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A new way of calculating the maximum seismic vibration velocities acting on a building's foundation and using them to assess the magnitude of the damaging effect on the building

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ABSTRACT

It is generally accepted that seismic vibrations caused by explosive detonation propagate in a circular manner around the vibration source. Currently, peak vibration velocity (PPV) measurements of the horizontal components of seismic vibration in the x direction (PPVx) and in the y direction (PPVy) are performed at different directional angles, assuming that their values are constant regardless of the directional angle of measurement 'α'. Seismic velocity values measured in the x direction are denoted by the subscript 'x' and in the y direction by the subscript 'y'. The aim of this paper was to demonstrate the effect of the directional angle of vibration velocity measurement 'α' on the maximum value of the horizontal components PPVx and PPVy. The methodology used involved the implementation of a Cartesian triaxial reference system, in which the horizontal y-axis coincides with the direction of the line of blast holes and the x-axis is perpendicular to it. This configuration made it possible to define the directional angle 'a' of the vibration velocity measurement with respect to the reference system. A theoretical analysis of the distribution of the resultant circular vibration velocity into two components, Vx and Vy, was carried out. The values of the horizontal radial components in the x direction and the tangential components in the y direction were then calculated using the directional measurement angle 'α'. Theoretical analysis and measurement results showed that the PPVx and PPVy velocities at a fixed distance from the vibration source depend on the value of the directional angle 'α' of the velocity measurements. Particle vibration velocity measurements of the medium PPVx, PPVy at any measurement angle 'α' can be quickly converted with the x direction to the maximum particle vibration velocity PPVx max for a directional angle of 90°, and with the y direction to the maximum particle vibration velocity PPVy max for a directional angle of 0° based on the equations given in the article. The values of PPVx max, PPVy max used to assess the harmfulness of seismic vibrations acting on buildings should not exceed the safe values read from the Polish Standard.

Keywords: opencast mining, seismic vibration, circular distribution of vibration velocity, safety of house structures.

INTRODUCTION

Explosives are usually used in rock excavation. This process induces vibrations in the rock being mined and in the soil surrounding the mine. These vibrations are transmitted in the form of seismic waves that can propagate in all directions and have harmful effects on residential buildings. It is assumed in the world literature that the seismic vibrations generated during the rock extracted with explosives rock propagate along a circular path with equal energy in each direction, similar to the waves on water from a stone thrown into it (Figure la) [1–11].

Figure lb shows the directional angle of measurement 'α' of the vibration speed between the direction of the line of blast holes and the direction of the line connecting the measurement point, for example a building, to the central blast hole in the rock block and gives the distance 'r' between the blast site and the building. This paper presents and solves a new scientific problem concerning the directional distribution of radial and tangential vibration speeds generated by an explosion [12]. Relationships are provided for calculating the effect of the directional angle of measurement, vibration speed on the value of the horizontal speed components of vibrations acting on the building. The maximum ground velocity calculated for buildings should not exceed the safe limit of velocity of vibrations (Fig. 3a, 3b).

Figure la illustrates that the circular directionality of Dx and Dy is equivalent to the distribution of the resultant speed value Vxy, Figure 2a in any direction. Figure lb, directional measurement angle, speed of vibration [13]. The source of seismic vibration is the detonation of an explosive charge in the quarry. The issues concerning the occurrence and conditions of circular distribution of velocity of seismic vibrations in radial x and tangential x directions generated by vibration sources have not been investigated so far. Many publications on seismic vibration measurements have not investigated the effect of the directional angle of measurements ‘α’ on the circular distribution of velocities of vibrations for the x and x directions, as the author has done. Instead, the authors of the publication investigated the effects of speed vibration on building structures and the type of damage that occurs depending on the model of building, the type of ground, at the maximum value of the explosive mass on the deceleration and frequency of speed vibration. The researchers have made many attempts to develop equations to accurately calculate the horizontal vibration velocity of the PPV without determining the directional angles ‘α’ of the measurements taken, taking into account the maximum value of explosive charge mass per deceleration, vibration frequency and safe distance from buildings during blasting operations. In the context of enhancing the precision of vibration velocity prediction, the utilisation of numerical methodologies, such as artificial neural networks (ANNs) [14–16], genetic algorithms (GA), neural-fuzzy techniques (NFT) [17], random forest algorithms and support vector machines [18], has been employed. In order to better predict the peak particle velocity (PPV) and dominant frequency [19, 20], a simulation was designed using signature hole analysis. Attempts have been made to generate PPV models that take into account the influence of rock discontinuities, rock types, rock formations, rock joints and their orientation, presence of water table, soil-rock interface, acoustic behaviour, etc. Despite extensive research, the above researchers have not been able to identify general relationships for all deposits, but only local relationships for the studied directions on the analysed deposits. This was probably due to the fact that the vibration velocity values adopted for the given directional angles "α" were not studied separately as circular radial and tangential directional distributions [6]. Directional angles are not yet included in the currently used predictions of peak vibration velocities PPVx and PPVy.

