

METHODOLOGY OF DYNAMIC MONITORING OF STRUCTURES IN THE VICINITY OF HYDROTECHNICAL WORKS – SELECTED CASE STUDIES

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Abstract: The constant development of geotechnical technologies imposes the necessity of monitoring techniques to provide a proper quality and the safe execution of geotechnical works. Several monitoring methods enable the preliminary design of work process and current control of hydrotechnical works (pile driving, sheet piling, ground improvement methods). Wave parameter measurements and/or continuous histogram recording of shocks and vibrations and its dynamic impact on engineering structures in the close vicinity of the building site enable the modification of the technology parameters, such as vibrator frequency or hammer drop height. Many examples of practical applications have already been published and provide a basis for the formulation of guidelines, for work on the following sites. In the current work the author's experience gained during sheet piling works for the reconstruction of City Channel in Wrocław (Poland) was presented. The examples chosen describe ways of proceedings in the case of new and old residential buildings where the concrete or masonry walls were exposed to vibrations and in the case of the hydrotechnical structures (sluices, bridges).

Key words: *sheet pile driving, vibration monitoring, probability of failure*

1. INTRODUCTION

Vibrations in the course of geotechnical works need to be monitored and their effects should be reduced to ensure safety of vicinity of hydrotechnical works and also to comply with environmental control requirements.

For instance, the Polish legal system, in the Law "Environmental Control Act" (2004) [23] states in the Article 3, inter alia, that *whenever the Act refers to:*

- 4) *emission – it shall be understood as direct or indirect introducing, as a result of human action, into air, water, soil and ground:*
 - a) *substances,*
 - b) *energy types such as heat, noise, vibrations or electromagnetic waves.*
- 49) *pollution – it shall be understood as emission which may be harmful for human health or environment condition, may cause damage to material assets, may deteriorate aesthetic values of environment or may collide with other justified ways of environment usage.*

According to this regulation, the emission of harmful vibrations means environmental pollution.

Safety of civil structures should be ensured as required by the Construction Law (1994) [24] in the Art. 5.

1. *Civil structure, together with all civil equipment, considering the expected useful life, should be designed and constructed as specified in relevant regulations, including the technical/civil ones, and in accordance with current state of art, assuring the following:*

- 1) *meeting fundamental requirements referring to:*
 - a) *structure safety,*
 - b) *fire safety,*
 - c) *appropriate hygienic and health conditions and environment al protection,*
 - d) *safety of use and availability of buildings,*
 - e) *protection against noise and vibrations.*

The Construction Law requires to make evaluation of the effect of vibrations on safety for structure and human being.

Vibration monitoring is required to ensure safety for buildings and structures located close to work consisting, to name a few, of driving in steel sheet piles or driven piles, and dynamic soil consolidation [2], [3]. Civil works, run while renewing old buildings or constructing the new ones within a built-up area

must be prepared accordingly due their impact on surrounding structures [11], [19].

In order to comply with legal requirements and the rules of art, proper technology of geotechnical work needs to be selected to reduce emission of vibrations [13]. For example, when driving steel sheet piles available technologies include static driving in, vibratory driving, preliminary soil drilling and vibratory driving, vibratory driving with water jetting. Static driving in causes no vibration, however, it requires longer operation periods and higher financial expenses.

The simplest solution is to move the source of vibration away from the responsive structure, however, such solution is not always possible.

There are two different approaches (active and passive methods) to reduce large vibration amplitudes resulting from geotechnical works. Considering passive methods, vertical/horizontal orientated trenches are commonly used. The obstacles can be filled by the different materials, such as concrete, water or Geo-Foam. However, the best results are obtained for the empty ones. On the other hand, active methods are based on the additional energy applied to the system, for example, by the use of an active generator as proposed by Herbut [8]. The idea of an active generator is to apply an additional vibration source and to generate new vibrations with similar vibration amplitudes and frequencies but directed opposite to the ones being attenuated. The idea of an additional generator was verified in case of harmonic excitation [8].

