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Principles for the Application of Vibration Intensity Scale for the Prediction and Assessment of Impact of Actions of Exploitation Mine on Buildings and People

Principles for the Application of Vibration Intensity Scale for the Prediction and Assessment of Impact of Actions of Exploitation Mine on Buildings and People

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Abstract. Discussed are results of evaluating selected scales for assessing the impact of seismic tremors on the subsoil in mining operations areas with engineering structures. Investigations were carried out to confirm scale analysis results of selected cases, including damage to the buildings. The analysis showed that in most cases there was no relationship between the design solutions for modern and traditional building structures and the type and form of damage caused by the analyzed dynamic interactions. Damage analysis of selected cases points to the need for updating the existing scale intensity levels. The nature of tremor impact on buildings and structures located in areas of mining activities is continuously studied and the results of our investigations will be presented in the final report. This research project's covering the analysis of an interdisciplinary approach to mining damage, including legal, engineering, construction, geotechnical, mining, economic, and financial aspects. This paper discusses methods for using certain tested scales to measure how mining operations interact with engineering structures and people. The results of our analyses, data from actual forecasts and evaluations of interactions induced by coal mining operations support our conclusions and validate comparisons to empirical and model investigations of certain selected types of mining interactions.

1. Introduction

The issue of repairing damage suffered by residential, service, commercial, and public buildings typically finds its resolution in a lawsuit. Mining operations continually interact with the soil and therefore with any buildings or engineering structures it must support. Major issues the courts must rule on include: identification of the underlying cause/s and the damage level to engineering structures; determination of the scope of repair or upgrade work required to restore the buildings or engineering structures; acceptance of their estimated market values; and award of costs for the most cost-effective repair method approved [1-4], [6], [12]. The court would typically appoint experts to prepare the necessary analyses, expert opinions, and cost estimates. The subsequent phase of the entire litigation usually consists of a classical struggle by the determined property owners - unable to use the buildings because they do not meet safety standards - with mining companies conducting operations either directly under the contested properties or in their immediate vicinity. Court proceedings follow procedures originated by respective specialists and legal advisors who failed to reach a consensus at the earlier stages of the dispute.

Respective acts and regulations on geology, mining, and construction apply to the entire procedure. Under the Polish law, owners of damaged properties, or properties most likely to suffer damage soon, do not have any rights to raise objections and try to prevent potential risks posed by the scale and extent of active underground mining operations. They are equally powerless to stop further operations or prevent damage to the engineering structures they own. They may only request all the damage attributable to mining operations be repaired; however, they must wait until the damage has already occurred, been verified, and its cause, level, type and repair costs defined. As a rule, all the damage is repaired by restoring the properties to their original condition.