Considering the influence of directional angles on the vibration values PPVx and PPVy will allow for a more accurate prediction of maximum vibrations and thus a more accurate determination of the safe seismic vibration zone for buildings. So far, seismic wave researchers have not taken into account the influence of the directional angle ‘α’ on the predicted velocity value of horizontal components of vibration velocity in a circular directional distribution. In the case of a circular directional distribution, the maximum value of the radial component of vibration velocity PPVx max occurs at a directional angle of α = 90°, and the maximum value of the tangential component of vibration velocity PPVy max occurs at a directional angle of α = 0°.

If possible, PPVx and PPVy measurements should be performed for the above directional

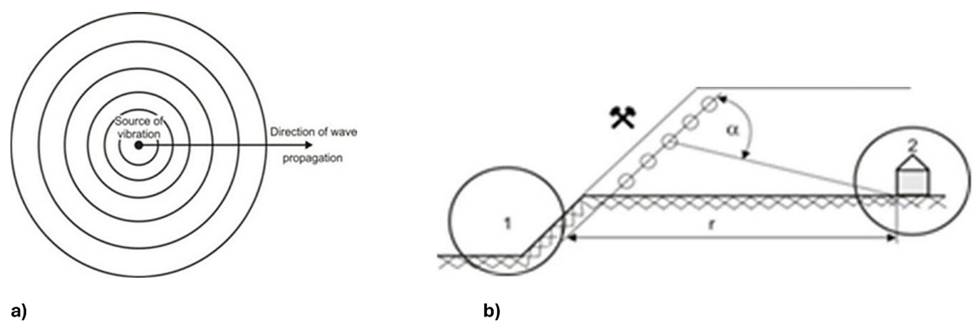

Figure 1. (a) Circular directivity Dx and Dy (a), directional measurement angle (b), vibration speed [13]: 1 – quarry with blasting bench and distance r between quarry (1) and building (2)

angles ‘α’. In the case of a circular directional distribution, if the horizontal components of the vibration velocity, the radial component PPVx and the tangential component PPVy are measured at any directional angle “α”. This maximum value of the horizontal radial component of the vibration velocity PPVx max vibration can be calculated from the equation given in the article for the angle α = 90°. similarly, the maximum value of the horizontal tangential component of the vibration velocity PPVy can be calculated from the equation given in the article for the angle α = 0°.

Currently, it is assumed that seismic vibrations propagate circularly in all directions, which is not always true. To claim that seismic vibrations have circular directionality, it would be necessary to perform vibration velocity measurements on a semicircle every 10° behind the free face for each extraction of rock with explosives. Nobody does this. Most often, the measurement team performs measurements on the line connecting the source of vibrations with the protected house, on the house at ground level. The directional angle “α” of the measurement is also not measured. Based on such a measurement, it is assumed that the velocity of seismic vibrations is the same on such a radius in every direction. For such a measured value of vibration velocity, the effects of damage to the house given in the SWD [25] (SWD-polish acronym, Dynamic Influence Scale) are read. For the vibration velocities measured in this way, the safe distance of the house from the quarry and the size of the charge explosive safe for the house are calculated. Publications state [8, 13] that the vibration frequency depends on the size of the charge and the distance, there is no information about its change with the change of the measurement direction angle.

For the first time in an international publication, it was documented by measurements (Table 1) that in a circular distribution of the vibration velocity at the same distance from the vibration source, the seismic velocity also depends on the direction of its measurement. Thus, it was experimentally proven that the theoretical radial velocity for a longitudinal wave has maximum value for the directional angle α = 90°. Similarly, the tangential vibration velocity for a longitudinal wave has maximum value for the directional angle α = 0°.

For the first time, it was documented in an international publication (Table 1) that the seismic frequency also depends on the direction of measurement. That is, there is a directional frequency distribution of the longitudinal wave vibration and this is described by a sinusoidal relationship. For the measurements given in Table 1, the radial frequency fx depending on the value of the angle α has the form $fx\alpha = 2.5 \sin\alpha$ and the theoretical dependence of the frequency on the direction x is $fxa = A \sin\alpha$, where A the measurement constant.

INVESTIGATIONS OF THE PEAK VIBRATION VELOCITY OF PARTICLES ON THE TESTED BUILDING

The peak particle vibration velocity of a building being tested is the most important factor in determining the extent and nature of structural damage. This speed is determined based on the maximum charge at a known distance from the explosion site to the measurement site. The relationship between the distance (D) of the explosion site from the measurement site (SD) and the maximum charge per delay (W) is expressed by the equation [21–24]:

$$SD = D/W^{½}\ (\mathrm{m/kg}^{1/2}) \tag{1}$$

where: D – is the distance between the explosion site and the measurement site (m) and W – is the maximum explosive (BM) charge per delay (kg).

In the x direction, the peak particle radial velocity $PPVx = Vx$ and in the y direction, the peak particle tangential velocity $PPVy = Vy$ of the vibrating particles is given by:

$$PPVx = PPVy = k(SD)^n\ (\mathrm{m/s}) \tag{2}$$

where: k and n are computational data from the computer program generated when calculating the correlation relationship (2).

