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NATURAL AND TECHNICAL VIBRATIONS: MEASUREMENT, INTERPRETATION, EVALUATION

PŘÍRODNÍ A TECHNICKÉ VIBRACE: MĚŘENÍ, INTERPRETACE A VYHODNOCENÍ

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Abstract

Design for earthquake resistance of structures is described in Eurocode 8. Monitoring of natural or technical (artificial and triggered) vibrations is a standard requirement for management of construction sites. Vibrations vary in periodicity, duration, time and location of occurrence etc. The intensity of vibrations depends on many parameters, first of all local geology, subsurface layers, type of source, prevailing source frequency, parameters of influenced structure … Significant diversity of sources influencing the intensity of a seismic event on the surface, is the reason why sufficiently credible results cannot be obtained and simple relations cannot be derived without a substantial number of seismic measurements. The acquired waveforms need to be interpreted both in amplitude and frequency domains. General assessments of the impact of vibrations on structures are based on international standards for vibration assessment; many countries also specify maximum permissible values in their national standards.

Abstrakt

Návrh hodnocení odolnosti konstrukcí proti zemětřesení je popsán v Eurokódu 8. Sledování přirozených nebo technických (umělých a spouštěných) vibrací je standardním požadavkem pro posouzení stavenišť. Vibrace se liší periodicitou, délkou trvání, časem a místem výskytu atd. Intenzita vibrací závisí na mnoha parametrech, především místní geologii, podpovrchových vrstvách, typu zdroje, převažující frekvenci zdroje, parametrech ovlivněné struktury… Široká rozmanitost zdrojů ovlivňujících intenzitu seismického jevu na povrchu je důvodem, proč nelze získat dostatečně věrohodné výsledky a odvodit jednoduché vztahy bez podstatného počtu seismických měření. Měřená data je třeba interpretovat v amplitudové i frekvenční oblasti. Obecná hodnocení vlivu vibrací na konstrukce vycházejí z mezinárodních norem pro hodnocení vibrací; mnoho zemí také specifikuje maximální přípustné hodnoty ve svých národních normách.

Keywords

Earthquake, artificial vibration, Eurocode 8, national standard, engineering seismology

Klíčová slova

Zemětřesení, vibrace vyvolané lidskou činností, Eurokód 8, národní normy, inženýrská seismologie

1. Introduction

Vibration is a dynamic quantity, it varies with time, and this requires caution during its measurement. From the physical viewpoint, the most natural manifestation is the movement that occurs as the vibration passes the given location. This movement can be described as displacement, velocity and/or acceleration in time domain. Equivalent dual integral relationships may be used in frequency domain (e.g. Doyle, 1995; Shearer, 1999). Rarely, in justified cases, not only the translational components of the particle, but also the rotational components are taken into account (e.g. Lee et al., 2009; Knejzlik et al., 2012).

Generally, the individual types of vibrations can be classified as deterministic or random phenomenon. Deterministic data are those that can be described by explicit mathematical functions (periodic, quasi-periodic, non-periodic). To evaluate measured vibrational data from the structural response of buildings, the following factors need to be taken into account (e.g. Towhata, 2008):

- Resonant frequencies of whole structure and significant components (walls, floors, windows);
- Damping characteristics of basic structure and components;
- Type of construction, its condition and material properties;
- Spectral structural features;
- Characteristics of excitation;
- Deflected form;
- Non-linearity in amplitude response.

The vibration generated in the source excites adjacent ground, creating vibration waves that propagate through various soil and rock strata to the foundations of nearby buildings. The waves propagate from the foundation throughout the body of the building. The maximum vibration amplitudes of the floors and walls of a building will often be at the resonance frequencies of various components of the building (according to Villaverde, 2009; Zeigler, 2021).

The natural environment needs to be taken into account, too. Eurocode 8: “Design of structures for earthquake resistance” (EC 8) provides harmonised international guidelines for investigation of the natural environment, in which the construction is taking place, and sets recommendations for monitoring of natural vibrations. EC 8 was approved by the European Committee for Standardization on 23 April 2004. When assessing the influence of man-made vibrations, national standards are usually recommended over the generalised international standard. Seismic loading is an important part of detailed evaluation of a construction site, for new buildings and/or repair of older and historical structures. Generalized procedures will be the basis for the administrative management of processes associated with vibration influences. However, it is essential that this assessment is a part of a comprehensive assessment of the geological environment and events in it.

2. Natural and technical vibrations

Natural and technical vibrations have been widely discussed in seismological literature, e.g. Lee et al. 2002, Towhaka, 2008, De Vallejo, Ferrer, 2011, Gupta, 2011. Usually, three types of natural vibrations are defined: tectonic earthquake, volcanic earthquake, and collapse earthquake. Tectonic earthquakes occur anywhere in the earth where there is sufficient stored elastic strain energy to drive fracture propagation along a fault plane. Intensity of earthquakes depends on many parameters; seismologists use different approaches to its description, first of all:

- Magnitude scales;
- Seismic moment;
- Seismic energy;
- Macroseismic intensities (EMS-98 – European macroseismic scale, MM – modified Mercalli scale, MSK-64 – Medvedev Sponheuer–Karnik scale etc.).

More detailed description of the MSK-64 macroseismic scale is presented in Tab. 1. With minor modifications in the mid-1970s and early 1980s, the MSK scale became widely used in Europe and the USSR. In early 1990s, the European Seismological Commission (ESC) used many of the principles formulated in the MSK in the development of the European Macroseismic Scale, which is now a de facto standard for evaluation of seismic intensity in European countries.

The following effects on the surface are often observed:

- Vibrations (ground shaking and rupture);
- Faults, fissures, cracks;
- Subsidence, soil liquefaction;
- Landslides and avalanches;
- Changes of river networks, floods;
- Tsunami;
- Volcanic eruptions;
- Damages of structures, fires of structures;
- Impacts on people.

