EVALUATION OF VIBRATION LIMITS AND MITIGATION TECHNIQUES FOR URBAN CONSTRUDTION

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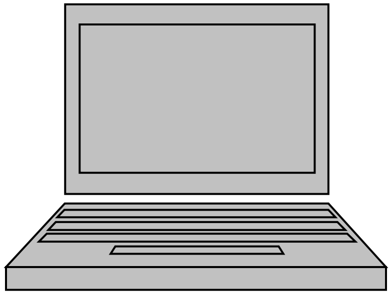


INTRODUCTION

- Benign and harmful dynamic effects of construction operations. Case histories from New York.
- Adjacent and remote structures.
- Potential problems for construction in urban areas. A case history of pile driving near a hospital.
- Different causes of damage to structures.
- Analysis of field data, application of known concepts, and development of reasonable assessments of vibration problems.

Pile Driving – Source of Vibrations

Impact Hammers

- Rated Energy: 4-220 kips-ft/blow
- Maximum Pile Velocity: 3-15 ft/s
- Maximum Pile Displacement: 0.5-1.4 in.
- Frequencies of pile oscillations: 7-50 Hz
- Transient Ground Vibrations

Vibratory Drivers

- Frequency Range: 5-30 Hz
- Steady-State Ground Vibrations

Double Acting Impact Hammers

- Operate at relatively high speeds
- Pseudo Steady-State Ground Vibrations

Vibration Effects on Structures

Damage to Structures

Siskind et al. (1980) and Dowding (1996)

- 1) cosmetic cracking threshold - opening of old cracks and formation of new plaster cracks.
- 2) minor or architectural damage - cracks not affecting structural capacity (broken windows, cracked plaster).
- 3) major or structural damage - cracks affecting the integrity of building support (large cracks in beams, columns or foundations, shifted foundations, wall put out of plumb).

Preconstruction Engineering Investigations

Condition Structure Survey

- The pre-driving condition survey has to be provided after the accomplishment of excavating and dewatering at a site.
- A pre-construction survey is the first step in the control of construction vibrations to ensure safety and serviceability of adjacent and remote houses, buildings and facilities.
- Surveys of structure responses provide more objective information about vibration effects on structures than vibration measurements.

Preconstruction Engineering Investigations

There are four goals of preconstruction survey

- Document the existing cracks and other damage.
- Analyze probable causes of existing damage.
- Classify susceptibility rating of structures.
- Determine mitigation measures of pile driving effects on structures.

Preconstruction Engineering Investigations

Document the existing cracks and other damage

- Preconstruction survey should be professionally performed to include all available damage.
- This survey should include observation and documentation of the existing condition of foundations, exterior and interior walls, ceiling, floors, roof and utilities.
- It is necessary to distinguish different types of cracking in structures as follows: cosmetic cracking, architectural or minor damage, and structural cracking which may resulting in serious weakening of buildings.

Preconstruction Engineering Investigations

Analyze probable causes of existing damage

- Environmental forces, geotechnical hazards, and dynamic forces from pile driving and dynamic compaction of weak soils can be the causes of similar structural damage.
- Case history from Vermont (blasting and pile driving).
- Case history from California (deep dynamic compaction).

Preconstruction Engineering Investigations

Classify susceptibility rating of structures

- Inspected houses and buildings should be classified into three different categories as a function of building's susceptibility to cracking during pile driving: **high, moderate, or low susceptibility**, Dowding (1996).
- Buildings identified as having high susceptibility have already experienced a significant amount of degradation to their primary structural and/or nonstructural systems.
- Buildings identified as having moderate susceptibility have not yet experienced significant degradation to their primary structural and/or nonstructural systems. Buildings with small to moderate quantities of fragile, potentially unstable contents which may be damaging during construction are included in this category.
- Buildings identified as having low susceptibility are not expected to experience cosmetic cracking when subjected to construction vibrations.