According to [8–11, 13, 21, 22, 24], they depend on geological conditions and the direction of x or y measurements (Figure 2). For the assumed size of the explosive charge (W) and the permissible vibration speed adopted from Figure 3a, the safe distance of the house from the explosion site is calculated from Equations (1) and (2). For the maximum value of the speed vector of horizontal radial vibrations PPVx max and tangential vibrations PPVy max and their frequency, the degree and type of building damage are precisely given by the Polish standard [25] PN-B-02170:2016-12. The permissible value of the safe speed of radial oscillation PPVx, and tangential oscillation PPVy, according to the Polish standard [25] for a building with one storey and 5 storeys is given in Figures 4a, 4b. Utilising Equations 1 and 2, it is feasible to ascertain with an accuracy of ± 50% the following: a) the value of the speed vector of horizontal oscillation PPVx and tangential oscillation PPVy, for a radius equivalent to the assumed distance value, in the entire area adjacent to the exploited deposit; b) the seismically safe distance from the explosion site for protected objects, with a constant mass of the explosive charge (W). The disadvantage of the applied relations 1 and 2 is that they do not take into account the change of the speed vector of radial vibrations PPVx and tangential oscillation PPVy with the change of the measurement direction angle "α" (Fig. 2a, 2b, 3). In the process of conducting field measurements, the measurement of the peak oscillation speed Vx = PPVx of a longitudinal wave in the *x* direction connecting the measurement site to the blast site is known as radial, and perpendicular to the *x* direction is known as tangential Vy = PPV. The measurement of the peak oscillation speed in the *z* direction, Vz = PPVz, in the direction perpendicular to the x and y directions is known as vertical. The measurement direction parallel to the shot hole lines is referred to as the y direction, and the measurement direction perpendicular to the shot hole lines is referred to as the x direction. Therefore, vibration parameters measured on the x-direction are designated by the x-index as PPVx and on the y-direction as PPVy. In this article, these parameters are also referred to as equidistant, i.e. Vx = PPVx and Vy = PPVy.

THEORETICAL ANALYSIS OF THE UNIT CIRCULAR DISTRIBUTION OF THE LONGITUDINAL VIBRATION VELOCITY

The distribution of the radial component Vx of the oscillation speed as a function of the value of the directional angle 'α' in Figure 2a shows that the radial component Vx of the oscillation speed for the directional angle 'α' in the range 'α' = 0–90° takes the shape of a semicircle in each quarter of the circle. Its value increases with the increase of the angle 'α' in the direction of the x axis, for α = 90°, Vx = Vx max. From the analysis of the tangential constituent Vy of the oscillation speed as a function of the value of the directional angle 'α' in Figure 2b, it can be seen that the tangential constituent Vy of the oscillation speed for the directional angle 'α' in the range 'α'= 0–90° has the shape of a semicircle in each quadrant of the circle. Its value increases as the angle 'α' increases in the direction of the *y*-axis, for α = 90°, Vy = 0, for α = 0°, Vy = Vy max. As shown in Figure (2a), the unit radial oscillation speed Vx and the unit tangential oscillation speed Vy (as shown in Figure 2b) show different values of the oscillation speed as in a function of the angle 'α'.

As demonstrated in Figures 2a and 2b, the y-axis and velocity Vy are found to be parallel to the direction of the line of blast holes. In contrast, velocity Vx is found to be perpendicular to the *y*-axis. The resultant unit vibration vector of velocity Vxy for a circular distribution can be written as the sum of the constituent vectors.

$$Vxy^2 = Vx^2 + Vy^2 = R^2 = 1 \tag{3}$$

$$Vx = Vxy \cdot \sin\alpha = 1 \cdot \sin\alpha \tag{4}$$

$$Vx = Vy \cdot \text{tg}\,\alpha \tag{5}$$

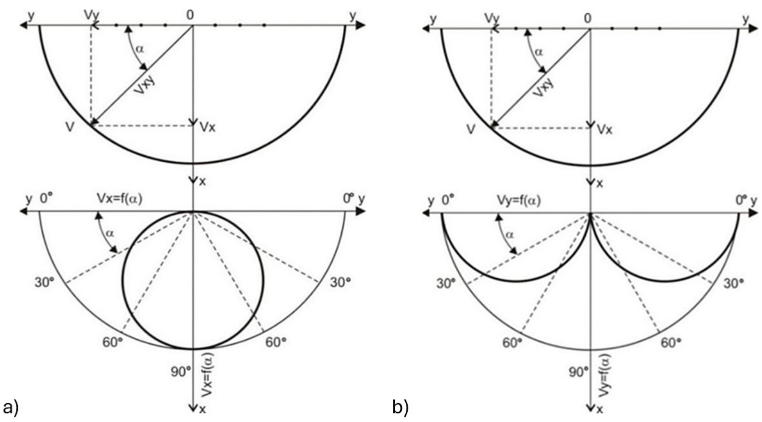

Figure 2. Variation in the shape (a) and value of the unit oscillation speed vector (b) of a longitudinal wave and its constituent [24]

$$Vy = Vxy \cdot \cos\alpha = 1 \cdot \cos\alpha \quad (6)$$

Given the measured radial vibration velocity $Vx\alpha$ for any angle α, the maximum vibration velocity Vx max for angle 90° is calculated from the equation [12]:

$$Vx\ max = Vx\ \alpha \cdot \sin 90° / \sin\alpha \quad (7)$$

Similarly, the maximum tangential of the oscillation speed [13]:

$$Vy\ max = Vy\ \alpha \cdot \cos 0° / \cos\alpha \quad (8)$$

where: $Vx\ \alpha$, $Vy\ \alpha$ – peak value of the oscillation speed measured for the directional angle α.

