The Approximate Assessment of the Impact of Mining Vibrations on Buildings

Alicja Kowalska - Koczwara[1)], Tadeusz Tatara[2*)]

[1)] Cracow University of Technology, Faculty of Civil Engineering, Warszawska 24St., 31-155 Krakow, Poland, E-mail: akowalska@pk.edu.pl; ORCID: 0000-0001-8088-7729

[2*)] Cracow University of Technology, Faculty of Civil Engineering, Warszawska 24St., 31-155 Krakow, Poland, E-mail; ttatara@pk.edu.pl, ORCID: 0000-0002-4071-2358

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Abstract

Mining operations, whether underground or surface-based, can lead to a negative phenomenon known as mining tremors. These anthropogenic tremors arise from activities involved in mineral extraction. They can occur in various mining basins, such as the Legnica-Glogow Copper District (LGOM), the Upper Silesian Coal Basin (GZW), and the Lublin Coal Basin (LZW). The causes of these tremors include the displacement of rock layers due to mining activities, sudden relaxation of rock mass, and the release of energy resulting from the abrupt release of stress in the Earth's crust. Mining tremors can be categorized based on their energy levels: weak-energy, high-energy, and regional tremors. These tremors can have detrimental effects on the surface, buildings, and the people residing within those structures. It is important to note that surface vibrations from mining operations are fundamentally different from those caused by natural earthquakes, although the research methods for both phenomena are similar. The intensity of surface vibrations originating from mining activities is assessed using numerical analyses of structural models, employing the Finite Element Method, or through approximate methods that utilize specific scales. In the analysed mining areas of GZW and LGOM, the Mining Intensity Scales (GSIS-2017), developed by the Central Mining Institute, are employed to evaluate the intensity of surface vibrations. The Higher Mining Office has assessed the efficacy of these scales, which have been implemented in the GZW and LGOM regions. Additionally, the Dynamic Impact Scales (SWD), proposed and integrated into Polish standards, can also be used to gauge the impact of these vibrations. The SWD scales were created based on numerical analyses, and their effectiveness was validated by in situ research results. This article provides insights into these scales and presents examples of analyses regarding the impact of surface vibrations on buildings. Evaluations of the harmful effects of vibrations on structures indicated consistency between the findings based on the GSIS-2017 and SWD scales.

Keywords: *Mining rockbursts, Surface vibration records, Mining scales, Building, Damage*

1. Introduction

Mining tremors are a dynamic phenomenon induced by underground and surface mining activities. Mining tremors are the most intense phenomena generated by human activity called paraseismic sources. They accompany the mining of copper ore, hard and brown coal, gold, diamonds, non-ferrous metals, and originate from pile driving, driving sealed walls, and cars, trains, trams, and subway. These vibrations can cause considerable damage to surface structures. In Poland, mining tremors occur in mining regions, such as the Upper Silesian Coalfield (GZW) and the Legnicko-Glogowski Copper District (LGOM). Mining tremors are not subject to human control and are random events in terms of their timing, location, and magnitude. There are numerous distinctions between earthquakes and mining tremors.

The major differences are, e.g. energy, intensive phase duration, peak ground accelerations (PGA), content of predominant frequencies, frequency of occurrence, and depths of hypocentre. Mining-related vibrations stand out by having the greatest intensity of all forms of paraseismic vibrations. It is therefore essential to assess the impact of this type of vibration on buildings. In areas affected by underground mining operations, mining companies in the past century commonly used the macroseismic MSK-64 scale [**1**], along with its subsequent versions, to assess the intensity of surface vibrations. This scale was the primary tool used, particularly in the LGOM areas and to a lesser extent in the GZW area. The scale was used to assess the risk to buildings from surface vibrations caused by mining tremors. In the MSK-64 scale, the measure of impact was the maximum acceleration value, taken as the geometric mean of the maximum values of horizontal and vertical acceleration components. It is worth noting that these maximum values of acceleration components occurred at various times. The frequency corresponding to the resultant acceleration determined in this way, was calculated as the arithmetic mean of the frequencies corresponding to the maximum acceleration values in the horizontal and vertical directions.

The MSK-64 scale is a descriptive scale of earthquake intensity (based on the description of earthquake effects). The MSK-64 scale is no longer used in Western countries. Currently, more accurate methods of assessing seismic activity are used. The MSK-64 scale, like other earlier ones, is not based on dynamic analysis. This scale describes the mass effects of earthquakes and should not be used to assess the harmfulness in individual buildings. Despite this, mining companies, when assessing the harmfulness of mining-induced tremors on surface structures, often referred to it. The MSK-64 scale can only be treated as providing some insight into the harmfulness of seismic vibrations from mining-induced tremors on buildings. The MSK-64 scale can be used to assess the harmfulness of vibrations from mining-induced tremors on wooden structures and roof coverings, e.g., in single-family houses [**2**]. Currently, the latest version of the MSK-64 scale is the European EMS-98 scale [**3**].

