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# A choice of proper criteria for soil and structural vibrations from construction and industrial sources

Un choix de bons critères pour le sol et vibrations structurelles de la construction et de sources industrielles

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**ABSTRACT:** Diverse construction and industrial machines generate body and surface waves in the soil medium which may detrimentally affect surrounding buildings, houses and their contents. The vibration effects range from a nuisance and disturbance of people and sensitive medical facilities to reduction of the integrity and serviceability of structures. These outcomes create significant practical problems. Each year, numerous buildings receive damage from construction operations, and these consequences result in litigations. It is necessary to use appropriate vibration limits to correctly manage vibration problems of different structures and sensitive devices.

**RÉSUMÉ:** Construction diversifiée et machines industrielles génèrent des ondes de corps et de la surface dans le milieu du sol qui peut-être nuire à leur contenu, des maisons et des bâtiments environnants. La vibration des effets allant d'une nuisance et la perturbation des personnes et des installations médicales sensibles à la réduction de l'intégrité et l'état de fonctionnement des structures. Ces résultats créent des problèmes pratiques importants. Chaque année, nombreux bâtiments reçoivent des dommages d'opérations de construction et ces résultats de conséquences dans les litiges. Il est nécessaire d'utiliser des limites de vibrations appropriées pour gérer correctement les problèmes de vibration des différentes structures et dispositifs sensibles.

**KEYWORDS:** construction and industrial vibrations, effects on structures, dynamic settlement, sensitive devices, vibration limits.

## 1 INTRODUCTION

Various construction vibration sources such as blasting, pile driving, dynamic compaction and also industrial dynamic sources such as forge hammers generate ground and structural vibrations which may harmfully affect diverse adjacent and remote structures, sensitive devices and people.

It is common to pay dominant attention to structural vibrations, and vibration limits of structural vibrations are mostly used in practice. However, availability of sensitive devices in buildings determines the application of the strict vibration criteria, established for sensitive devices, for evaluation of building vibrations. It is typical that the effects of construction vibrations on people in houses are not assessed, but when construction operations are carried out near medical facilities, it is necessary to evaluate the vibration effects on medical devices and people.

The paper provides a guideline for a choice of proper criteria for structural vibrations and also considers different criteria for evaluation of vibration effects on sensitive devices and people.

## 2 STRUCTURAL VIBRATIONS

The application of the International Standard ISO 4866-1990 is the best solution for assessment of vibration effects on different parts of buildings. ANSI S2.47-1990 is the U.S. counterpart of ISO 4866-1990. The evaluation of the effects of building vibrations is primary directed at structural response, and includes appropriate analytical methods where the frequency, duration and amplitude can be defined. This standard provides assessment of vibration effects on buildings from outside or inside vibration sources. However, the standard does not take into account the effects of dynamic settlement triggered by plastic soil deformation generated by outside vibration sources. Therefore a combination of the standard application with assessment of possible dynamic settlement is beneficial.

Nevertheless, there are a number of national standards, codes and regulations which determine vibration limits in terms of the peak particle velocity (PPV) for structural vibrations to prevent cosmetic cracking of structures with an emphasis of short-term vibrations. These criteria also do not consider the effects of plastic soil deformations from outside vibrations.

### 2.1 U.S. Bureau of Mines RI 8507

The United States Bureau of Mines (USBM) RI 8507 provide vibration limits for 1- and 2-story houses which are the most typical structures in urban and rural areas, and these limits, the peak particle velocity or the displacement as functions of the dominant vibration frequency, are applied to ground vibrations as the criteria for possible crack formation in houses (Siskind et al. 1980). This is the document which does not use measurements of structural vibrations for assessment of the vibration effects on buildings. The major goal of the USBM criteria was the prevention of damaging resonant horizontal house vibrations at large distances from surface coal mine blasting. The vibration limits in the resonance zone are 12.7 mm/s and 19.0 mm/s for walls with plaster and dry walls, respectively. The USBM criteria without doubt are good for specific blast design, soil conditions, and types of structures for which they were developed. However, it is necessary to underline that there is no scientific and legal basis for the application of the USBM vibration limits for construction vibrations for which they were not developed (Svinkin 2015).