2. LEGAL BASIS FOR VIBRATION IMPACT ASSESSMENT

Vibrations caused by civil works, vehicle traffic, etc. are monitored according to respective guidelines and standards which specify admissible amplitudes of vibrations depending on their frequency and the type of civil structure. Assumptions were made that vibrations are harmonic and long-lasting.

The basis for the result analysis and the assessment of safe vibration levels is typically constituted by the following codes of practice: DIN 4150 (1999), EN1993-5, PN-B02170 (1985).

The Polish Standard [15] provides detailed descriptions of sensitivity to vibrations and lists the following sensitivity thresholds: limit of perceptibility, stiffness, strength and stability. The Standard admits the full and approximate assessment of vibration impact on civil structures.

Full assessment can be applied for each type of civil structures. It requires to run a modal analysis of the facilities under monitoring. The full assessment requires modelling of the building, calculation of inertial forces and verification of the construction for its strength properties. It is seldom used due to the necessary work involved and limited data available for the facilities under monitoring.

The approximate assessment is carried out according to SWD-I and SWD-II scales.

The SWD I scale refers to compact buildings with small dimensions of horizontal projection (up to 15 m), with one or two storeys and the height not larger than any dimension of horizontal projection.

The SWD II scale applies to buildings with several storeys (up to five aboveground floors) with brick or mixed structure meeting the condition: $h/b < 2$, where h – building height, b – its smallest height, and also to low buildings up to 2 storeys, but those which fail the conditions specified for SWD-I.

According to the authors of the standard, the above limitation is binding and excludes monitoring of facilities with other construction (steelwork, frame) and with other dimensions. Assessment is made for peak (maximum) displacement or accelerations of components of horizontal vibrations taken at the foundation or ground level at rigid node of construction from the side of vibration source. Table 1 presents 3 categories of structures of structures according to their response to vibrations of 3 different frequencies.

The SWD scales include five zone of harmfulness for brick and prefabricated tower block buildings:

- zone I – vibrations are not perceptible by building;
- zone II – vibrations are perceptible by building, however they are harmless for its construction; there are only an accelerated deterioration of the building and first cracks in coating materials and plasters;
- zone III – vibrations are harmful for building, they cause local scratches and cracks, thus impairing building construction and reducing its load-carrying capacity and resistance to further dynamic effects (coating material and plasters may fall out);
- zone IV – vibrations are very harmful for building jeopardizing people safety; numerous cracks appear, local wall destruction and other single elements of a building may occur;
- zone V – vibrations cause building failure by tumbling down the walls, floor system falling down, etc.; total danger.

Application of the Standard to two types of facilities and other limitations specified by its authors cause

Table 1. Guideline values for vibration velocity to be used when evaluating the effects of short-term vibration on structures [5]

Line	Type of structure	Guideline values for velocity v_i in mm/s			
		Vibration at the foundation at frequency of			Vibrations at horizontal plane of highest floor at all frequencies
		1 Hz–10 Hz	10 Hz–50 Hz	50 Hz–100 Hz*	
1	Buildings used for commercial purposes, industrial buildings, and buildings of similar design	20	20–40	40–50	40
2	Dwellings and buildings of similar design and/or occupancy	5	5–15	15–20	15
3	Structures that, because of their particular sensibility of vibration, cannot be classified under lines 1 and 2 and are of great intrinsic value (e.g., buildings listed under preservation order)	3	3–8	8–10	8

* At frequencies above 100 Hz, the values given in this column may be used as minimum values.

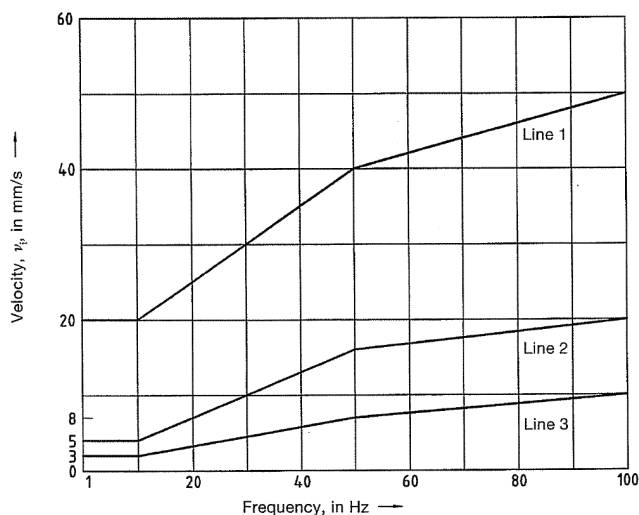


Fig. 1. Curves for guidelines specified in Table 1 for velocities measured at the foundation [4]