The MSK-64 scale should not be used to assess the risk to surface infrastructure in the mining tremors areas because this scale pertains to the assessment of the effects of natural seismic events. Seismic tremors cover incomparably larger areas where negative impacts on surface structures are evident compared to the small areas affected by mining tremors. The MSK-64 scale is a twelve-degree scale that assigns observed natural effects of earthquakes on people, their surroundings, buildings, and other structures, as well as the natural environment, to specific degrees of earthquake intensity. The scale distinguishes degrees of vibration intensity, which are correlated with ground acceleration

and velocity. The individual degrees of earthquake intensity are correlated with seismometric measurement results. The scale classifies and describes damage to buildings; it distinguishes degrees of damage, which it assigns to building damage. Structures are categorised into three groups based on their durability, which depends on the type of structure and the materials used for construction. Building damage according to the MSK-64 scale is classified based on quantitative characteristics and the degree of damage.

When determining the degree of vibration intensity caused by earthquakes and mining tremors according to the MSK-64 scale, there is no justification for calculating a_{max} and the frequencies given in the scale due to the irregularity of these vibrations. In the case of surface vibrations caused by earthquakes and mining tremors, there is generally no need to consider the vertical components of vibrations. The vertical component should be considered in specific cases where horizontal load-bearing elements have large spans; vertical components of vibrations should be included in the dynamic analysis.

Instead of the MSK-64, the EMS-98 macroseismic scale is used; it is more detailed and distinguishes six classes of buildings. It provides a more comprehensive description of phenomena corresponding to individual degrees of intensity, including the expected degrees of damage in individual building classes. It is also a scale that defines the effects of earthquakes.

In Poland, because of extensive research, empirical Mining Intensity Scales have been developed. Differences in the observed and described effects of vibrations on buildings in the LGOM and GZW areas led to the creation of two separate scales for these regions. The GSI-2004 scale was first developed for the LGOM area [**4**]. The development of the GSI-2004 scales was based on the strongly recognised primary role of velocity as the fundamental measure of vibration intensity in the LGOM area.

After several years of experience with this scale, it was updated in 2011 (GSI-2004/11) [**5**]. In the GZW area, the beginning of the development of Mining Intensity Scales dates to 2004 (GSI-2004). The verification of the GSI-2004 scale conducted between 2006 and 2010 formed the basis for modifying the description of damage in individual intensity levels, expanding and refining certain groups of damage. The fundamental fact remains unchanged that the damage described in the individual levels may or may not manifest.

At the Cracow University of Technology, Dynamic Impact Scales (SWD) were developed, which took into account the characteristics of the object itself (Ciesielski 1961). Attempts were made to apply the SWD scales to assess mining-induced tremors, especially since these scales have been included in the applicable Polish standards since 1985. The SWD scales and the principles of their application were included in the Polish Standard PN-B5/B-02170 "Assessment of the harmfulness of vibrations transmitted through the ground to buildings." For the assessment of the impact of vibrations on people, the Polish Standard PN-88/B-02171 "Assessment of the impact of vibrations on people in buildings" was developed. Both mentioned standards are cited as mandatory in the Regulation of the Minister of Infrastructure of April 12, 2002, with subsequent amendments regarding the technical conditions that buildings and their location should meet. Currently, both mentioned standards have been updated (PN-B-02170:2016-12, PN-B-02171:2017-06) [**6, 7**].

2. Dynamic Impact Scale (SWD) and criteria for assessing the impact of mining vibrations on building structures according to this scale

An approximate assessment of the impact of vibrations transmitted through the ground on certain types of buildings can be carried out using SWD scales [**8**]. The SWD scales can be applied to masonry buildings (i.e., buildings made of manually laid elements) and prefabricated buildings (large blocks, large panels). Based on the measurement of horizontal vibration parameters of the building's foundation and the analysis of vibrograms (maximum amplitude of the measured quantity and its corresponding frequency in ⅓ octave bands), the locations of points with coordinates corresponding to the vibration parameters relative to the vibration damage zones for the building are determined. On this basis, the effects of dynamic actions in relation to the building are assessed.

The SWD-I scales, presented in terms of velocity (SWD-Iv, in Fig. 1a) and acceleration (SWD-Ia, in Fig. 2a), apply to compact buildings with small external horizontal dimensions (not exceeding 15 m), one or two stories, and a height not exceeding any of the horizontal dimensions.

The SWD-II scales, presented in terms of velocity (SWD-IIv, in Fig. 1b) and acceleration (SWD-IIa, in Fig. 2b), apply to buildings no taller than five stories, with a height less than twice the smallest width of the building, as well as low-rise buildings (up to two stories) that do not meet the conditions specified for the SWD-I scales.

In assessments using the SWD scales, records of horizontal vibration components (in the x and y directions) recorded at a rigid structural node on the building's foundation or the basement wall at ground level on the side facing the vibration source are used. These are analysed in 1/3 octave bands, obtaining maximum vibration acceleration (velocity) values in each band.

