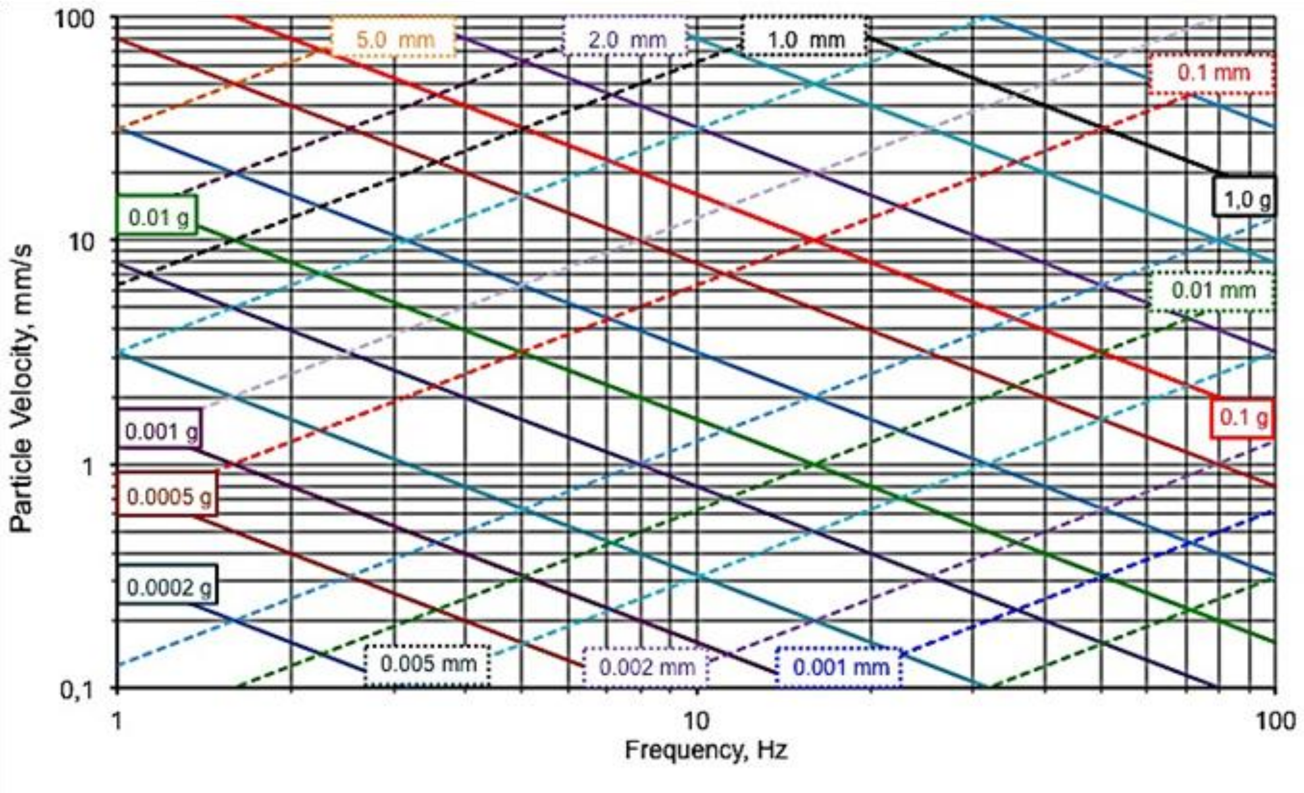

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GROUND VIBRATIONS FROM PILE AND SHEET PILE DRIVING
Part 2 — REVIEW OF VIBRATION STANDARDS

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Abstract Vibration limits for buildings with respect to ground vibrations from pile driving published in international standards are reviewed. At first, relevant vibration parameters are defined and the evaluation of vibration records is described. The sensitivity of structures to different vibration parameters (displacement, velocity and acceleration) is discussed. Most vibration standards relate to blasting activities, the dynamic characteristics of which can be significantly different to those from construction activities and in particular, pile driving. Several vibration standards are reviewed. The Swedish vibration standard is described in detail, as it is the only one accounting for several important factors, such as ground conditions, building material, and type of building foundation. Many standards limit the guidance to values based on the dominant vibration frequency and a wide scatter of frequency-dependent vibration limits exists. It is difficult to compare limiting values of ground vibrations proposed in different standards.

1. INTRODUCTION

For poor ground conditions, placing structures on piles is the most common foundation solution, while sheet piles are widely used to support deep excavations. Piles and sheet piles must often be installed in the close vicinity to buildings, structures or installations in the ground, which can be affected by ground movements and vibrations, (Massarsch and Fellenius, 2014). In many areas, environmental concerns with respect to noise and ground vibrations can restrict or even prohibit driving of piles or sheet piles or reduce the efficiency of installation. The design engineer must prescribe – often at an early stage of a project — the permissible levels of ground vibrations in order to minimize the potential risk of building damage. When seeking guidance from the literature, little or practically no applicable information can be found on how to assess permissible levels of ground vibrations.