Preconstruction Engineering Investigations

Measurement of Background Vibrations and Sensitive Equipment

- As a part of the preconstruction survey, measurement of existing vibration background should be made to obtain information regarding effects of exiting vibration sources.
- The presence of sensitive devices and/or operations, such as electronics, medical facilities, optical and computerized systems placed usually on the floors, requires measurement of floor vibrations.
- Case Histories from London and Duluth.

Preconstruction Engineering Investigations

Distances for Preconstruction Condition Survey

- Dowding (1996) suggested a radius of 400 ft of construction activities or out to a distance at which vibrations of 0.08 in/s occur (dynamic settlement).
- Kaminetzky (1991) mentioned an interesting case with building settlement developed at a distance of about 1000 ft away from a pile driving site.
- Woods (1997) considered distances of as much as 1300 feet to be surveyed to identify settlement damage hazard.

Preconstruction Engineering Investigations

Choice of Appropriate Distances for Condition Surveys

- Three groups of factors can affect a choice of distances for condition surveys: soil conditions, pile driving system and vibration receivers.
- The survey will include all buildings within a radius of about 150-250 ft of the pile driving activities depending on local conditions.
- The condition survey should be selectively performed at the areas with a radius of 1300 ft for historic buildings and areas with possible dynamic settlement.

Condition Survey during and after Construction

- Importance of condition surveys during and after construction for analysis of possible causes of damage to structures.
- Each construction site is unique and even similarity of soil deposits does not mean the same condition of the dynamic settlement development.
- Physical evidences of damage to structures from dynamic sources are very significant. Crack measurements. **Crack width and length**.
- Case histories from Vermont and Kharkov.

Mitigation Measures to Decrease and Control Vibration Effects

Direct Vibration Effects

- First, installation of low soil displacement piles, e.g. H-piles, instead of high soil displacement piles, e.g. concrete piles, can reduce ground and structure vibrations.
- Second, hard pile driving to a depth about 30 ft from the ground surface may increase ground vibrations, but hard pile driving at a greater penetration depth much less affects ground vibrations. Predrilling and jetting may be helpful for overcoming the high penetration resistance in upper soil layers, but both operations in sands should be done with caution.
- Third, substantial decrease of the hammer energy can be helpful; however, slight reduction of the hammer energy will have a small effect because PPV of ground vibrations depends on the square root of the hammer energy.
- Forth, according to D'Appolonia (1971), pile driving operations should start nearby the existing structures and continue away from the structures because previously driven piles act as a shield and soil movements are greater in the direction away from the stiffer zone around the driven piles.

Mitigation Measures to Decrease and Control Vibration Effects

Resonant Soil and Structural Vibrations

- Vibratory drivers may trigger resonant vibrations of soil layers and structures, but vibratory drivers with variable frequency can eliminate these phenomena, Woods (1997).
- An existing experience of evaluation of pile driving vibration effects demonstrate no case histories of resonant structural vibrations triggered by low-frequency ground vibrations from pile driving.

Mitigation Measures to Decrease and Control Vibration Effects

Dynamic Settlement in Sands

- First, reduce the level of ground vibrations as much as possible.
- Second, use predrilling holes for pile installation or use jetting to install piles, but predrilling or jetting in sand should be done with caution. According to Lucas and Gill (1992), jetting reduced blow count about three times in comparison with pile installation without jetting.
- Third, choose a light hammer.
- Fourth, monitor and control vibrations and structure settlements at a site.
- Fifth, underpinning of adjacent buildings supported by shallow foundations can prevent building settlements. **However, if pile driving triggered settlements of pile foundations of adjacent buildings, the technology of pile installation should be changed.**

Mitigation Measures to Decrease and Control Vibration Effects

Dynamic Settlement in Clays

- First, the type of piles is very important. Low soil displacement piles reduce the volume of soil displaced during pile driving.
- Second, predrilled holes improve conditions for using displacement piles. The cross section of the auger and the drilled depth can strongly affect the volume of soil movements.
- Third, the spacing of the piles characterized by the average pile density per unit foundation area affects soil movements: the bigger the density the larger the movement.
- Fourth, the sequence of pile driving operations should be directed away from the existing structures.

