Impact of Ground-Borne Vibrations Emanating from Construction Activities

1. Scope

Presently, there are no Canadian standards or guidelines to be consulted by professionals developing a vibration monitoring plan or assessing the possible impact of vibrations from construction activities near existing buildings. Therefore, Canadian professionals are forced to rely on international resources when dealing with claims of damage due to construction vibration. This technical note provides a review of the frequently cited references on evaluating ground vibration damage from the use of construction equipment. The note does not cover noise and airborne vibration damage due to vehicular traffic, explosions, or mining activities. The focus of the technical note is on assessing the potential damage to structures and as such, the impact of vibrations on humans, although recognized, is beyond its scope.

2. Objective

This technical note was developed to help the expert and non-expert reader alike gain a general, but comprehensive, understanding of the effects of vibration on structures and the vibration threshold that would indeed cause damage. The note also explains how humans respond differently to vibrations than the buildings they occupy. The reader is introduced to two main parameters in vibration damage analysis: the Peak Particle Velocity (PPV)[1] and the Zone of Influence (ZOI). Investigators, building owners, property managers, risk assessors, insurance adjusters, and construction litigators will find this technical note to be a highly useful resource in understanding potential damage due to construction activities.

3. Vibrations from Construction Activities

Construction activities can cause vibrations that affect surrounding properties. The effect of vibrations can range from a minor nuisance to significant structural damage, depending on many factors, including the vibration source, the type of soil, interaction between the soil and the building, and the susceptibility of the building to the effects of vibrations. Damage from vibrations is classified as either direct or indirect. Direct damage is the effect of vibrations on buildings. Vibrations can also cause indirect damage by triggering ground movements in certain soils (Svinkin 2014).

Structures generally have substantial resistance to damage from vibrations that do not trigger a resonant response. However, resonant vibrations can be triggered if the ground vibrations match the structure's natural frequency[2]. The effect of resonant vibrations is analogous to the effect of synchronizing one's push with the free oscillation of a swing; the swing will go higher. Strong resonant amplification will not develop if the building is only briefly exposed to ground vibrations equal to the building's natural frequency (Svinkin 2014). Hence, recommended vibration limits for machine and traffic sources are lower than the limits recommended for brief events like blasting activities. Natural frequencies are commonly in the 2 to 12 Hz[3] range for horizontal vibration of the whole building, and 8 to 30 Hz for vertical vibration

[1] The maximum velocity amplitude (rate of displacement change with respect to time, measured in mm/s) with which a particle would travel due to the propagation of vibrations through the ground. Seismographs are used to measure the PPV.

[2] The frequency at which a system oscillates when not subjected to a continuous or repeated external force.

[3] Hertz = one cycle per second.

of individual floors (Svinkin 2014). The effect of resonance in residential buildings has been reported to amplify vibration as much as tenfold (Svinkin 2012, Watt 1988).

Some researchers have also suggested that the accumulated effect of repeated vibrations must also be taken into consideration, especially in relation to old and historic structures (Crockett 1980, Lacy and Gould 1985). Hence, some standards have recommended lower vibration limits for long-term exposure.

As mentioned earlier, ground vibrations can also damage buildings indirectly by their effects on soils. A phenomenon known as liquefaction[4] can be triggered in some clay soils when ground vibrations reach about 100 mm/s PPV (Svinkin 2014). Such high levels of vibration would typically cause direct damage as well. However, granular soils (sands and gravels) are susceptible to vibration-induced densification[5] at vibration levels as low as 2.5 mm/s PPV (Lacy and Gould 1985). Such vibrations can lead to significant foundation settlement if the foundation is bearing on loose or poorly compacted sand. Siskind (2000) found that loess[6] soils may sometimes be even more sensitive to vibration-induced settlement, and reported that damage had occurred from blasting operations at PPV of just 0.5 to 1.5 mm/s.

4. Vibration Threshold Causing Damage

Several sources have recommended damage threshold criteria limiting ground vibration levels based on numerous studies of the effects of construction activities. In general, thresholds vary depending on the dominant frequency of the ground vibrations, the type and condition of the structure affected, and the duration of the exposure to vibrations.

The City of Toronto By-law 514-2008 requires a pre-construction consultation and monitoring program for any properties likely to experience vibrations greater than 5 mm/s PPV due to a proposed construction project. The By-law prohibits ground vibrations higher than the levels shown in Table 1.

Table 1: Construction vibration levels prohibited by City of Toronto By-law 514-2008

Frequency of Vibration (Hz)	PPV Vibration Limit (mm/s)
< 4	8
4 to 10	15
> 10	25

The By-law does not provide different thresholds to account for the type of structure or the duration of exposure. However, if vibrations will exceed 5 mm/s, a professional engineer must perform pre-construction consultation and monitoring. Presumably, the limits given in the By-law are intentionally lenient so as not to be overly restrictive of development near robust buildings built of engineered steel or reinforced concrete. The professional engineer conducting the pre-construction study can specify lower thresholds where necessary. It is important to note that operating within the limits of Table 1 does not guarantee that property damage will not occur.

The British Standard BS 7385-2:1993 gives the threshold values shown in Table 2 for cosmetic damage due to transient (short-duration) vibrations. These values are also depicted graphically in Figure 1.

[4] Saturated or partially saturated soil substantially loses strength and stiffness (behaving like a liquid) in response to shaking.
[5] Increase soil density by removal of air voids.
[6] Loess soils are composed primarily of silt particles deposited by wind.