Most vibration standards and guidance documents have been developed for rock blasting but are widely used also to asses damage risk due to vibrations caused by other types of construction activities, such as pile driving and soil compaction. However, such standards cannot be applied without taking into account the significance of different vibration parameters. Another limitation of existing standards is that these usually have been prepared by vibration specialists with little or no understanding of geotechnical problems. For instance, ground conditions, location of the groundwater table, and type of building foundation are important when assessing the risk for vibration damage. Moreover, ground vibrations can cause settlement in loose and medium dense soils below a building and give rise to differential movements in the building, which are not directly related to dynamic effects. Massarsch and Fellenius (2014) have discussed the importance of geotechnical conditions and the influence of foundation types on building damage.

National vibration standards are not generally applicable as these were developed empirically and are based on regional experience, taking into account geological and geotechnical conditions, building types and construction methods, and building materials. Therefore, such standards need to be interpreted with judgment when applied to other geographic regions. Another important aspect is the fact that different standards use different parameters to define limiting values, which need to be taken into account when planning vibration measurements and interpreting the results. Also, equipment and measurement procedures vary in different standards and can have significant consequences when applied incorrectly.

This paper deals with damage to buildings caused by ground vibrations from driving of piles and sheet piles. It does not address the mechanism of how vibrations are generated during the driving process. For a detailed description of how vibrations are generated during impact pile driving, reference is made to Massarsch and Fellenius (2008). Vibrations caused by vibratory driving and soil compaction has been discussed by Massarsch (2002).

As an introduction to this paper, different vibration parameters are discussed and defined. Thereafter, an overview of some national standards and vibration guidance documents is given.

2. DEFINITION OF VIBRATION PARAMETERS

The understanding of which parameters can be used to describe vibrations is an important requirement when assessing building damage. The following sections describe the most important parameters required for evaluating the effect of ground vibrations on buildings and building foundations. A comprehensive discussion of these parameters and their interpretation is given by Chameau et al. (1998).

2.1 Vibration Amplitude

Vibration amplitude can be defined as the departure of a point on a vibrating body from its equilibrium position. It is equal to one-half the length of the vibration path. A typical vibration record from pile driving is shown in Figure 1. The following relationship exists between different expressions of vibration amplitude.

$$a = 2\pi f v = (2\pi f)^2 d \qquad (1)$$

where a = acceleration, v = particle velocity, d = displacement and f = vibration frequency. It is thus possible to derive the corresponding amplitude values if one of value of vibration amplitude (displacement, velocity or acceleration) and the vibration frequency are known. The maximum value of vibration velocity (peak value) occurring during the measuring period is in many standards defined as peak particle velocity (*PPV*). If particle motions are measured in three orthogonal directions (x, y, and z) simultaneously, it is possible to calculate the vector sum, $|v_i|$ of the three components.

$$|v_i| = \sqrt{v_{x1}^2 + v_{y1}^2 + v_{z1}^2} \qquad (2)$$

In the case of sinusoidal vibrations, the average vibration amplitude can be expressed by the ratio of root-mean-square (*RMS*).

$$x_{max} = \sqrt{\frac{1}{n}(x_1^2 + x_2^2 + x_3^2 + x_{41}^2 + \ ... + x_{1n}^2)} \quad (3)$$

where x_n etc. are the set of n vibration values. The *RMS* value, which is frequently used to describe the average vibration intensity, corresponds to the area under the half wavelength. In case of sinusoidal vibrations— and only then—it is related to the peak amplitude, v_{peak}.

$$x_{max} = 0.7 v_{peak} \quad (4)$$

The relevance of the *RMS* value depends strongly on the duration of the signal. The so-called CREST factor (peak to average) is the ratio between the peak value and the *rms* value. In the case of transient vibrations, which are typically generated by impact pile driving, the duration of the largest motions is small compared to the total length of the signal. For such vibrations, it is possible to choose the minimum amplitude of interest (i.e. minimum value which is of relevance) and calculate the *RMS* amplitude from the time that the minimum amplitude is exceeded for the first time to the time that the minimum amplitude is exceeded for the last time in the record.

The peak value of the wave is the highest value the wave reaches above a reference, normally zero. This definition is used in the above equations. Note that in engineering applications, frequently the peak-to-trough value (vertical distance between the top and bottom of the amplitude) is used to express vibration intensity. The ambiguity has been the reason for numerous interpretation errors.

2.2 Strain

Vibrations passing through material impose strain, which can be calculated from the particle velocity and the wave speed. Strain, ε, caused by propagation of a compressional wave (P-wave) can be determined from Eq. (5), if the particle velocity, v_P measured in the direction of wave propagation, and the wave speed, c_P are known.

$$\varepsilon = \frac{v_p}{c_p} \quad (5)$$

Similarly, shear strain, γ can be calculated from the particle velocity measured perpendicular to the direction of wave propagation and the shear wave speed, c_S (Eq. 6).

$$\varepsilon = \frac{v_s}{c_s} \quad (6)$$

As will be shown, shear strain is an important parameter when assessing the settlement in granular soils or disturbance of cohesive soils.