The scales are presented in a coordinate system where the horizontal axes represent the central vibration frequencies in 1/3 octave bands, and the vertical axes represent the maximum horizontal vibration acceleration (velocity) values in the 1/3 octave bands.

Criteria used in dynamic diagnostics for building structures subjected to the impact of vibrations transmitted through the ground can be directly expressed in the form of specified non-exceedable values of displacements or stresses, or indirectly defined in appropriate dynamic impact scales. In the first approach, design standards (e.g. [**9, 10**]) are utilised, taking into account the requirements specified in standards describing seismic [**11**] or paraseismic actions [**6**]. In dynamic diagnostics related to building structures, diagnostic criteria are most often derived from strength and stiffness conditions. As early as in the work [**6**], it was shown that the assessment of the impact of this type of vibration can, for certain selected classes of buildings, be presented in a simplified manner by linking it to parameters characterizing the horizontal vibrations of the foundations of these buildings.

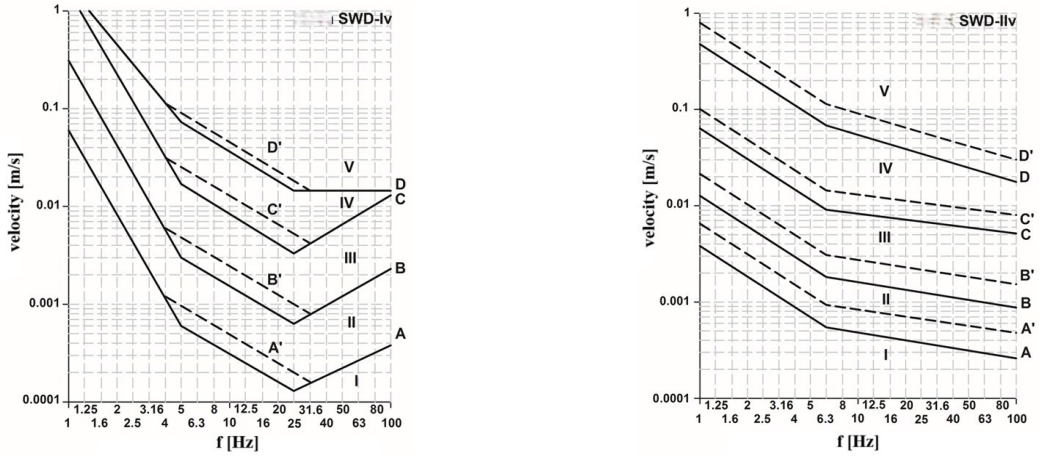
In the calculations (cf. [**6**]), which resulted in the construction of dynamic impact scales SWD, two model buildings with masonry construction, founded on the ground, were taken into account. The criteria for dividing the vibration impact zones on the mentioned buildings were formulated based on appropriately defined conditions of stiffness, strength, and stability. The kinematic excitation of the buildings was assumed to be harmonically variable with a constant vibration frequency (ranging from 1 to 100 Hz) at different vibration amplitudes. In this way, the criteria for assessing the impact of vibrations transmitted from the ground to typical masonry buildings were constructed and presented in a simple form.

Five vibration impact zones separated by lines A-D were distinguished. These lines respectively indicate:

- the lower limit of vibration perceptibility by the building and the limit of considering dynamic impacts; for vibrations below this limit, dynamic impacts can be disregarded (line A),
- the stiffness limit of the building, i.e., the lower limit of the occurrence of cracks and fissures in structural elements (line B),
- the strength limit of individual building elements, the lower limit of severe building damage (line C),
- the stability limit of the structure, the lower limit of the entire building's failure; vibrations above this limit can cause building failure and threaten human life safety (line D).