Table 2: Transient vibration damage thresholds prescribed by BS 7385-2:1993		
Line	**Type of Building**	**PPV Vibration Threshold (mm/s)**
1	Reinforced or framed structures. Industrial and heavy commercial buildings.	50 at frequencies 4 Hz and above
2	Unreinforced or light-framed structures. Residential or light commercial buildings.	15 at 4 Hz, increasing to 20 at 15 Hz 20 at 15 Hz, increasing to 50 at 40 Hz and above

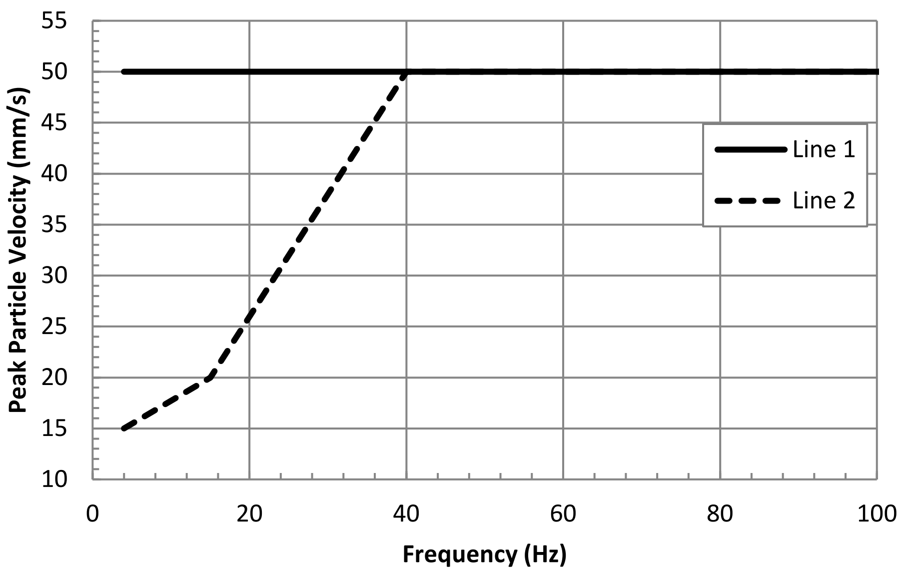

Figure 1: Transient vibration limits in BS 7358-2:1993

BS 7385-2:1993 further states that the limits for transient vibrations should be reduced by 50% for continuous (long-duration) vibrations. The standard also notes that some soils, particularly loose and water-saturated granular soils are vulnerable to vibration-induced densification and consolidation. However, no specific vibration limits are provided to prevent building damage due to vibration-induced settlements.

The German Standard DIN 4150-3:1999 has set limits on ground vibrations that are intended to ensure building serviceability is not adversely affected, which for the purposes of the standard includes cracked plaster in residential buildings.

Table 3: Vibration damage thresholds prescribed by DIN 4150-3:1999					
Type of Structure	**PPV Vibration Threshold (mm/s)**				
	Short Term				**Long Term**
	At foundation			Uppermost floor	Uppermost floor
	0 to 10 Hz	10 to 50 Hz	50 to 100 Hz	All frequencies	All frequencies
Commercial/Industrial	20	20 to 40	40 to 50	40	10
Residential	5	5 to 15	15 to 20	15	5
Sensitive/Historic	3	3 to 8	8 to 10	8	2.5

Note: when a range is given, the limit increases linearly over the frequency range

Similar to the British standard, the German standard also notes that low vibration levels may cause consolidation in some soils, particularly cohesionless sands and silts that are relatively uniformly graded. The German standard also provides no guidance to prevent damage due to vibration-induced settlement and recommends that a geotechnical expert be consulted if dynamic settlement could be an issue.

As shown in Table 4, the Swiss Standard VSS-SN640-312a:1992 prescribes separate vibration limits for blasting and machines or traffic, based on the frequency of the vibrations and the type of construction. Class 1 construction refers to steel or reinforced concrete structures, such as factories, bridges, and towers. Class 2 construction refers to concrete or masonry floors, walls, or foundation walls. Class 3 construction refers to wood-framed buildings or masonry buildings with wood-framed floors. Class 4 construction refers to structures highly sensitive to vibration or of historical interest.

Table 4: Vibration damage thresholds prescribed by VSS-SN640-312a:1992

Construction Class	Vibration Source	Frequency (Hz)	PPV (mm/s)
1	Machines, traffic	10 – 30	12.7
		30 – 60	12.7 – 17.8
	Blasting	10 – 60	30.5
		60 – 90	30.5 – 40.6
2	Machines, traffic	10 – 30	7.6
		30 – 60	7.6 – 12.7
	Blasting	10 – 60	17.8
		60 – 90	17.8 – 25.4
3	Machines, traffic	10 – 30	5.1
		30 – 60	5.1 – 7.6
	Blasting	10 – 60	12.7
		60 – 90	12.7 – 17.8
4	Machines, traffic	10 – 30	3.0
		30 – 60	3.0 – 5.1
	Blasting	10 – 60	7.6
		60 – 90	7.6 – 12.7

The U.S. Federal Transit Administration (FTA) has also recommended vibration limits to be used as a preliminary screening tool to identify problem locations for proposed projects (Hanson et al 2006). Their recommendations, summarized in Table 5, are based on the limits from the Swiss standard. The FTA conservatively uses the lowest vibration limits from each building category of the Swiss standard.