2.3 Vibration Frequency

The time history of the vibration record shown in Figure 1 can be transferred into the frequency domain, Figure 2. The frequency content of a signal is important when assessing the effect of vibrations on structures. The simplest method of estimating the dominant frequency is by examining "*zero crossings*" of the time history. This method works reasonably well for simple, periodic signals, but is less reliable for complex, multiple-frequency signals. A common method of estimating the frequency content (spectrum) of a signal is to perform a Fast Fourier Transformation (FFT). The resulting values are usually presented as amplitude and phase, both plotted versus frequency. A related quantity, which is also widely used to estimate the power of a signal, is the power spectrum, which in the frequency domain is the square of FFT´s magnitude. Despite its widespread use, there are several limitations associated with the use of Fourier methods for estimating spectra. The Fourier method implicitly assumes that the signal is stationary. For transient signals such as impact pile driving and blasting and for many dis-continuous signals, this assumption is not strictly valid.

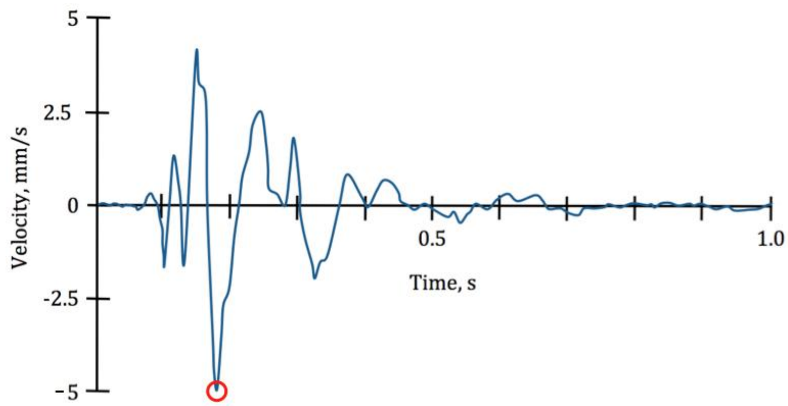

Figure 1. Vertical vibration velocity as function of time, measured at 10 m distance, with the pile toe 3 m below the ground surface during driving of precast concrete pile into sandy soil. The value of the peak particle velocity (PPV) is indicated by the red circle.

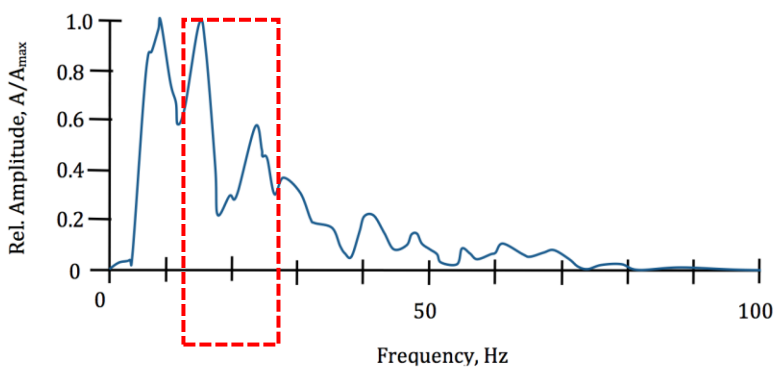

Figure2. Frequency spectrum of the time history shown in Fig. 1. The red rectangle inidcates the dominant frequency range.

A valuable method for estimating the response of a structure to an incoming ground motion is the response spectrum. The response spectrum is expressed as a pseudo-velocity or pseudo-acceleration versus the natural period (or frequency) of the structure, which is modeled by a single-degree-of freedom (SDOF) system.

2.4 Wave Length

The wave length is an important parameter when assessing the risk of damage due to propagation of waves in the ground. The wave length, λ can be determined from the following relationship (Eq. 7).

$$\lambda = 2\pi f \qquad (7)$$

where f is the vibration frequency.

2.5 Cyclic Loading

Another parameter, to consider in connection with pile-driving induced vibrations, is the number of vibration cycles. While structures usually are not very sensitive to fatigue (i.e. the number of vibration cycles), repeated vibration cycles can cause settlements in loose, granular soils (sand and silt) and/or lead to a reduction of the shear strength in fine-grained soils (clay, silt). In loose, water-saturated sand and silt, cyclic loading can lead to a build-up of pore water pressure and to a corresponding reduction in effective stress, which can result in a gradual or complete loss of shear strength (liquefaction). In the case of vibratory driving of piles and sheet piles, the number of significant vibration cycles during driving can be large and should not be neglected. Also, when a group of piles is driven, the accumulated effect of repeated vibrations can cause settlement or reduce the stability of slopes due to temporary increase in pore water pressure.