Mitigation Measures to Decrease and Control Vibration Effects

Alternative Construction Techniques

- Cast-in-place Piles.
- Low Soil Displacement Piles
- Press-in Pile Installation

Simple Equations to Calculate PPV of Ground Vibrations

Assessment of Expected Peak Particle Velocities

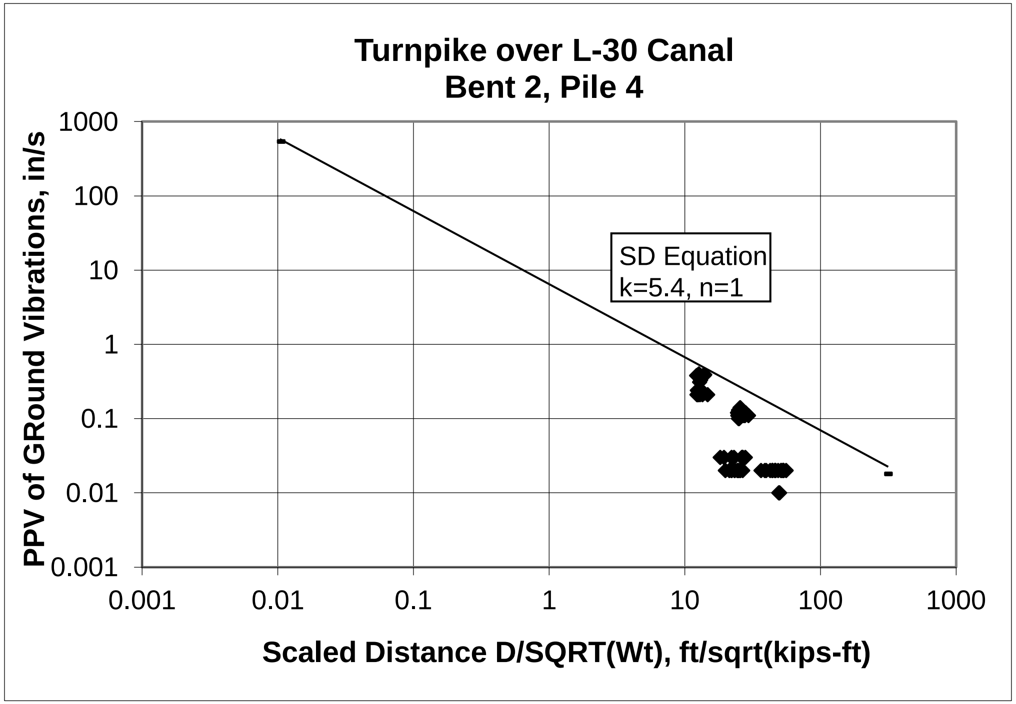
- The scaled-distance approach, ground velocity-distance-energy relationship, was proposed by Wiss (1981) to calculate the peak ground velocity at surface distance, D, from a source normalized with energy as

$$v = k[D/\sqrt{W_r}]^{-1}$$

  Where k = value of velocity at one unit of distance, Wr = energy of source, rated energy of impact hammer or maximum explosive weight in pound per delay, D = a distance from the source.
- Adjustment of this equation to local conditions.