Table 5: Vibration damage thresholds recommended by the U.S. FTA, 2018

Building Type	PPV (mm/s)
Reinforced concrete, steel, or timber (no plaster)	12.7
Engineered concrete and masonry (no plaster)	7.6
Non-engineered timber and masonry buildings	5.1
Buildings extremely susceptible to vibration damage	3.0

Cenek et al (2012) recommended a limit of 5 mm/s PPV as a simple guideline for preliminary assessment of whether construction activities would be damaging to buildings, with the caveat that the limit is not applicable for soils sensitive to densification or liquefaction and that a geotechnical engineer must be consulted in those cases.

Due to the difficulty in accurately predicting the soil-structure interaction and the amplification effect of structural resonant response, Svinkin (2014) suggests that vibration limits should be placed on the structure vibrations rather than the ground vibrations, and proposes a limit of 51 mm/s peak particle velocity (PPV) inside the building. Assuming a maximum amplification factor of 10, this alternative limit appears to generally agree with the limit of 5 mm/s PPV for ground vibrations recommended for typical residential structures in the German standard DIN 4150-3:1999. Svinkin's proposed limit is for direct vibration effects only. Svinkin also recommends limiting ground vibrations to 2 to 3 mm/s PPV for historically significant buildings, 2.5 mm/s for sandy sites vulnerable to dynamic settlement, and 0.5 to 1.5 mm/s for loess soils.

It should come as no surprise that a national standard would be conservative. This is analogous to the design of a beam to support a load. One expects that the "safe" load-carrying capacity, as determined by the applicable design standard, is much lower than the true load-carrying capacity that would be observed in a laboratory test. Similarly, researchers who have studied real buildings have reported true vibration damage thresholds that are typically much higher than the limits set out in the Swiss or German standards. It is important to note that much of the published experimental research involved blasting. As mentioned previously, longer duration exposure to a vibration source is more likely to result in damage to a building due to factors like the resonant amplification effect and the accumulation of microdamage. Damage thresholds that were based on blasting studies may be inappropriately high for assessing the risk of damage to buildings from long-duration sources of vibration. It is important to select damage thresholds appropriate for the construction activities involved when conducting vibration damage risk assessments.

5. Ground Vibration Damage due to Blasting

Langefors et al. (1958) studied vibrations from short-range blasting on a large reconstruction project in Stockholm. They reported no noticeable cracks below 70 mm/s PPV. A Canadian study conducted in 1958 that involved performing blasting near 6 houses, moving progressively closer until damage occurred, indicated that damage was not likely to occur before PPV exceeded 100 mm/s (Edwards and Northwood 1960). The U.S. Bureau of Mines conducted several field studies of ground vibration and air blast damages in the 1970s (Siskind et al. 1980). A total of 76 houses were monitored during blasts performed at construction sites, quarries, and surface coal mines. The minimum PPV threshold reported to cause cosmetic damage was 18 mm/s. Siskind et al. (1980) applied probabilistic methods to the data and developed the thresholds given in Table 6.

Table 6: Vibration damage thresholds due to blasting developed by Siskind et al. (1980)

Damage Type	PPV (mm/s) at Probability of			
	5%	10%	50%	90%
Threshold damage: loosening of paint, small plaster cracks at joints between construction elements	12.7	17.8	63.5	229
Minor damage: loosening and falling of plaster, cracks in masonry around openings near partitions, hairline to 3 mm wide cracks, fall of loose mortar	45.7	55.9	127	406
Major damage: cracks of several mm in walls, rupture of opening vaults, structural weakening, fall of masonry, load support ability affected	63.5	76.2	152	432

Several blasting studies were also conducted in Sweden during the 1970s. Holmberg et al. (1981) compiled and analyzed the data collected from 91 buildings subjected to blasting vibrations of varying magnitudes. Holmberg et al. (1981) indicated the probability of cosmetic damage was approximately 40% at 50 mm/s

PPV. The damage reported in Siskind et al. (1980) and in Holmberg et al. (1981) are based on a comparison of pre- and post-blast inspections.

Bogdanoff et al. (1975) investigated a house of lightweight concrete masonry construction founded on good quality rock and subjected to vibrations from progressively closer blasts. No damage was reported below 90 mm/s PPV, and the major damage they observed occurred at PPV of 300 mm/s. A house of poured concrete construction and brick cladding founded on hard rock was tested by Bergling et al. (1977). No damage was observed below 110 mm/s PPV and no major damage occurred below 185 mm/s PPV.

Gad et al. (2005) monitored cracks in a single-storey brick house near an Australian coal mine for a period of one year. The house was exposed to 43 blasts ranging from 50 m to 1000 m away. No new damages were observed for PPV less than 75 mm/s. The researchers also observed that the opening and closing of cracks appeared to be more sensitive to rainfall than to blast-induced vibrations.

Singh and Roy (2010) completed a study of six test buildings close to opencast mines in India. Blasts started at about 1800 m distance and were advanced progressively closer until within about 20 m distance. Cosmetic cracks were not detected until about 52 mm/s PPV in the houses of native mud-brick and cement construction and about 69 mm/s PPV in the houses of reinforced concrete construction.