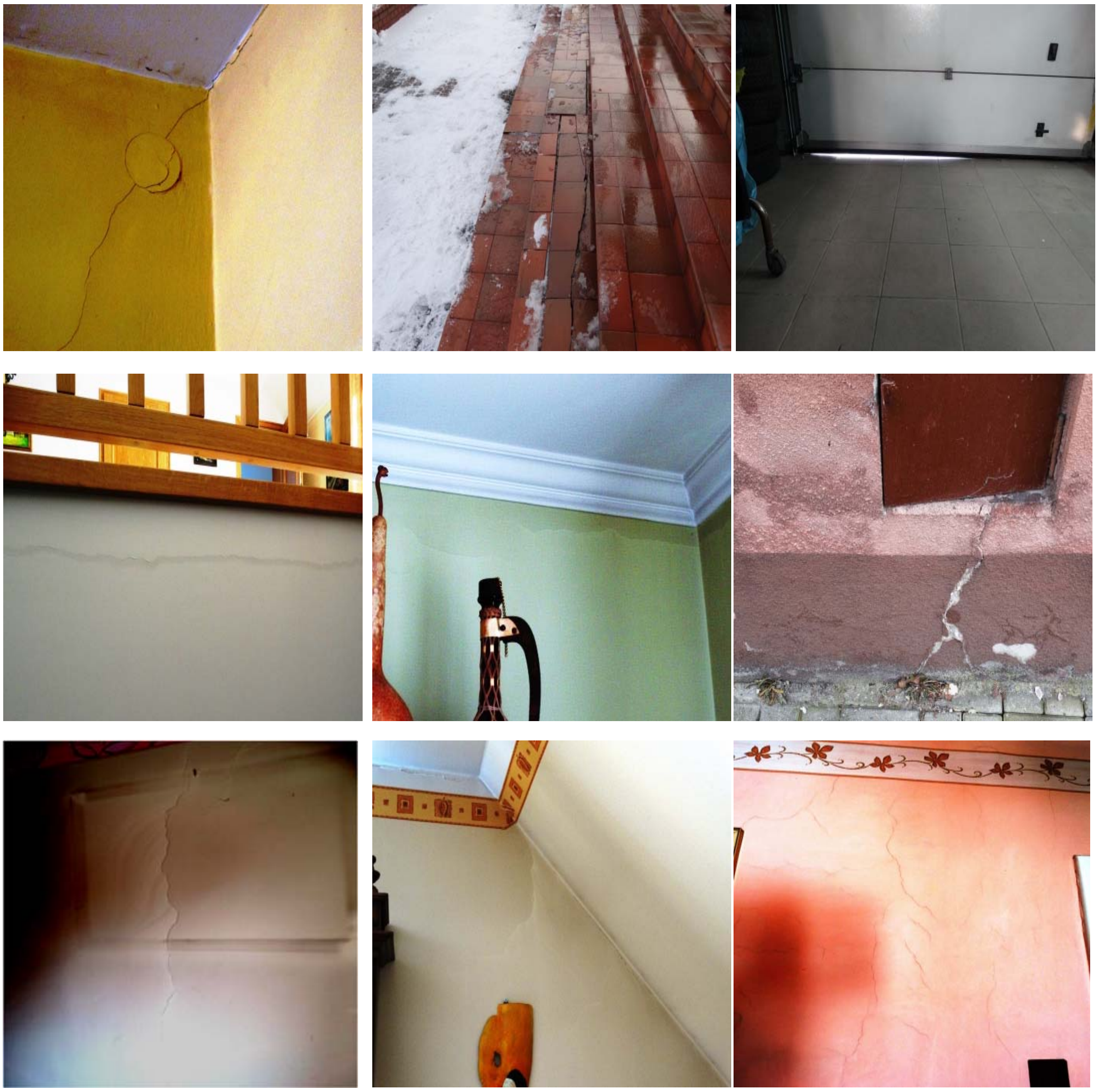


Figure 1. The cause–effect analysis of structural damage resulting from mining operations as a tool to define the level and type of damage, the optimum repair method, as well as the repair and upgrade costs

It means all the properties and assets thereon, such as entire or parts of buildings (apartments, office or service space), including any systems, installations, plus other assets attached to the analyzed properties must be restored to their original condition prior to the damage caused by mining operations and all defects corrected.

When analysing damages payable for losses attributable to mining operations, forensic engineering is primarily concerned with defining the date the damage first occurred in order to choose specific regulations applicable to various types of data and the appropriate analytical method. The Supreme Court has ruled provisions of the Geology and Mining Law Act of 1994 shall apply to mining damage occurring before 2012 whereas the Geology and Mining Act of 2011 applies to damage occurring later. The two acts take a different approach to the grounds for seeking compensation with respect to the manner of repairing mining damage and the statute of limitations for filing claims. Thus, determining the date when the damage had first occurred – regardless of any arguments and grounds listed in the cases we have analyzed – is of utmost importance for a legal analysis of the claims.

One way the law offers to pay for the damage is payment of damages to cover the repair costs incurred by the owners; the other option is to have the damage repaired by the offending mine's maintenance personnel. When the property cannot be restored to its original condition, or if the repair costs grossly exceed the entire value of the property, one must use different loss valuation methods and apply the provisions of the Civil Code concerning mining damage, property valuation, and economic analyses. Claims for damages cover not just the losses suffered but also loss of profits, which the owner might have rightfully anticipated had the loss not occurred. It happens because the Polish law considers compensation for damages to be the primary objective [5], [6]. It means the amount of damages should be sufficient to restore the injured party's assets to their original condition, and cover any loss of assets attributable to the triggering event, as well as any loss of profits. The concept represents one of the basic assumptions for analysing mining damage: the need to apply the right laws governing the extent and manner of defining the loss. Such assumptions will also affect certain later issues: the definition of the property technical condition, the extent and number of repairs, and mining interactions within the previously defined time history.

