Minimizing Construction Vibration Effects

Mark R. Svinkin, M.ASCE[1]

Abstract: Harmful vibration effects of construction operations occur frequently. Ground vibrations may affect adjacent and remote structures. The level of structure vibrations depends on a number of factors such as characterized sources of vibrations, soil conditions, and susceptibility of structures. There is no unique solution to minimize the effects of construction vibrations at every site. Monitoring and control of construction vibrations are made to be in compliance with safe vibration criteria. Reasonable vibration criteria should be chosen for a site.

DOI: 10.1061/(ASCE)1084-0680(2004)9:2(108)

CE Database subject headings: Construction management; Vibration effects; Construction equipment; Vibration control.

Introduction

Construction activities such as blasting, pile driving, dynamic compaction of loose soils, and operation of heavy construction equipment induce ground and structure vibrations. Their effects range from nuisance for the local population and disturbance of working conditions for sensitive devices, to diminution of structure serviceability and durability.

The influence of construction vibrations on surrounding buildings, sensitive devices, and people in the urban environment is a significant consideration in obtaining project approvals from appropriate agencies and authorities. Implementation of construction projects in areas adjacent to existing structures creates additional difficulties. Disruption of some businesses, possible structural damage, and annoying people are problems that need to be dealt with.

The level of ground and structure vibrations caused by construction work depends on the construction method, soil medium, heterogeneity and uncertainty of soil deposits at a site, distance from the source, characteristics of wave propagation at a site, dynamic characteristics and susceptibility ratings of adjacent and remote structures, and sensitivity of the local population to vibrations. It is likely that intolerable structure vibrations may be induced in close proximity of the dynamic sources. However, substantial structure damage may also occur at long distances from the sources for an account of the dynamic effect of low-frequency ground vibrations. Besides, foundation settlements resulting from soil vibrations in loose soils may happen at various distances from the source.

There is an increasing need to minimize vibration effects imposed by construction operations, but it is important to use reasonable vibration criteria to eliminate increasing construction cost. The dynamic effect can be assessed before the beginning of construction activities and at the time of construction. Therefore monitoring construction vibrations need to be started prior to the beginning of construction work at a site and be continued during construction to provide safety and serviceability of sound and vulnerable structures.

This paper reviews soil and structure vibrations generated by construction work; demonstrates advantages and disadvantages of the existing vibration criteria; considers mitigation measures such as preconstruction survey, prediction, monitoring and control of soil and especially structure vibrations, changes in construction procedures; and underlines the important role of instrumentation in minimizing problems related to construction induced vibrations.

Ground Vibrations

Sources of construction vibrations generate body and surface waves in soil medium. Body waves propagate through the soil deposits and rock. Compression and shear waves are the main types of body waves that should be taken into consideration at relatively small distances from the construction sources. Surface waves, of which Rayleigh waves are the primary type, propagate along the upper ground surface. Rayleigh waves have the largest practical interest for structural engineers because building foundations are generally placed near the ground surface. In addition, surface waves contain more than 2/3 of the total vibration energy and their peak particle velocity are dominant on velocity records. Rayleigh waves induce vertical and radial horizontal soil vibrations. In a horizontally layered soil medium, a large transverse component of motion could be caused by a second type of surface waves called Love waves.

Time-domain records of ground vibrations measured near construction sources can be roughly separated into two categories: transient and steady-state vibrations. Also, there is an intermediate category of pseudo-steady-state vibrations.

The first category includes single event or sequences of transient vibrations where each transient pulse of varying duration is dying away before the next impact occurs. Such vibrations are excited by air, diesel, or steam impact pile drivers, by dynamic compaction of loose sand and granular fills, and also by site, highway, and quarry blasts. The dominant frequency of propagating waves from impact sources ranges mostly between 3 and 60 Hz, but for some cases lower and upper values could be between about 1 and 100 Hz, respectively.

[1]VibraConsult, 13821 Cedar Rd., #205, Cleveland, OH 44118. E-mail: msvinkin@stratos.net

Note. Discussion open until October 1, 2004. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on August 7, 2002; approved on September 13, 2002. This paper is part of the *Practice Periodical on Structural Design and Construction*, Vol. 9, No. 2, May 1, 2004. ©ASCE, ISSN 1084-0680/2004/2-108–115/$18.00.

The second category contains continuous harmonic forms of relatively constant amplitude. These forced vibrations are caused by vibratory pile drivers and heavy machinery. The dominant frequency of steady-state vibrations has the major range of 5 to 30 Hz. High frequency machines operate at frequencies of more than 30 Hz.

Pseudo-steady-state vibrations contain a series of transient vibrations merged into continuous waveforms or quasi-harmonic motion with variable amplitude. Double acting impact hammers operating at relatively high speeds and heavy machinery excite such vibrations. The dominant frequency range is about 7 to 60 Hz.

According to Steffens (1974), vibration records of ground vibrations from impact pile drivers are similar to those from forge and drop hammers. The vibration effects from impact hammers are similar to those from vibrations generated by forge hammers because of the comparable energy released and the dominant frequency range.

Analysis of experimental data reveals that soil vibrations are mostly vertical near sources of vertical dynamic loads, but as distance increases, vertical and horizontal soil vibrations become similar in magnitude and, for some locations on the ground surface, amplitudes of horizontal vibrations might be up to three times greater than those of vertical vibrations.