Sayed-Ahmed and Naji (2013) presented two case studies involving low-rise reinforced concrete buildings with concrete block masonry partition walls near a rock blasting excavation site. All measured PPVs were below 30 mm/s; however, both buildings sustained cosmetic damage and one sustained structural damage. It must be noted that reported frequencies were as low as 5 Hz, which are exceptionally low for blasting vibration.

Norén-Cosgriff et al. (2020) presented a study to test buildings constructed near a rock quarry in Norway. One building was of cast-in-place concrete construction and the other of lightweight block masonry construction. Both buildings were founded on a layer of compacted gravel over rock. Blast tests produced vibrations up to 260 mm/s PPV in the frequency range of 50 to 130 Hz. No damage to either building was reported.

Kwan and Lee (2000) conducted experiments on 1440 prism specimens (150x150x750 mm) in six different mix designs, subjecting them to shock vibrations. They plotted the estimated vibration damage threshold with the compressional wave[7] velocity (V_C) of the concrete and calculated a characteristic equation for which only 5% of the data was below. They then proposed a safety factor of 10 due to the effect of large uncertainties observed and expected differences between laboratory tests and real applications, resulting in the proposed safe vibration limit for concrete of:

$$PPV_{conc} = 16 \cdot V_c \qquad \text{Eq. 1}$$

Where PPV_{conc} is in mm/s and V_c is in km/s.

Tripathy and Gupta (2015) suggested the damage threshold should account for the density (ρ) and tensile strength of the concrete (f_t'), proposing the following equation:

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[7] Also known as longitudinal waves: waves in which the vibration of the medium is parallel to the direction the wave travels and the displacement of the medium is in the same direction of the wave propagation

$$PPV_{conc} = \frac{f_t'}{\rho V_c} \times 10^6 \qquad \text{Eq. 2}$$

Where PPV_{conc} is in mm/s, f_t' is in MPa, ρ is in kg/m^3 and V_c is in km/s.

Tripathy and Gupta (2015) also conducted field experiments with the goal of developing frequency-dependent safe blasting vibration thresholds for mass concrete. Large blocks (1200x600x1800 mm) of 16 MPa concrete were cast partially embedded into hard rock, cured for 28 days, and then charges were detonated at different distances. Tripathy and Gupta (2015) suggested the following damage thresholds expressions for vibration frequencies in the range of 40-500 Hz.

$$PPV_{conc} = \begin{cases} 17.6\ \omega^{0.355} & \text{for minor damage} \\ 32.8\ \omega^{0.355} & \text{for major damage} \end{cases} \qquad \text{Eq. 3}$$

Where, PPV_{conc} is in mm/s and ω is the frequency in Hz.

We note that blasting vibration damage criteria for mass concrete appears to have been developed for vibrations with relatively high dominant frequencies. Tripathy and Gupta (2015) ultimately recommended a single safe blasting vibration threshold of 75 mm/s PPV and suggested that the frequency-based criterion can be used for blast vibrations at close distances and high dominant frequencies.

Clearly, there is substantial variation in vibration damage thresholds reported in the literature. Norén-Cosgriff et al. (2020) have pointed out that many of the field studies were sensitive to how accurately pre-existing conditions were documented. Pre-existing damage that was overlooked and then mistakenly identified as caused by vibration in post-blast inspections would skew results toward more conservative damage thresholds. This would offer some explanation for the wide range of thresholds that have been reported to be tolerated by different buildings. Another confounding factor is that the magnitude of resonant amplification in the structure is often not reported. Lack of standardized definitions of types of damage in the literature also makes direct comparisons of various studies difficult, if not impossible. Engineers must thus exercise professional judgement and sensible conservatism when selecting damage thresholds for a particular site.

6. Human Response to Vibrations

Humans are much more sensitive to vibrations than structures. When occupants perceive nuisance vibrations, they are likely to look for and identify damage on their properties that had not been noticed before. Hence, there are a large number of complaints of cracking even at relatively low vibration levels that are unlikely to be damaging to structures (Dowding 2000). Researchers have also found that long or continuous exposures to vibrations are much more discomforting than shorter exposures (Wiss and Parmelee 1974, Siskind et al. 1980), as shown in Figure 2.

The British Standard BS 5228-2:2009 provides further guidance on vibrations causing human disturbance as summarized in Table 7. CalTrans (2013 & 2020) recommends the vibration annoyance criteria given in Table 8. Cenek et al (2012) recommended a limit of 0.5 mm/s PPV as a simple guideline for preliminary assessment of whether construction activities would be disturbing to building occupants.