Tab. 1 MSK-64 scale with description of behavioural, structural and geologic effects (according Grunthal, 1998)

Intenzity	Definition	Behavioural effects	Structural effects	Geologic effects
I	Not felt	Not felt	—	—
II	Scarcely felt	Felt sporadically	—	—
III	Weak	Felt only by people at rest	—	—
IV	Largely observed	Felt indoors, many awakened	Windows vibrate	—
V	Strong	Widely felt outdoors	Interior plaster cracks, hanging objects swing, tables shift	—
VI	Slightly damaging	Fright	Damage to chimneys and masonry	Isolated cracks in soft ground
VII	Damaging	Many people flee their dwellings	Serious damage to buildings in poor condition, chimneys collapse	Isolated landslides on steep slopes
VIII	Heavily damaging	General fright	Many old houses undergo partial collapse, breaks in canals	Changes in wells, rock falls onto roads
IX	Destructive	Panic	Large breaks in substandard structures, damage to well-constructed houses, underground pipe breakages	Cracks in ground, sand eruptions, widespread landslides
X	Very destructive	General panic	Brick buildings destroyed	Rails twisted, landslides on riverbanks, formation of new lakes
XI	Devastating	—	Few buildings remain standing, water thrown from canals	Widespread ground disturbances, tsunamis
XII	Completely devastating	—	Surface and underground structures completely destroyed	Upheaval of the landscape, tsunamis

Different international and/or national standards must be followed during the design and construction of buildings and civil engineering works in seismic regions (see below).

Seismic events caused by an artificial source or induced seismicity are called technical seismicity. The character of a record on a time scale depends predominantly on the source; it is a character of a rapidly attenuating seismic impulse, a longer-lasting sequence of impulses or continuous manifestation. Among activities generating seismic waves, we can name blasting, pile driving, drilling, vibrating machines, traffic, mining, filling of large dams etc. (e.g., Pijush, 2005; Bartak, 2007; Kalab et al. 2013; Kalab, Hrubesova, 2015).

While the magnitude of a natural earthquake cannot be influenced, the magnitude of the vibrations generated by an artificial source can be estimated in advance and, if necessary, reduced. The basic methodological steps for evaluation of vibrations on structures due to man-made seismicity are:

- Determination of acceptable load;
- Prognosis of load;
- Determination of risk, eventually safe distance and other parameters;
- Description of failures including their photographs, with special attention to historical and fissured structures;
- Measurement of seismic effects;
- Evaluation of safety for the measured load, remediation of the current state if not compliant;
- Monitoring of existing fissures and failures.

Parts of this methodology are usually defined in international and national standards. In the project design, the investor and the contractor must clearly specify which standard is to be implemented. This is particularly important if the investors and/or the contractors are from different countries.

3. Vibration measurement

Seismogram is an analogue or digital time series that records the amplitude of vibrations as a function of time as the seismic wave passes through the site (e.g., Kulhanek, 1990). The basic parameters are the amplitude (measured as movement, velocity or acceleration) and the frequency of individual waves or wave groups. The quality of the recording of a given seismic effect depends not only on the intensity of the source, but also on its frequency range and the intensity of other vibration at the measuring point, which are superposed (added) to the measured signal.

Obtaining seismograms is enabled by the conversion of the Earth's movements into electrical signals, their subsequent amplification, filtering and registration on a recorder - seismological apparatus (Scherbaum, 1994). Modern recording systems allow data registration and writing directly to a PC.

The first step of measuring design is defining the aims and the geographic region of interest taking both socio-economic and seismic information into account. If the main goal of the new seismic network is monitoring of the general seismicity in an entire country, this stage is largely simplified. For more specific purposes, the monitoring projects involves thorough examination of all known major geologic faults from geological maps and assessing their neotectonic activity and potential, identification of seismotectonic features from seismotectonic maps, if available, and compilation of all available information on the seismicity in the area of interest. It is also useful to gather historical and instrumentally recorded events in the broader region from earthquake catalogues and other sources.

Selection of potential construction sites of significant structures usually includes long term seismic monitoring. Maps and gather information about the potential sites from local and regional authorities need to be obtained. Once we have gathered all this information, it is likely that many potential sites will be eliminated due to unsuitable conditions. This will minimize future fieldwork and its associated costs. A list of parameters usually included in the off-site study includes (Trnkoczy et al., 2012):

- Geographic region of interest;
- Seismo-geological conditions;
- Topographic conditions;
- Accessibility;
- Seismic noise sources in the region;
- Data transmission and power considerations;
- Land ownership and future land use plans;
- Climatic conditions.

When preparing experimental measurements of artificial vibrations, the above described rules are reduced proportionally to the purpose of measurement. On the other hand, vibration measurement in a structure or its parts requires an individual approach. Closely related to this, it is the often discussed issue of where and how to anchor the sensor for measuring the induced vibrations.

Sensors in the building should be placed near the walls on the lowest floor or on the foundations of buildings to measure vibration affected building not response on vibration. In case of damage to the building, the detected vibration velocities may be greater than the values measured at the reference station (e.g. due to the object's response to seismic vibration). An important parameter is the natural frequency of the building, at which a significant resonant increase in the amplitude of the forced vibration of the building is manifested. The most damaging scenario occurs if the external vibration effect coincides in frequency with the object's own frequency (e.g. Chandramohan et al., 2017). For details on the importance of amplitude, frequency, and dynamic ranges of the seismic channel see Scherbaum, 1994.

4. Vibration interpretation

Earthquake engineering is the field of civil engineering focused on the protection of buildings, structures and engineering networks against earthquakes (selection of construction sites, building materials and techniques, use of anti-seismic structural elements). It is based on seismological predictions of the magnitude of the earthquake and the nature of the expected strong earthquake motion (including possible soil instabilities), as well as the knowledge of devastating effects of large earthquakes and measuring the dynamic response of buildings to artificial vibration. It is a key discipline in compiling building codes and standards and is of particular importance in the design of dams, nuclear power plants, important factories, and other fundamental infrastructure. It is also closely related to territorial planning.