Nevertheless, USBM provides a great field experience which can be used for assessment of other vibration limits. First, the tolerable limits of ground vibrations for prevention of cosmetic cracking from resonance horizontal house vibrations were determined for the maximum 4.5 amplification. Multiplying the tolerable limits of ground vibrations (12.7 mm/s and 19.0 mm/s) on 4.5, we receive maximum structural vibrations of 57 mm/s and 86 mm/s which do not trigger cosmetic cracking, Fig. 1. Second, analyses of data available in Siskind (2000) showed that direct minor and major structural

damage to 1- and 2-story residential houses without resonant structural responses were observed in the velocity range of 33-191 mm/s for frequencies of 2-5 Hz and in the velocity range of 102-254 mm/s for frequencies of 60-450 Hz. It is necessary to point out that super structures of investigated residential houses were built with wooden materials, sidings and sometimes with brick or stucco walls which is typical for residential houses.

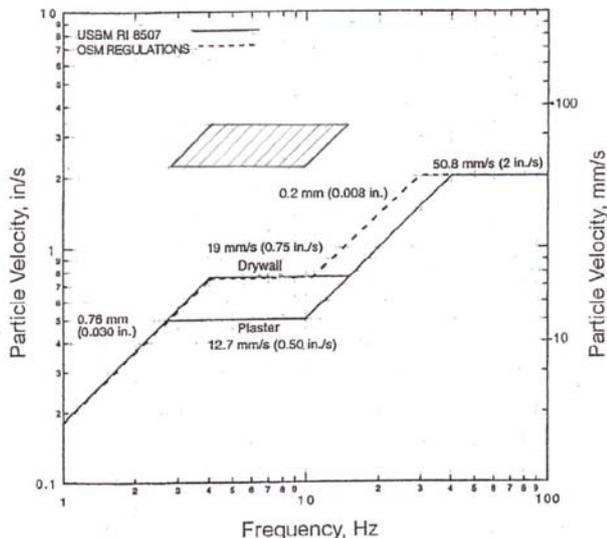


Figure 1. Safe level blasting criteria from USBM RI 8507 and the derivative version (dashed line shows the Chart Option from OSM surface coal mine regulations; shaded area shows maximum velocities of structural vibrations with amplification of 4.5 at resonance. Data used from Siskind (2000) and Svinkin (2008) with permission.

2.2 British Standard BS 7385-1993

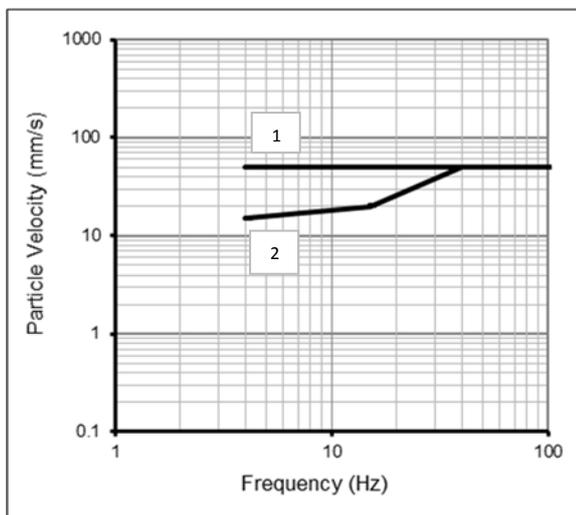


Figure 2. Vibration guidelines from BS 7385. Line 1: reinforced or framed structures, industrial and heavy commercial buildings; Line 2: unreinforced or light framed structures, residential or light commercial type buildings. Data modified from BSI 1993.