A fundamental problem when analyzing the effect of ground vibrations on a soil deposit is the fact that the time history of vibrations usually consists of an erratic series of cycles of varying amplitude. It is therefore useful to convert the irregular series of vibration cycles into an equivalent number of uniform cycles. A concept was developed for liquefaction analysis to determine the number of equivalent vibration cycles, which has the same effect as the irregular vibration pattern, Seed (1976). This concept was developed for assessing the risk of liquefaction in medium dense to loose granular soils. Massarsch (2000) has adapted this concept to determine equivalent vibration cycles for settlement analysis in granular soils. Figure 3 shows a relationship to convert an irregular vibration record into equivalent, uniform vibration cycles. For example, the effect of one vibration cycle of maximum amplitude, v_{max} on soil compaction is assumed to have the same effect as for instance 10 cycles of $0.4 x v_{max}$. Experience has shown that the method of converting irregular vibration records in soils is robust and not too sensitive to variation of the assumed conversion relationship.

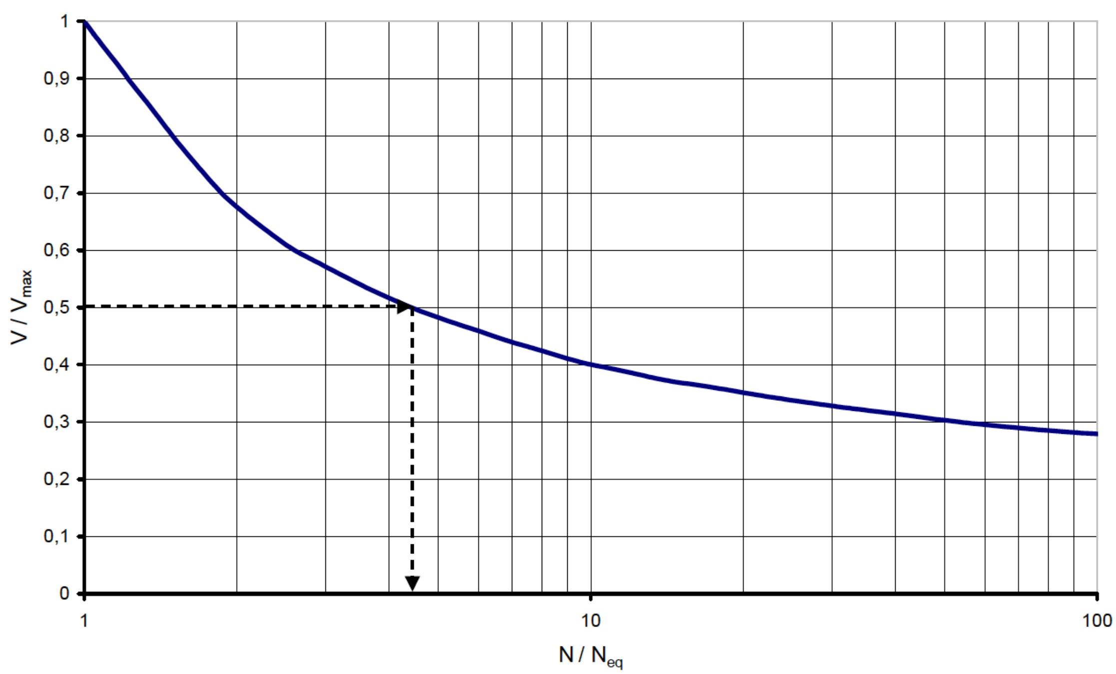

Figure 3 Conversion of irregular time history into equivalent number of uniform (sinusoidal) vibration cycles, Massarsch (2000). In the example, the effect of one uniform cycle (1x v_{max}) corresponds to 4.3 x cycles of 0.5 v_{max}.