Eurocode 8: “Design of structures for earthquake resistance” (2004) applies to the design and construction of buildings and civil engineering works in seismic regions. Its purpose is to ensure that in the event of earthquakes:

- Human lives are protected;
- Damage is limited; and
- Structures important for civil protection remain operational.

The EC8 emphasizes the reliable establishment and simplicity of building construction systems. It also allows them to be distinguished according to their importance, dimensions and mechanical action. The standard stipulates, among other things, the conditions for site selection, soil characteristics and criteria that the foundation soil and the foundation system of structures must meet in design of seismic events. The random nature of seismic events and the limited resources available to counter their effects are such that the attainment of these goals is possible only partially and only measurable in probabilistic terms. The extent of the protection that can be provided to different categories of buildings is a matter of optimal allocation of resources and is, therefore, expected to vary from country to country, depending on the relative importance of the seismic risk with respect to risks of other origin and on the global economic resources. Special structures, such as nuclear power plants, offshore structures and large dams, are beyond the scope of the EC8.

Structures in seismic regions must be designed and constructed in such a way that the following requirements are met, each with an adequate degree of reliability (EC8 – 3.2.2):

- No-collapse requirement,
- Damage limitation requirement.

In order to satisfy these fundamental requirements, the following limit states shall be checked:

- Ultimate limit states are those associated with collapse or with other forms of structural failure which might endanger the safety of people.
- Damage limitation states are those associated with damage beyond which specified service requirements are no longer met.

Within the scope of the EC8, the earthquake motion at a given point on the surface is represented by an elastic ground acceleration response spectrum, called an "elastic response spectrum". The shape of the elastic response spectrum (Fig. 1) is assumed to be the same for the two levels of seismic action for the no-collapse requirement (ultimate limit state - design seismic action) and for the damage limitation requirement. The seismic motion may also be represented in terms of ground acceleration time-histories and related quantities (velocity and displacement) (EC8 – 3.2.2, 3.2.3).

Main parameters of the elastic response spectrum S_e are (see Fig. 1):

- T is the vibration period of a linear single-degree-of-freedo111 system;
- a_g is the design ground acceleration on given type ground;
- T_B is the lower limit of the period of the constant spectral acceleration branch;
- T_C is the upper limit of the period of the constant spectral acceleration branch;

- T_D is the value defining the beginning of the constant displacement response range of spectrum;
- S is the soil factor.

The basic principles of building design in seismic areas are specified in EC8 through a guideline specifying the conceptual design:

- Structural simplicity;
- Uniformity, symmetry and redundancy;
- Bi-directional resistance and stiffness;
- Torsional resistance and stiffness;
- Diaphragmatic behaviour at storey level;
- Adequate foundation.

Only selected parts of Eurocode 8 are presented in this paper. For detailed study of this topic, the complete Eurocode 8 must be used. The advantages of EC8 include:

- Pan-European validity,
- Specifics of individual countries are given in national annexes,
- State-of-the-art of earthquake engineering and knowledge of the behaviour of structures during recent strong earthquakes are used,
- Great attention is paid to plastic deformation (ductility) of structures under seismic loading,
- Maps of seismic activity are provided for each country, with border areas compiled jointly by the neighbouring countries,
- The increase in additional construction costs is not caused by a self-serving change in the norm, but by about a continuously improving and updating knowledge of earthquakes that allows us to find ways of preventing the consequences of catastrophic earthquakes.

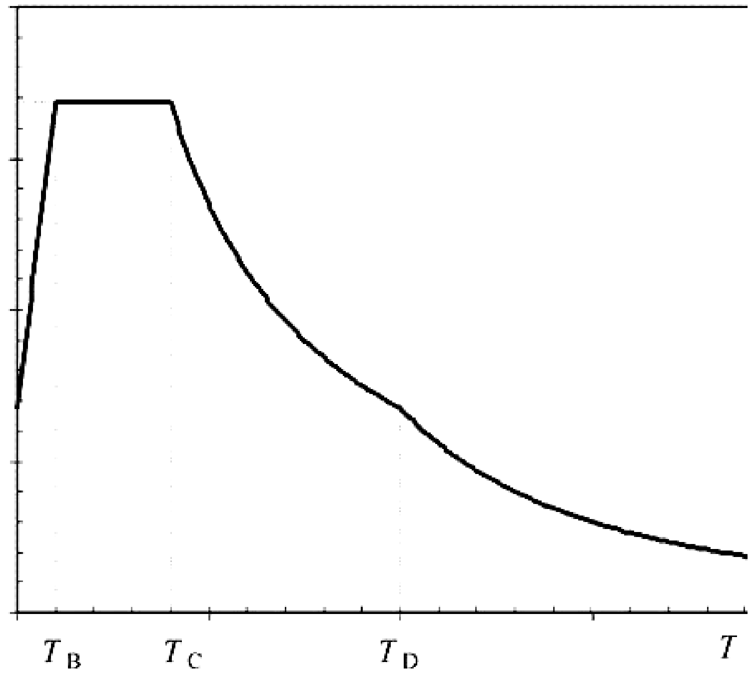

Fig. 1 ***Shape of the elastic response spectrum, horizontal axis is vibration period of a linear single-degree-of-freedom system, vertical axis is elastic response spectrum / design ground acceleration for detail see EC8 (Eurocode 8, 2004)***

5. Vibration evaluation

Prior to evaluation of the vibrations it is necessary to define the aims and objectives. The rules and recommendations contained in the standards and regulations are used as a basis for evaluation. However, these rules are based on generalized knowledge and therefore cannot fully address the various specifics of the assessed situation.