Referring Figures 2a and 2b to the rock extraction conditions, point 0 indicates the central blast hole, with Vx = PPVx and Vy = PPVy. The arrow in the figure indicates the X direction perpendicular to the free face. The peaks of the radial oscillation speed constituent PPVx and tangential oscillation speed constituent PPVy are measured on the test house at any directional angle 'α'

RESEARCH AND MEASUREMENT METHODOLOGY

Confirmation of the derived theoretical dependence of the maximum vibration velocity on the directional angle of measurement was made on the basis of the results of research compiled in Onderka's doctoral thesis [26]. The research and measurement methodology described in detail in the doctoral thesis did not differ from the commonly used one. These were measurements of peak vibration velocities generated during extracted clay in the overburden of the Konin mine by explosives. In 1970, peak vibration velocities in the x direction as Vx and in the y direction as Vy and their corresponding frequencies were measured as part of the field work. The distance of the vibration source from the measurement point was measured. The detailed results of the measurements are summarised in Table 1. The results of the measurements are shown in Figure 3, from which it can be seen that the actual circular directional vibration velocity distribution and its shape coincide with the shape of the theoretical circular directional vibration velocity distribution for a longitudinal wave. It was experimentally proven that the maximum value of the peak vibration velocity under both real and theoretical conditions depends on the directional angle of the measured vibration velocity. It was proven that the measured vibration velocities relate to the vibrations induced by a longitudinal seismic wave. The method of performing the work was to calculate the maximum value of the peak velocity PPVx max in the x direction according to Equation (7) and in the y direction according to Equation (8). With the maximum value of the peak velocity PPVx max in the x direction and the measured distance between the vibration source and the point of measurement of the vibration velocity, the maximum value of the peak velocity PPVx max can be calculated by varying the distance so that it is safe for the building structure. Such calculations are made using proportional relationships, as in the example given in the article.

Assumptions, justification of assumptions and their influence on the results of the analysis

Publications [21–24] often provide correlation relationships for the calculation of vibration velocities and describe the values of vibration velocities and their effects on residential buildings. The type of wave, the type of directionality of the vibration velocity produced by the vibration source and the reference system are not analysed [29–33]. Therefore, the authors of this paper deal with a vibration source that generates a directional circular vibration velocity field, placed in a triaxial reference system. The value of the horizontal directional angle of the vibration velocity measurement influences the value of the measured vibration velocity. According to literature and engineering practice, the peak velocity and frequency of vibrations generated during extracted rock with explosives in mining were adopted to assess the harmful effects on buildings. The Polish Standard [25] allows the equivalent use of the horizontal component of peak displacement, peak velocity and peak acceleration value of vibration of a measuring point and the corresponding value of vibration frequency to assess their harmful effects on buildings. British Standard BS 7385-2:1993 considers the peak value of the velocity component (PPV) in terms of the dominant vibration frequency. The German damage scale (DIN 4150-3), the Austrian standard ÓNORM S 90207, as well as the damage scale according to the Bureau of Mines, USA, the Langefors and Kihlstrom damage scale take the maximum value

Table 1. Parameters of vibrations during mining of boulder clays in the mine Adamów [27]

No.	*fx*	*Vx*	*Vy*	*r*	*W*	*α*°	*n*	Wsk	*Vxs*	*Vys*	Vxmax	Vymax	Burden	Spacing
	(Hz)	PPVx (cm/s)	PPVy (cm/s)	(m)	(kg)	(angle)	(pices)		(cm/s)	(cm/s)	PPVX max(cm/s)	PPVy max(cm/s)	(m)	.[m]
10	1.8	0.28	0.49	800	250	30°	3	1.02	0.29	0.50	0.58	0.57	14	6
14	2.2	0.81	0.60	700	200	53.5°	5	0.89	0.72	0.53	Heterogeneity		17	6
15	2.5	0.56	0.15	810	200	75°	5	1.03	0.58	0.18	0.60	0.69	15	6
16	1.4	0.50	0.07	930	250	82°	4	1.19	0.60	0.08	0.61	0.57	15	5
17	2.0	0.50	0.06	1080	250	83°	4	1.38	0.69	0.08	0.70	0.67	14	5
24	2.5	0.49	0.48	600	250	45.5°	6	0.76	0.37	0.36	0.52	0.51	14	7
25	2.5	0.48	0.27	700	250	60°	6	0.89	0.43	0.24	0.49	0.48	14	7
31	2.4	0.60	0.28	650	220	65°	15	0.83	0.50	0.23	0.55	0.55	16	7
The mean value of Vxmax and Vymax is 0.58 cm/s; the maximum deviation of a single measurement from the mean value for Vx; is below (-0.09), above (+0.12) cm/s. The maximum deviation of a single measurement from the mean value for Vy; is below (-0.10), above (+0.09) cm/s.											0.58	0.58		

Note: No. firing in the table, *fx* – vibrations frequency at measuring points outside the deposit, *Vx* and *Vy* – horizontal vibrations velocity in radial and tangential direction at measuring points outside the deposit, *r* – distance of the measuring point from the vibration source, *W* – explosive charge per hole and a delay / for one detonator /, *a* – directional angle defined for circular distribution as tgα = *Vx*/*Vy*, *n* – number of fired holes, *Wr* – distance indicator calculated according to the Polish patent no. P 23100.