Simple Equations to Calculate PPV of Ground Vibrations

Scaled distance equation for driving of 18” PSC pile



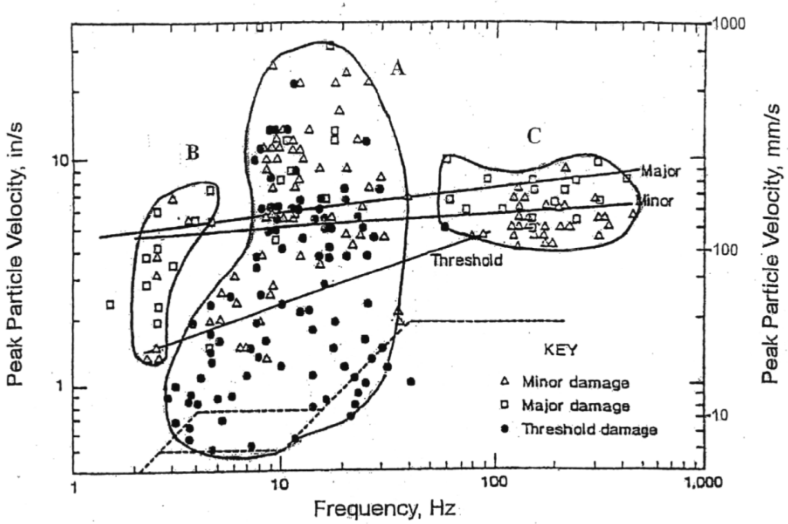
Simple Equations to Calculate PPV of Ground Vibrations

No.	District	County	Number of piles or vibratory rollers	Coefficient ‘k’	Comments
Pile Driving					
1	2	Clay	1	5.5	
2	4	Palm Beach	3	5.4	
3	4	Broward	40	5.6	
4	5	Orange	4	3.4	
5	5	Orange	3	9.4	Low attenuation wave paths
6	5	Osceola	10	7.6	
7	5	SR 417	1	5.0	
8	6	Miami-Dade	6	1.7	
Sheet Pile Driving					
1	4	Palm Beach	N/A	19.0	Vibratory pile driving
2	5	SR A1A	N/A	6.4	Impact pile driving
3	5	SR A1A	N/A	14.9	Vibratory pile driving
Casing Installation and Removal					
1	2	Duval	6	3.1	
Vibratory Rollers					
1	5	SR A1A, SR 207, SR 580	5	43.0	Compaction & paving 3 rollers have incomplete data

Structural Responses as the Basis for Determining Vibration Limits

Direct Vibration Effects

Three zones with closely grouped structure responses and damage summary from ground vibrations generated by blasting, and USBM recommended safe limits-dashed lines. Data were modified from Siskind (2000) and plot was adapted from Svinkin (2006)



Structural Responses as the Basis for Determining Vibration Limits

Resonant Structure Vibrations

- The proximity of the dominant frequency of ground vibrations to one of a building's natural frequency can amplify structural vibrations and even generate the condition of resonance. The resonant structural vibrations are independent of the structure's stiffness, being limited only by damping.
- There are no case histories of generation of resonant structural vibrations at large distances from impact pile driving. It is reasonable for practical goals do not consider such effects.
- Vibratory drivers with various operating frequencies may produce resonant floor vibrations because the natural frequencies of vertical floor vibrations range from 8 to 30 Hz.
- A case history from Michigan

Structural Responses as the Basis for Determining Vibration Limits

Resonant Soil Vibrations

- Matching the dominant frequency of propagated waves to the frequency of a soil layer can create the condition of resonance and generate large soil vibrations. Such amplification of soil vibrations may happen during vibratory pile driving.
- Woods (1997) noted that layers between about 1-5 m thick may produce a potential hazard for increasing vibrations when vibrators with operating frequencies between 20-30 Hz install piles in soils with shear wave velocities of 120 to 600 m/s (390 to 1970 ft/s).
- The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to accidental augmentation of ground vibrations.

Structural Responses as the Basis for Determining Vibration Limits

Dynamic Settlement is the Major Cause of Damage to Structures

- There is the different nature of dynamic settlements in sand and clay soils. Relatively small ground vibrations can be the cause of dynamic settlement in sand soils. Horizontal ground displacements, not vibrations, can be the cause of heave and following settlement in soft and medium clay.
- Non-uniform ground and foundation dynamic settlements in loose sand soils may happen beyond the zone of densification at various distances from pile driving.
- Soil liquefaction (4 in/s) and soil settlement (0.1 in/s).