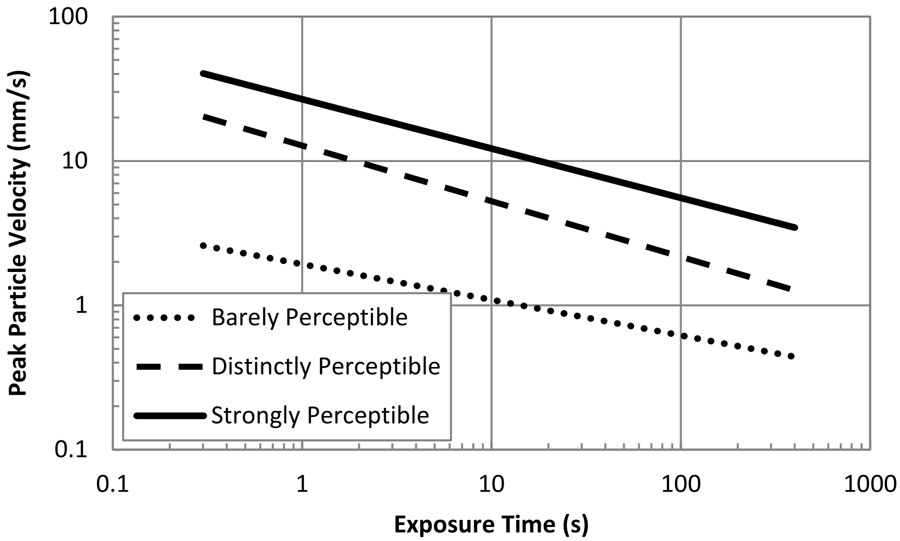

Figure 2: Human response to vibration of varying duration (Source: Dowding 2000).

Table 7: Vibration causing human disturbance prescribed by BS 5228-2: 2009	
PPV (mm/s)	**Effects**
0.3	Vibration might be just perceptible in residential environments
1.0	Likely to cause complaints in residential environments, but can be tolerated if prior warning and explanation is given to residents
10.0	Vibration likely to be intolerable at more than very brief exposure

Table 8: Vibration annoyance criteria recommended by CalTrans (2013 & 2020)		
Human Response	**Maximum PPV (mm/s)**	
	Transient Sources	**Continuous or Frequent Intermittent Sources**
Barely perceptible	1.02	0.25
Distinctly perceptible	6.35	1.02
Strongly perceptible	22.9	2.54
Severe	50.8	10.2

7. Prediction of Vibration Intensity (PPV)

Ground vibrations decay the further the vibrations propagate away from their source. Peak particle velocity of vibrations due to most construction activities are typically predicted using an attenuation relation (Dowding 2000). If the PPV is known (by previous measurement) at a given distance from the source, then PPV at any distance can be reasonably estimated provided that the soil attenuation coefficient is known, and no soil layer resonance occurs.

The procedure discussed in this section is based on Transportation and Construction Vibration Manual by the California Department of Transportation (CalTrans 2013) and the Transit Noise and Vibration Impact Assessment by the US Federal Transportation Administration (FTA 2018). Based on CalTrans (2013), the PPV produced by impact pile drivers and hydraulic breakers can be estimated from Equation 4:

$$PPV\ (in/sec) = PPV_{Ref}(\frac{25}{D})^n \times (\frac{E_{Equip}}{E_{Ref}})^{0.5} \quad \text{Eq. 4}$$

For other construction equipment, the PPV at the location of the receiver is estimated by Equation 5:

$$PPV\ (in/sec) = PPV_{Ref}(\frac{25}{D})^n \quad \text{Eq. 5}$$

Where, *D* is the distance from the equipment to the receiver in feet, E_{Equip} is the rated energy of the equipment found from the specifications published by the manufacturer, and *n* is a parameter for the vibration attenuation rate through soil that varies with the type of soil. Table 9 provides recommended values of the attenuation parameter *n* based on the soil classification. E_{Ref} is the rated energy of the reference equipment, which is 36,000 lb-ft for an impact pile driver and 5,000 lb-ft for a hydraulic breaker. The PPV_{Ref} is a reference PPV value expressed in in/sec measured at 25 feet distance from the equipment. Table 10 gives the reference PPV value for different equipment.

Table 9: Values of n for different types of soil (CalTrans 2013)

Soil Class	**Soil Description**	**n**
I	*Weak or soft soils* (shovel penetrates easily): loose soils, dry or partially saturated peat and muck, mud, loose beach and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soil, topsoil	1.4
II	*Competent soils* (can dig with shovel): most sands, sandy clays, silty clays, gravel, silts, weathered rock	1.3
III	*Hard soils* (cannot dig with shovel, must use pick to break up): dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock	1.1
IV	*Hard, competent rock* (difficult to break with hammer): bedrock, freshly exposed hard rock	1.0

Table 10: Reference PPV for construction equipment (Hanson et al. 2006, FTA 2018, and CalTrans 2020)

Equipment		**PPV at 25 ft (7.62 m)**	
		(in/sec)	**(mm/s)**
Pile driver (impact)	Upper range	1.518	38.6
	Typical	0.644	16.4
Pile driver (sonic)	Upper range	0.734	18.6
	Typical	0.170	4.32
Pile driver (vibratory)		0.65	16.51
Hydraulic breaker		0.24	6.10
Clam shovel drop (slurry wall)		0.202	5.13
Hydromill (slurry wall)	In soil	0.008	0.20
	In rock	0.017	0.43
Vibratory roller		0.210	5.33
Hoe ram		0.089	2.26
Large bulldozer		0.089	2.26
Caisson drilling		0.089	2.26
Loaded trucks		0.076	1.93
Jackhammer		0.035	0.89
Small bulldozer		0.003	0.08

Based on measured data from several published studies of construction vibrations, the U.S. FTA has recommended the vibration source levels given in Table 10 for typical construction activities. Hanson et al (2006) warn that source vibration levels from construction activities can vary considerably but indicate that the data presented can be used to obtain a reasonable estimate of PPV for the purposes of preliminary assessments. Actual field measurements of source vibrations should be used when possible. Using the attenuation relationship, the typical vibration source levels, and the soil attenuation coefficients proposed for different soil types, it is possible to construct a quick reference chart to roughly estimate PPV at various distances and compare it to a certain threshold. The charts shown in Figures 3, 4, and 5 were produced by Cenek et al (2012) and show typical vibration levels for excavators, dozers, and rollers, including the 5 mm/s damage threshold criterion and the 0.5 mm/s disturbance criterion.