Measurement of vibration in a structure is carried out for a variety of purposes (ISO 4866:2010):

- Problem recognition, where it is reported that a structure is vibrating at such a level as to cause concern to occupants and equipment, possibly making it necessary to establish whether the levels warrant concern for structural integrity;
- Control monitoring, where maximum permitted vibration levels have been established by an agency and those vibrations have to be measured and reported;
- Documentation, where dynamic loading has been recognized in design, and measurements are made to verify the predictions of response and provide new design parameters (These may use ambient or imposed loading. Strong motion seismographs, for example, may be installed to indicate whether the responses to earthquake warrant changes on operating procedure in a structure.);
- Diagnosis, where it has been established that vibration levels require further investigation, measurements are made in order to provide information for mitigation procedures (another diagnostic procedure is to use structural response to ambient or imposed loading to establish structural condition, e.g. after a severe loading, such as an earthquake).

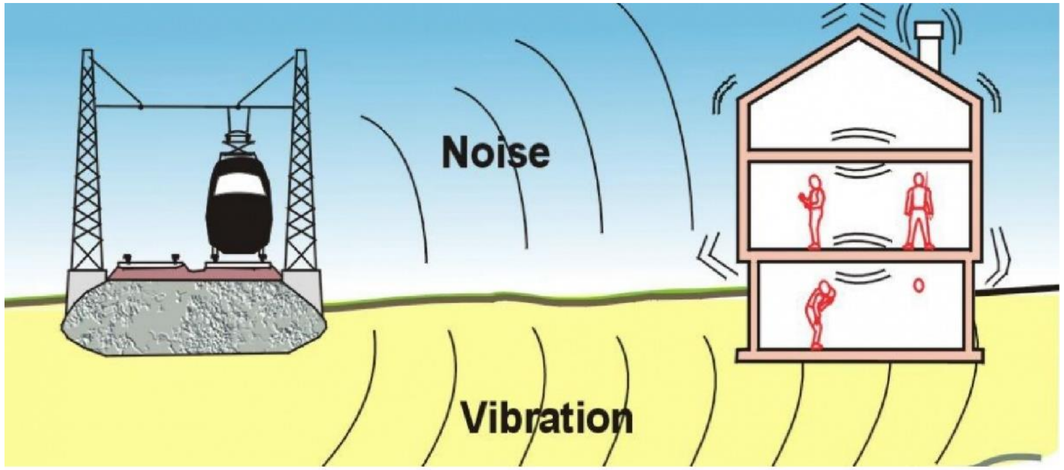

Fig. 2 Vibration from railways (Vibrations and earthquakes, 2021)

Such diverse purposes call for a variety of measuring systems, ranging from simple to sophisticated, deployed in different types of investigations.

Common example of this topic is presented e.g. by NGI, which is an independent international centre for applied research and consultancy in engineering-related geosciences, integrating geotechnical, geological and geophysical expertise. Vibrations from railways (Fig. 2), heavy transport, construction work etc. are a nuisance to many people (Vibrations and earthquakes, 2021). An increasing number of laboratories and production facilities are extremely sensitive to even small vibrations, which requires special considerations in foundation design. Waves and wind cause vibrations that have negative effects on the safety and service life of offshore platforms, wind turbines and other fixed structures.

Over the last centuries, more than one million people have died due to earthquakes, and earthquakes have resulted in damage worth of several hundred billion dollars in many parts of the world. Modern buildings and structures must be dimensioned to tolerate loads of prospective earthquakes.

As mentioned above, the most intensive vibrations are generated by earthquakes. 10 Most Powerful Earthquakes in Earth History (2021) are listed below, for details see mentioned website):

10. Sumatra Earthquake (2012) – magnitude 8.6
9. Assam-Tibet Earthquake (1950) 8.6
8. Rat Islands Earthquake (1965) 8.7
7. Ecuador-Colombia Earthquake (1906) 8.8
6. Maule (Chile) Earthquake (2010) 8.8
5. Kamchatka, Russia Earthquake (1952) 9.0
4. Tōhoku Earthquake (2011) 9.1
3. Sumatra Earthquake (2004) 9.1
2. Great Alaska Earthquake (1964) 9.2
1. Valdivia Earthquake (1960) 9.5

Natural disasters are an unfortunate part of life on Earth. Earthquakes are no exception, especially in areas of the world that are more susceptible to them. They occur when blocks of the planet's layers move past each other, as they have done throughout the world's history. While we are only 20 years into the 21st century, more than 657,000 people have already been killed by earthquakes. Many more have been injured and made homeless (The deadliest earthquakes of the 21st century, 2021).

Earthquakes are very difficult to predict and impossible to prevent. They can also trigger other natural disasters, such as tsunamis and landslides. Tragically, earthquakes often occur in countries that are least prepared to deal with such disasters. Tab. 2 presents the deadliest earthquakes of the 21st century.

The vibration to which the human body can be exposed is complex. It may be composed of various frequencies, occur in several directions and contact the body at more than one point. The vibration will often vary from moment to moment and may contain shocks. The useful evaluation of vibration with respect to human response requires that the manner in which the responses depend on the frequency, direction duration of the vibration and the occurrence of shocks is adequately taken into account (according to Griffin, 1990).

Tab. 2 The deadliest earthquakes of the 21st century (The deadliest earthquakes of the 21st century, 2021)

Rank	Event	Fatalities	Magnitude	Location	Date
1	2004 Indian Ocean earthquake and tsunami	227,898	9.1	Indonesia, Indian Ocean	December 26, 2004
2	2010 Haiti earthquake	160,000	7.0	Haiti	January 12, 2010
3	2008 Sichuan earthquake	87,587	7.9	China	May 12, 2008
4	2005 Kashmir earthquake	87,351	7.6	Pakistan	October 8, 2005
5	2003 Bam earthquake	26,271	6.6	Iran	December 26, 2003
6	2011 Tōhoku earthquake and tsunami	20,896	9.0	Japan	March 11, 2011
7	2001 Gujarat earthquake	20,085	7.7	India	January 26, 2001
8	2015 Nepal earthquake	8,964	7.8	Nepal	April 25, 2015
9	2006 Yogyakarta earthquake	5,782	6.4	Indonesia	May 26, 2006
10	2018 Sulawesi earthquake and tsunami	4,340	7.5	Indonesia	September 28, 2018
11	2010 Yushu earthquake	2,968	6.9	China	April 13, 2010
12	2003 Boumerdès earthquake	2,266	6.8	Algeria	May 21, 2003
13	2005 Nias-Simeulue earthquake	1,313	8.6	Indonesia	March 28, 2005
14	2009 Sumatra earthquake	1,115	7.6	Indonesia	September 30, 2009
15	2002 Hindu Kush earthquakes	1,000	7.4	Afghanistan	March 25, 2002