This paper discusses one stage of my research project covering the analysis of an interdisciplinary approach to mining damage, including legal, engineering, construction, geotechnical, mining, economic, and financial aspects [5-10], [13] and [14]. Despite being so different, all of them show certain common variables and significant interactions. Depending on the number of variables available for the analysis in selected cases, for some carefully tested and classified output data, the comprehensive function we have developed for a three-component model, i.e. engineering structure – subsoil – mining interactions, has yielded results comparable to the empirically established structural damage [1], [3], [8], [14] and [18]. The analyzed mining interactions scales, combined with conclusions supported by our investigations, made it possible to attempt verification of their adequacy against selected and analyzed human, environmental, engineering, geotechnical, and standard response, in the context of static and dynamic interrelations, as well as versus estimates and calculations for various engineering structures investigated, in the aftermath of documented mining operation interactions. The presented interactions have been defined for several variables, which depend on interactions induced by mines operating mining equipment, and mining interactions which affect the strength and physical parameters of the soil supporting buildings and structures exposed to additional harmful static and dynamic interactions [15], [17].

2. Output Data for Analyses

The input data for this part of our analysis comes from vibrograms, or information on vibration timeline of the soil and structures within the investigated area. In the interpretative process, micro-seismic and macro-geotechnical measuring scales define certain parameters characterizing interactions between the soil and engineering structures, or any combinations thereof [7], [8], [13], [14], [18]. They also define the type of static and dynamic interactions between all the known additions to the soil and the initially defined maximum loads generated by buildings and engineering structures on the maximum predefined cubic capacity (footprint and building foundation depth), and over a predefined timeline [17], [19].

Major parameters describing the type of dynamic interactions include all the horizontal components of the soil–structure interactions. Vibration, frequency, displacement, velocity, acceleration, and the amplitude values are used to calculate the interactions with various types of engineering structures, which receive dynamic interactions from the elastic - plastic soil. The input data also include tentatively classified groups and subgroups of buildings and engineering structures, mostly considered for their technical characteristics, such as the shape, surface, cubic capacity, structure, parameters of materials used, and their technical wear and tear. Vibrations of engineering structures may derive from various phenomena, but in this case, we analyze only interactions attributable to mining operations. All the analyzed, verified, and properly classified data has been saved in respective databases, which help determine the quality and number of variables, as well as the potential for grouping and standardizing them with corresponding factors in Table 1.

Table 1. Output data analysis for analysing the extent of mining interactions

Scale attribute features for interaction evaluation	Number of attribute features - n; min.= 3 F (f_1; f_2; f_3; f_4; … ; f_n)	Statistical values of the analyzed data group
Weights of a $w_{i,n}$ feature, with feature variability accounted for	$w_{1,n}$ - results obtained using statistical methods; i=1	Mean weight of a selected feature $w_n = (w_{1,n} + w_{2,n} + w_{3,n}) / i$ Correction factor for estimated k_w weights $w_{n'} = w_n \cdot k_w$ $\Sigma\, w_n \cdot k_w = 100\%$ $\Sigma\, w_{n'} = 100\%$
	$w_{2,n}$ – results obtained using a classical method *„ceteris paribus”* i=2	
	$w_{3,n}$ – results obtained using an empirical method; i=3	
Range of analyzed scale features	f_1 0 - 3 f_2 0 - 5 f_3 0 - 4 f_4 0 - 5 …	

All the analyzed data serve to calculate mean values, medians, maximum and minimum values, as well as standard deviations for investigators deemed satisfactory.

3. Discussion of the Investigated Cases

The rock mass tremors analyzed here represent another type of active mining interactions generating tremors, both of the surface and structures thereon. The analyzed rock mass tremors represent another effect of mining operations, which generate surface vibrations of the developed area. Rock bursts give rise to natural threats over a large area with ongoing underground bituminous coal mining operations. The elastic properties of any mined coal seam determine the intensity and mining interaction forces. The distribution of stresses occurring in the rock mass with known physical and mechanical parameters is demonstrated by the seismic wave propagation velocity measured with the seismic profiling method.

The history of mining operations and the soil attributes play an important role in harmful interactions with existing engineering structures and people. Former, current or future mining operations in the areas included in our analysis require making certain assumptions concerning changing mechanical and physical parameters of the soil. Plastic and elastic properties of the soil interacting with engineering structures will greatly change over time. The scope and timing of the changing load bearing capacity and serviceability limit states depend on mining interactions, the type of operations, as well as the primary and secondary geotechnical characteristics of the soil [5], [6], [7], [8], [9], [11], [12], [13] and [16]. In the case of tremors produced by mining operations, one can determine the underlying causes of damage and anticipate potential consequences for the planned mining operations in the analyzed area.