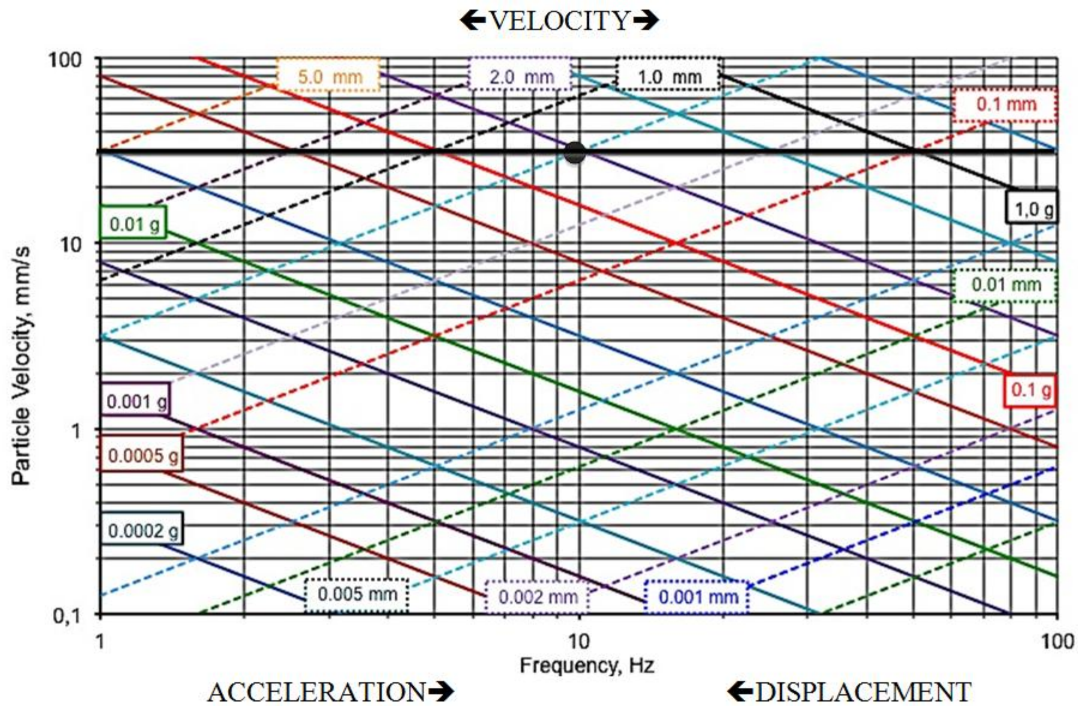

Figure 4 Relationship for sinusoidal vibrations between frequency of vibration and vibration amplitudes, cf. Eq. (1). At 10 Hz, the relationship between particle velocity of 30 mm/s the corresponding displacement is 0.5 mm and the acceleration is 0.2 g.

The black line in Figure 4 marks a vibration velocity of 30 mm/s. At a vibration frequency of 10 Hz, the corresponding displacement amplitude is 0.5 mm. If the vibration frequency decreases at constant vibration velocity, the displacement amplitude will increase. Correspondingly, if the vibration frequency increases at constant vibration velocity, the acceleration amplitude increases.

It is difficult to give general recommendations regarding the damage effects of displacement, velocity and acceleration as the sensitivity of structures can depend on many factors. However, the following general observations can be made, which are not generally appreciated:

Displacement: at low frequencies, displacement is the most relevant measure of structural damage as the failure mode is generally due to "static" stress caused by displacement (Hooke's law), i.e. damage caused by exceeding material strength.

Velocity: measures how often the displacement is applied in a given time period and is thus related to the fatigue mode of failure (material degradation). As can be seen from Eq. (5) and (6), shear strain, which causes material distortion (settlement), depends on vibration velocity and is thus particularly important when assessing settlement in loose granular soils.

Acceleration: at high frequencies, the failure mode is normally related to the applied dynamic force caused by inertial forces (Newton's law).

It should be pointed out that the above failure modes (stress – fatigue – dynamic force) can overlap and the proper selection of vibration parameter must reflect the type of problem.

3. VIBRATION STANDARDS

Environmental authorities in many countries are increasingly aware of the importance of environmental problems and apply standards more rigorously than in the past. Vibrations from construction activities are normally not likely to cause damage to buildings or building elements. Only in the case of very sensitive buildings with poor foundation conditions, damage may be initiated or existing cracking aggravated. However, in the case of vibration-sensitive foundation conditions, such as mixed foundations or foundations on loose, granular soils, damage can be caused by total and/or differential settlements. This aspect is not included in most vibration standards.

In practice, vibration standards, which were primarily developed for blasting applications, are also often used to regulate vibrations from construction activities. The following review of existing standards deals with damage criteria for buildings.

4.1 Swedish Standard

Due to difficult ground conditions in Sweden, pile driving is used frequently also in vibration-sensitive areas and extensive experience regarding the effects of driving preformed piles has been accumulated. The Swedish Standard SS 02 52 11, "*Vibration and shock – Guidance levels and measuring of vibrations in buildings originating from piling, sheet piling, excavating and packing [sic] to estimate permitted vibration levels*" was established in 1999. This standard – which is not widely known outside Scandinavia - was particularly developed to regulate construction activities and is probably the most elaborate standard currently available. It deals with vibrations caused by piling, sheet piling, excavation and soil compaction. Guidance levels of vibrations acceptable with respect to potential building damage have been established based on more than 30 years of practical experience in a wide range of soils. Under the Swedish standard, a risk analysis must be carried out for construction projects, involving the prediction of maximum ground vibration levels and statement of permissible vibration levels for different types of structures. The proposed vibration values do not take into account psychological effects (noise or comfort) on occupants of buildings. Neither do they consider the effects of vibrations on sensitive machinery or equipment in buildings. The vibration levels in the standard are based on experience from measured ground vibrations (vertical component of particle velocity) and observed damage to buildings, with comparable foundation conditions. The vibration level, *v*, is expressed as the peak value of the vertical vibration velocity. It is measured on bearing elements of the building foundation closest to the vibration source and is determined from the following relationship

$$v = v_0 \, F_b \, F_m \, F_g \qquad (8)$$

where: v_0 = vertical component of the uncorrected vibration velocity in mm/s, F_b = building factor, F_m = material factor and F_g = foundation factor. Values for v_0 are given in Table 1 for different ground conditions and construction activities, and are maximum allowable values at the base of the building. It should be noted that in the Swedish standard, the limiting vibration values are independent of vibration frequency. The main reason is that within the frequency range of vibrations generated by pile driving and soil compaction, the dominant frequency usually varies within a narrow range.