British Standard provides vibration guidelines for two types of buildings shown in Fig. 2. For industrial and heavy commercial buildings (Line 1), the limit of 51 mm/s is used for frequencies from 4 to 100 Hz. For residential or light commercial type buildings (Line 2), the limits are: 15 mm/s at 4 Hz increasing to 20 mm/s at 15 Hz and then increasing to 50 mm/s at 40 Hz and above.

Below a frequency of 4 Hz, where a high displacement is associated with relatively low PPV, a maximum displacement of 0.6 mm should be used.

The British Standard points out that minor damage is possible at vibration magnitudes which are greater than twice those shown in Fig 2, and major damage to building structures may occur at values greater than four times the tabulated values. It means this standard provides highly conservative vibration criteria.

It is necessary to point out that the vibration limits, allowable for the second types of buildings (residential houses), are substantially smaller than PPV of the actual structural vibrations of such types of residential houses which do not trigger cosmetic cracking, Fig 1.

2.3 German Standard DIN 4150-1986

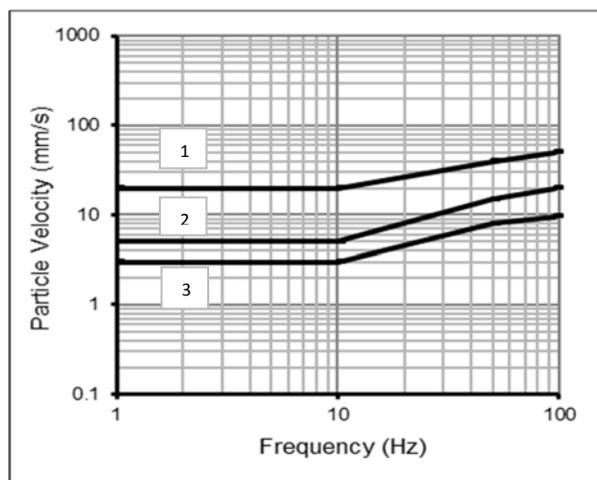


Figure 3. Vibration guidelines from DIN 4150. Line 1: Buildings used for commercial purposes, industrial buildings of similar design; Line 2: dwellings and buildings of similar design and/or use; Line 3: structures that, because of their particular sensitivity to vibration, do not correspond to those listed in lines 1 and 2 and are of great intrinsic value (e.g. buildings that are under a preservation order). Data modified from DIN 1986.

German Standard supplies vibration guidelines for three types of buildings shown in Fig. 3. For commercial and industrial buildings (Line 1), the limits are: 20 mm/s for less than 10 Hz increasing to 40 mm/s at 50 Hz and increasing 50 mm/s at 100 Hz. For dwellings and buildings of similar design (Line 2), the limits are: 5 mm/s for less than 10 Hz increasing to 15 mm/s at 50 Hz and increasing 20 mm/s at 100 Hz. For structures sensitive to vibrations (Line 3), the limits are: 3 mm/s for less than 10 Hz increasing to 8 mm/s at 50 Hz and increasing 10 mm/s at 100 Hz.

Lines 1 and 2 in Fig 3 are similar to Lines 1 and 2 in Fig. 2. Line 3 actually represents historic or similar buildings.

2.4 Russian Criteria

Simple limits of 30-50 mm/s for vibrations of sound structures have long been used in Russia (Sadovsky 1946). There is much similarity between these criteria and the upper limits of British and German Standards.

2.5 Swiss Standard SN 640 312a-1992

Swiss Standard provides two groups of the structural vibration limits: first for blasting and second for other equipment. The first group has higher limits which are shown below.

Table 1. Building structures. Data modified from SN 640 312a-1992.