In general, faster attenuation of high frequency components is the primary cause of changes of soil vibrations with distance from the source. However, some records cannot be explained by this mechanism and the effect of soil strata heterogeneity and uncertainties of the geologic profile should be taken into account (Svinkin 1996). Ground vibrations propagating from impact sources in different directions usually have unequal frequencies and amplitudes. Sometimes wave paths may have very low attenuation and even certain amplification of soil vibrations at some locations. For example, Dowding (1996) has showed that shear waves will selectively amplify within soil or rock layers at a frequency which is a function of the propagation velocity of the shear wave and the thickness of the layer. In another example, the writer experienced an interesting case where forge hammer foundation vibrations with a frequency of 14 Hz excited soil vibrations with a similar dominant frequency except at one location where the dominant frequency was 25 Hz with enhanced amplitudes.

In addition to the peak amplitude and the dominant frequency, the duration of vibrations is one more important parameter that describes time-domain vibration records. Waves travel in all directions from the source forming a series of quasi-harmonic waves with the dominant frequency equal to or smaller than the frequency of the source. This phenomenon is particularly developed in saturated sands and areas where soil deposit is underlain by rock. Typical displacement records of ground vibrations from the impact source are depicted in Fig. 1. Here the source was the foundation for a sizeable drop hammer with a falling weight of 147.2 kN dropped from height of 30 m. Foundation contact area was 158 m^2. The soil profile consisted of approximately 1.6 m of loose sand underlain by about 6.8 m of medium dense sand and 1 m of sandy clay underlain by about 10 m of slightly moist sand. The water table was about 6 m below grade. It can be seen that the record duration increased from 0.55 to 3.11 s when a wave propagated between 18 and 247 m from the impact source. Quesne (2001) reported results of ground vibrations at distances approximately 1.6 to 6.4 km (1 to 4 miles) from the nearest quarry blasts. Ground vibrations lasted at times over 16 s in duration.

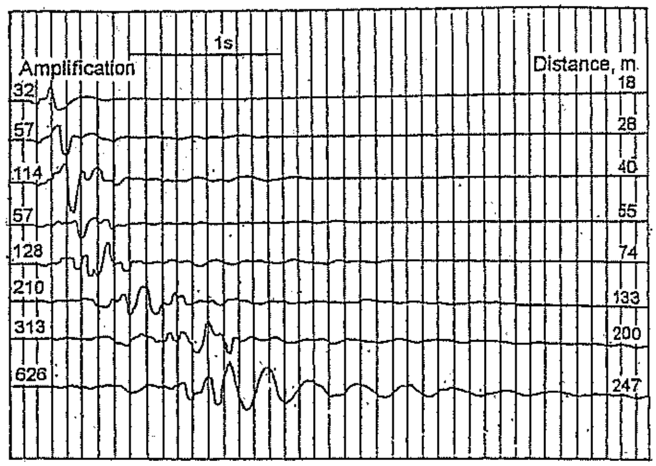

Fig. 1. Ground vibrations at various distances from impact source-drop hammer foundation

Structure Vibrations

Harmful vibration effects of construction activities occur frequently. This is a field of growing concern. In questionnaire responses regarding dynamic effects of pile installations on adjacent structures, 28 State Departments of Transportation (DOTs) and 26 pile driving contractors confirmed their experience with vibration damage from driving bearing, sheet, and soldier piles, Woods (1997). U.S. Bureau of Mines (USBM) investigated blast vibration effects for years. Intensive field studies of ground vibrations and structure responses from blasting were conducted by USBM in 1976–1979. Efforts were directed at measurements of ground, wall, floor, and racking vibration responses and also observations of damage in connection with specific vibration events. Siskind (2000) presented USBM accumulated results of ground vibrations measured near low-rise residential structures and actual observations of structural damage (Fig. 2). These results were obtained from 718 blasts and 233 documented observations of cracks. Non-damaging blasts are not shown although some of them produced relatively high level of ground vibrations.

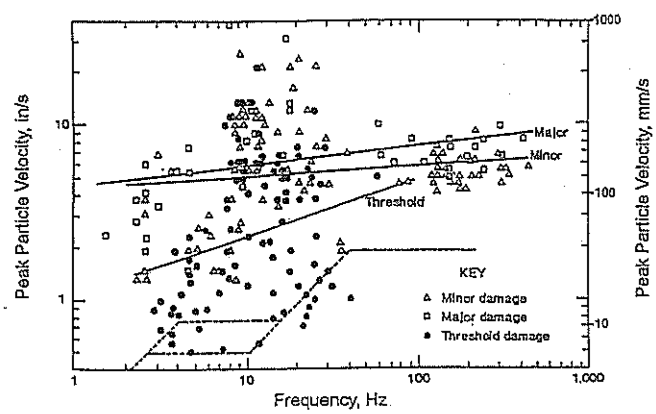

Fig. 2. Ground vibrations generated by blasting and structural damage summary: solid lines are regressions representing data means, and symbols shown are positive damage observations; dashed lines define U.S. Bureau of Mines recommended safe limits (Siskind 2000). Data and plot were adapted from RI 8507 (Siskind et al. 1980).