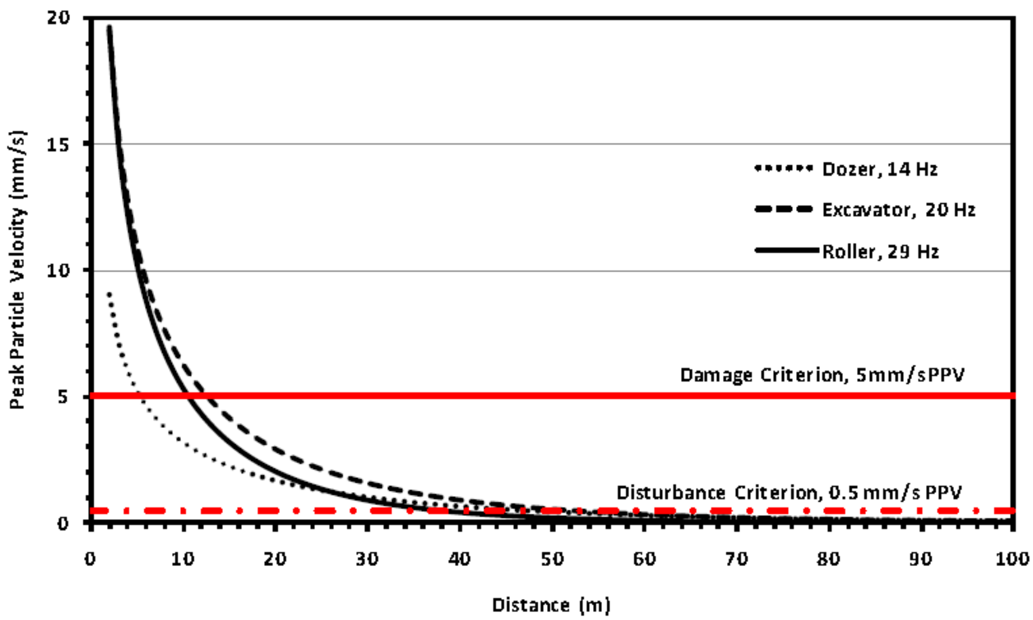

Figure 3: Expected peak particle velocities for Class I soils (Source: Cenek et al 2012)

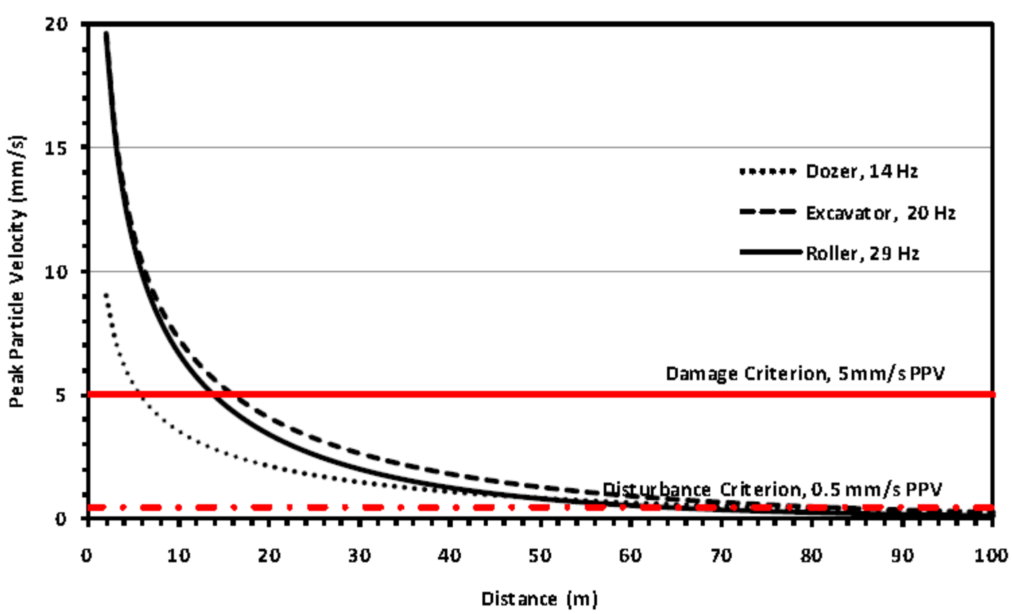

Figure 4: Expected peak particle velocities for Class II soils (Source: Cenek et al 2012)