that in practice, other standards are used to assess the impact of vibrations to environment: Eurocode 3 [5], DIN 4150 [4]. Recommendations included in these publications are discussed in detail by Brząkała et al. [2]. Numerous examples of case studies are given in works of Brząkała and Baca [3] and Rybak and Schabowicz [17]. The peak value of amplitudes of horizontal PPV is decisive for assessment of vibrations.

Of great importance are the definitions (acc. to Eurocode EC-3) of instantaneous, long-term and short-term vibrations [5].

Vibration emission generated by civil works cause dynamic effects of various amplitudes. A vibrating hammer is propelled by means of eccentric mechanisms installed in gearbox to make single-direction vertical vibrations. The eccentric mechanisms are

arranged in pairs and rotate with the same angular velocity in opposite directions. Large amplitudes at low frequencies are usually observed during initial and final phases of sheet pile immersing operation. Harmful amplitudes and frequencies occur in different periods. Typical “resonance-free” vibration hammers operate at high frequencies of 30–40 Hz, and are higher than typical resonance frequencies of buildings (4–6 Hz). Dynamic measurements and results of Operational Modal Analysis (OMA) of a weir were performed by Wójcicki et al. [22].

The standards do not specify which are the short-term effects – are they, for example, individual pulses, total period over a working day, or percentage share of amplitudes higher than those admissible for long-term effects. Definition of short-term vibrations is essential for delineating the assessment of vibration effects in cases of ambiguous measurement results, for instance when the amplitudes are at the border of impact zone. Literature describes cases of vibration, especially resonant vibration, excitations in the structures and its influence on the failure of buildings [22].

3. MAKING USE OF SHM SYSTEM

Nowadays, the idea of a “smart” or “intelligent structure” has been extended from controlled structural systems to the field of Structural Health Monitoring (SHM) where sensor networks, actuators and computational capabilities are used to enable a structure to perform a self-diagnosis [1]. The reason behind SHM is that this configuration can release early

warnings about a critical health state, locate and classify damage or even forecast the remaining life-time. SHM system must cover the following elements [7].

(1) Data Collection:

- Sensors (passive and active);
- Data acquisition and Integration;

(2) Information Processing:

- Understanding wave propagations;
- Signal Processing;

(3) Diagnostics – Defining current state.

Defining the current state can may be based on the classification of Rytter [18]. This damage state classification system has been very well accepted by the community dealing with damage detection and SHM. The damage state is described by answering the following questions [20]:

1. Is there a damage in the system? (existence)
2. Where is the damage in the structure? (location)
3. What kind of damage is present? (type)
4. How severe is the damage? (extension).

The standards [4], [5], [15] referring to vibration monitoring do not take into account the technical condition of facilities, but just the type of their construction and related sensitivity to vibration emissions. As far as it is reasonably possible, vibration monitoring during vibration emission can be run in regard to existing SHM system of construction testing.

Civil facilities subjected to continuous observation by SHM systems have an extended base of sensors providing data from numerous points. Measurements for facilities subjecting to the SHM system are useful as they provide data on current technical condition and sensitivity to loads.

Continuous monitoring during works emitting vibrations can be treated as a simplified form of SHM for a civil structure. Increasing amplitudes during civil works bear testimony to “ageing” of the structure.

Long-term impact of vibration causes fatigue. Palmgren [14] introduced the first damage-accumulation theory, which is now known as the linear rule, and then Miner expressed the linear rule in mathematical form as a summation of the damage with different loadings, which were calculated as the ratio between the number of applied cycles and the number of total cycles until failure for the i -th constant-amplitude loading level [12].