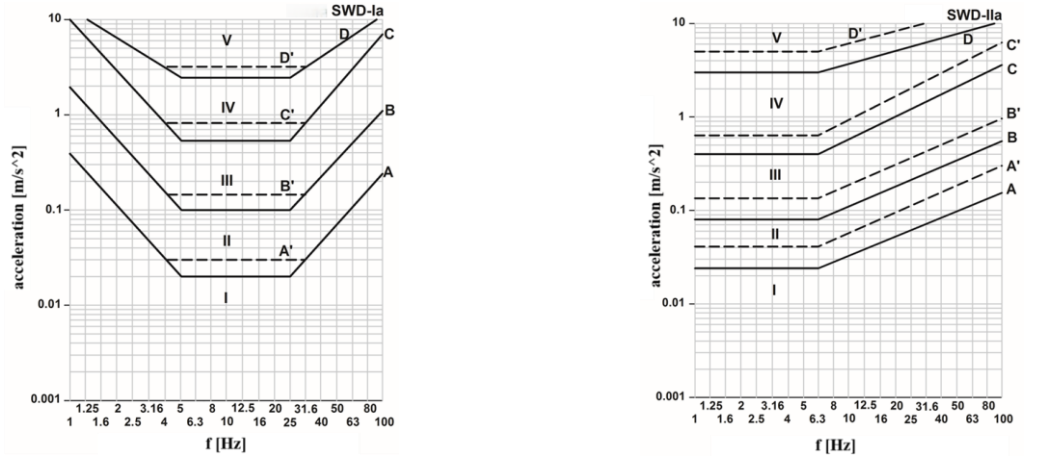
The boundaries of zones are provided in two variants based on the assessment of the building's condition, the type of ground, and the nature of vibrations. Classification into the appropriate variant is determined by the predominant number of relevant features, listed approximately in Table 1. If all the conditions specified in column 3 of Table 1 are met, it is permissible, when verifying the harmfulness of vibrations on a building, to raise the zone boundary by one level (e.g., vibrations with parameters falling within Zone II in Fig. 1 and Fig. 2 can, under the given conditions, be assigned effects corresponding to Zone I). For historical buildings and buildings with valuable wall paintings, stuccoes, etc., the zone boundaries should be lowered, assigning Zone II effects to Zone III.

The boundaries of the zones are given in variants according to the assessment of the building condition, type of ground, type of material and construction, and type of vibrations. Detailed information on which of the above-mentioned factors influence the adoption of the line separating the zones of harmfulness is provided in Fig. 1 and Fig. 2, and in table 1, referred to here as [**6**].



a) b)

Fig. 1. Lines describing the zones of vibration impact on buildings according to the SWD-Iv (a) and SWD-IIv (b) scales, given in coordinates: frequency [Hz] - maximum vibration velocity [cm/s]



a) a)

Fig. 2. Lines describing the zones of vibration impact on buildings according to the SWD-Ia (a) and SWD-IIa (b) scales, given in coordinates: frequency [Hz] - maximum vibration acceleration [cm/s²]

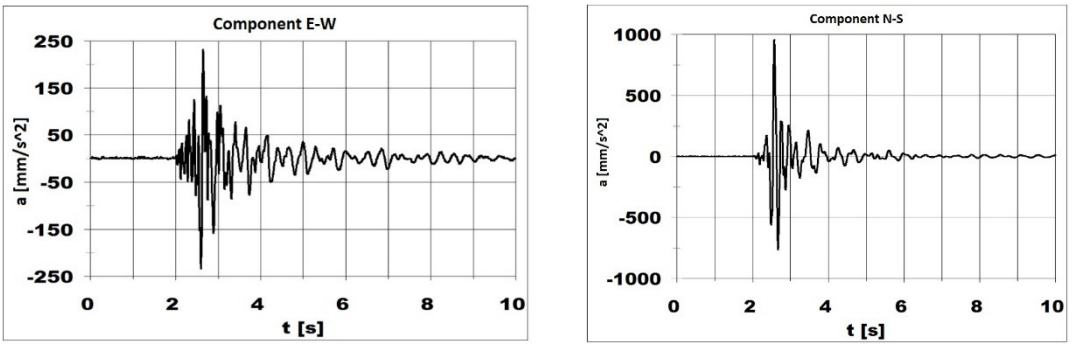
Tab. 1. A summary of features enabling the application of lines separating vibration damage zones (according to [**6**]).

Assessment according to	**Features enabling the application of the boundary**	
	Lower-lying (lines from A to D in Figure 1.22-1.23)	**Higher-lying (line from A' to D' in Figures 1.22-1.23)**
1	2	3
Condition of the building	Old buildings with damage, renovated or reinforced buildings	Undamaged buildings without structural modifications
Materials and construction of the building	Buildings made of slag concrete masonry or stone, poorly executed, lacking foundations, lacking bond beams, vaulted ceilings, large wall openings, or irregular openings	Walls made of solid brick, carefully constructed, with reinforced concrete or concrete foundations, and massive ceilings connecting walls with a ceiling bond beam
Type of ground and method of foundation	Ground with low rigidity (e.g., dusty or loose sands), discontinuous foundations (of varying heights), or intermediate foundations	Rigid ground (e.g., stiff-plastic clays and loams), flat foundations
Nature of vibrations	Long-lasting or continuously occurring vibrations	Short-term vibrations

Based on the measurement of horizontal vibration parameters of a building's foundation and the analysis of vibrograms (maximum amplitude of the measured quantity and its corresponding frequency in ⅓-octave bands), the position of points with coordinates corresponding to vibration parameters is determined concerning the vibration hazard zones for the building. This serves as the basis for assessing the impact of dynamic actions on the building.

