equation 6.

$$U = K_4 \left({}^{r_c}/_{Q_{equ}^{1/3}} \right)^{-n} = 10 \left({}^{r_c}/_{Q_{equ}^{1/3}} \right)^{-1.05} = 0.22 \text{ cm/s} \tag{6}$$

where $K_4 = K_3 \cdot (Q_{equ}^{1/3})^{-1.05} = 45 \cdot 0.222 = 10$

2.4 Determination of the seismic and acoustic wave parameters for the TV tower attack

Applying the above algorithm, the seismic safe distance or permissible charge mass in the situation of a missile attack on the foundations of the Kyiv television tower was calculated in accordance with the monitoring protocol shown in Figure 4. The amplitude of the velocity of oscillations (vertical component (U^Z) in cm/s) in the soil massif at a distance ($r = 4500$ m) near the apartment building (Obolon), excited in the scenario of a missile attack on the television network with the full mass of its charge ($Q = 500$ kg), can be as shown in the form of Equation 7.

$$U^z = K_2 ({}^{r}/_{Q^{1/3}})^{-1.09} = 225 ({}^{4500}/_{500^{1/3}})^{-1.09} = 0.22 \text{ cm/s} \tag{7}$$

The real mass of the charge ((Q_{at}) in kg) that attacked the TV tower and caused vibrations (amplitude of the vibration rate ((U_{at}) in cm/s) of the soil at a distance (r_c = 4500 m) near the apartment building (Obolon) will be:

$$Q_{at} = \left(\frac{U^z}{\mathrm{K_c}}\right)^{3/n} \mathrm{r_c^3} = \left(\frac{0.22}{225}\right)^{2.8} 4500^3 = 340\ kg, \tag{8}$$

$$U_{\mathrm{at}} = K_2({}^{r}/_{Q^{1/3}})^{-1.09} = 225({}^{4500}/_{340^{1/3}})^{-1.09} = 0.13 \text{ cm/s} \tag{9}$$

where U_{at} is the amplitude of the oscillation velocity in the case of a missile impact with a charge mass of Q_{at} =340 kg, r_c is the seismic safe distance (in m) to buildings and structures with an acceptable surface (Rayleigh) or transverse wave for these objects and the oscillation velocity of their soil foundations (U_{sf}, in m/s). In this particular case, this is the distance from the epicentre of the impact to the building (4500 m) where the seismic station was installed (Figure 3).

Analysis of the results (Figure 4) showed that the resultant oscillation velocity U_{at} = 0.13 cm/s, occurred in the frequency range from 0 to 10 Hz, U_{at} > 2 cm/s in the range of 20 to 25 Hz. When the missile attacked the base of the television tower, the latter was not damaged, so unlike the chimney (a technogenic civilian explosion), the television tower remained standing and the seismic components (vert (Z), long (X) and tran (Y)) arose only from the transmission of vibrations of the television tower itself to the earth's surface, and according to the microphone recording (see the acoustic graph in Figure 5), the maximum residual air pressure at a distance of 4500 m (SAW 103.5 dV) was 1.2 Pa.

Calculating the r_{SAW} distance of the impact of the SAW from the TV station attacked by a missile with the full mass of its charge (Q = 500 kg), one can obtain:

$$r_{SAW} = 63\sqrt[3]{Q^2} = 63\sqrt[3]{500^2} = 2600 \text{ m}$$

Analysing Equations 4 and 6, it can be argued that the attenuation coefficient of the wave process, n = 1.05 is more appropriate than n = 1.5 and n = 2.5, which are accepted in [1-3], because firstly, the coefficient n = 1.05 is taken from the actual data recorded by the seismometer complex during the chimney collapse, and, secondly, the wave processes are taking place in soft soil in the elastic region during the distribution of the seismic surface wave, and this shows that the value of n should be approximately in the range of 1.0-1.2. The coefficients 1.5 or 2.5 refer to elastic-plastic and plastic volume waves.

The peculiarity of the surface wave caused by the impact on the ground when the missile debris collapsed is that its propagation speed is approximately half that of the blast wave.

Information about the intensity of wave oscillations (Figure 6) during the chimney collapse is given by the data presented in Figure 2. Figure 6 shows the difference and similarity of the seismic effects in the case of explosions of underground charges, surface charges, explosion of chimney bottom charges, the impact of a chimney on the ground surface and a missile attack on the TV tower (into the ground) – Figure 6 lines 1-4, respectively. Figure 6 shows that the displacement velocity in the surface wave generated by an underground explosion (Q = 70 kg) in sandy loam soil (line 3) is 2 times higher than that of a collapsed chimney (line 2). Approximately the same ratio is observed in the intensity of oscillations when comparing the blast waves generated by the impact (line 1) with the waves caused by the impact on the ground surface of the falling chimney (line 2) and the residual intensity of seismic waves after the missile attack on the television tower (line 4).