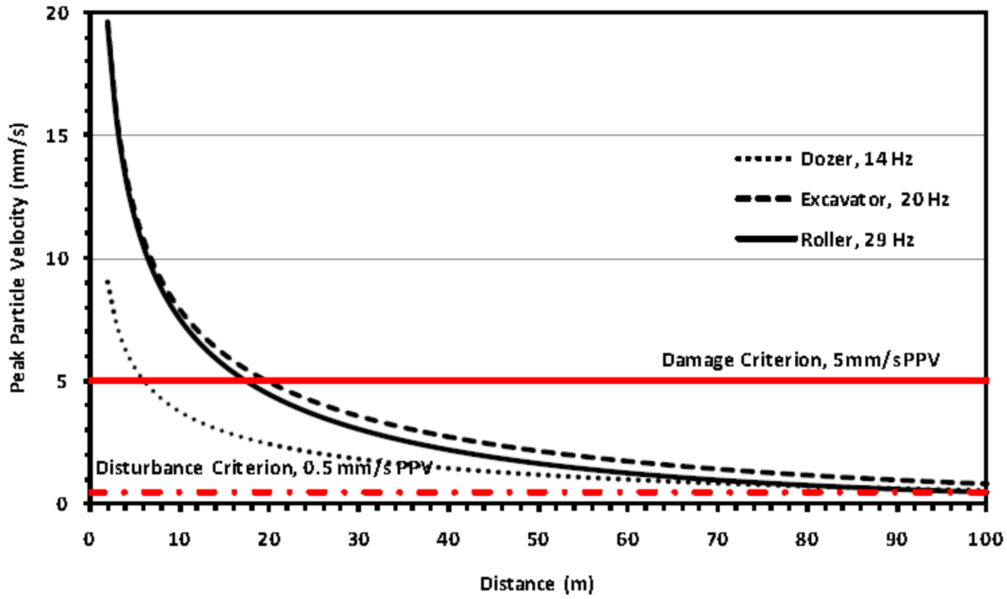

Figure 5: Expected peak particle velocities for Class III soils (Source: Cenek et al 2012)

8. The Zone of Influence (ZOI)

Where construction activities are expected to generate ground vibrations, engineers assess the potential for vibration impact on nearby structures within an area known as the Zone of Influence (ZOI). The zone of influence is defined as the area where vibration could reach or exceed a threshold level. The typical threshold used is the 5 mm/s PPV damage criterion. Sites that are within this zone of influence should have pre-construction inspections completed in order to document existing cracks. Based on the preliminary assessment, a vibration monitoring program may also be specified during the project to ensure actual ground vibrations remain within acceptable thresholds.

Multiple zones of influence might be checked to satisfy different criteria. For example, City of Toronto By-law 514-2008 requires pre-construction surveys everywhere within the ZOI based on 5 mm/s PPV. The By-law also prohibits vibration exceeding 25 mm/s PPV, so a smaller zone based on 25 mm/s PPV may need to be monitored during construction to ensure compliance. A separate, larger zone of influence might also be defined based on the 0.5 mm/s PPV disturbance criterion. This would be to assess the extent of the surrounding area where occupants are likely to feel the vibrations. Warning people ahead of time of what to expect may reduce the number of complaints received (Dowding 2000).

A hypothetical example of a pile-driving operation for a bridge construction project is shown in Figure 6. The area within the red circle is the ZOI based on a 25 mm/s PPV threshold. No buildings were inside the red circle. The area within the yellow circle is the ZOI based on a 5 mm/s PPV damage threshold. Pre-construction inspections should be completed for all the buildings within the yellow circle. The area within the blue circle is the ZOI based on a 0.5 mm/s PPV disturbance threshold. It would be prudent to send letter to all the households within the blue circle ahead of time to inform that they may experience vibration while the pile-driving work is being completed.

Sources of vibration are often not static points. For example, road construction projects will involve vibratory rollers making passes up and down the road. Therefore, the zone of influence for a road construction project is not circular but a band that follows the road. A hypothetical example is shown in Figure 7. The work zone is shown in blue, the ZOI based on the 5 mm/s PPV damage criterion is shown in red, and the ZOI based on the 0.5 mm/s PPV disturbance criterion is shown in green. Under the City of Toronto by-law, pre-construction inspections would be required at every house within the red zone to document existing cracks and damage. While a few other Canadian jurisdictions have similar requirements, many still do not. Nonetheless, even where it is not a legal requirement it would still be prudent to conduct pre-construction inspections within the red zone in this example. It may also be prudent to send letters to everyone further out in the green zone to inform them that they might perceive vibrations while the work is being completed.