Structural Responses as the Basis for Determining Vibration Limits

Examples of Damage to Structures from Dynamic Settlements in Sand Soils

- Swiger (1948) described a case where driving H piles through about 100 ft of saturated loose fine silty sand caused subsidence of the **foundation area with a maximum settlement of 1.5 ft**, and installation of a few piles in the immediate proximity of an adjacent building founded on deep piles resulted in **0.25-0.5 in. settlement** of **the building exterior wall.**
- Lynch (1960) reported installation of 12 in. piles and 14 in. shells to the depth of about 60-80 ft with a 34 kip-ft Vulcan hammer. The soil at a site consisted of sand fill, organic silt, loose to medium dense sand, limestone, and compact sand. Telltale measurements of the test piles indicated downdrag loading the pile tip caused by sand compaction that **settled previously driven piles up to 7in**, Port Everglades.

Structural Responses as the Basis for Determining Vibration Limits

Examples of Damage to Structures from Dynamic Settlements in Sand Soils

- In a field study described by Horn (1966), pile driving in sand soils caused **settlement of 5.9 in.** within the driving area and ground settlements at distances to 75 ft from driven piles.
- Feld and Carper (1997) reported a case of **significant settlements and severe damage to adjacent structures including one 19-story building** caused by installation of H piles in sand with impact and vibratory hammers. The soil consisted of uniform medium dense sand.
- Kaminetzky (1991) mentioned an interesting case with **building settlement developed at a distance of about 1000 ft away from a pile driving site**. Foundations of the buildings were underpinned on piles down to the tip elevation of the new driven piles to prevent building settlements.

Structural Responses as the Basis for Determining Vibration Limits

Pile Driving in Sand Soils without Damage

- Svinkin (2008) reported **installation of concrete piles in wet sand soils in the proximity of the five-story brick industrial building**. The conclusion about a possibility of safe pile installation nearby the existing building was based on the results of building structural responses to driving a few test piles at a distance of 9.8 ft from the existing building.
- Ashraf et al. (2002) described a case history of driving 356-mm diameter concrete filled steel pipes for a new constructed bridge adjacent to existing abutments and two story houses. The piles were installed in holes pre-bored to a depth of 6 m below the ground surface. Besides, the top 2.4 m of the piles was encased in 508 mm diameter steel shells filled with sand to accommodate the pile movement. These measures reduced vibration effects from pile driving and **no structural damage occurred during and after driving.**

Structural Responses as the Basis for Determining Vibration Limits

Dynamic Settlements in Clay Soils

- D'Appolonia (1971). End bearing piles were driven into **the slightly oversized pre-bored holes** made for approximately **75-87 % of pile's final embedment depth**. During pile driving the adjacent structures **heaved up to 9 mm**. Subsequently, these structures settled. The maximum settlements were up to 38 mm during five years after the end of construction. Measurable settlement occurred at distances greater than 30 m.
- Bradshaw et al. (2005). The results of installation of 350 concrete piles for highway construction into the pre-bored holes. The **auger cross sectional area was about 21 % less than the pile cross sectional area**. Depths of the holes were about **50-60 % of the pile's final embedment depth**. The total maximum **heave values ranged from 26 to 86 mm** at the distance about **16 m from driven piles**.

Structural Responses as the Basis for Determining Vibration Limits

Accumulated Effects of Pile Driving

- The accumulated effect of repeated dynamic loads from production pile driving should be taken into account. This approach is especially important for historic and old buildings. It is known that increasing number of driven piles can trigger a development of significant dynamic settlements.

Choice of Appropriate Vibration Limits

Standard ANSI S2.47-1990

- ANSI S2.47-1990 is a guide known as the American National Standard: Vibration of Buildings – Guidelines for the Measurement of Vibrations and Evaluation of Their Effects on Buildings.
- This standard is the U.S. counterpart of the International Standard ISO 4866-1990. It is intended to establish the basic principles for carrying out vibration measurement and processing data with regards to the evaluation of vibration effects on buildings. **The evaluation of the effects of building vibration is primarily directed at structural responses and includes appropriate analytical methods in which the frequency, duration, and amplitude can be defined**.