Having analyzed the duration, type and scale of mining interactions, we now move on to the other major set of variables with a view to analyze sub-variables, such as the type, extent, directions, locations and the number of losses suffered by structures and buildings. Mining damage including building tilt and displacement; tilted ceilings, staircases, balconies, and porches; deformations, cracking and scratches of various structural or finishing components, such as ceilings, floors, headers, flues, load-bearing and partition walls, tiled walls, cladding, cornices, expansion joints for flashings, bay windows, balconies, gates and wickets, etc.; deformations of window and door woodwork; loosening of assorted building components; or damage to draining, water, sewer, and central heating systems must be analyzed for any potentially diagnosable variables of the set because of problems with standard design draining slopes.

Perceived human distress/comfort caused by the analyzed structures represents yet another major variable resulting from mining interactions with respect to structure usability, comfort of use, nuisance, stress-free environment, and safety of people living or working in residential or commercial buildings.

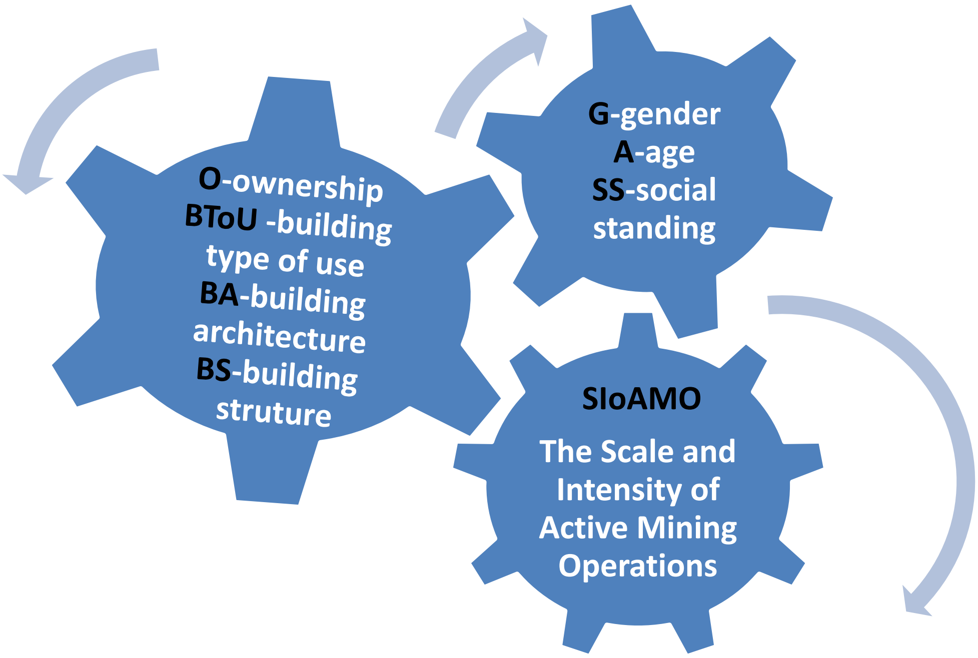


Figure 2. The analyzed structures represent yet another major variable resulting from mining interactions with respect to structure usability, comfort of use, nuisance, stress-free environment, and safety of people living or working in residential or commercial buildings.

We have investigated levels of human response to the scale and intensity of active mining operations by gender, age, social standing, building type and use; type of ownership, building structure, number of floors, technical wear and tear, finishing standard, and the building architecture - Figure no 2.

In summary, using an empirical measurement scale one can evaluate the intensity of surface vibrations caused by mining tremors. The scale must account for specific character of the recorded vibrations and the engineering structures erected over the active mining operations areas, as well as for the empirically defined levels of mining tremors affecting such buildings, linear underground technical infrastructure, and the internality of vibrations perceived by humans.

4. Classification of Mining Operation Interaction Scales

Some mining interaction scales analyze the type, frequency, and strength of vibrations affecting the environment, i.e. the soil in areas earmarked for development or areas already built over and with technical infrastructure installed. In order to study the operation of and response to mining interactions correctly one must rely on adequately verified, specialized scale developed based on practical and statistical measurement results.

In Poland, the Central Mining Institute, or GIG, and various other specialized research centers carry on studies of the scale of vibrations attributable to mining operations. Every new comparative scale developed is a product of a specifically formulated hypothesis concerning the methods applied and comparison of individual analyses, evaluations, and modifications of results with their actual impact. For attributes defining the effect of mining interactions on buildings and engineering structures, various scales assessing the impact of rock mass tremors measure the dynamic resistance of buildings and soil.