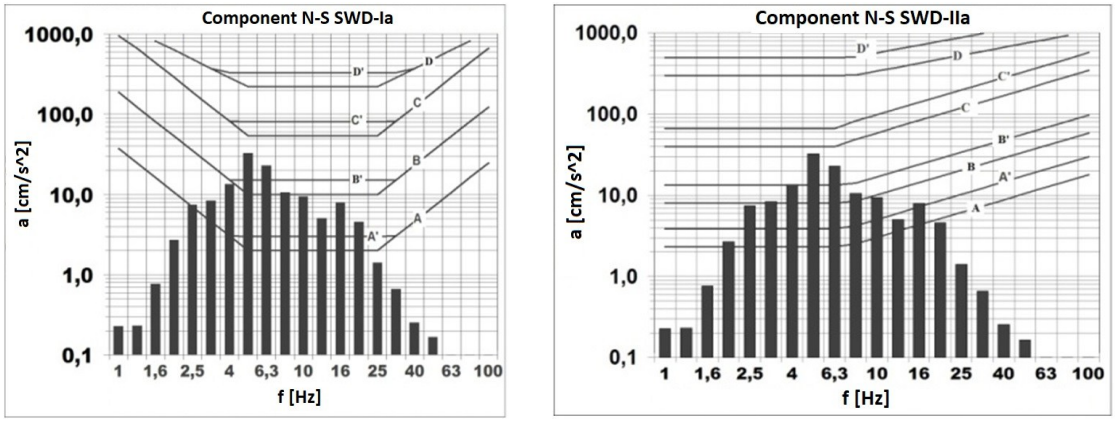
The straightforward formulation of the diagnostic criterion described above has led many authors to apply it in diagnoses of various structures, often overlooking its intended scope and the conditions for obtaining vibration parameter data. Reference [**6**] explicitly defines the applicability of the criterion, specifying the types of structures for which the SWD scales can be used in diagnostics. It also provides requirements for conducting vibration measurements and analysing their results. Before using SWD scales as a diagnostic evaluation criterion, it is essential to verify whether the structure under diagnosis meets the conditions necessary for applying SWD scales in this manner.

The horizontal component N-S of ground vibration acceleration is shown as an example in Fig. 3. The maximum value of vibration acceleration is nearly 1000 mm/s². The analyses were conducted independently according to the SWD-I scale and for cognitive purposes according to the SWD-II scale. The analysis of vibration waveforms in the third-octave bands of both vibration acceleration components indicates that the vibration parameters are in impact zone III-comp. Fig. 4. Vibrations whose parameters fall within Zone III are considered harmful to the building, causing local cracks and fissures, thereby weakening the building's structure and reducing its load-bearing capacity and resistance to further dynamic impacts; plaster and render may detach, and cracks may appear at the joints of structural elements.



a) b)

Fig. 3. Horizontal acceleration components of vibrations from a shock in the Upper Silesian Coal Basin (GZW) with an energy of 7E8J.



a) b)

Fig. 4. Result of the interpretation of the N-S component of the shock from Fig. 3 according to SWD scales.

3. GSIS-2017 scale and levels of intensity of vibrations

The Mining Seismic Intensity Scale, GSI-2017 [**12**], is an empirical and measurement-based scale that allows for an approximate assessment of the impact of mining tremors on buildings. It encompasses a range from harmless vibrations, through vibrations causing damage to finishing elements, to structural damage. It also enables an evaluation of the discomfort of using buildings in areas affected by mining tremors and an assessment of the perception of tremors by people.

For buildings located in areas affected by mining activities, empirical scales GSIS-2017 are applied.

The GSIS-2017 scale refers to buildings with the following construction types:

a. traditional and improved traditional, meaning generally masonry buildings made of brick or other small-sized elements, featuring wall-bearing systems. There is a rich database of experiences regarding the impact of mining tremors on this type of building structure.
b. concrete and reinforced concrete structures are characterized by higher resistance to mining tremors than buildings with traditional and improved traditional construction. Therefore, the effects of tremors occurring in such buildings can be described as corresponding to the effects of tremors with an intensity one degree lower than that resulting from the recorded (predicted) vibration parameters (this does not apply to intensity level 0).
c. skeleton structures made of reinforced concrete or steel, featuring column-beam load-bearing systems, exhibit similar resistance to mining tremors as buildings with traditional and improved traditional construction. For these buildings, the assessment of the effects of tremors can be directly applied using Table 1.3.
d. Historical and heritage buildings with high sensitivity to vibrations. Tremors at seismic intensity level 0 GSIS-2017 (PGV_{Hmax} ≤ 5 mm/s) are not harmful to historical and heritage buildings with high sensitivity to vibrations in the case of single seismic

events (fewer than 100 seismic events per year). In the case of repeated tremors at intensity level 0 (more than 100 seismic events per year), the first harmful effects may occur when the vibration level exceeds PGV_{Hmax} = 3 mm/s.

A synthetic description of the effects, expressed in degrees of vibration damage for individual levels of seismic intensity and specific surface vibration parameters, is presented in table 2.