To determine fatigue life damage is now calculated for each cycle using the Palmgren-Miner damage accumulation rule, which can be written as:

$$D = \sum_{i=1}^n \frac{n_i}{N_i} \quad (1)$$

where D , n_i and N_i denote, respectively, the accumulated damage, the number of load cycles considered for the load sequence and the number of cycles the component would endure under the specific load at a constant amplitude sequence. Once D achieves value of 1, the component is considered to have failed.

In the case of vibration monitoring, vibration amplitude can be inserted in to equation (1).

For the example in the Fig. 2 the accumulated damage involving by vibrations is equal:

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \frac{n_3}{N_3}. \quad (2)$$

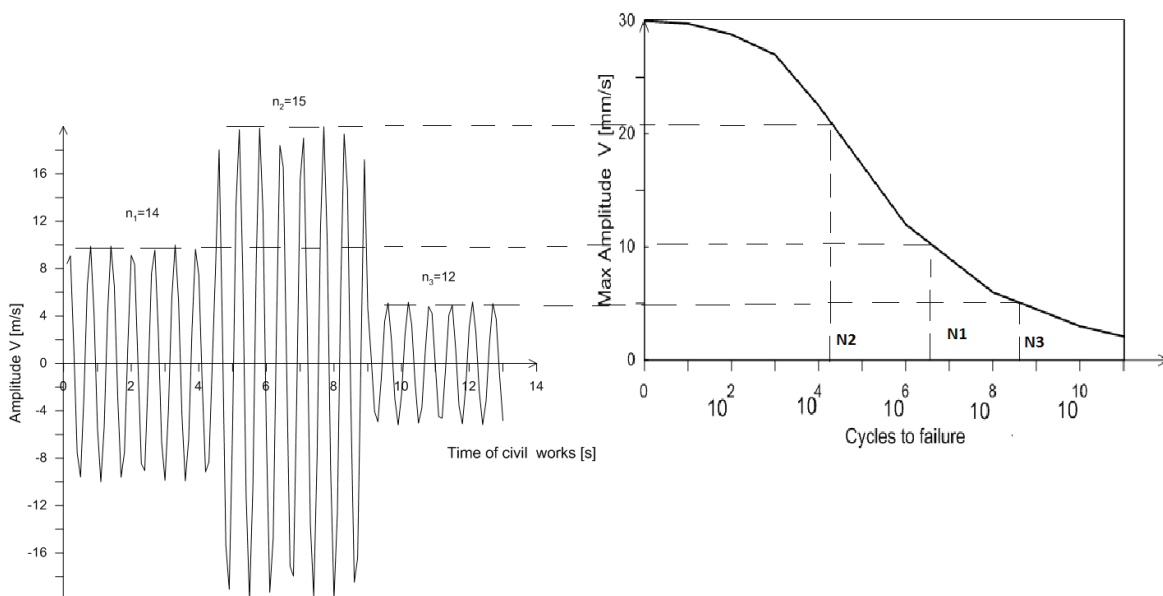


Fig. 2. Elements for performing a fatigue life evaluation [12]

Damage D for each structural component is therefore estimated according to the rule as the accumulation of damage D_i of each individual load cycle, where N_i is the number of cycles the component is able to endure [1], [21].

It is known from fatigue testing that fatigue life spreads significantly for specimens being tested under the same load. Scatter of a factor 2 to 4 in fatigue life is usual. The use of cumulative damage concept is common in buildings equipped with SHM system.

4. RELIABILITY-BASED ASSESSMENT OF VIBRATIONS IMPACT

Apart from the above-mentioned standards and methods of vibration impact estimation, the use of reliability methods is also justified [6], [10], [16].

Vibration monitoring is not just about control as to not exceed allowed amplitudes or cumulative destruction value. It is permissible to exceed the admissible amplitudes, but the probability of exceeding them is limited and compared to the recommended probability of failure. Recommended reliability indices provide the ISO 2394 standard [9]. Maximum acceptable target failure probabilities are also given in ISO 2394 standard [9]. Table 2 presents the results of monetary optimization in the form of tentative target reliabilities.