Table 1. Uncorrected vibration velocity, v_0.

Foundation Condition	Piling, Sheet piling or Excavation	Soil Compaction
Clay, silt, sand or gravel	9 mm/s	6 mm/s
Moraine (till)	12 mm/s	9 mm/s
Rock	15 mm/s	12 mm/s

Buildings are divided into five classes with respect to their vibration sensitivity cf. Table 2. Classes 1 – 4 apply to structures in good condition. If they are in a poor state, a lower building factor should be used.

Table 2. Building Factor, F_b.

Class	Type of Structure	Building Factor, F_b
1	Heavy structures such as bridges, quay walls, defence structures etc.	1.70
2	Industrial or office buildings	1.20
3	Normal residential buildings	1.00
4	Especially sensitive buildings and buildings with high value or structural elements with wide spans, e.g. church or museum buildings	0.65
5	Historic buildings in a sensitive state as well as certain sensitive historic buildings (ruins)	0.50

The structural material is divided into four classes with respect to their vibration sensitivity, cf. Table 3. The most sensitive material component of the structure determines the class to be applied.

Table 3. Material Factor, F_m.

Class	Type of Building Material	Material Factor, F_m
1	Reinforced concrete, steel or timber	1.20
2	Unreinforced concrete, bricks, concrete blocks with voids, light-weight concrete elements	1.00
3	Light concrete blocks and plaster	0.75
4	Limestone, lime-sandstone	0.65

Table 4 defines a foundation factor. Lower factors are applied to buildings on shallow foundations, whereas buildings on piled foundations are accorded higher factors due to their reduced sensitivity to ground vibrations.

Table 4. Foundation Factor, F_g.

Class	Type of Building Material	Foundation Factor, F_g
1	Slab, raft foundation	0.60
2	Buildings founded on friction piles	0.80
3	Buildings founded on end-bearing piles	1.00

The following example illustrates the practical application of the standard: Piles are to be installed in the vicinity of a residential building with brick walls, which are supported by toe-bearing piles in clay. If the following factors are chosen according to Tables 1 to 4: v_0 = 9 mm/s, F_b = 1.00, F_m = 1.00, F_g = 1.00, the maximum allowable vertical vibration velocity, v, measured at the base of the foundation is 9 mm/s.

4.2 US Bureau of Mines

In North America, vibration codes are based on experience and statistical information, mainly from vibration damage caused by blasting and less from construction activities. One widely used vibration criterion for assessment of building damage is the frequency-dependent vibration limit, proposed by the U.S. Bureau of Mines, which is based on an extensive study of damage to residential structures from surface mine blasting. Siskind et al. (1980) found that horizontal peak particle velocity measured on the ground outside of a structure correlated well with "*threshold damage*", defined as cosmetic damage (e.g. cracking) within the structure. Although other descriptors of the ground motion were considered, peak particle velocity was chosen for its effectiveness and simplicity. These vibration criteria are presented in Table 5 and Figure 5, with transitions between frequency ranges. The lower limits at frequencies smaller than 40 Hz reflect the fact that the structural and mid-wall resonant frequencies are usually within this range for residential structures.

Table 5. Simplified USBM Vibration Criteria for Peak Particle Velocity causing cosmetic damage (from Siskind et al., 1980). Note: developed for blast-induced vibrations.

Type of Structure	Ground Vibration	
	Low Frequency (< 40 Hz)	High Frequency (> 40 Hz)
Modern Homes (Drywall)	19.1 mm/s	50.8 mm/s
Older Homes (Plaster)	12.7 mm/s	50.8 mm/s

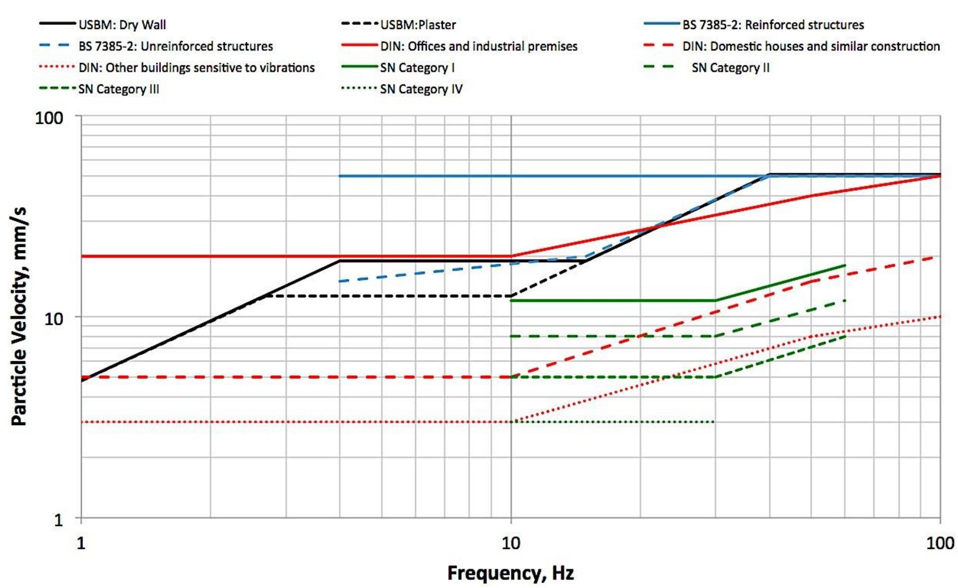

Figure 5 Comparison of frequency-dependent vibration parameters.