4.1. Building Dynamic Resistance Classification

One of the classification scales used - the building dynamic resistance classification, or KDOB in Polish – was developed and practically tested at the Central Mining Institute between 1984 and 1990. The practical scale compares maximum values of selected soil / building vibration acceleration amplitudes to the effects produced by such vibrations. It may be used to evaluate the effect of tremors caused by mining operations, as well as to analyze how such vibrations affect selected properties. The method has been discussed in a number of expert opinions and court decisions.

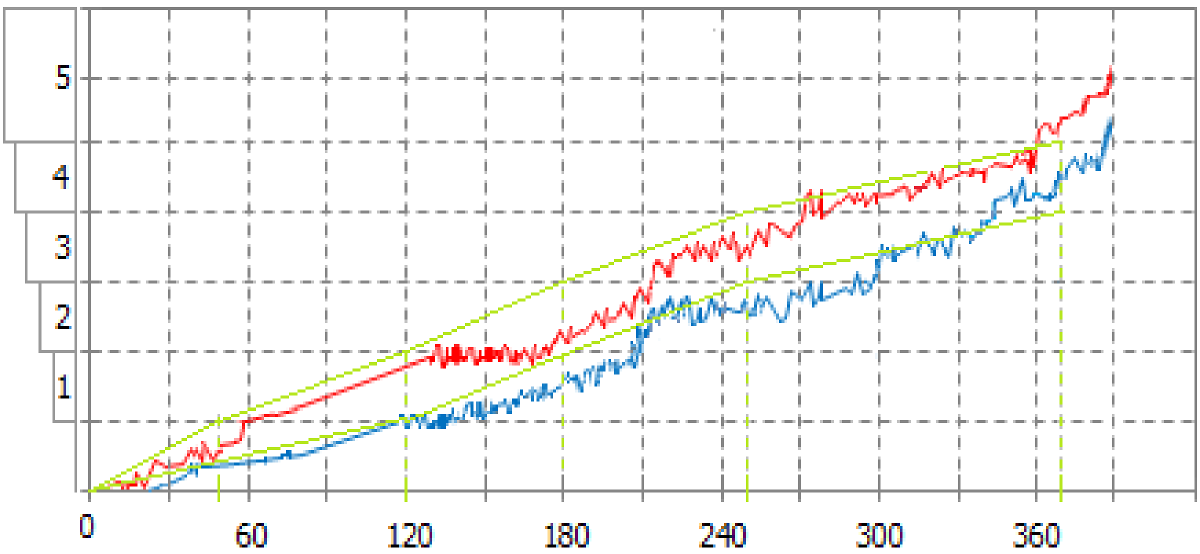


Figure 3. Estimated relationship between x – or maximum acceleration amplitudes of Class D and Class E building vibrations, and y – or classified tremor detection threshold

Estimated relationships between vibration acceleration amplitudes for new Class D and Class E building structures and the mining tremor detection threshold using a local, non-parametric, polynomial regression method – figure no 3. Table 2 shows detailed characteristics of the KDOB scale

Table 2. Revised KDOB scale for new Class D and Class E

Detectable Mining Tremor Level	Maximum Amplitude of Building Vibration Acceleration [mm/s^2]	Building Class	Extent of damage caused by mining tremors, depending on the building class and its technical condition		
			GooD Technical Condition	GooD Technical Condition with Negative Effect of supplementary factors	PooR Technical Condition
1	2	3	4	5	6
1	50 ÷ 120	A	0	1	1
		B	0	0	0
		C	0	0	0
		D	0	0	-
		E	0	0	-
2	120 ÷ 180	A	1	2	2
		B	0	1	1
		C	0	0	0
		D	0	1	-
		E	0	1	-
3	180 ÷ 250	A	2	2	2
		B	1	2	2
		C	0	1	1
		D	1	1a	-
		E	1	1a	-
4	250 ÷ 370	A	2	2	2
		B	2	2	2
		C	1	2	2
		D	1a	2	-
		E	1a	2	-
5	> 370	A	2	2	2
		B	1	2	2
		C	2	2	2
		D	2	2	-
		E	2	2	-

The scale generally applies to three classes of buildings, which – based on certain tentative assumptions - apply to buildings erected between the end of the 19th century and the 80's of the 20th century when such defined standards came into force.