Choice of Appropriate Vibration Limits

Existing Vibration Regulations

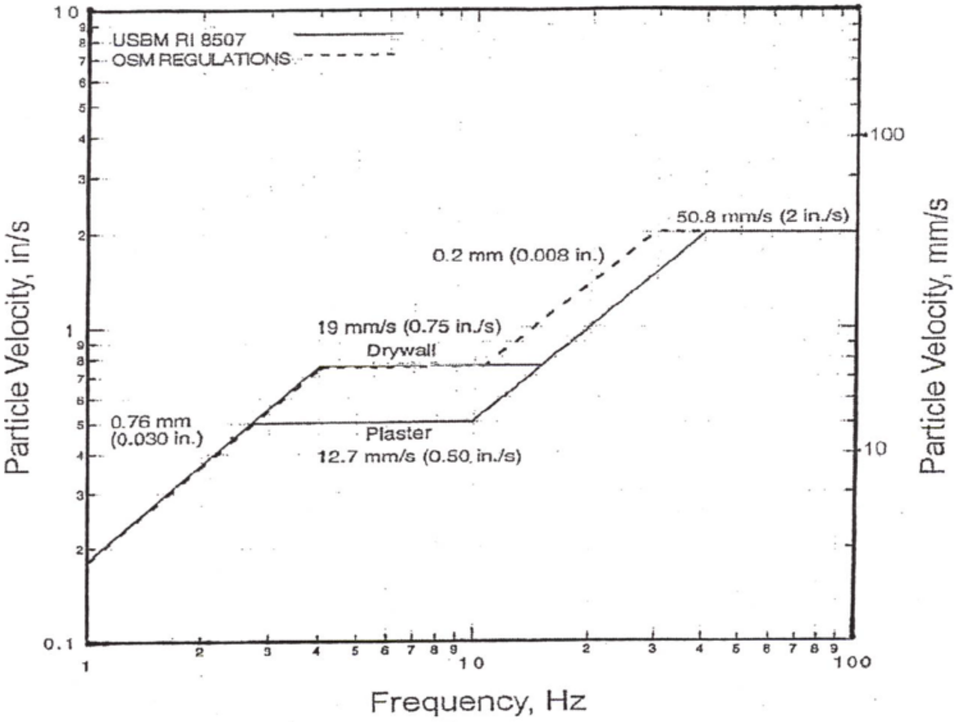


Figure 2. Safe level blasting criteria from USBM RI 8507 and the derivative version, the Chart Option from OSM surface coal mine regulations. Data were modified from Siskind (2000).

Choice of Appropriate Vibration Limits

Existing Vibration Regulations

- The USBM and OSM criteria were built up on the basis of the two decades research studies of a **correlation between ground vibrations and observations of cracking damage in 1-2 story houses**, and **these limits are applied for ground vibrations as the criteria of the possible crack formation in structure**.
- These vibration limits can be successfully used for similar blasting, ground conditions and structures they were developed for
- On one hand these criteria are very restrictive for direct vibration effects on structures and on other hand they cannot protect low-rise structures from appearance of cosmetic cracks under amplification of ground vibrations higher than 4.5x and beyond the 4-12 Hz frequency range.

Choice of Appropriate Vibration Limits

Existing Vibration Regulations

- Other blast design, soil conditions and structures require different vibration limits.
- Siskind and Stagg (2000). Ground vibrations and damage to low-rise residential houses at distances about **1 to 4 miles from quarry blasting** in Florida. Structural vibrations with **duration of about 17 s** were superposition of vibrations with various frequencies, including a low frequency of about 8 Hz, which was close to the natural frequency of horizontal house vibrations.
- Resonant structural vibrations were a possible cause of damage to house walls. On the basis of measured vibrations, the authors of the report have believed that **the highest ground vibrations there would likely be under 0.12 in/s. This criterion is about four times less than the smallest vibration limit of 0.5 in/s** permitted by the USBM safe criteria.