6. Evaluation of natural seismicity in shallow medieval mine: case study

The first case study represents evaluation of vibration effects in a shallow underground medieval mine. This is an exceptional opportunity to know the condition of the rock massif exposed to the long-term effects of the mining environment without further influences (mining areas have not been known for about 500 years, no connection with the surface). The most important information is this effect on old weathered underground spaces that is necessary for modelling of ageing of tunnels, underground storages, spaces for the public such as caves etc.

The beginning of underground mining of tin-tungsten deposits in granite in the area of the Slavkovsky les Mts. (Czech Republic) dates back to the first half of the 16th century. A detailed description of mining history in the locality of shallow medieval mine named Jeronym was compiled by Zurek and Korinek (2004) or Kalab et al. (2006). All medieval mining methods (rock breakings) can be documented here, e.g. manually made spaces using hammers of different sizes and so-called bits, setting a fire, and/or blasting later (Fig. 3).

Fig. 3 Jeronym Mine – underground chamber with rest of medieval mining methods (Photo by Rosnerova)

Preserving underground spaces of the Jeronym Mine and securing the surface above the underground spaces is conditioned by the mine stability. Therefore, an extensive distributed monitoring system is gradually being developed and operated (Kalab, Lednicka, 2016; Lyubushin et al., 2014; Telesca et al., 2011; Kalab et al., 2008). The Jeronym Mine is located at a distance about 25 km to the southeast of the Novy Kostel focal zone where the most intensive seismic activity in West Bohemia is documented. Therefore, measurement of vibration effect measured in the underground spaces is part of this stability evaluation (Lednicka, Kalab, 2013, 2016; Kalab, Lednicka, 2011; Kalab, Lyubushin, 2020).

The key results of seismological studies are summarized in Fig. 4. Maximum measured values of component vibration velocity for individual sources are represented depending on prevailing frequency range of measured signals. For natural earthquakes from the Novy Kostel focal zone, component vibration velocities for maximum expected earthquake with ML = 5.0 is predicted and included below. The summary is significant for stability evaluation, numerical modelling of seismic loading of underground spaces or a definition of resonant frequency of selected mine structure.

This study presents the results of a long-term seismic monitoring performed in the shallow medieval mine. The mine is located about 25 km southeast of Novy Kostel focal zone, where seismic activity occurs in the form of seismic swarms. Maximum vibration effect is caused by these earthquakes. Additionally, man-made seismicity also causes vibration effect in underground spaces. It was documented that maximum velocity values and prevailing frequencies of records from individual sources range significantly. This information is important especially for stability assessment and numerical modelling of seismic loading of the mine. Based on presented results, we can state that the Jeronym Mine, as the whole complex of underground spaces, should be stable from the viewpoint of damage caused by vibrations.

This case study documents the need for an individual approach to assessing the effect of vibrations on specific structures. On the other hand, this example reminds that the standards for common objects are quite sufficient, but the mentioned individual approach is necessary in the case of objects requiring increased attention (historical monuments, dams, objects with technological equipment sensitive to vibration etc.).