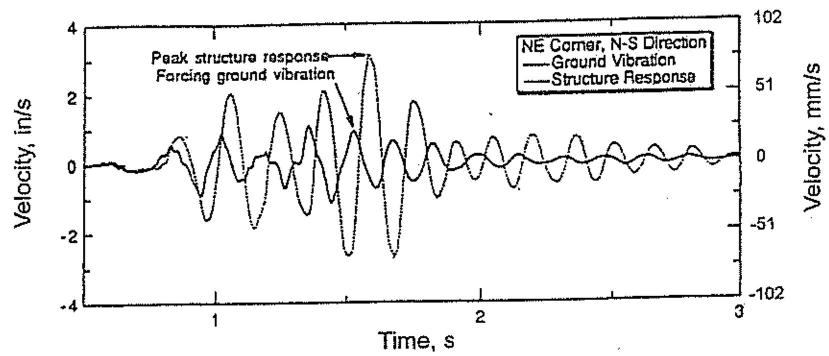

Fig. 3. Ground and structure vibrations with frequency of 5.8 Hz near structure resonance (Siskind 2000). Plot was originally from Crum (1997).

RI 8507 (Siskind et al. 1980) suggested the following damage classification with a description of damage. Threshold: loosening of paint, small plaster cracks at joints between construction elements, lengthening of old cracks. Minor: loosening and falling of plaster, cracks in masonry around openings near partitions, hairline to 3 mm cracks (0–1/8 in.), fall of loose mortar. Major: cracks of several millimeters in walls, rupture of opening vaults, structural weakening, fall of masonry, load support ability affected.

In general, ground vibrations from construction sources may affect adjacent and remote structures in three different ways as follows.

Structure vibrations: Vibrations may produce direct damage to structures when excitation frequencies of ground vibrations do not match natural frequencies of structures. Such damage usually occurs in nearby structures at distances about one pile length from driven piles and about 100 m (328 ft) from blasts. Intensity of structure vibrations depends on soil-structure interaction which determines structure response to the ground excitation. Building vibrations having low and high frequencies are usually generated by Rayleigh and compression waves, respectively. There are two frequency ranges of structure responses in Fig. 2: 2–30 Hz and 30–450 Hz. Perhaps structure vibration damage obtained without the effect of resonant structure response can be considered for most peak particle velocities (PPV) of ground vibrations higher than about 51 mm/s (2 in./s) for frequencies of 2–30 Hz and all PPV obtained in the frequency range of 30–450 Hz.

Resonant structure response: The proximity of the frequency of ground vibrations to one of the building's natural frequencies may generate the condition of resonance. Ground and structure vibrations with a frequency near the natural structure frequency are shown in Fig. 3. The PPV of structure vibrations increased 2.7 times and structure vibrations started to increase after the first cycle of ground vibrations. Under the condition of resonance, the maximum dynamic amplification could be much higher. For example, Quesne (2001) measured vibrations at exterior walls and corners of exterior masonry walls and found the amplification factors from four to nine times as high as vibrations measured at the ground. In Fig. 2, the damage in structures observed for the PPV of ground vibrations in the range of about 13–51 mm/s (0.5–2 in./s) for frequencies between 2 and 30 Hz could be the results of resonant horizontal building (2–12 Hz) and wall (12–20 Hz) vibrations and also vertical floor (8–30 Hz) vibrations.

Two more examples of resonance in structures. Rausch (1950) described a case history where intolerable vibrations occurred in an administrative building located 200 m from the foundation of a hammer with a falling weight of 14.7 kN Svinkin (1993) reported a similar situation with resonant structure vibrations of a five story apartment building located at approximately 500 m from the foundation under a vibroisolated block for a sizable forge hammer with a falling weight of 157.0 kN.

Dynamic settlements: Ground and foundation settlements as a result of relatively small ground vibrations in loose soils may occur at various distances from the source. Densification and liquefaction of soils can occur under the vibration effects of construction activities. Lacy and Gould (1985) analyzed 19 cases of settlement from pile driving in cohesionless sands and silts. In some cases, damage to structures caused by soil movements was more significant than structural damage due to transmitted vibrations. Dowding (1994) made comparisons of settlement and ground motions from blasting and pile driving. At short distances from the dynamic sources, densification is expected and vibration measurement should be made with high frequency transducers. These short distances can be described in terms of scaled distance for blasting and pile length for pile driving. However, surface settlements extend beyond the zone of densification. At long distances from the source, sometimes a few miles from blasting, surface waves with low frequencies and long durations produce considerable structure vibrations which may provoke surface settlements. Perhaps this is one of the causes of structural damage at a distance of a few miles from quarry blasting in the case described by Quesne (2001).

Additional causes of damage: Soil excavation associated with pile driving and made in close proximity to existing building can produce structural damage. Dowding (1996) observed that permanent excavation deformations induced in adjacent structure generally exceeded those from pile driving equipment. 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 old buildings. Lacy and Gould (1985) concluded that increasing the number of driven piles can change a situation from insignificant vibration effects to damaging settlements. Siskind (2000) analyzed structure fatigue from repeated blasting, available in USBM and other publications, and concluded that load levels well below failure strength of construction materials will not produce failure no matter how long they are applied.

Limited Liability of Vibration Criteria

The frequency-based safe limits for cosmetic cracking threshold shown in Fig. 2 were prepared by USBM, RI 8507 (Siskind et al. 1980). The USBM criteria were modified for regulation of blasting by U.S. Office of Surface Mining (OSM). These criteria are