Buildings in poor technical condition and/or subjected to the influence of continuous deformations of mining ground, with deformation index values corresponding to mining areas of categories III-V, are generally characterized by lower dynamic resistance than buildings not affected by mining ground deformations. Based on existing experience, it can be assumed that vibrations cause effects typical of those with an intensity one degree higher than those resulting from the recorded (forecasted) vibration parameters. For example, in the case of vibrations classified as intensity level III, effects characteristic of intensity level IV vibrations (described in Table 2) may be expected.

The seismic intensity levels in the GSI-2017 scale are presented in appropriate graphs or tables as a function of ground surface vibration parameters PGV_{Hmax} and t_{Hv} (and/or PGA_{H10}, t_{Ha}), with the main phase frequency of vibrations used as supplementary information. The scale has been validated based on a database of mining seismic tremors occurring in the GZW (Upper Silesian Basin) and, additionally, tremors observed in German and Czech mining basins.

The ground vibration parameters used in the GSIS-2017 scales are determined based on the following relations:

a) The maximum value of horizontal vibration velocity PGV_{Hmax} is determined as the maximum length of the ground vibration velocity vector:

$$PGV_{\max} = \max(\sqrt{v_x^2(t) + v_y^2(t)} \tag{1}$$

b) Maximum horizontal vibration acceleration PGA_{H10max} determined in the frequency band up to 10Hz, as the maximum length of the vibration vector:

$$PGA_{H10\max} = \max\left(\sqrt{a_{x10}^2(t) + a_{y10}^2(t)}\right) \tag{2}$$

c) The duration t_{Ha} of the intense phase of horizontal vibration acceleration is determined from the normalised Arias intensity graph [**13**], according to the following relation:

$$I_{Ha}(t_k) = \frac{\int_0^{t_k} \left(a_x^2(t) + a_y^2(t)\right)dt}{\int_0^{t_a} \left(a_x^2(t) + a_y^2(t)\right)dt} \tag{3}$$

and it is defined as the time elapsed between the moment when the value of expression (4.2) reaches 5% and the moment when it reaches 95%. The variable t_k describes the dependence of Arias intensity on time, which represents the total duration of the recorded vibration acceleration.

d) The duration t_{Hv} of the intense phase of horizontal vibration velocity is defined based on the distribution function of relative energy density over time, i.e., it is determined from the normalized Arias intensity graph [**13**], according to the following relation:

$$I_{Hv}(t_k) = \frac{\int_0^{t_k} \left(v_x^2(t) + v_y^2(t)\right)dt}{\int_0^{t_a} \left(v_x^2(t) + v_y^2(t)\right)dt} \tag{4}$$

The duration of the tremor is defined as the difference between the two moments when the relative energy density reaches values of 0.05 and 0.95 (i.e. 5% and 95%).

During the scale's development and validation, various types of buildings were observed, including those with the weakest structures and in poor technical condition. Consequently, the defined intensity level thresholds in the GSI-2017 scale also account for the harmful effects of mining tremors on typical building structures with the weakest construction and those in poor technical condition.

Vibrations assigned to a specific intensity level may—but do not necessarily—cause the effects associated with that level of the scale.

From 2017 year the new empirical-measurement GSIS-2017 scale [**12**] for monitoring and assessing the influence of mining-related ground vibrations both for structures and human perceptibility of vibrations in the GZW area has been applied. The GSIS-2017 scale [**12**] is another version based on the previous GSI-$GZW_{KW\text{-}2012}$ scale. The results of records and observation of several strongest shocks occurring in the GZW area in the years 2015-2016, with seismic energies exceeding 10^8 J and the maximum values of vibration velocity PGV > 0,05 m/s, and acceleration with PGA > 1,0 m/s^2, were additionally included in the scale. In the scale, the technical condition and type of the building structure for its dynamic resistance were taken into account. On the GSIS-2017 scale, the impact of the shock is also expressed by measuring the level of seismic intensity. These levels are classified based on the recorded

and/or predicted free-field vibration parameters. These parameters are correlated with macro-seismic observations in buildings described by levels of vibration harmfulness. The parameters of the classification are the same as parameters used in the case of the GSI-GZW$_{KW-2012}$ scale. The GSIS-2017 scale contains 7 levels of seismic intensity (from 0 to VI), which were assigned the effects of free-field vibrations on buildings and linear underground infrastructure and human perceptibility on vibrations and the discomfort of using buildings, in correlation with parameters of free-field vibration (see Figs. 5 and 6). The GSIS-2017 scale gives the level of vibration intensity (IV-VI) at which structural damage of buildings may occur, together with a description of building damage and the level of harmfulness of vibrations – comp. Table 2. It should be noted that the VI level has not been verified by measurements. Two versions of the GSIS-2017 scale are shown in Fig. 5.