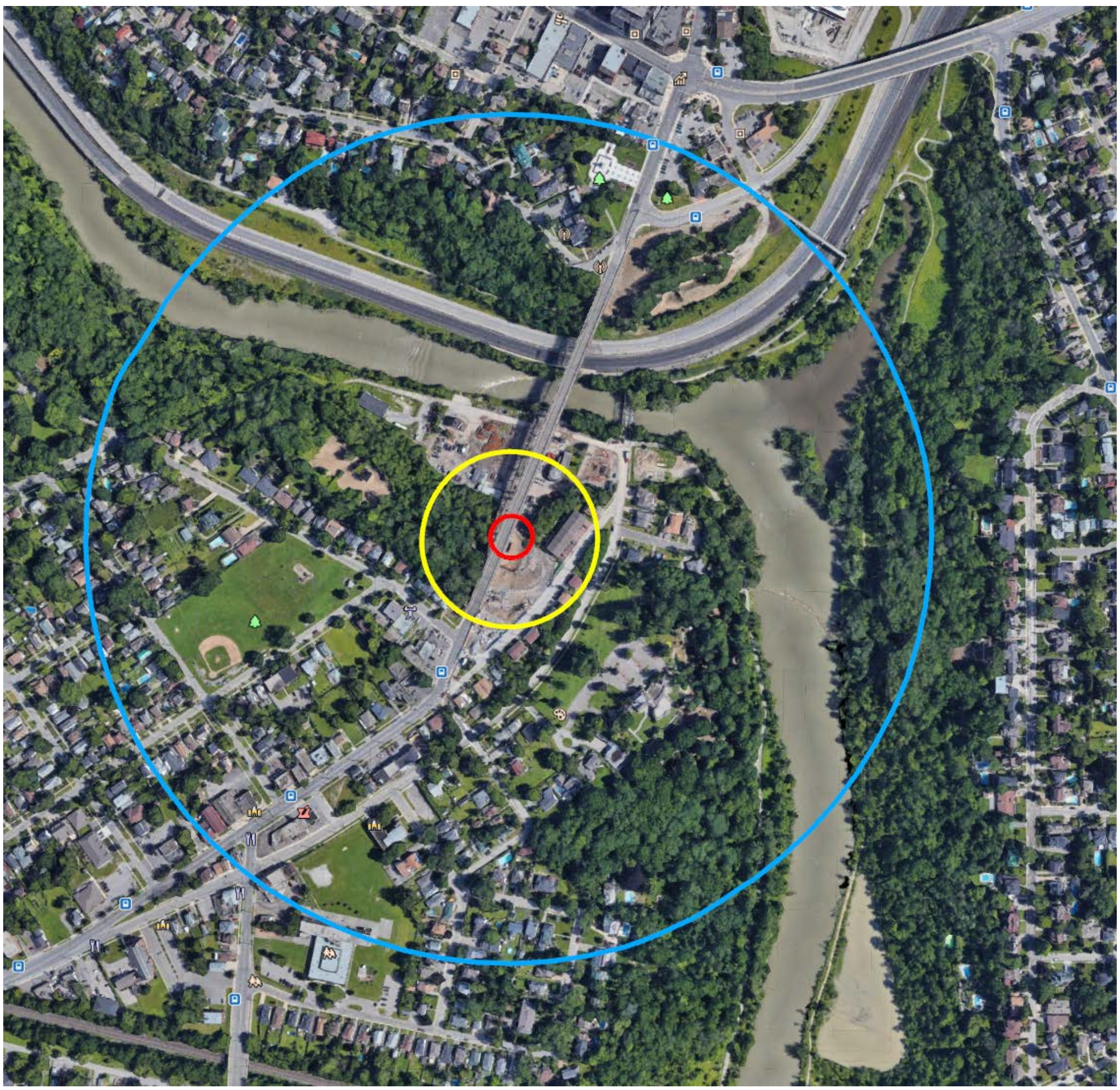

Figure 6: Approximate zones of influence based on 25 mm/s (red), 5 mm/s (yellow), and 0.5 mm/s (blue) PPV thresholds for a hypothetical pile driving operation (centre of concentric circles).

Figure 7: Approximate zones of influence based on 5 mm/s (red) and 0.5 mm/s (green) vibration thresholds for a hypothetical road replacement project (middle blue).

9. Closure

In summary, humans perceive vibrations at thresholds far below those necessary to cause damage to buildings. Tolerance of nuisance vibrations varies from person to person. In general, one's tolerance decreases with the increasing duration of exposure. Tolerance also tends to be lower when vibration is unexpected and/or when one is trying to sleep or relax. Often damage that is reportedly caused by vibration is actually pre-existing. Hence, it is important to define "disturbance" and "damage" zones in order to identify where people should be informed about vibrations ahead of time and where pre-construction inspections should be conducted. Pre-construction inspections must be thorough and even minor pre-existing damage must be well-documented, otherwise the inspections are of little value in the event that damage claims arise from the construction project.

Whether vibrations can damage a building depends on many factors, including, but not limited to, the vibration peak particle velocity (PPV), duration of exposure, building-soil interaction, local soil conditions, resonant frequencies of the soil and building, and the quality and type of building construction. Long-duration exposure to vibrations is more damaging to buildings than short-duration exposure. Older or poorly constructed buildings are more susceptible to vibration damage than new buildings. It is important to consider all these factors when selecting appropriate thresholds. Thresholds developed from blasting research for the mining industry may not be appropriate for assessing the potential for damage caused by traffic or construction activities where buildings will experience much longer exposures to vibration.

Several sources, including the Swiss and German vibration standards, agree that a sensible vibration damage threshold for long-duration exposure should be taken as 5 mm/s for typical wood-framed and unreinforced masonry structures. It is important to note that this is a conservative threshold to limit complaints and is based on minor cosmetic damage to plaster and drywall finishes. The threshold to damage stronger materials, like reinforced masonry or concrete, is much higher.

The City of Toronto By-law 514-2008 requires that preconstruction studies and inspections be performed on any properties within the zone of influence based upon 5 mm/s PPV. Only a few other Canadian jurisdictions have adopted similar requirements so far. Therefore, while it is prudent to assess vibration hazards before commencing a project, many projects are still undertaken in Canada without any preliminary vibration damage assessment, pre-construction inspections, or vibration monitoring. Furthermore, many pre-construction inspections are poorly documented, which defeats the purpose of completing them.

This note may be used as a quick reference by owners, contractors, property managers, or adjusters to gain a general understanding of the impact of vibration on structures and the vibration threshold that could cause damage. This note is intended to provide a general review of available technical literature on the topic of ground vibrations emanating from construction activities. While the authors have made every reasonable effort to ensure the information in this technical note is accurate, the note is nevertheless intended for educational purposes only and does not in any way replace the need for project-specific investigative services by a qualified Professional Engineer.

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