Class A – buildings with a traditional structure with stone or brick foundations; masonry or stone walls; wooden ceilings, masonry or steel and brick vaults; flat or arched masonry headers; wood or steel staircases; wood roofs;
Class B – buildings with traditional, improved structure and buildings with large block structure, i.e. featuring concrete or reinforced concrete foundations; masonry, concrete or reinforced concrete basement walls; aboveground floor walls made of brick or other small-size components; reinforced

concrete or ceramic, Ackerman-type rib-and-slab floors, DMS floors, DZ floors, etc.; staircases, headers and reinforced concrete beams; wooden roofs, or flat roofs;
Class C – same as Class B buildings with maximum 2 floors and a basement, with a footprint ≤ 225 sq. m., i.e. large pre-cast panel and monolithic panel buildings.
Moreover, buildings with structures typical for those dating back to the 1990's have been included in two additional classes to define their interactions. Buildings erected in the last 18 years make up two or three more subclasses defined for new scales; however, we still lack sufficient data to verify the obtained results and to develop conclusions for future new building subgroups. Based on the already analyzed group of real properties, two additional classes – D and E – have been defined for buildings exposed to mining activities, namely:
Class D – buildings with a masonry structure or built with hollow core blocks so popular in previous years, mounted on reinforced concrete continuous footings, with or without basement, usually designed as row houses, duplexes or detached homes. Reinforced concrete or rib-and-slab floors above the basement and ground floor at least, wooden roof trusses with thermal insulation covered with asphalt roofing, metal sheeting or tiles; reinforced concrete and /or wooden staircases. Windows for buildings in this class made of wood and / or PVC. Buildings in the class also feature all the systems and installations, such as electric wiring, water, gas, and sewer, with the same number of floors and footprint size as for Class C buildings. Furthermore, the wear and tear of all the buildings in this class must be at least good, like for buildings with a good and proper maintenance history.
Class E – new buildings erected in the last ten years and sitting on reinforced concrete slabs or foundation plate gratings, with no or part basement, usually built as duplexes or detached homes; with a structure considered traditional now, i.e. brick or reinforced concrete. Reinforced concrete ceilings supported by load-bearing walls. Timber roof trusses with thermal insulation covered with metal sheeting or tiles; monolithic reinforced concrete or wooden staircases. Windows for buildings in this class made of PVC, aluminum, or wood; otherwise, buildings featuring all the same installations and systems as Class D buildings and intelligent buildings; the number of floors and footprint area limited as for Class C.

Furthermore, the wear and tear for all the buildings in this class must be at least more than good, like for buildings with a good and proper maintenance history.
Another aspect of the scales discussed here which calls for defining relates to the damage potential from rock mass vibrations. See classification of vibration damage levels tolerated by buildings and engineering structures below:

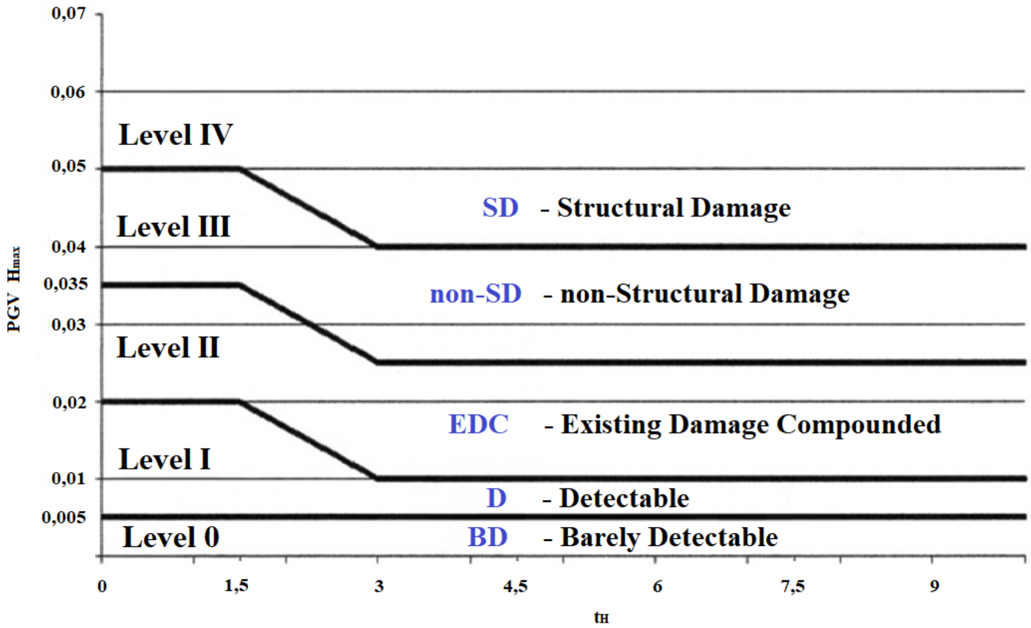
Level 0 – vibrations harmless for buildings, not causing any damage to load-bearing, finishing or filling components or building fixtures;
Level 1 – detectable building vibrations resulting in damage to finishing / filling components and building fixtures, such as roofing, flues, etc. Level 1 assumes no damage to the building load-bearing structure, except for some minor cracking allowed under the standards and regulations in force;
Level 1a – vibrations identical with those in Level 1, including cracking of building load-bearing components, passing from safe to less safe zones of load-bearing capacity and serviceability discussed in [5-9], [11], [15], [16] and of course in norms [19];
Level 2 – vibrations destructive to buildings and causing all kinds of Level 1 damage, including impairment of the building load-bearing structure capacity to withstand various ultimate and serviceability limit states, and consequently resulting in building collapse.