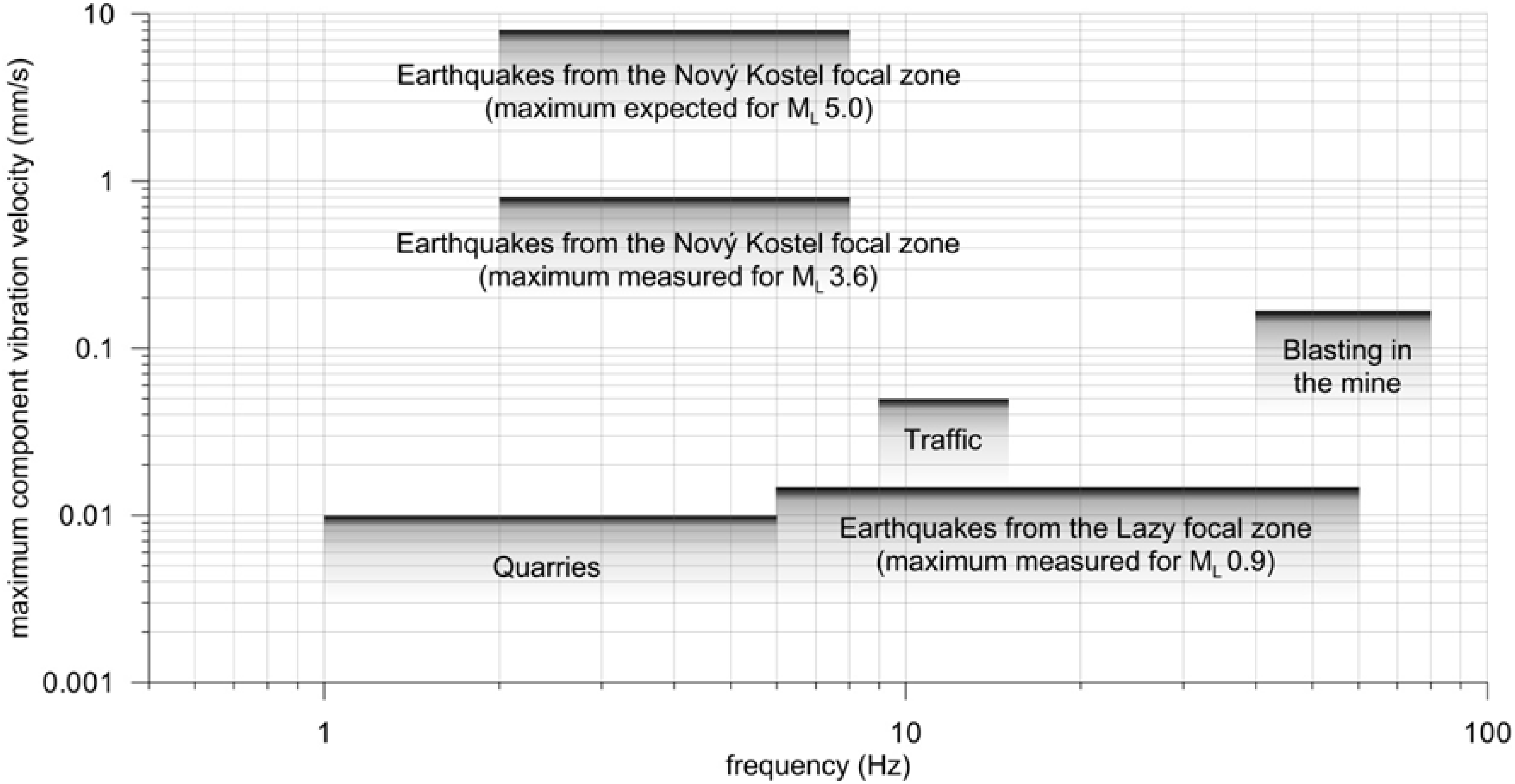

Fig. 4 Summary of maximum component vibration velocity and prevailing frequency range for individual sources in the Jeronym Mine (Kalab et al., 2015a)

7. Seismic stability of the survey areas: case study

The second example describes the methodology for assessing the seismic stability of the survey areas of potential sites for the deep geological repository of the spent nuclear fuel in the Czech Republic (e.g., Kalab et al., 2017). The principal contractor of all activities of project named "Research support for the safety assessment of a deep geological repository" is the Radioactive Waste Repository Authority in the Czech Republic. Methodology of seismic stability of territory contains three main parts:

- Analysis data for historical earthquakes of given territory and its surroundings,
- Detailed review of current earthquake in narrower surroundings and the area of interest,
- Evaluation of seismicity and assessing the impact of seismic effects at depth of hypothetical repository for the next 100,000 years (theoretical modelling).

Selected results of unspecified potential site for the deep repository of the spent nuclear fuel in the Czech Republic are presented below.

The search for historical earthquakes in the area of the Czech Republic and its surroundings, which was processed based on the data of the AHEAD database (www.seismicportal.eu), showed that no major earthquake occurred in the defined area in the defined time period (1000-1899). Strong and moderate earthquakes are located in the vicinity of the Czech Republic but their macroseismic manifestations in the territory of the Czech Republic are not documented. An exception is formed by the earthquake of Lower Austria in 1590. After this earthquake, reports of its manifestations are documented scarcely, but virtually "throughout the territory of the Czech Republic". The result is summarized in maps. The most intensive ("extra large") historical earthquakes documented near the defined area are the events of January 25, 1348 which is localized in the Carinzia region (Italy Their intensity is given at I_0 = 9-10 and magnitude at Mw = 6.99 ± 0.30. Its macroseismic manifestation in the territory of the Czech Republic is unlikely. Thus, it can be stated that in the studied historical period, no very intensive earthquake occurred in the defined area.

To evaluate earthquakes since 1900, current seismological databases were used. It is apparent here that in the territory of the Czech Republic, no earthquakes of magnitude higher than 5.0 have been recorded (see Fig. 5). Thus, it was stated that in the studied period, no very intensive earthquake occurred in the defined area. Also, the design acceleration according to Czech Technical Standard - Eurocode 8 was defined (using National annex).

Based on the literature review, it was generally concluded that:

- Overall, the earthquake amplitude decreases with depth, and the decline extent is more dramatic in shallower layers than that in deeper ones.
- The reduction of amplitude with depth is affected by the magnitude and site geology. In general, for soil site, the decline extent decreases with the increment of magnitude as well as the amplitude.
- In seismic response analysis, the input motion for structures is generally deduced from the design intensity of surface, and then the surface motion is applied to the bottom of the buildings. Obviously, this approach would lead to an overestimate of seismic response for underground structure or high-rise buildings (more than 10 m).

To estimate the peak ground acceleration (PGA), neo-deterministic method was selected (e.g., Panza et al., 2012). The neo-deterministic approach is based on the concept of scenarios of particular earthquakes. This concept and a precise synthesis of the wave-field available thanks to gathering the detailed information on the properties of the medium allow to determine useful engineering parameters quantifying the seismic loading.

This scenario maximizes the benefit from the available information on the medium between the earthquake focus and the site of observation and from the pattern of the seismic energy radiation as well. Various alternatives of the approach are at hand in dependence of the knowledge available from a detailed field survey: (i) on the magnitude of the particular event only, (ii) with additional information on the strike and possibly also the dip of the fault nesting the particular earthquake, (iii) finally with full information on the direction and amount of the slip along the fault.