Building Class	Type of Structures
I	Industrial reinforced concrete and steel buildings and structures
II	Buildings with concrete foundations and floors. Underground structures
III	Buildings with concrete foundations and basement floor, wooden floors and brickwork walls
IV	Buildings sensitive to vibrations or requiring protection

Table 2. Limits for structural vibrations from blasting. Data modified from SN 640 312a-1992.

Building Class	Frequency Hz	Vibration Limits mm/s
I	10 - 60	30
	60 - 90	30-40
II	10 - 60	18
	60 - 90	18-25
III	10 - 60	12
	60 - 90	12-18
IV	10 - 60	8
	60 - 90	8-12

It can be seen that the limits for industrial buildings are close to the criteria of other standards, but the limits for residential houses may be considered as highly conservative.

#### 2.6 Swedish Standard SS 02 52 11-1999

Swedish Standard deals with vibrations caused by piles driving, sheet piles driving and compaction. The vibration limits are calculated as the product of  $v_0$  = vertical component of uncorrected vibration velocity in mm/s,  $F_b$  = building factor,  $F_m$  = material factor and  $F_g$  = foundation factor. On the one hand this standard provides good safety for structures, but on the other hand this standard is very conservative and makes obstacles for construction.

#### 2.7 Norwegian Standard NS8141(ITAtech 2016)

Norwegian Standard uses the similar approach as Swedish Standard.

#### 2.8 Italian Standard UNI 9916-2014

Italian Standard includes as reference the limits stated by the German DIN 4150 which proposes different limits for short-duration and for long-duration vibrations. These limits are considered to be conservative for the typical historical buildings existing in Italy.

#### 2.9 French Standard A.F.T.E.S and Ministry of the Environment (ITAtech 2016)

Both French Standards deal with the effects of blast vibrations on buildings. A.F.T.E.S. (Association française des Tunnels et de l'Espace Souterrain) published in 1974. This Standard defines three building classes depending on low, average and high mechanical quality which vibration limits also affected by soil conditions, specifically by a velocity of propagation of longitudinal waves. For a velocity of 3000 m/s the maximum limit is equal 50 mm/s.

The recommendation of the Ministry of the Environment was published in 1986 and expanded in 1993. There are

resistant, sensitive and very sensitive buildings, and the vibration limits depend on the frequency. The maximum limit for resistant construction equals 15 mm/s at frequencies between 90-100 Hz. This is the very conservative limit for buildings because the PPV of 51 mm/s is the highest vibration level generated inside buildings by human activities (Siskind 2000).

#### 2.10 Finland Standard RIL 253-2010 (ITAtech 2016)

Finland Standard uses guideline values for PPV as functions of a distance from the source, soil and building types. The maximum PPV of 35 mm/s is used for compact sand and gravel soils at distances of 1-10 m from the source. The maximum building coefficient, which values depend on the specialist qualification, equals 2.00 for heavy structures and 1.00 for residential houses. The maximum tolerable limits are higher than those in British and German Standards.

#### 2.11 Brazilian Standard NBR 9653-2005

Brazilian Standard adopted BS 7385, but unlike of BS 7385, the limits are applied for ground vibrations, not for structural ones.

#### 2.12 Canadian Standard NPC-207-1983

Canadian Standard uses a vibration limit of 12.5 mm/s when vibration monitoring is conducted. This criterion is close to the vibration limit of 12.7 mm/s for ground vibrations developed by USBM RI 8507.

### 3 DYNAMIC SETTLEMENT

There are numerous case histories of the destruction effects of dynamic settlements on buildings (Lynch 1960, Horn 1966, D'Appolonia 1971, Clough and Chameau 1980, Lacy and Gould 1985, Kaminetzky 1991, Feld and Carper 1997, Svinkin 2006), and these settlements are the major cause of damage to structures (Svinkin 2013).