of the horizontal component of vibration velocity and the corresponding frequency to assess the damage of seismic vibrations. In the description [29] of the Mining Seismic Intensity Scale (Polish acronym GSIS-2017), it is reported that the correlation of observed vibration effects (degrees of damage) is better for vibration velocity, PGVHmax, than for vibration acceleration, PGAH max (Polish acronym). The authors of the publication, similarly to other researchers mentioned above and on the basis of the Polish Standard [25] (SWD scale – Polish acronym), used the maximum value of the velocity of horizontal vibration components and the corresponding frequency most commonly used in practice by blasting engineers worldwide to assess seismic hazard. The authors do not have data from a detailed analysis of a large number of measurements to be able to conclude unequivocally that the horizontal component of vibration acceleration more accurately determines the degree of damage to buildings than the previously commonly used horizontal component of vibration velocity.

Main difficulties and challenges and original achievements in overcoming them

The main difficulty with a small number of measuring instruments is the measurement of vibration velocity and frequency at different directional angles at a fixed distance from the vibration source. Publications state [8, 13] that the vibration velocity and the corresponding vibration frequency depend on the size of the load and the distance. In order to take into account the effect of distance on the value of the vibration velocity and the corresponding vibration frequency, their value was calculated for an average distance of 784 m. The effect of distance on the value of the vibration velocity was taken into account by multiplying the measured velocity value by the distance index Wr. The distance factor Wr is calculated as the ratio of the distance of the measuring point to the average value of the distance of all measuring points in accordance with Polish patent no. P 23100. Similarly, the value of the corrected vibration frequency was calculated. Using this patent, the peak distance-corrected vibration velocity and corresponding frequency were calculated. It was then found that the distribution of the measuring points follows the circumference of the wheel in accordance with the theoretical analysis of the longitudinal wave vibration velocity components as well as in accordance (with Patent application P432966 of 10.02.2020. This means that the directional angle of the measurement can be used to calculate the maximum value of the horizontal component of the vibration velocity. Similarly, the vibration frequency of the longitudinal wave can be calculated. At the maximum value of the horizontal component of vibration velocity and its vibration frequency, possible seismic damage to residential buildings can be determined based on the Polish Standard [25] and SWD. The solutions developed in this article can also be used in the analysis and measurement of seismic vibration acceleration.

Empirical verification of directional horizontal circular radial and tangential vibration velocity in a lignite deposit

The detonation of an explosive in a rock block, which is the source of vibrations, causes a horizontal circular distribution of oscillation speeds measured in the X-PPVx direction and in the Y-PPVy direction, propagating in the medium through which the wave passes (Fig. 3). The measured peak values of the horizontal radial constituent Vx = PPVx and the tangential constituent Vy = PPVy of oscillations during mining of the overburden of the Adamów lignite deposit [26] are shown in Figure 3. As demonstrated in Figure 3, the measured values of Vx and Vy exhibit a shape that is analogous to the theoretical distributions depicted in Figures 2a and 2b. The angle ‘α’ is defined as 55° in Figure 3, representing the directional angle of overburden inhomogeneity, as evident in the graph plotting horizontal radial oscillation speeds (Vx) and tangential oscillation speeds (Vy).

As for the vibration velocity, the table shows the distance-corrected measured frequency value. In the next column, the relative error is given as the ratio of the value calculated from the sine correlation relation fc/fm to the measured /corrected/ value.

Vxmax is the maximum vibration velocity in the x direction calculated from Equation (7), for angle α = 90°. Vymax is the maximum vibration speed in the Y direction calculated from equation 8, for angle α = 0°. In the medium in which the seismic wave propagates, there is a circular directional distribution of; radial vibration velocities for the x – PPVx direction and tangential vibration velocities for the y – PPVy direction. In the world mining literature, when determining the vibration velocity in a medium in which a seismic wave propagates, there is no division of the velocity vibrations field into directional circular distributions separately for x direction-PPVx and for y direction PPVy [6]. For the circular distribution of vibration velocities for the same distance, the value of radial and tangential velocities depends on the measurement direction x or y and of the measurement direction angle “α”.

The maximum value of the vibration velocity measured in the X direction (Vx = PPVx) or in the y direction (Vy = PPVy) is used to determine the safe distance between the vibration source and the protected building and the safe charge mass of the explosive. Table 1 shows that for a directional angle α = 45.5° the value Vx = PPVx α = 0.37 cm/s, The value of 0.37 PPVx α represents 64% of the average PPVx max. from Table 1. The safe distance between the vibration source and the protected building for a directional angle α = 45.5° and a PPVx value would be calculated with an error of approximately 36%. Using the PPVxmax values calculated from Equation 7, PPVx max = PPVx α·sin 90^{o}/sin 45.5^{0} = 0.37/0.71 = 0.52 cm/s, the calculation error is reduced to approximately 10%. The value of 0.52 PPVxmax represents 90% of the average PPVxmax value for all measurements. A similar error will occur when calculating Vy = PPVy.