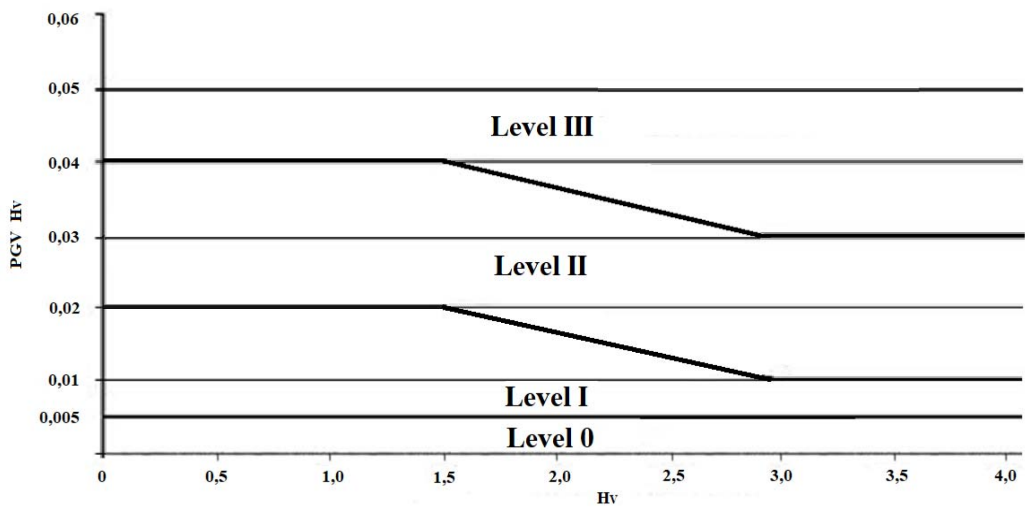
4.2. Mining Vibration Intensity Scale, or MVIS

Vibration parameters required to evaluate levels of surface vibration intensity in the MVIS scale include duration of the horizontal component vibration velocity - t_{Hv} and the maximum amplitude of horizontal vibration velocity - PGV_{Hmax} as a resultant of the vector length horizontal maximum. Receivers of horizontal component vibrations x and y are arrayed in the same plane and reciprocally perpendicular. This calculation procedure assures independence from the orientation of the vibration receiver setup. An analysis of the type of building damage occurring in the mining interaction area and the vibration parameters measured in representative monitoring spots assure continuous verification and modification of the current intensity level limits for each scale.

All the scales are open-end and designed to provide the basis for an approximate, tentative assessment of the effect produced by mining tremors on the built environment - from harmless vibrations through vibrations resulting in damage to decorative, finishing, and structural components. The vibration force, frequency, the dynamic and static effect on the structures and foundation soil they interact with, make up a scale to measure the vibration effect on load-bearing and serviceability limits of the built environment and human distress.

The scale changes because it is the result of empirical and measurement modifications of the analyzed responses and their verification. A description of the empirical MVIS scale intensity includes a definition of four and five levels (0-II or 0-IV), as per Figure no 4a, b, c (analyses carried out in 2012), for intensity levels depend on duration and velocity amplitude or horizontal soil vibration acceleration.