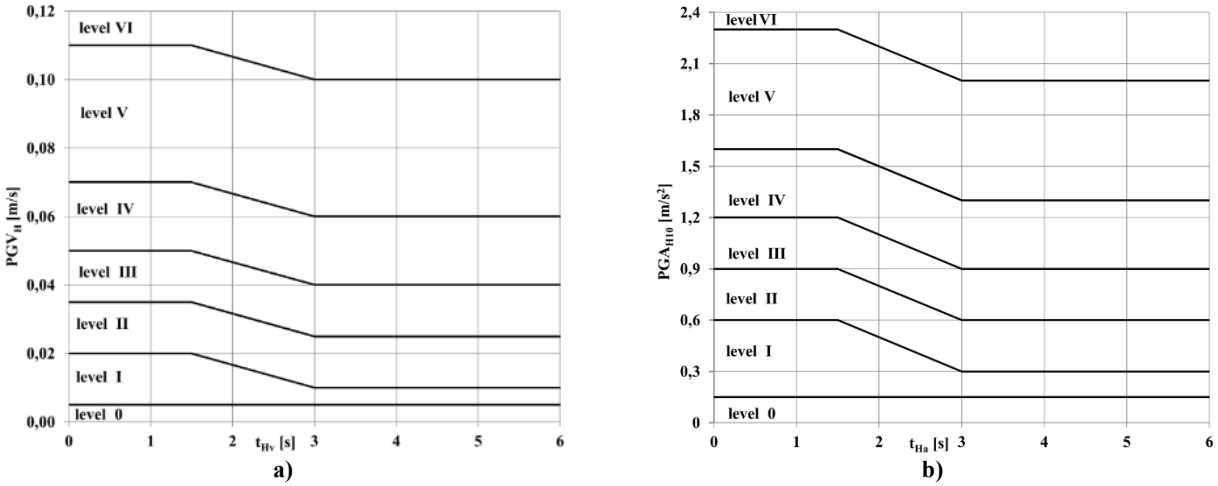


Fig. 5. The levels of seismic intensity on the GSIS-2017 scale in velocity (a) and acceleration (b) version

The GSIS-2017 scale originates from the former GSI-GZW$_{KW-2012}$ scale. The GSIS-2017 scale refers to buildings and very important underground structures (e.g. water, gas, sewage network) whose failure-free functioning provide the safety of residents. The GSIS-2017 scale includes the following types of buildings with traditional and traditional-improved construction, i.e. buildings made of brick or other small-size elements, having wall bearing systems; concrete and/or reinforced concrete bearing structure; frame buildings of reinforced concrete or steel construction. In addition, the scale includes: effects of vibrations on buildings in poor technical condition and subjected to the influence of continuous deformations characteristic of the III–V category of mining area [**12**]; effects of vibrations on sensitive historic buildings of historical significance; criteria for empirical evaluation of dynamic resilience of buildings subject to seismic effects of mining, developed using the GSIS-2017 scale.

It also deals with evaluations of the impact of mining vibrations on people staying in buildings. The GSIS-2017 scale consists of two versions. The basic is a velocity version. The acceleration version of the scale is treated as auxiliary. The GSIS-2017 scale associates values of the ground parameters with macro-seismic effects in structures and their perceptibility by people. Impact evaluation of surface mining-related vibrations is made using the maximum value of the resultant of ground velocity PGV_{Hmax} - (velocity version of the scale) and the maximum value of the resultant ground acceleration calculated using the filtered components of the horizontal vibration in the band to 10 Hz (PGA_{H10}) in auxiliary version of the scale. The second parameter used in impact evaluation is duration of the intensive phase of vibrations, t_{Hv} and t_{Ha} for the velocity and acceleration, respectively [**13**].

Tab. 2. Results of mining tremors corresponding to the levels of intensity given in the GSIS-2017 scale.

Level of vibration intensity I_{GSIS}	**Specification of potential building damages and degrees of vibration harm**
0	No damage caused
I	No damage caused
II	Intensification of existing cracks or fractures
III	First new damages to non-structural elements
IV	Initial damage to certain elements of the structural system (load-bearing or bracing), which, however, does not threaten the stability of the building nor reduce its dynamic resistance. Numerous new damages to the building's non-structural elements
V	Damage to structural system elements (load-bearing or bracing) significantly reducing the building's dynamic resistance, but not yet threatening the stability of the structure. Severe damage to non-structural elements, including falling roof tiles and bricks from truncated external chimneys. Vibrations particularly dangerous at the upper values of level V and with a low frequency of the main phase of horizontal vibrations, f < 5 Hz
VI	Severe damage to structural system elements of the building (load-bearing or bracing) that could lead to the loss of stability of the structure. None of the mining tremors that have occurred so far have caused such consequences, although they cannot be ruled out in the event of a further increase in the intensity of ground surface vibrations due to mining tremors. Extensive destruction of non-structural elements of the building. Vibrations are particularly dangerous in the range of low frequencies of the main phase of vibrations, f < 5 Hz.