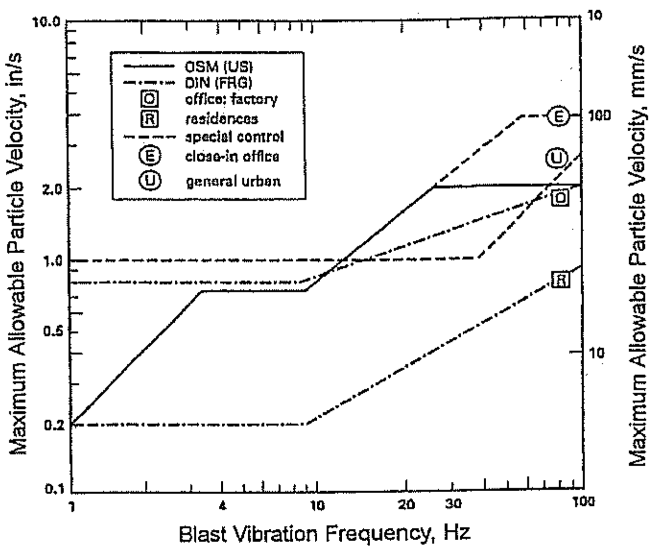

Fig. 4. Comparison of different frequency-based velocity-displacement control limits (Woods 1997). Plot was originally from Dowding (1996).

presented by the solid line in Fig. 4 and have the following displacement and velocity values for the four ranges of the dominant frequency: 0.76 mm (0.03 in. for 1–3.5 Hz, 19 mm/s (0.75 in./s) for 3.5–12 Hz, 0.25 mm (0.01 in.) for 12–30 Hz, and 51 mm/s (2.0 in./s) for 30–100 Hz. Dowding (1996) noted that the RI 8507 study focused on residential houses adjacent to mining facilities and involved no direct measurement of blasts with dominant frequencies below 5 Hz and also very few construction blasts with dominant frequencies above 40 Hz. Therefore, the frequency zones below 4 Hz and above 30 Hz are not well defined regarding the relationship between PPV and frequency and are a subject of further research. In contrast to OSM criteria, the German DIN 4150 Standard (1986) bounds are annoyance limits and are not damage based.

Siskind (2000) mentioned the simple approximate workable distance-dependent PPV criteria used by OSM and other regulatory bodies: 32 mm/s (1.25 in./s) for 0 to 91 m (0–300 ft), 25 mm/s (1.0 in./s) for 91 to 1,524 m (300–5,000 ft), and 19 mm/s (0.75 in./s) for distances greater than 1,524 m (5,000 ft). Nevertheless, Siskind (2000) recognized that a more rigorous treatment may be needed in special cases such as outlined in RI 8507.

It is important that recommended existing safe limits are applied for ground vibrations as the criteria of possible structural damage. The safe vibration criteria are used for indirect assessment of construction vibration effects on different structures even though the USBM safe criteria are based on structural responses and actual observations of cracking damage in residential houses. It appears that the existing USBM-OSM criteria work for cases of similar PPV of ground and structure vibrations and also resonance structure vibrations with amplification from 2 to 4.5 times in the frequency range from 4 to 12 Hz. However, these cases do not include the whole range of superstructures and underground structures undergoing vibrations. In reality, various building or house structures and room contents will have different values of an amplitude and a dominant frequency generated by the same ground vibrations. Data presented in Fig. 2 indicates that threshold damage could occur for some cases at the substantially higher vibration level up to 279 mm/s (11 in./s). Besides, according to Siskind (2000), many of the nondamaging blasts produced relatively high-level ground vibrations that were not shown in Fig. 2.

The existing criteria provide no distinction of type, age, and stress history of structures and do not take into account building configuration. These are some of the major disadvantages of the criteria. To satisfy practical goals in compliance with vibration criteria, some State Departments of Transportation (DOTs) prepared vibration specifications with reasonable precautions to prevent damage of existing structures. These specifications required different levels of vibration monitoring and control depending on structure susceptibility rating, proximity to construction sources of vibrations, sensitivity of the local population to nuisance, and city or state policy.

The existing vibration criteria should be used as a guideline, and structure conditions must be taken into account in a choice of the safe vibration limits. It is necessary to make direct measurement of structural vibrations accompanied by observation of the results of dynamic effects. In the middle of the 1940s, the safe vibration limits of 30–50 mm/s (1.18–1.97 in./s) for sound structures were found by the Moscow Institute of Physics of the Earth. According to data obtained from 718 blasts and shown in Fig. 2, all major damage, except one case, and all minor damage, except six cases, occurred in structures at ground vibration levels higher than 30–50 mm/s (1.18–1.97 in./s). It is reasonable to assume that for these seven cases, resonant structural vibrations were substantially higher than mentioned above safe limits. These limits take into account the condition of resonance and can be helpful in the assessment of vibration effects in structures.

Certain flexibility should be used in the choice of safe vibration criteria. For example, consider a construction site which is located in close proximity to a historic brick building. On the one hand PPV of 19 mm/s (0.75 in./s) or even 12 mm/s (0.5 in./s), Woods (1997), is the vibration limit for historic and some old structures. On the other hand at the time of pile driving at the neighboring site, this building being not residential is under remodeling construction and vibration criteria for such a building can be increased up to 51 mm/s (2 in./s) (Dowding 1996; Woods 1997), and even up to 102 mm/s (4 in./s) (Wiss 1981). Cosmetic and architectural cracks are not important for the building in this case. If conditions of structures are good, the PPV limit can be considerably higher than 12 mm/s (0.5 in./s). In most cases, major attention has to be brought to finding and assessing structural crack behavior during pile driving because structural cracks (such as of several millimeters in beams, columns or foundations, settlement cracks in masonry, structural weakening) may affect the integrity of building support.