Choice of Appropriate Vibration Limits

Existing Vibration Regulations

- Application the USBM vibration limits for assessment of pile driving vibration effects can yield wrong results.
- Svinkin (2008). Vibration effects from vibratory sheet pile driving on a two story new house. **The vibration limit of 0.2 in /s was used**. However, such decreasing the vibration limit did not prevent vibration damage to the house. **A settlement crack was found in the brick chimney and vibratory sheet pile driving with the frequency about 26 Hz triggered resonant vertical floor vibrations which made architectural damage to the house.**

Choice of Appropriate Vibration Limits

Direct Vibration Effect

- It is reasonable to accept the limits of 19-25.4 mm/s (0.75-1.0 in/s) as the sensible limit range for ground vibrations which cannot damage residential structures due to only direct vibration effects on structures. These criteria are not accepted for resonance structure, soil vibrations, or dynamic settlement. As each construction site is unique, the engineer shall make a decision based on conditions at the specified site.

Choice of Appropriate Vibration Limits

Resonant Structural and Soil Vibrations

- There are no case histories of generation of resonant structural vibrations at large distances from impact pile driving. Therefore, it is reasonable do not consider such effects for practical goals.
- Vibratory pile driving may produce resonant floor vibrations and also resonant vibrations of soil layers. The best way is to use vibratory drivers with variable force and frequency.
- The application of **51 mm/s (2 in/s) limit for measured structural vibrations** can help to determine unacceptable vibrations of various structures.

Choice of Appropriate Vibration Limits

Dynamic Settlement

- Ground and foundation settlements as a result of relatively small ground vibrations in diverse sand soils may occur at various distances from the source.
- This phenomenon is quite different from liquefaction because liquefaction can be triggered by relatively high ground vibrations with PPV of about 100 mm/s (4 in/s) (Svinkin 2008), but ground vibrations with PPV 20 to 40 times smaller may be the cause of dynamic settlement in vulnerable granular soils. Such soil deformations may also occur at adjacent and remote locations.
- Lacy and Gould (1985) found that the peak particle velocity of 2.5 mm/s (0.1 in/s) could be considered as the threshold of possible significant settlements at vulnerable sites. **Woods (1997) pointed out that the prudent approach is to always proceed with caution when the condition of settlement is known to be present.**

Choice of Appropriate Vibration Limits

Additional Causes of Structural Damage

- Crockett (1980) and Dowding (1996) suggested taking into account the accumulated effect of repeated dynamic loads, for example, from production pile driving. This approach is especially important for historic and older buildings.
- Lacy and Gould (1985) concluded that increasing the number of driven piles can change a situation from insignificant vibration effects to damaging settlements.

Choice of Appropriate Vibration Limits

Historic and Old Structures

- Kesner et al. (2006) performed an analysis of vibration limits applied to historic structures. According to those results, the vibration limit of 2.5 mm/s (0.1 in/s) at historic structures is the sufficient criterion.
- In addition, daily structure inspection shall be provided.

Choice of Appropriate Vibration Limits

Equipment and Devices Sensitive to Vibrations

- If medical or computerized equipment and devices are found on the floors of buildings, it is necessary to measure structural vibrations at the floors and use vibration limits specified for sensitive equipment and devices (Svinkin 2012).
- The vibration limits for sensitive equipment and operations should be received from manufacturers.
- Case Histories in London, Duluth and Florida.

Choice of Appropriate Vibration Limits

Final Comments

- For structures with more than two stories, the vibration limit of 51 mm/s (2 in/s) shall be used for measured structural vibrations (at window-sills and floors). For a more comprehensive assessment of structural vibrations from construction sources, ANSI S2.47-1990 shall be used.

Specifications for Controls of Ground and Structural Vibrations from Roadway and Bridge Construction

- Introduction
- Pile Driving – Source of Vibrations
- Pile Driving Effects on Structures
- Surveys of Sites and Structures
- Calculation of Peak Particle Velocities of Ground Vibrations Prior to Pile Driving
- Vibration Limits for the Control of Ground and Structure Vibrations
- Monitoring of Vibrations
- General Comments on Pile Driving