4.3 British Standard

Vibration effects on buildings in the UK are covered by British Standard BS 7385. Part 2: (1993), "*Evaluation and measurement for vibration in buildings - Part 2: Guide to damage levels from groundborne vibration*". This part of BS 7385 provides guidance on the assessment of the possibility of vibration-induced damage in buildings due to a variety of sources and sets guide values for building vibration based on the lowest vibration levels above which damage has been credibly demonstrated. It also provides a standard procedure for measuring, recording and analyzing building vibration together with an accurate record of any damage occurring. The vibration criteria published in BS 5228-2:2009. "*Code of practice for noise and vibration control on construction and open sites – Part 2: Vibration*" are identical to those in BS 7385. Sources of vibration which are considered include blasting (carried out during mineral extraction or construction excavation), demolition, piling, ground treatments (e.g. compaction), construction equipment, tunnelling, road and rail traffic, and industrial machinery. Table 6 gives vibration limits for cosmetic damage expressed as the maximum value of any one of three orthogonal component particle velocities measured during a given time interval. In the standard, the resultant of the vibration levels in the three orthogonal axes is used.

The values in Table 6 relate to transient vibrations, which do not give rise to resonant responses in structures, and to low-rise buildings. Where the dynamic loading caused by continuous vibration is such as to give rise to dynamic magnification due to resonance, especially at the lower frequencies where lower guide values apply, then, the guide values in Table 6 might need to be reduced by up to 50%. Also, for unreinforced or light-framed structures below 4 Hz, a maximum displacement of 0.6 mm (zero to peak) is not to be exceeded.

Table 6. Transient vibration guide values for cosmetic damage, measured at base of the building. BS 5228-2:2009.

Type of building	Peak component velocity in frequency range of predominant pulse	
	4 to 15 Hz	15 Hz and above
Reinforced or framed structures Industrial and heavy commercial buildings	50 mm/s at 4 Hz and above	50 mm/s at 4 Hz and above
Unreinforced or light framed structures Residential or light commercial type buildings	15 mm/s at 4 Hz increasing to 20 mm/s at 15 Hz	20 mm/s at 15 Hz increasing to 50 mm/s at 40 Hz and above

Vibration limits, which can cause structural damage, will be higher than those for cosmetic damage, but are not stated in the standard.

4.4 German Standard

The German standard, DIN 4150, Part 3 (1999), "*Vibration in buildings - Part 3: Effects on structures*" addresses the effects of construction-induced vibrations on buildings for short-term and continuous vibrations. The code is applied to problems where vibrations affect buildings and structures, located on or below the ground surface. For short-term loading, the vibration velocity shall be measured at the building foundation level and is based on the largest maximum value of the three components. For continuous vibrations, the horizontal vibration components are measured at the top floor of the building and are set independent of vibration frequency. Table 7 gives frequency-dependent guidance values of peak particle velocity for different types of structures or buildings.

Table 7. Guidance values of vibration velocity for the evaluation building damage for short-term and long-term impact, DIN 4150, Part 3.

Structure/Object Type	Frequency Hz	Peak Velocity mm/s Short-term:	mm/s Long-term	Location of measurement
Offices and industrial premises	1	20	-	
	10	20	-	
	10	20		
	50	40	-	Foundation
	50	40	-	
	100	50		
	1	-	10	Top floor,
	100	-	10	horizontal
Domestic houses and similar construction	1	5	-	
	10	5	-	
	10	5		
	50	15		Foundation
	50	15	-	
	100	20		
	1	-	5	Top floor,
	100	-	5	horizontal
Other buildings sensitive to vibrations	1	3	-	
	10	3	-	
	10	3		
	50	8		Foundation
	50	8	-	
	100	10		
	1	-	2,5	Top floor,
	100	-	2,5	horizontal

DIN 4150-3 also gives guidelines regarding the execution of vibration measurements in buildings. If resonance can be expected in the structure, vibration measurements shall be performed on several floor levels (not only on the top floor). In the case of floor vibrations, the vertical vibration amplitude shall be used. The code also points out the risk of cumulative damage effects from vibrations on buildings with existing (locked-in) stresses. Buildings, which are subjected to differential settlements, are considered particularly sensitive to ground vibrations.