Vibration effects on residents are important for many projects. Human intuition is founded on sensitive and inaccurate physiological perception. Results of instrumentation yield actual soil and structure behavior under dynamic excitation and give an opportunity to eliminate false impression and wrong conclusions regarding construction related vibrations. However, restrictions of vibrations effected people are very tough (ANSI S3. 18-1979; S3. 29-1983) and these limits are sometimes applied to assess structural vibrations. For example, the German DIN 4150 (1986) criteria intended to minimize human perceptions and complaints. This approach would be sensible if construction operations affect houses constantly and even at night. However, if blasts are made 1–2 times per day, such an approach is unreasonable.

Different criteria are used for assessment of ground settlements. Significant foundation settlements caused by pile driving in vulnerable sands can result from PPV of ground vibrations as low as 2.5 to 5.1 mm/s (0.1 to 0.2 in./s) (Lacy and Gould 1985), or acceleration levels exceeded 0.05 g (Clough and Chameau 1980).

In general, displacement of 0.1 mm (0.004 in.) and acceleration of 2.5 m/s^2 (8.2 ft/s^2), not velocity, are vibration limits for computer hardware (Boyle 1990).

Preconstruction Engineering Investigation

Assessment of the expected vibration effects from construction sources should be started before the beginning of construction operations at a site. A survey for estimating preconstruction status of houses, buildings, and facilities is usually accompanied by instrumentation on the ground surface and structures. The targets for instrumentation should be existing cracks in structures and existing vibration background (Svinkin 2002b).

Preconstruction Survey

A preconstruction survey is the first step in the control of construction vibrations to ensure safety and serviceability of adjacent and remote houses, buildings, and facilities.

For buildings within about 25 m radius of the construction site and all historic buildings within about 125 m radius, a line and grade survey should be performed to establish control and grade lines to detect movements along the exterior faces of the buildings (Woods 1997). Referenced benchmarks should be taken at distances where they are well beyond of influence of construction operations.

There is no single opinion regarding the maximum radius of a preconstruction survey area with houses and buildings surrounding a construction site. Dowding (1996) suggested a radius of 120 m of construction activities or out to a distance at which vibrations of 2 mm/s (0.08 in./s) occur. Woods (1997) considered distances of as much as 400 m to be surveyed to identify settlement damage hazards. Even larger distances should be taken into account for assessment of possible resonant structural vibrations. It is clear that a radius of the area of a preconstruction survey varies and depends on soil conditions, building susceptibility, and utilization. Obviously, in the areas with low attenuation of propagating waves, like in the State of Florida, a radius of the area of a preconstruction survey should be increased up to a few miles from the construction site.

The preconstruction survey includes inspection of existing conditions of surrounding buildings and an evaluation of a damage susceptibility study to determine levels of vibration monitoring and control.

Adjacent and remote structures can be cracked by construction induced vibrations through the following major causes: vibratory cracking from ground vibrations, resonant structure vibrations, and vibratory settlement of foundations. According to an overview of studies for cracking thresholds (Dowding 1996), there are three categories of observed cracks: (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); and (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). These categories are similar to the damage classification from RI 8507 (Siskind et al. 1980).

During preconstruction survey undertaken before the start of any activities at the site including the test pile program, existing cracks found in various structures need to be marked and divided into categories. Most attention should be paid to cracks in the structures themselves. It is necessary to analyze crack movements from everyday activities and environmental changes. Determining the causes of cracking is important to predict lengthening and dilatation of old cracks under the vibration effect of construction activities. The width of cracks should be measured with a proper ruler and monitored with special crack gauges. The results of crack analysis will reveal the picture of existing deformations of building structures.

Vibration Background

As a part of the preconstruction survey, measurement of existing vibration background should be made to obtain information regarding effects of exiting vibration sources. Besides, 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.

For relatively flexible floor systems, construction vibrations may create conditions for complaints about disturbance and malfunctioning of sensitive equipment from vibrations. Therefore it is important to measure floor vibrations from regular occupant motions like footstep force pulses, moving a chair close to the transducer measuring vibration levels, the dropping of boxes with computer paper, and other footfall events. It is necessary to point out that footfalls-induced concrete floor slab movements often produce relatively large vertical floor vibrations with the dominant frequency in the range from 5 to 32 Hz (Svinkin 1970; Dowding 1996). Boyle (1990) indicates that noticeable levels of peak particle velocity have been recorded from heavy footfalls may yield unrealistic guidelines regarding permissible PPV of ambient vibrations for computer systems. However, footfall events constitute a regular environment at rooms for computer systems and measured vibration background can be at least considered as the survival limit for computer hardware.

Assessment of Expected Peak Particle Velocities

The scaled-distance approach, ground velocity-distance-energy relationship, was proposed by Attwell and Farmer (1973) to calculate the peak ground velocity at surface distance D from a source normalized with energy as

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

Where k=value of velocity at one unit of distance and W_r=energy of source, rated energy of impact hammer, or maximum explosive weight in pound per delay.

According to accumulated experience of assessing blast vibration effects on structures, the scaled distance should be limited to 20 at the beginning of blasting operations in order to avoid cracking of plaster in homes (Wiss 1981).