The maximum values of the horizontal components of the vibration velocity PPVx = PPVy = 0.58 cm/s and the maximum value of the

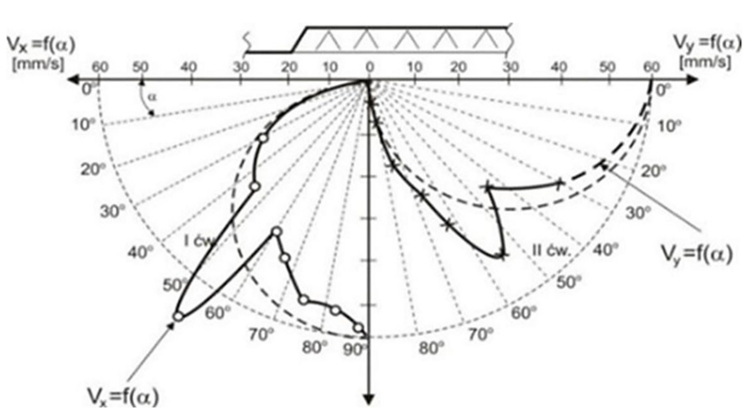

Figure 3. Circular directional distribution of the horizontal contributions of radial speed V_x = PPVx and tangential speed V_y = PPVy [27]

frequency fxa = 2.5 Hz calculated on the basis of measurements (Table 1) and plotted on the SWDI graph allow us to conclude that in the case of single-storey buildings constructed at a distance of 784 m from the source of vibration and charge on delay 250 kg does not cause cracks in structural elements such as building walls.

For the first time in an international publication, it was documented by measurements (Table 1) that in the circular distribution of vibration velocity at the same distance from the source of vibration, the vibration velocity also depends on the direction angle of its measurement. In this way, it was experimentally proven that the radial velocity for a longitudinal wave has a maximum value for the direction angle α = 90°. Similarly, the tangential vibration velocity for a longitudinal wave has a maximum value for the direction angle α = 0°.

For the first time in an international publication it has been documented (Table 1) that the frequency of vibrations also depends on the directional angle of its measurement.

This means that there is a directional distribution of the frequency of longitudinal wave vibrations and it is described by a sinusoidal relationship. The correlation relationship is.

$$fxa = A\sin\alpha \tag{9}$$

where: A is the value of the measurement constant.

For the measurements given in Table 1, the radial frequency fx depending on the value of the directional angle α has the form $fxα$ = 2.5 sin$α$.

CRITERIA OF HARMFULNESS OF SEISMIC SHOCKS AS PER POLISH NORM

The scale for assessing the dynamic actions of buildings SWD (SWD-polish acronym) is categorised into two distinct variants: SWD-I for single-storey buildings and SWD-II for five-storey buildings. The SWD scale constitutes a diagram delineating the five zones of damage to buildings consequent to the exceeding of peak seismic velocities or accelerations. To assess the damage caused to buildings by the velocity or acceleration of seismic vibrations, the value of the horizontal components measured on buildings at ground level is used.

SWD-I and SWD-II have zones I, II, III, IV and V, which are separated by four lines A, B, C and D. These lines are located in Figures 4a and 4b. The drawings in the coordinate system indicate: on the vertical axis velocity (mm/s) or acceleration (m/s^2); on the horizontal axis vibration frequency, f (Hz). The following criteria for division into harmfulness zones were adopted:

- Zone I: oscillations that do not have a harmful effect on buildings. Limit A: lower limit of vibrations perceptible by buildings.