Reliability is defined as the probability that a component or system will continue to perform its intended function under stated operating conditions over a specified period of time.

The reliability level is derived by monitoring of the functional stability of a number of representative subjects operating under elevated stress or amplitude conditions, resulting in a statistical prediction of reliability. The most common method is to calculate the probability of failure or Rate of Failure (λ).

Failure Rate (λ) in this model is calculated by dividing the total number of failures or rejects by the cumulative time of operation.

$$\lambda = \frac{r}{t} \tag{3}$$

where:

r – number of failures or rejects

t – observation (monitoring) time

Number of rejects r is number of exceeding the allowable vibration amplitude.

To derive a more statistically accurate calculation for Failure Rate (λ), the number of rejects (r) is replaced with the probability function using *Chi-squared* (X^2).

$$r = \frac{X^2(\alpha, \vartheta)}{2} \tag{4}$$

where:

$X^2/2$ (Chi-squared/2) is the probability estimation for the number of failures or rejects.

α – confidence level or probability, is the applicable percent area under the X^2 probability distribution curve; reliability,

ν – degrees of freedom, determine the shape of the X^2 curve; reliability calculations use $\nu = 2r + 2$, where r = number of failures or rejects.

The values most commonly used when calculating the level of reliability in industry are FIT (Failures in Time) and MTTF (Mean Time to Failure) or MTBF (Mean Time between Failures) depending on type of component or system evaluating failures or rejects by the cumulative time of operation.

An exact and general expression for the failure probability of a time varying process [9] on a time interval (0, t) can be derived from integration on the conditional failure rate $h(\tau)$ according to formula (5):

$$p_f(0, t) = 1 - \exp\left[-\int_0^t h(\tau) d\tau\right]. \tag{5}$$

The conditional failure rate is defined as the probability that failure occurs in the interval ($\tau, \tau + d\tau$) given no failure before time τ . When the failure threshold is high enough, it can be assumed that the conditional failure rate $h(\tau)$ can be replaced by the

Table 2. Tentative target reliabilities related to one year reference period and ultimate limit states, based on monetary optimization [9]

Relative cost of safety measure	Consequences of failure		
	Class 2	Class 3	Class 4
Large	$\beta = 3.1$ ($p_f \approx 10^{-3}$)	$\beta = 3.3$ ($p_f \approx 5 \times 10^{-4}$)	$\beta = 3.7$ ($p_f \approx 10^{-4}$)
Medium	$\beta = 3.7$ ($p_f \approx 10^{-4}$)	$\beta = 4.2$ ($p_f \approx 10^{-5}$)	$\beta = 4.4$ ($p_f \approx 5 \times 10^{-4}$)
Small	$\beta = 4.2$ ($p_f \approx 10^{-5}$)	$\beta = 4.4$ ($p_f \approx 5 \times 10^{-6}$)	$\beta = 4.7$ ($p_f \approx 10^{-6}$)

average out-crossing intensity $\nu(\tau)$, see formula (6):

$$\nu(t) = \lim_{\Delta \rightarrow 0} \frac{P(g(X(t)) > 0 \cap g(X(t+\Delta)) \leq 0)}{\Delta}. \quad (6)$$

The mathematical formulation of the outcrossing rate $\nu(\tau)$ depends on the type of loading process, the structural response, and the limit state [9]. Formula might need to be extended to include several processes with different fluctuation scales and/or time invariant random variables.

5. THE MONITORING PROCESS

Signals generated during geotechnical works are of variable nature, which means that these vibrations require individual approach and detailed analyses to get as much information as possible. In most cases vibrations can be described as non-stationary stochastic process, i.e., the average value, variance and autocorrelation function varies along time.

The intensity and frequency characteristics of vibrations can be determined by :

- a) time-domain analysis,
- b) frequency-domain analysis – Fourier Transform,
- c) filtration of time signal – third octavo analysis,
- d) short-time Fourier Transform(STFT),
- e) time- and frequency-domain analysis – Wavelet Transform,
- f) time- and frequency-domain analysis – Matching Pursuit Algorithm.