On the basis of the actual range of energy transferred to piles and the range of the measured peak particle velocity at the top of steel, concrete and timber piles, Svinkin (1999) adapted Eq. (1) to calculate the peak ground velocity prior to the beginning of pile driving. The peak vertical ground velocity versus scaled distance from driven piles is depicted in Fig. 5. The reasonable pile velocity range for steel, concrete, and timber piles is 4.6 to 2.4, 2.4 to 0.9, and 4.6 to 1.5 m/s, respectively. The latter is actually the same as for steel piles. Values of 4,600, 2,400, and 900 mm/s have been marked as extreme left values on the slope lines. There are two areas constructed on the diagram: the upper area for steel

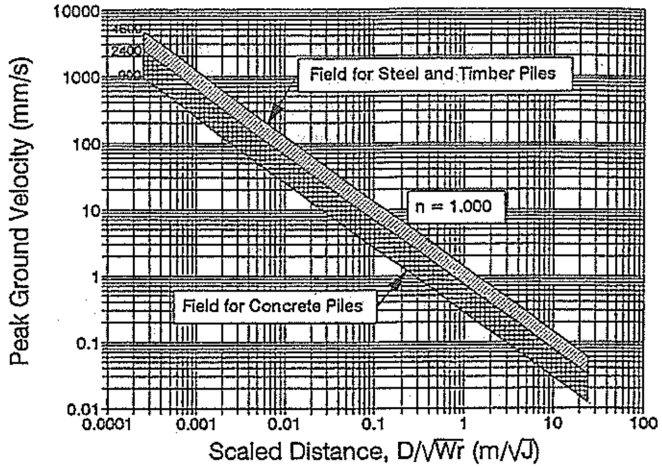

Fig. 5. Peak ground velocity versus scaled distance for pile driving

and timber piles and the lower one for concrete piles. Data presented in Fig. 5 provide an opportunity to construct curves of the expected maximum peak ground velocity for various distances from pile driving sources and different magnitudes of transferred energy. The peak particle velocity at the pile head can be calculated in advance as (Svinkin 1999)

$$v=\sqrt{2\frac{c}{ZL}W_t} \qquad (2)$$

where $Z=ES/c$ is pile impedance; E=modulus of elasticity of pile material; S=pile cross-sectional area; c=velocity of wave propagation in pile; and W_r=energy transferred to the pile.

This new development of the scaled-distance approach eliminates the need to know in advance the factor k, and enhances accuracy of predicted peak ground velocity before pile installation.

Frequency of Vibrations

Frequency and peak particle velocity are basic parameters for the assessment of ground vibrations. Dowding (1996) has underlined the importance of frequency because structural responses depend on the frequency of ground vibrations. The dominant frequency of an impacted pile and expected ground vibrations can be calculated as (Svinkin 1992)

$$f_w=k\frac{\xi c}{2\pi L} \qquad (3)$$

Where ξ=adjustment factor (Table 1); η=pile weight to ram weight ratio; c=velocity of wave propagation in pile; L=pile length; k=coefficient is equal to 0.4 for concrete piles at the end of initial driving (EOID), 0.5 for concrete piles at the beginning of restrike (BOR), 0.95 for steel pile at EOID, 1.15 for steel piles at BOR, and 0.7 for timber piles at BOR.

Prediction of Ground and Structure Vibrations

A new impulse response function prediction (IRFP) method has been originated by Svinkin (1999, 2002a) for determining com-

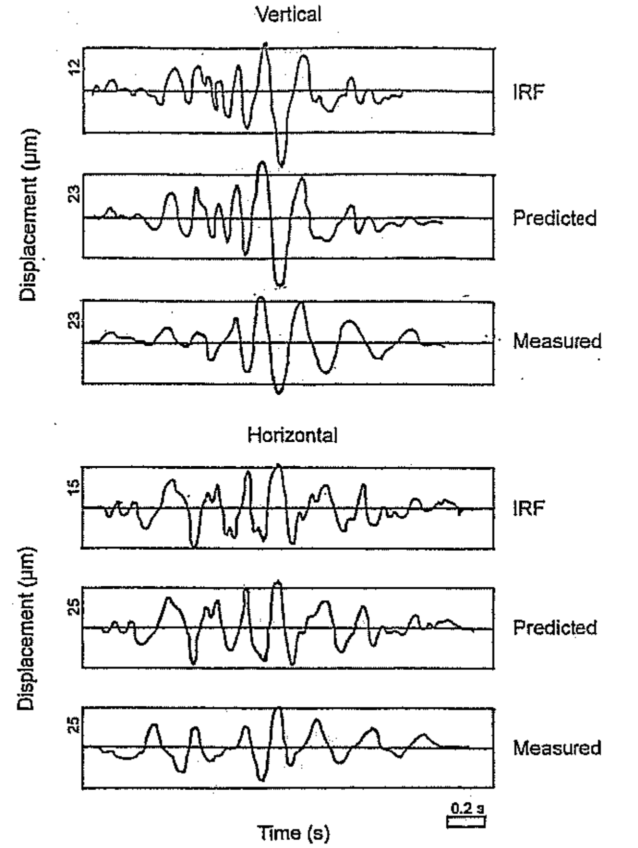

Fig. 6. Vertical and horizontal ground vibration displacements at distance of 266 m from drop hammer foundation: impulse response functions, predicted and measured records

plete time domain records on existing soils, structures, and equipment prior to installation of construction and industrial vibration sources.

An example of predicted results is shown in Fig. 6. Measurement and prediction of vertical and horizontal ground surface displacements were made at a distance of 266 m from the foundation under a sizeable drop hammer with a falling weight of 147.2 kN and a maximum drop height of 30 m. For both vertical and horizontal displacement components, three records are depicted: IRF, predicted, and measured curves. Correlation of predicted and measured vibration displacements is quite satisfactory. The differences between the highest calculated and measured amplitudes of oscillations are 16 and 30% for horizontal and vertical components, respectively.

The IRFP method can be used during dynamic testing to (1) determine a radius of the area of the preconstruction survey, and (2) for prediction of ground, structures, and sensitive objects vibration levels before the start of construction or industrial activities.