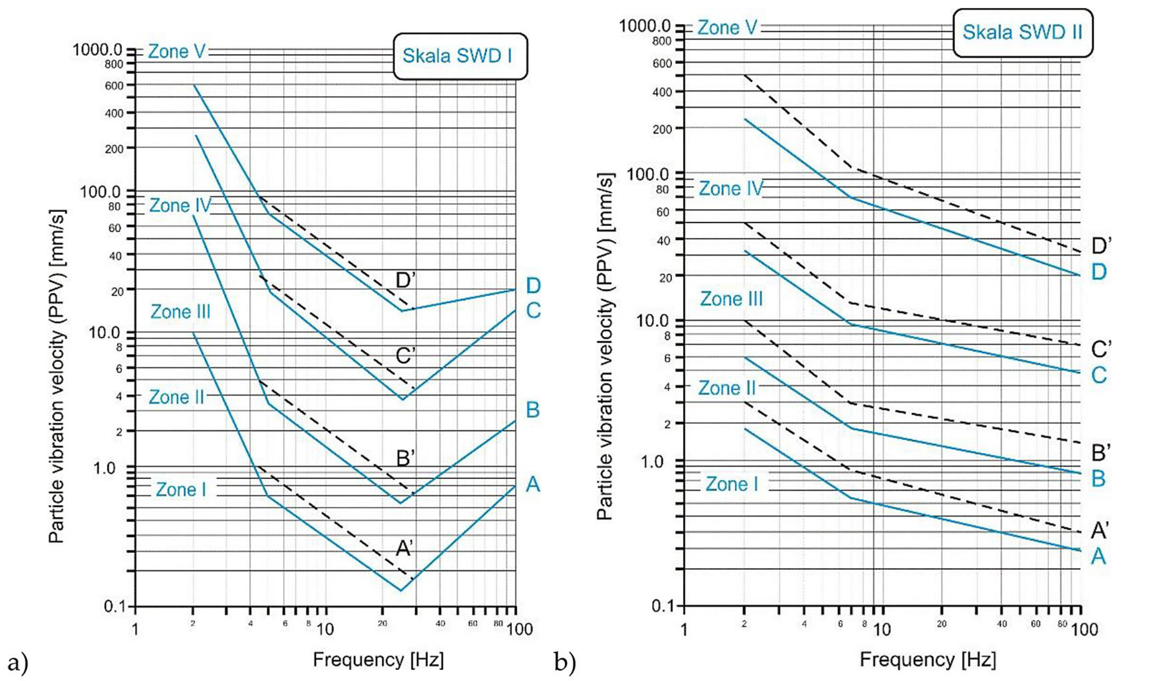

Figure 4. The lines A,A'; B,B'; C,C'; D,D' give the limiting values of the vibration velocity of the medium for each zone SWD I (a), for buildings up to one storey and SWD II (b) [25]

- in Zone II, oscillatory phenomena are perceptible to the structure of the building; however, these do not pose a threat to its integrity. The building exhibits accelerated wear and tear, manifesting as cracks and scratches in the plasterwork.
- boundary B: lower limit of crack formation in structural elements.
- Zone III: vibrations harmful to the building, causing local cracks; possible plaster flaking.
- boundary C: lower limit of severe damage, durability limit of individual building elements. Zone IV: Vibrations posing a threat to people; numerous cracks, local damage to walls and individual elements; falling of suspended objects and fragments of plaster on ceilings. Limit D: lower damage limit for the entire building; appearance as above.
- Zone V: vibrations causing collapse of walls; collapse of ceilings.

The limits of the various zones are delineated for two distinct alternatives: a continuous line and a dashed line, which are selected in accordance with the conditions stipulated in Table 2. The building is included in the appropriate variant in accordance with the applicable number of appropriate features included in Table 2. In the case of short-term vibrations or ful fillment of all the conditions specified in column 3 of Table 2, it is permissible to shift the damage limit by one zone up. In such a case, vibrations of the magnitude of the higher zone are assigned the effects of vibrations of the lower zone. The SWD is one of the most modern scales of dynamic influences since it takes into account not only the frequency – as the American norm – but also the state of the building, type of the materials used as well as its construction (not included in the Swedish or American scales of the harmfulness of vibrations).

A PRACTICAL EXAMPLE OF THE APPLICATION

A practical illustration of the implementation of the information presented in the article is the actions of a civil engineer in the context of building a house located at a distance of R = 1200 m from the edge of a quarry. In a letter to the quarry management, he attaches a fragment of a map on which a single-storey house is planned to be built on the plot marked x on the map of the quarry and its surroundings. He gives its dimensions of 15×15×7 m and then asks questions. First, whether the distance of R = 1200 m is safe for such a house; second, whether the seismic vibrations generated in the quarry will not cause the walls to crack. The following statement was provided in response: In a comparable new residential structure located at a distance of R = 800 m from the quarry at a directional angle of 45°, the measured value of the horizontal radial component Vx 45° was: 7 Hz and 3 mm/s, which was 0.2 mm/s less than the allowable structural damage value given by SWDI [25] (SWDI Polish acronym) Figure 4a. The quarry mining front is moving towards the planned house construction and will reach a directional measurement angle of 90°. The directional measurement angle α is defined as the angle between the line of blast holes and the line connecting the measuring point (i.e. the building) with the center of the block of rock extracted with explosives in the quarry. Using the relationship (7) presented in the article, the maximum value of PPVx max = Vx 45°· sin 90°/sin45° = 3·1/0.705 = 4.25 mm/s was calculated. From the proportional relationship, the safe distance "Rx" for a newly built house was calculated as follows:

(800 m = 3 mm/s) and (Rx(m) = 4.25 mm/s),

hence Rx = (800 · 4.25)/3 = 1133.3 m

Table 2. Conditions for assigning a house to a boundary

Assessment as per	Characteristics that allow to use the limit	
	Lower – the solid line	Higher – the broken line
Shape of the building	Buildings that are damaged, old, remodelled or strengthened	Undamaged buildings without structural remodelling
Materials and building structure	Buildings with aggregate concrete walls, stone walls, lack of foundations, large or irregular openings in the walls, improperly finished/built	Walls made out of bricks, reinforced concrete foundations, massive ceilings, high quality work
Type of subsoil and foundation	Of low stiffness (dust or lose sands); foundations not continuous of varying height	Stiff subsoil: silts and stiff clays, flat foundation
Type of vibrations	Long-term or continuous vibrations	Short-term vibrations

The calculation results show that a distance of 1200 m is a safe distance. If the directional angle of measurement were not taken into account, the calculated distance would be (800 m = 3 mm/s) and (Rx = 3 mm/s), i.e. Rx = (800 · 3)/3 = 800 m. In this case, the relative calculation error would be 1133.3/800 = 142%. Such a small distance from the vibration source – 800 m would cause cracking of structural elements, such as walls in a newly built house and would significantly shorten the expected life of the building.