4.5 Swiss Standard

Swiss standard SN 640 312 has been introduced in 1979 and considers the effect of vibrations from transient (shock) and continuous vibrations. Buildings are divided into four categories, cf. Table 8.

Table 8. Building categories, SN 640312.

Building Category	Building Type
I	Reinforced concrete structures for industrial purposes, bridges, towers etc.
	Subsurface structures such as caverns, tunnels with or without concrete lining
II	ildings with concrete foundations and concrete floors, buildings made of stone an concrete masonry/blocks
	Subsurface structures, water mains, tubes and caverns in soft rock
III	lings with concrete foundations and concrete basement, timber floors, masonry wa
IV	Especially vibration-sensitive structures and buildings requiring protection

Recommended vibration levels for continuous disturbance are presented in Table 9. Two different frequency ranges have been chosen, 10 – 30 and 30 – 60 Hz, respectively.

Table 9. Swiss recommendation of max vibration levels for continuous vibrations, SN 640312.

Building Category	Frequency Range Hz	Recommended vibration velocity mm/s
I	10 – 30	12
I	30 - 60	12 – 18
II	10 – 30	8
II	30 - 60	8 – 12
III	10 – 30	5
III	30 - 60	5 – 8
IV	10 – 30	3
IV	30 - 60	3 - 5

4.6 Hong Kong Government Regulations

The Hong Kong Buildings Department has issued a Practice Note, APP-137 "*Ground-borne Vibrations and Ground Settlements Arising from Pile Driving and Similar Operations*" which provides guidelines on the control of ground-borne vibrations and ground settlements generated from pile driving or similar operations with a view to minimizing possible damage to adjacent properties and streets. It is worth noting that of the standards reviewed in this document, this standard is the only one which suggests limiting values with regard to ground settlement and ground distortion.

The effect of ground-borne vibration from piling works on adjacent structures is assessed by the maximum peak particle velocity (PPV). The maximum PPV shall be evaluated from the peak particle velocities at three orthogonal axes measured at ground levels of the structures in question. The guide values of maximum PPV presented in Table 10 are suggested to give minimal risks of vibration-induced damage.

Table 10. Empirical guidelines according to HK Practice Note, APP-137, Appendix A.

Type of building	Guide values of maximum PPV (mm/s)	
	Transient vibration (e.g. drop hammer)	Continuous vibration (e.g. vibratory hammer)
Robust and stable buildings in general	15	7.5
Vibration-sensitive/dilapidated buildings	7.5	3.0

Due attention shall also be paid to sensitive buildings close to the piling site such as hospitals, academic institutes, declared monuments, old buildings with shallow foundations, old tunnels/caverns, buildings installed with sensitive equipment, masonry retaining walls or sites with history of instability, monuments or buildings with historical significance, etc. A more stringent control on the allowable limit of PPV for these buildings may be specified based on site and building conditions together with the duration and frequency of the exciting source.

As different structures will have different tolerance in accommodating movements of their foundations, acceptance of estimated ground settlements should be considered on a case-by-case basis with respect to the integrity, stability and functionality of the supported structures. Provided that there are no particularly sensitive adjacent buildings, structures, and services, the guide values, Table 11, may be taken as the trigger values in accordance PNAP APP- 18.

Table 11. Empirical guidelines according to HK Practice Note, APP-137.

Instrument	Criterion	Alert	Alarm	Action
Ground settlement marker	Total settlement	12 mm	18 mm	25 mm
Service settlement marker	Total settlement and angular distortion	12 mm or 1:600	18 mm or 1:450	25 mm or 1:300
Building tilting marker	Angular distortion	1:1000	1:750	1:500

4. CONCLUSIONS

Driving of piles or sheet piles can cause ground vibrations, which under unfavorable conditions can adversely affect buildings or other structures. Therefore, it is important to perform a risk analysis and to define limiting values with respect to ground vibrations. Little guidance is found in the geotechnical literature with respect to the selection of appropriate vibration parameters. The paper defines different vibration parameters and offers guidance regarding the evaluation of vibration records.

Damage to buildings can be caused by different mechanisms, such as deformation, velocity and acceleration, or a combination of these parameters. For pile-driving induced vibrations the most relevant parameter is vibration velocity. Vibration velocity is related to material strain and thus a measure of material deterioration (settlement).

The Swedish standard SS 02 52 11was specifically developed for pile-driving induced ground vibrations. It is the only known standard specifically addressing vibrations due to pile-driving. It is based on the vertical vibration velocity and chosen independently of vibration frequency and takes into consideration ground conditions, building material, and type of building foundation.

The frequency-dependent vibration parameters presented above are summarized in Figure 5. The blasting standard of the US Department of Mines (USBM) is also included as reference. The difference in particle velocity between different standards is large and cannot be explained on a rational basis. As the dominant vibration frequency of pile-driving induced vibrations usually is in the range of 10 to 30 Hz, there appears to be little justification to use frequency-adjusted velocity values.

Based on the comparison in this paper, the Swedish standard appears to provide more relevant guidance values, as it takes into account important aspect, such as ground conditions and building foundation parameters.

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