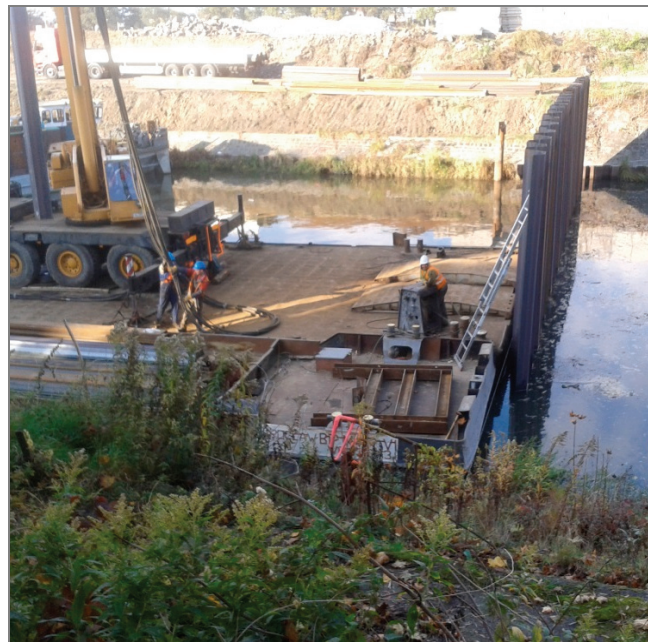


Fig. 3. a) Location of vibration sensor, b) location of vibration works

The monitoring process involves the observation of a system during long periods of time, using samples of experimental data acquired periodically, using adequate sensors. It also involves sensitivity feature extraction and statistical correlations to determine the actual 'health' of the system.

The notion of analysis is associated with decomposition of some entirety into elementary components. With reference to signals, the knowledge domain dealing with such actions is called the signal processing.

6. CASE STUDY

The examination of vibration was carried out on July 2015 during sheet piling works for the reconstruction of City Channel in Wrocław (Poland). The monitored structures were: a building made in traditional technology (Fig. 3.). The sensors were located as presented in the photographs (Fig. 3) below.

According to the standard [5] a monitored object falls into second category.

During the selected monitored time interval (11:32 – 12:12), the sensors recorded the highest amplitude of observation from the whole working day. The graph describing frequency domain is presented in Fig. 3. Each point in Fig. 3, above line 2, describes the coordinates of V_{\max} and the frequency.

The allowable horizontal amplitude was exceeded six times (Fig. 3). These six 2-second sections were