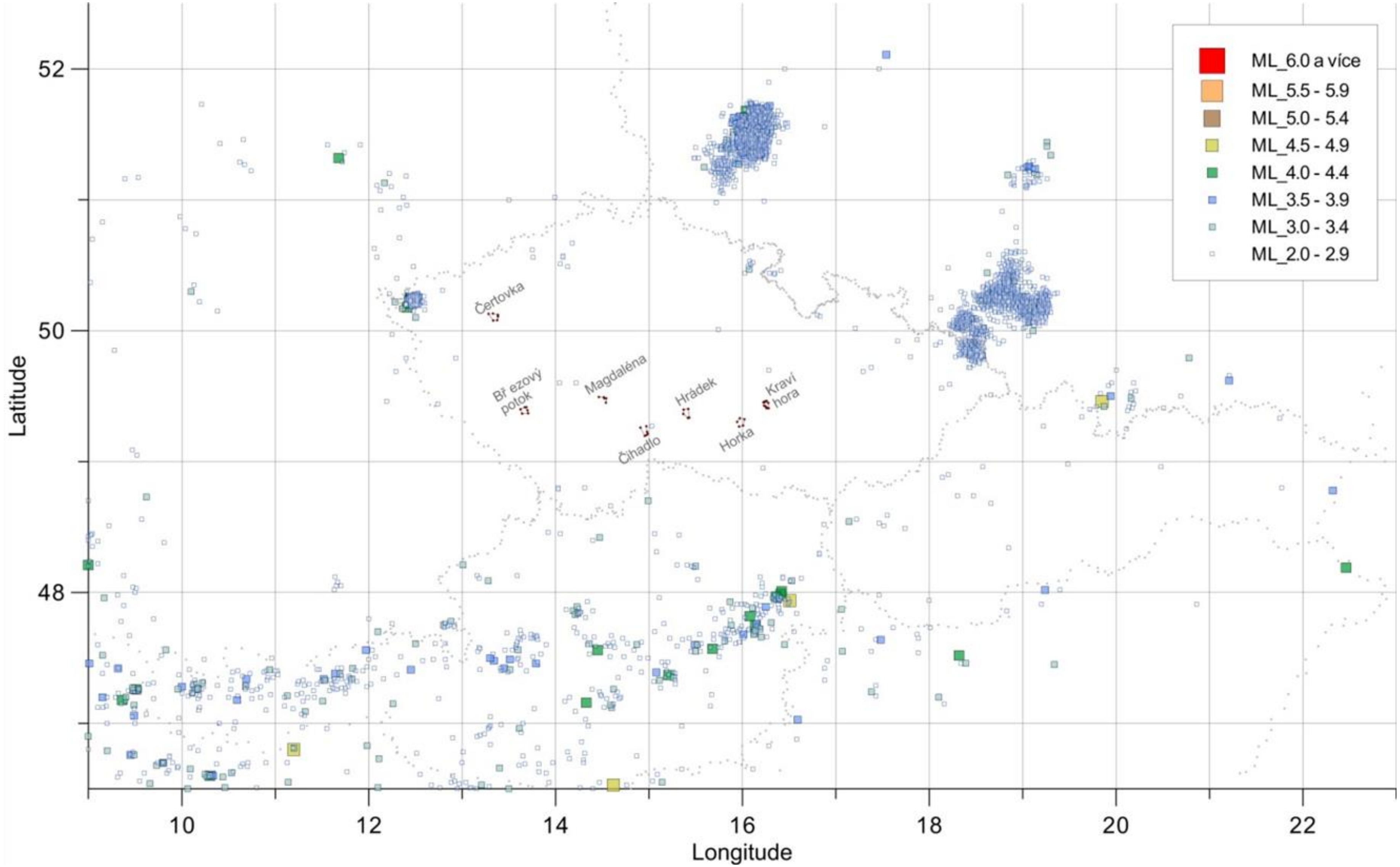

Fig. 5 Map of earthquakes epicentres occurred during 1991 – 2014 according database of the Czech Regional Seismological Network. All seismic events with magnitude ML ≥ 2 (local magnitude estimated by stations of the Czech Regional Seismological Network)