No regulations are known for critical vibration levels of ground vibrations which may trigger dynamic settlements beyond the densification zone. There are a couple of published papers with information about the critical vibration levels of ground vibrations, which may trigger dynamic settlements. Lacy and Gould (1985) analyzed 19 cases of settlements from piles driven by mostly impact hammers in narrow-graded single sized clean sands with the relative density less than about 50 to 55 %. They found that the peak particle velocity of 2.5 mm/s could be considered as the threshold of possible significant settlements at vulnerable sites.

### 4 SENSITIVE DEVICES AND EQUIPMENT

Knowledge of allowable vibration limits for sensitive devices and equipment installed on the building floor is important for evaluation of the vibration effects on them. It is necessary to measure structural vibrations on the floor near sensitive objects. There are case histories of pile driving and blasting conducted near buildings with sensitive equipment and computerized systems where pile driving or blasting parameters were adjusted to allowable vibration limits (Svinkin 2013).

### 5 VIBRATION EFFECTS ON PEOPLE

It is typical during construction operations that major attention is applied to structural damage and the vibration effects on people is taken into account if a construction site is located in

the proximity of hospitals.

Industrial vibrations can strongly affect people because of prolonged effects in time. The author experienced a case history of the vibration effect of a vibration isolated foundation under 16 tonnes forge hammer which triggered resonance horizontal vibrations of a five story apartment building. Parameters (dashpot stiffness) of isolated foundation were corrected and building vibrations left the resonance zone (Svinkin 1993).

## 6 DISCUSSION

Unlike ISO 4866-1990 which requires stress calculations in various structures of buildings, the national standards provide the vibration limits for general assessments of vibration effects on building structures. Such an approach can be more convenient because it is much less expensive and time-consuming.

The national standards actually consider two types of buildings: industrial and commercial concrete or steel buildings and residential houses with much lighter structures. The first type of structures has maximum PPV of 40-50 mm/s for about 40-100 Hz and the second one has maximum PPV of about 20 mm/s for 90-100 Hz. Nevertheless, the results of USBM field measurements show that even at the resonance zone (4-12 Hz) residential houses vibrated with tolerable PPV higher than 50 mm/s without damage, Fig. 1. Besides, the PPV of 50 mm/s is the highest vibration level generated inside residential houses by walking, jumping, slamming doors, etc. (Siskind 2000).

It is necessary to point out that the frequency-independent safe limit of 50 mm/s for measured structural vibrations can be used for various structures like residential houses, multistory apartment buildings, industrial and commercial buildings.

In comparison with blasting, construction and industrial impact sources do not trigger low frequency horizontal resonant building vibrations. Vibratory equipment can generate vertical resonant floor vibrations. If such vibrations occurred, it is necessary to change the vibrator frequency (Svinkin 2015).

Also, USBM experiments demonstrate vibrations of good soils with PPV below 33 mm/s (2-5 Hz) and 100 mm/s (60-450 Hz) before or after resonance, respectively, of horizontal building vibrations which do not trigger damage to structures. Low PPV of ground vibrations are especially important in collapsing soils because they can trigger dynamic settlement: 4.3 mm/s in sands with rubble and broken rock, 2.5 mm/s in narrow-graded, single-sized clean sands, 0.5-1.5 mm/s in loess soils (Clough and Chameau 1980, Lacy and Gould 1985, Siskind 2000).

It is imperative to use the control of vibration levels together with condition surveys of structures before, during and after construction because such surveys demonstrate actual structural responses to dynamic excitations (Svinkin 2015).

## 7 CONCLUSION

For evaluation of the vibration effects on structures of construction and industrial sources, structural vibrations have to be measured. Ground vibrations should be measured for assessment of possible dynamic settlement.

In general, the vibration limit of 50 mm/s can be used for sound structural vibrations and the basic limit of 2.5 mm/s should be used for assessment of dynamic settlement in collapsing soils.

Notwithstanding, it is necessary to take into account that each construction site is unique with soil conditions, various structures, sensitive equipment and human responses from residential houses or medical facilities. Therefore, vibration limits has to be adjusted to local conditions and experience.

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