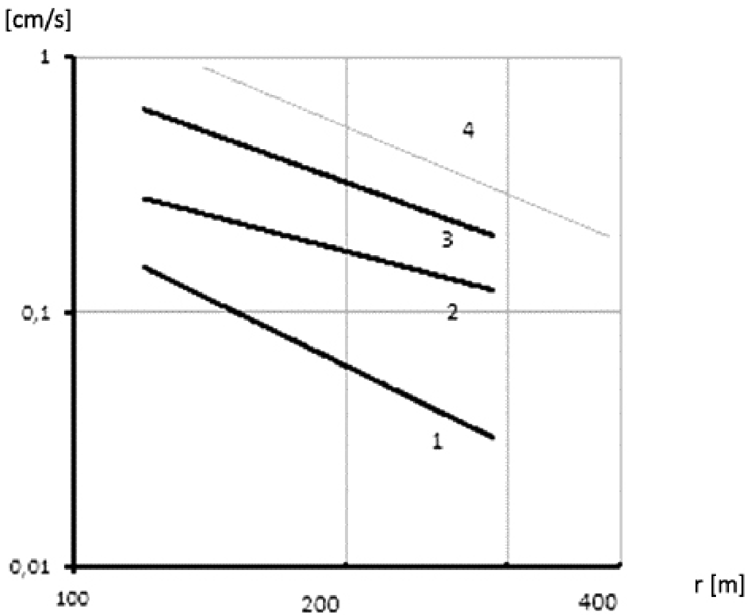

Figure 6. Comparison of seismic wave intensity: 1 - chimney bursting (Q = 4.12 kg); 2 - impact of a crashing chimney on the ground surface; 3 - underground explosion of a concentrated explosive charge (Q = 70 kg); 4 - residual seismic wave intensity after a missile crashed into the TV tower (Q = 340 kg at a distance of 4500 m)

An important feature of the waves generated by the impact is the magnitude of their oscillation periods, which vary from 0.23 to 0.25 s on a profile of 120 to 290 m, and exceed the similar data for explosions of contact (external) charges weighing 40 to 80 kg by 4 to 5 times [3]. The oscillation periods of the waves generated by the impact and the underground explosion are practically at the same level. Low-frequency vibrations under impact loads that fall within the resonant region of vibrations of buildings and structures (4-5 Hz) require special seismic safety attention when performing work on the collapse of high-rise structures. It all depends on the distance to the protected structures, the permissible values of seismic hazard criteria and frequency characteristics.

Using the examples of real-life research, it can be shown how the permissible rate of elimination of the ratio of the periods of oscillations in the wave to the natural oscillations of the protected object depends on the ratio of the oscillation periods in the wave. The oscillation period when the chimney hits the ground T = 0.25 s, the period of self oscillations of the protected object T_o = 0.2 s, logarithmic decrement of attenuation, oscillation period of a standard pendulum T_{cm} = 0.25 s, allowable displacement speed of the protected object U_{add} = 5 cm/s, without taking into account frequency characteristics. The permissible oscillation speed of the protected object, taking into account the frequency characteristics specified above, can be determined using the following relationship [4, 7]:

$$U_{add} = U_0 \cdot {}^{C}\!/_{\mathrm{B}_{ob}} \tag{10}$$

where C is the spectrum of oscillations and is determined by the equation:

$$C = {}^{T_0^2}\!/_{T_{cm}^2} \cdot {}^{1}\!/_{\sqrt{2\lambda_0}}$$

and B_{ob} is the frequency response of the system "soil - protected object":

$$\mathrm{B}_{ob} = \left[\left(1 - {}^{T^2}\!/_{T_0^2}\right)^2 + {}^{4\lambda_0^2}\!/_{(\pi^2 + \lambda_0^2)} \cdot {}^{T^2}\!/_{T_0^2}\right]^{-1/2}$$

After calculating for Equation 10, the allowable displacement rate for the object is obtained, which is U_{add} = 0.25 cm/s, and as a result of the impact of the falling load on the ground surface at a distance of 120 m from the foundations of the chimney, the vertical displacement rate of the soil was 0.3 cm/s.

Therefore, the low intensity of seismic vibrations during the collapse of the chimney should not cause problems with seismic safety, but “due to” significant low-frequency issues, *y* vibrations arise in the wave upon impact and the onset of the resonance effect, problems do arise.

3 Conclusions

- ♦ Based on the data obtained from seismometric measurement of the parameters of the wave process during the collapse of a high-rise chimney (pipe), some features of the formation and propagation of wave oscillations were established.
- ♦ Wave oscillations that occur during the explosion of the hole charges of the chimney lining and a missile attack on the TV tower spread in the soil massif based on the laws of a seismic blast wave, rather than a wave that retains the design features of a “rigid stamp”.
- ♦ It has been established that the surface wave, which arose both from the impact directly on the ground and from the transmission of the missile impact directly through the TV tower into the ground, spreads in soft soil with an attenuation coefficient n = 1.05, which corresponds to this type of wave. The coefficients n = 1.5-2.5, which are assigned to wave process when a chimney hits a soil massif by a volitional decision [1-3], refer to elastic-plastic and plastic waves.
- ♦ The present article shows the difference and similarity of the seismic effect in the case of explosions of underground charges, surface charges, explosion of chimney bottom charges, impact of a chimney on the ground surface and a missile attack on a television tower (into the ground).
- ♦ This particular example uses the method of determining the permissible rate of ground displacement at the base of the structure, taking into account the frequency characteristics of the wave process and the natural vibrations of the protected object.

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Contribution

Boiko V.:	conception
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Khlevnyk T.:	methods, performing the statistical analysis
Zagoruyko E.:	performing the experimental part, other contributions to the publication
Han O.:	performing the experimental part, performing the statistical analysis
Zakusylo R.:	foundations, other contributions to the publication

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