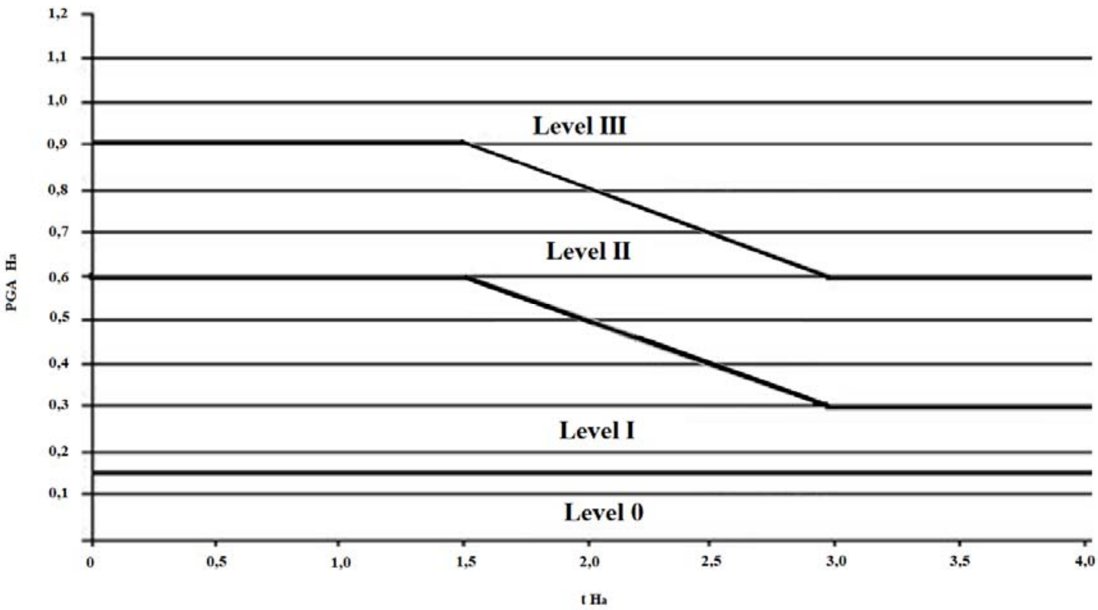


Figure 4 a) b) c) Multiple versions of verified and empirically measured modified open scales of intensity levels and dynamic interaction duration depending on: a) vibration velocity amplitude; b) vibration acceleration amplitude; c) maximum horizontal vibration amplitude

In our analyses, we relied on certain soil mechanics principles describing the current rock mass stress and deformation to attempt developing the right calculation model. Such a model would take into account all the interactions observed and diagnosed over a pre-designed time interval, their effect on soil physical and mechanical parameters, as well as on the structural and engineering parameters of the analyzed buildings and structures, including the comfort/distress of people who live or work there.

5. Results and conclusions

During the entire analysis of the mining operations so far, no vibrations have been observed to cause significant damage or interfere with the building load-bearing or stiffening systems, to the extent we were able to measure and classify them. The analyzed scale should incorporate newly derived variables for individual interaction levels in order to analyze changes to both the extent and type of damage over time. A number of Level I or Level II tremors have been investigated which – because of additional negative mining interactions - evolve, over time, into Level IV damage. Perhaps, one should consider changing every level of the mining interaction scale to a function with an additional interaction derivative and a primary time variable. Sporadically recorded mining tremors classified – in line with such scale levels – as Level V tremors may not cause any building damage right away but rather launch a chain reaction. Such a reaction – when analyzed using appropriate numerical models for any types of load and relief – will yield information about structural damage to the structure or building in the calculated, anticipated time interval. New guidelines for new interactions, as well as for new and already investigated classes of engineering structures, and the interactions scale have been discussed in the author's 2013 – 2018 papers and court opinions and will be published as the final result of the entire analytical process.

Analyzing the type of damage caused by specific tremor magnitudes points to the need for an update of the existing impact levels by introducing a time variable. Level III lower limit would be reduced for the new classes of buildings and engineering structures analyzed here. New time lines must be defined for building/structure damage that may or may not appear in the analyzed mining interaction areas and in the proposed areas of engineering structure response to mining activities. Damage affecting the structure safety and leading to building stability loss, as well as any life-threatening damage must be definitely qualified for immediate and extensive repair. On the other hand, damage to the building or structure causing serviceability limit states to shift towards an unsafe zone is not subject to an in-depth analysis, because of, say, variable time frames of the interactions and the resulting damage. A comparison of existing and revised boundaries between the intensity levels begs additional verification with real-life examples for which the interaction extent is predicted using the new guidelines. In a few months from now, it may be possible to publish a report comparing the accuracy of interactions forecast based on guidelines for individual scales and the actual interaction results. The nature of mining tremor impact on buildings keeps being updated and evolving, mainly with respect to delayed effects of mining tremor interactions with buildings. Vibration intensity evaluation using data analysis and an acceleration scale turns out to be less reliable than one carried out using the velocity scale. The intensity level boundaries defined in verified scales for a selected measurement–observation data set indicate an 82.5% probability for the intensity level to be underestimated vs. the actual interaction extent.

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