For example, based on 156 recorded ground vibration waveforms from tremors in the selected mining area, the results of the interpretation of these tremors according to the GSIS-2017 scale in the velocity and auxiliary acceleration versions are presented in Fig. 6.

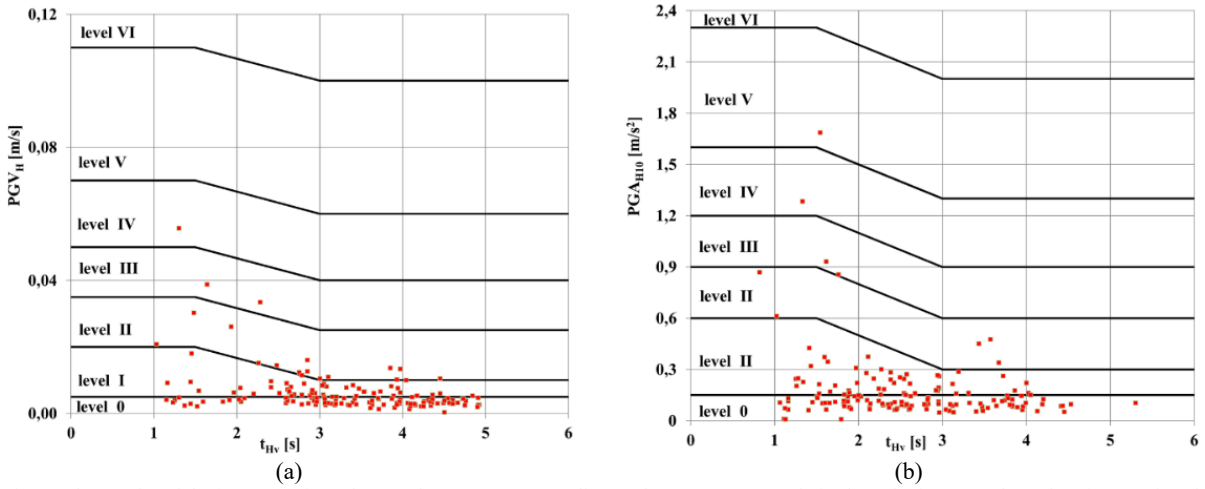


Fig. 6. The results of the interpretation of exemplary tremors according to the GSIS-2017 scale in the velocity (a) and acceleration version (b).

For each tremor, the necessary parameters were determined to assess the level of vibration intensity (IGSIS) associated with potential building damage. The vast majority of the analysed tremor parameters correspond to level 0 intensity, meaning these tremors are imperceptible to buildings and do not cause any damage. The tremor with the highest intensity, evaluated according to the GSIS-2017 scale in the velocity version, falls within zone IV. It may cause initial damage to certain structural elements (load-bearing or bracing), though this damage does not threaten the stability of the building or reduce its dynamic resistance. Additionally, it may result in numerous new damages to the building's non-structural elements (see Table 3). The tremor parameters evaluated based on the acceleration version of the scale indicate an intensity level V. Such a tremor causes initial damage to certain structural elements (load-bearing or bracing), but similar to the velocity assessment, this does not threaten the building's stability or reduce its dynamic resistance. Furthermore, it leads to numerous new damages to non-structural elements. A comparison between the velocity-based and acceleration-based intensity assessments shows that a higher intensity level is assigned to the tremor when evaluated using the acceleration scale. Building damage is directly related to the tremor's energy, which is influenced by vibration velocity. Therefore, the acceleration scale provides a more reliable assessment. In my view, using the acceleration scale is appropriate for preliminary evaluations of tremor intensity.

The comparison of the results concerning the impact of vibrations from Figure 3.10 on the building using the GSIS-2017 scale and the SWD scale in the acceleration version is also made. The vibration parameters used in the assessment according to the GSIS-2017 scale were 0,81 m/s² and a duration of 1,55 s. Vibrations with such parameters fall within Zone II of vibration intensity and can intensify existing cracks or fractures. This result is consistent with the result obtained using the SWD scale - see Fig. 4.

4. Conclusion

The paper presents the scales used to assess the impact of vibrations on buildings. The GSIS scale is an empirical measurement scale. The velocity version of the GSIS scale is based on the resultant values of horizontal ground vibration velocity and the duration of the intense phase of the tremor. The acceleration version of the scale uses the maximum horizontal vibration acceleration determined in the frequency band up to 10 Hz, as the maximum length of the vibration vector and the duration of the intense phase of the tremor. The SWD scale is built based on the results of computational analyses of model buildings. The SWD scale uses vibration waveform parameters calculated in third-octave bands. The scales provide a specification of potential building damage and degrees of vibration harm. The analysis of vibration components (velocity or acceleration) indicates that a higher intensity level is assigned to the tremors when evaluated using the acceleration scale. Building damage is directly related to the tremor's energy, which is influenced by vibration velocity. The assessments of the harmful impact of vibrations on buildings showed consistency between the evaluations according to the GSIS-2017 and SWD scales.

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