Vibration Mitigation during Construction

In addition to preconstruction survey and vibration prediction, vibration monitoring has to be made during construction. Moni-

Table 1. Adjustment Factors ξ for Calculation Frequency f_w (after Weaver et al. 1990)

η	0.01	0.10	0.30	0.50	0.70	0.90	1.00	1.50	2.00	3.00	4.00	5.00	10.0	20.0	100	∞
ξ	0.10	0.32	0.52	0.65	0.75	0.85	0.86	0.98	1.08	1.20	1.27	1.32	1.42	1.52	1.57	π

toring schedule and locations of monitoring stations should be designed in accordance with a construction schedule, an operation plan (e.g., pile driving or blast operations plans) and a layout of houses, buildings, and facilities surrounding the construction site, Svinkin (2002b).

Two kinds of transducers are used for vibration measurements. Some seismographs or geophones record velocity waveforms as a function of time, while others measure only the peak particle velocity. The number of transducers required for vibration measurement at a specific site depends on the number, characteristics, position, and motion of dynamic sources and also on quantity and susceptibility rating of structures and/or equipment sensitivity.

It is necessary to point out that a geophone's sensor has the natural frequency between 6.5 and 9.5 Hz and therefore a flat velocity-frequency response starts at the frequency about 15 Hz. Manufacturers use software to compensate resonance amplification of the sensor and receive a flat frequency response between 3 and 15 Hz. Therefore the set of measured calibration curves of the transducer is generally provided by manufacturers to eliminate misleading results.

Three components (vertical, radial, and transverse) of ground vibrations are measured to control the vector sum of all the components at some locations and determine dynamic properties of soil medium at the site like wave attenuation and a velocity of wave propagation. Acceleration is best measured by means of accelerometers. Vertical components of measured acceleration and velocity will yield required information regarding possible densification and liquefaction of soils at location suspected. Major attention should be paid to structure vibrations in order to receive structure responses in waveforms after soil-structure interaction. When a general picture of structural vibrations is clear, transducers for monitoring only peak particle velocity can be used at some places.

Certain cracks should be selected for monitoring and control with crack monitoring gauges.

Results of monitoring have to be verified using safe vibration levels. Displacement, velocity, and acceleration control limits were presented in the previous section. Control of measured vibrations may sometimes detect overlimited vibrations. If exceeding vibrations are substantial, it is necessary to take measures to reduce vibration levels. Sources of vibrations, wave paths, and receivers of vibrations affect vibration levels, Svinkin et al. (2000). The best approach to reduce ground and structure vibrations is a decrease of dynamic loads from construction sources.

- Blasting: Explosive type and weight, delay-timing variations, size and number of holes, distance between holes and rows, method and direction of blast initiation, geology and overburden are the most important factors which effect ground vibrations,
- Dynamic compaction: A smaller falling weight will produce smaller vibrations. A change of a falling height is less effective, and
- Pile driving: There is a big choice of measures that may be taken to decrease intensity of such construction vibration sources. For example, predrilling, prejetting, replacement of displacement piles with nondisplacement ones, switch impact hammer to vibratory one, and replacement of driven piles with augered cast-in-place piles or drilled shafts.

If construction vibrations disturb sensitive devices and processes, there is an option to perform construction work in different shifts. Survival limits rather than functional ones can be applied for assessment of vibration effect on sensitive objects.

Special attention should be brought to human response to vibrations (Wiss 1981). In spite of precautions regarding construction activities, the occupants of the nearby and even remote residences may complain of the violence of construction-induced vibrations. This problem is connected with different human perception and evaluation of vibrations.

Conclusions

Construction operations involve various sources of vibrations such as blasting, pile driving, dynamic compaction, and operating heavy equipment. Construction work often develops problems of disruption of some businesses, annoying people, and possible structural damage.

Ground vibrations from construction sources may affect adjacent and remote structures in three major ways: structure vibrations without the effect of resonance structure responses, the condition of resonance in the building, and dynamic settlements for account of soil densification and liquefaction. Soil excavation associated with pile driving and the accumulated effect of repeated dynamic loads may be additional causes of structural damage.

There is no unique conclusion regarding the effect of construction vibrations at every site. Characteristics of dynamic sources, soil conditions, and structure susceptibility at each specific construction site should be considered. Vibration measurement and analysis are vital for managing vibration problems. Instrumentation serves as the basis (1) for preconstruction survey of existing structural cracks and measurement of vibration background, (2) for prediction of construction vibrations at the time of engineering vibration investigation at the site, (3) for vibration monitoring, and (4) for control of actual vibrations during construction with the vibration thresholds for disturbance of sensitive objects and damage to structures.

Cracking limits were developed for residential structures subjected to surface mining blasting. Such criteria work for cases of similar PPV of ground and structure vibrations and also resonance structure vibrations with amplification from 2 to 4.5 times in the frequency range from 4 to 12 Hz. However, these cases do not include the whole range of superstructures and underground structures undergoing vibrations. The existing criteria provide no distinction of type, age, and stress history of structures.

Certain flexibility should be used in a choice of safe vibration criteria depending on actual structure conditions. It is important to measure structure vibrations together with ground vibrations and provide inspection of structures before and after vibration event.

A scaled-distance approach should be used for assessment of expected PPV of ground vibrations. The impulse response function prediction (IRFP) method can be employed to predict complete records of ground and structure vibrations prior the beginning of construction activities.

Occupants of houses and buildings should be aware about possible vibration influence on people. Therefore contractors have to provide proper public relations to inform residents regarding possible negative effects of construction vibrations.