CONCLUSIONS

The analysis presented in this article, in connection with measurements carried out in the lignite deposit, showed that during blasting operations in the overburden there is a circular distribution of directional vibration velocities: radial PPVx and tangential PPVy. In the world mining literature, the division of the vibration velocity field into circular directional distributions separately for the x – PPVx direction and the y – PPVy direction is not used when determining the vibration velocity in rocks in which the seismic wave propagates. In the context of the prevailing consensus in the mining literature regarding the circular distribution of vibration velocity, there are no established equations for determining the radius of the seismic safe zone and the mass of the safe explosive charge, taking into account the measurement of the directional angle of vibration velocity. This paper offers a comprehensive overview of the measurement conditions and relations for calculating the maximum value of the radial and tangential components of the vibration velocity, taking into account the directional measurement angles, for the circular distribution of vibration velocity. Using these findings, a safe seismic vibration distance can be established for protected buildings. The damage scale caused by the vibration velocity is also given for a single-storey (SWDI) and a five-storey (SWDII) building.

It is possible to estimate the value of the vibration velocity acting on the tested house based on the given damage scale and types of damage to the house. The value of the safe seismic velocity for residential buildings was determined based on the given SWDI and SWD II scales. The example given in the article shows the calculation of the safe distance from a nearby quarry for a house under construction based on the maximum value of the seismic vibration velocity. It is important to note that the circular distribution of vibration velocity, which is commonly accepted in the mining literature, does not include Equations (4, 6, 7, 8), which are used to determine the radius of the safe seismic vibration zone and the mass of the safe explosive charge taking into account the directional angle of the vibration velocity measurement. To determine the maximum vibration velocity for the x direction (PPVx max) and the y direction (PPVy max), it is necessary to measure the radial vibration velocity (PPVx) and tangential vibration velocity (PPVy) values for a single directional angle (α). Equations (7) and (8) can be used to determine their maximum values.

After calculating the maximum vibration velocity for PPVx max, the safe distance of the explosion point from the building and the maximum safe value of the explosive charge for each delay in the x direction can be calculated from Equations (1) and (2). Similar calculations are made for the y direction. The structural integrity of the new building is ensured if the maximum horizontal values of the radial vibration velocity PPVx max and the tangential vibration velocity PPVy max do not exceed the value above the line B'. Based on field measurements of the vibration velocity distribution, it is possible to avoid building a house in the direction of the highest vibrations.

The article contributed to the acquisition of new knowledge in the field of seismic vibrations generated during the exploitation of rocks by explosives. The new knowledge concerns the circular distribution of vibration velocity generated by the source of vibrations, which is charge explosive:

a) it was experimentally proven and the measurement results confirmed that the theoretically derived circular distribution of horizontal components of the longitudinal wave vibration velocity is the same as that obtained from measurements,
b) a new practical method of determining the maximum value of horizontal components of the velocity and acceleration of vibrations was given,
c) a new practical method of determining the type of seismic wave causing vibrations was given,
d) the frequency of vibrations in the x direction depends on the value of the directional angle,
e) a correlation relationship was given that is suitable for the practical determination of the frequency in the x direction depending on the value of the directional angle,
f) a directional elliptical field of the velocity and

acceleration distribution may occur during the exploitation of rocks using explosives,

g) the shape and type of the directional field of velocity and acceleration of vibrations depends on the type of wave causing vibrations.

Based on results the following conclusions can be drowned:

1. For a circular distribution of oscillation speed at the same distance from the blast site, the radial peak horizontal oscillation speed (PPVx) and the tangential peak oscillation speed (PPVy) depend on the angle of measurement (α).
2. When calculating the maximum values of the speed of oscillation, PPVx max and PPVy max, it is necessary to take into account the angle of measurement 'α' according to Equations (7) and (8). These values are used to determine the degree of seismic damage to the houses.
3. The assessment of the safety of building structural elements for circular directional distribution and horizontal radial and tangential seismic speed of oscillation can be based on measurements carried out at any directional angle 'α', taking into account its influence on the maximum value of the speed of oscillation velocities PPVxmax and PPVymax using the given Equations (7) and (8).
4. The safety of the structural elements of the new protected building is ensured if the maximum values of the radial horizontal speed oscillation PPVx max and the tangential horizontal speed. oscillation PPVy max do not exceed the values marked with line B".
5. The measurement direction angle is defined as the angle between the line of blast holes and the line connecting the measurement point, e.g. a building with the center of a block of rock extracted by an explosive charge.
6. The seismically safe distance of a newly constructed building from a nearby quarry can be calculated based on the maximum value of the horizontal component PPvx max, which is calculated as the product of the peak vibration velocity PPVx α for the measurement direction angle α and the sine of 90° divided by the sine of the measurement direction angle α.
7. For the first time in an international publication, it was documented by measurements that in a circular distribution of vibration velocities at the same distance from the source of vibrations, the vibration velocity also depends on the directional angle of its measurement.
8. It was experimentally proven that the radial vibration velocity of a longitudinal wave has a maximum value for a directional angle of α = 90°. Similarly, the tangential vibration velocity of a longitudinal wave has a maximum value for a directional angle of α = 0°.
9. For the first time in an international publication, it was documented that the vibration frequency also depends on the directional angle of its measurement.
10. The directional distribution of the vibration frequency of a longitudinal wave in the x direction is described by a sinusoidal relationship. The theoretical equation is $fxa = A \sin a$, where A is the value of the measurement constant.

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