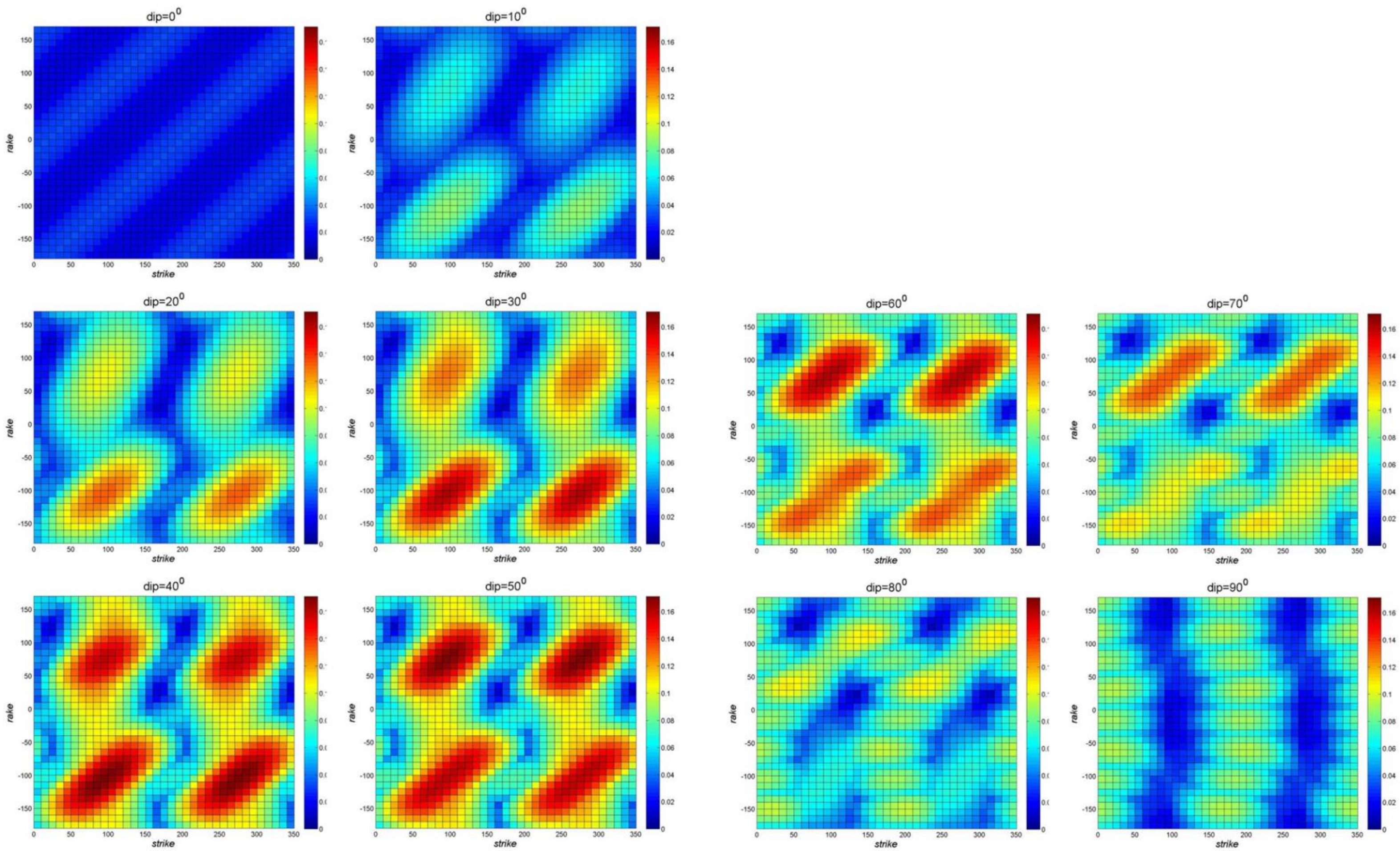

***Fig. 6** Maps of the peak ground acceleration (PGA) in m.s-2 in dependence of the mechanism of the earthquake – orientation of the shear-slip along a fault, described by angles dip (inclination of the fault plane from the horizontal plane), strike (azimuth of the fault trace on the surface, counted in positive numbers from the North to the East), and rake (inclination angle of the slip vector within the fault plane from the horizontal plane). The step of 100 in the regular sampling grid of all three angles in their definition ranges is chosen. The evaluation was performed for the given locality and the earthquake Niederösterreich September 15, 1590 (Kalab et al., 2015b)*

In addition to the coordinates of the station and the hypocentre as well as to the properties of the medium, the wave-field on the site of the observation depends also on the mechanism of the source. It is naturally unknown for historical earthquakes, thus it appears reasonable to evaluate the PGA for various mechanisms (Fig. 6). Then, the requested estimate of the PGA for the earthquake hazard assessment is the maximum across the varying mechanism.

Based on the previously published information, database review and numerical modelling, it is possible to conclude that the impact of seismic events (vibration) on the stability of rock massif at the depth of 500 m and on the deep geological repositories in the horizon of 100,000 years will be very low. The maximum estimated vibration effect did not exceed the surface acceleration of 0.518 $m.s^{-2}$, and the underground acceleration is 0.22 $m.s^{-2}$ at the depth of 500 m. It is not possible to include in the estimation additional related information, such as the degradation of the rock massif, type of the fill around the containers and the containers themselves as a result of on-going geochemical processes and ageing. It cannot be expected from these studies that earthquakes exceeding the magnitude of 5 or more could occur in any one of the sites, and therefore the load of the underground structures in question by vibrations will obviously not be substantial or damaging.

8. Conclusion

This paper discusses influences of vibrations on structures. It is increasingly recognized that buildings must sustain vibrations, and recognition of this is needed both in design for structural integrity, serviceability and environmental acceptability, and in the preservation of historic structures. Measurement of vibration in a building is carried out for a variety of purposes (ISO 4866:1990):

- Problem recognition,
- Control monitoring,
- Documentation,
- Diagnosis.

Such diverse purposes call for a variety of measuring systems ranging from the simple to the sophisticated, deployed in different types of investigation. Technical guidance is needed by many interested parties on the most appropriate ways of measuring, characterizing and evaluating those vibrations that affect buildings.

Vibrations are necessary to take into account if their effect extends into populated areas. The ground vibration is a complicated problem because vibration values depend on several parameters as mentioned above; initial information about vibration effect is possible to derive from experimental measurements. International and national standards dealing with vibration, first of all is necessary named Eurocode 8, define common rules and also (for selected type of structures) precise rules of structure design. Selected parameters of different vibration sources are summarized in Tab. 3 (according ISO 4688:1990). Here, it is possible to find very wide ranges both in amplitude and frequency domains. Monitoring of the natural or technical vibrations is a standard requirement for management of building sites.

We can also support the approach to measuring, interpreting and evaluating vibrations with the statement of prof. Leopold Muller of Salzburg: "Complicated things do not became simpler through simplification at all cost. Things in geomechanics are complicated by their very nature. Only when we have fully understood something in all it´s intricacy, we can put it into simple words and formulas." Although geomechanics is mentioned, it fully applies to most geological studies and works, including seismology.

Tab. 3 Typical range of structural response for various sources (according International standard ISO 4866:1990)

Vibration forcing function	Frequency range [Hz]	Amplitude range [10^{-6} m]	Particle velocity range [10^{-3} m.s^{-1}]	Particle acceleration range [m.s^{-2}]
Traffic (road, trail, ground-borne)	1 - 80	1 – 200	0.2 - 50	0.02 – 1
Blasting vibration (ground-borne)	1 - 300	100 – 2500	0.2 - 500	0.02 – 50
Pile driving (ground-borne)	1 – 100	10 – 50	0.2 - 50	0.02 – 2
Machinery outside (ground-borne)	1 – 300	10 – 1000	0.2 - 50	0.02 – 1
Acoustic (traffic, machinery outside)	10 – 250	1 – 1100	0.2 - 30	0.02 – 1
Machinery inside	1 – 1000	1 – 100	0.2 - 30	0.02 – 1
Human activities impact direct	0.1 – 100 0.1 – 12	100 – 500 100 – 5000	0.2 – 20 0.2 - 5	0.02 – 5 0.02 – 0.2
Earthquakes	0.1 – 30	10 - 10^5	0.2 - 400	0.02 – 20

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