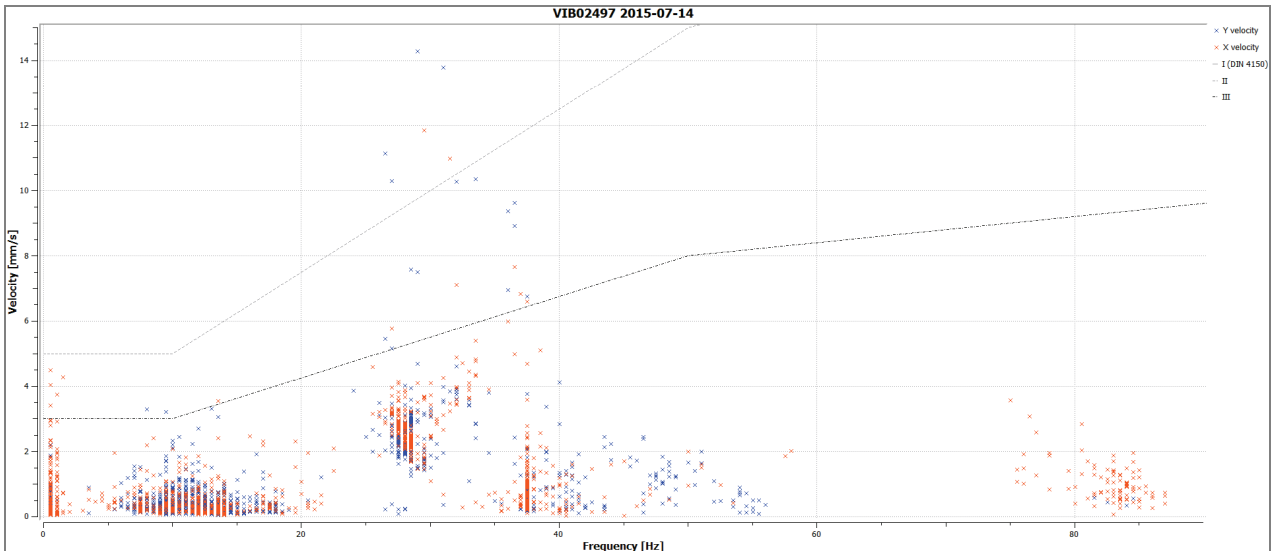


Fig. 3. Velocity in frequency (FFT) domain

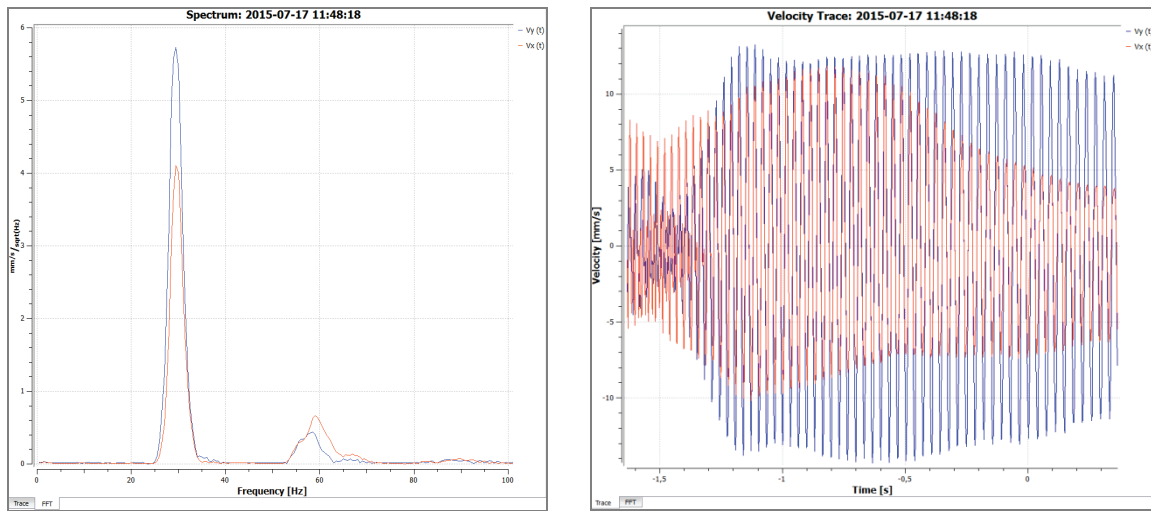


Fig. 4. Trace 11:48:20 a) velocity in frequency domain, b) velocity in time domain

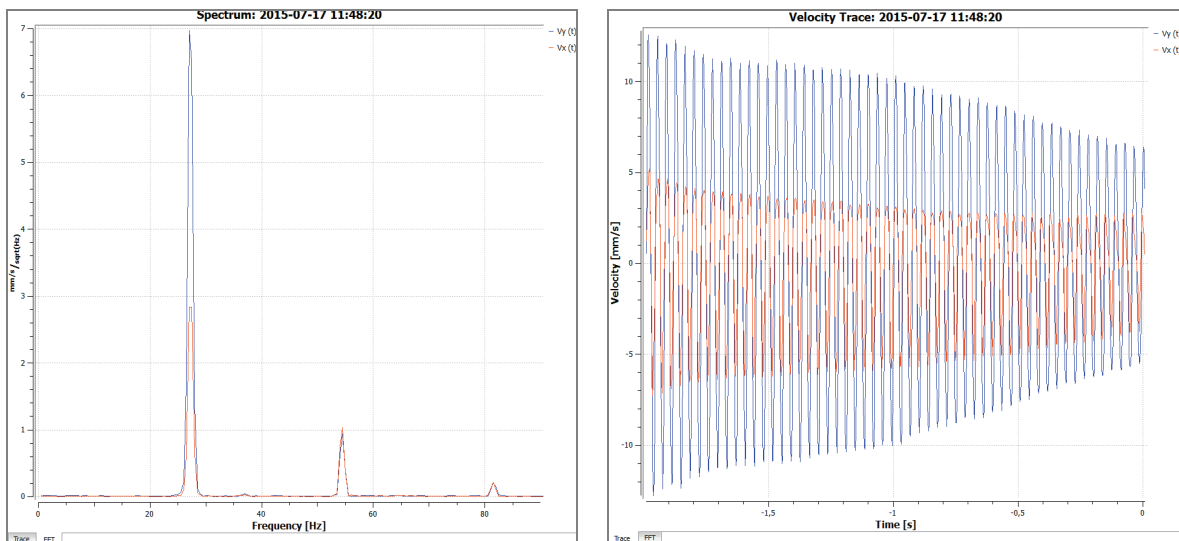


Fig. 5. Trace 11:48:18 a) velocity in frequency domain, b) velocity in time domain

analyzed, where the vibration frequency was about 29–31 Hz (Figs. 4 and 5).

The data for the six sections is set in the Table 3.

It is practical to count the time when the amplitude limit value is exceeded (Fig. 4b). It is easier than counting the actual threshold exceeding number of amplitude during vibrations.

For the section under consideration (Fig. 4), the vibration frequency was 26.48 Hz and the permissible amplitude was 9.0 mm/s. Based on accurate graphs of amplitude values, the effective time of amplitude exceedances was calculated.

An example of an amplitude graph for “trace 11:48:18”, two second long is shown in figure 4b, the time of amplitude exceedances is 1.75 s.

Table 3. Data for selected traces

Trace (time)	Frequency [Hz]	Velocity	Threshold time [s]
11:48:18	28.94	14.20	1.75
11:48:20	31.09	13.78	1.10
11:42:02	29.65	11.87	0.76
11:38:12	26.48	11.03	0.20
11:38:58	27.04	10.27	0.10
11:56:55	31.35	10.95	0.05

Maximum amplitude overrun time may be 12 seconds. In this case, the result obtained as the sum of the column “threshold time” in Table 3 is 3.96 seconds.

The probability of failure calculated for the whole working day (12 hours) can be expressed as:

$$p_f(0.43200) = 1 - \exp\left[-\frac{3.96}{43200}\right] = 9.16 \cdot 10^{-5}.$$

The probability of failure $p_f = 9.16 \cdot 10^{-5}$ in the case of monitored geotechnical works is acceptable, despite exceeding the permissible amplitudes. Reliabilities summarized in Table 2 are related to one year reference period. Vibration works last usually for a short time, the probability calculated for the year reference period will be lower.

7. CONCLUSIONS

For dynamically excited engineering structures, an appropriate prediction of damage accumulation prediction is one of the most important issues. Unfortunately for most buildings not covered by the SHM system it is difficult to apply. In these cases, standard guidelines, like DIN 4150 [4], EN 1993 [5], PN B02170 [15]

should be followed. Obligatory and rigorous application of the normative guidelines for vibration amplitude limitation is debatable for short-term vibrations.

There is no explanation of whether this is permissible for any amplitude exceedances: either temporal or quantitative. Vibration generated during geotechnical works are of variable nature. Therefore, the assessment of the impact vibration in a probabilistic approach is justified. The original meaning of the presented work is the application of the probability of structural failure due to vibration works using standard ISO 2394 [9] principles.

Based on monitoring results probability of failure should be calculated. On the basis of individual exceedances of code of practice indications, the works technology should not be disqualified. Suggested reliability indicators propose the standard ISO 2394 [9]. Failure is a combined result of a cumulative damage process and another load with relatively high value

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