Monitoring and control of ground and structure vibrations provide the rationale to select measures for prevention or mitigation of vibration problems, and settlement/damage hazards. Accumulated experience in vibration measurements is the basis for assessment of contribution of different factors to construction vibrations. Some of these factors can be used to minimize vibration effects and ensure safety and serviceability of surrounding structures.

Acknowledgment

The writer is thankful to the reviewer for a constructive review of the paper.

References

American National Standards Institute (ANSI). (1979). "Guide to the evaluation of human exposure to whole body vibration." *ANSI S3.18-1979*, New York.

American National Standards Institute (ANSI). (1983). "Guide to the evaluation of human exposure to vibrations in buildings." *ANSI S3.29-1983*, New York.

Attwell, P. B., and Farmer, I. W. (1973). "Attenuation of ground vibrations from piles." *Ground Eng.*, 6(4), 26–29.

Boyle, S. (1990). "The effect of piling operations in the vicinity of computing systems." *Ground Eng.*, 23(6), 23–27.

Clough, G. W., and Chameau, J. L. (1980). "Measured effects of vibratory sheetpile driving." *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.*, 106(10), 1081–1099.

Crockett, J. H. A. (1980). "Piling vibrations and structural fatigue." *Recent developments in the design and construction of piles*, The Institution of Civil Engineers, London, 305–320.

Crum, S. V. (1997). "House responses from blast-induced low frequency ground vibrations and inspections for related interior cracking." S-Wave GeoTech, Minneapolis, *Final Rep. to Office of Surface Mining, Contract ID: 143868-PO96-12616*, Office of Surface Mining, Washington, D.C.

Deutsches Institut für Normung. (DIN 4150). (1986). Deutsche Normen: Erschütterungen im Bauwesen—Einwirkungen auf bauliche Anlagen, Germany (in German).

Dowding, C. H. (1994). "Vibration induced settlement from blast densification and pile driving." *Vertical and Horizontal Deformations of Foundations and Embankments*, Geotech. Special Publication 40, ASCE, New York, 1672–1680.

Dowding, C. H. (1996). *Construction vibrations*, Prentice-Hall, Upper Saddle River, N.J.

Lacy, H. S., and Gould, J. P. (1985). "Settlement from pile driving in sands." *Proc., Symp. on Vibration Problems in Geotech. Eng.*, G. Gazetas and E. T. Selig, eds., ASCE, New York, 152–173.

Quesne, J. D. (2001). "Blasting vibration from limestone quarries and their effect on concrete block and stucco homes." *Vibration problems. Geo Discussion Forum.* ⟨http://www.geoforum.com⟩ (May 6, 2002).

Rausch, E. (1950). *Maschinen fundamente*, VDI-Verlag, Dusseldorf, Germany (in German).

Siskind, D. E. (2000). *Vibrations from blasting*, International Society of Explosives Engineers, Cleveland.

Siskind, D. E., Stagg, M. S., Kopp, J. W., and Dowding, C. H. (1980). *Structure response and damage produced by ground vibrations from surface blasting, RI 8507*, U.S. Bureau of Mines, Washington, D.C.

Steffens, R. J. (1974). "Structural vibration and damage." *Building Research Establishment Report*, Her Majesty's Stationery Office, London.

Svinkin, M. R. (1970). "Arrangement of precise equipment on floors." *Machines and Instrument*, 5, 4–5 (in Russian).

Svinkin, M. R. (1992). "Pile driving induced vibrations as a source of industrial seismology." *Proc., 4th Int. Conf. on the Application of Stress-Wave Theory to Piles*, The Hague, The Netherlands, F. B. J. Barends, ed., A. A. Balkema, Rotterdam, The Netherlands, 167–174.

Svinkin, M. R. (1993). "Analyzing man-made vibrations, diagnostics and monitoring." *Proc., 3rd Int. Conf. on Case Histories in Geotechnical Engineering*, Univ. of Missouri-Rolla, Rolla, Mo., **1**, 663–670.

Svinkin, M. R. (1996). "Overcoming soil uncertainty in prediction of construction and industrial vibrations." *Proc., Uncertainty in the Geologic Environment: From Theory to Practice, Geotechnical Special Publications No. 58*, C. D. Shackelford, P. Nelson, and M. J. S. Roth, eds., ASCE, New York, 2, 1178–1194.

Svinkin, M. R. (1999). "Prediction and calculation of construction vibrations." *DFI 24th Annual Members' Conf., Decades of Technology—Advancing into the Future*, Deep Foundation Institute, Englewood Cliffs, N.J., 53–69.

Svinkin, M. R. (2002a). "Predicting soil and structure vibrations from impact machines." *J. Geotech. Geoenviron. Eng.*, 128(7), 602–612.

Svinkin, M. R. (2002b). "Instrumentation of construction vibrations." *Ninth Int. Conf. on Piling and Deep Foundations*, Presses Ponts et chaussees, Paris, 23–29.

Svinkin, M. R., Shaw, A. G., and Williams, D. (2000). "Vibration environmental effect of construction operations." *DFI 25th Annual Meeting and 8th Int. Conf. and Exhibition, A Global Perspective on Urban Deep Foundations*, Deep Foundation Institute, Englewood Cliffs, N.J., 483–491.

Weaver, W., Jr., Timoshenko, S. P., and Young, D. H. (1990). *Vibration problems in engineering*, 5th Ed., Wiley, New York.

Wiss, J. F. (1981). "Construction vibrations: State-of-the-art." *J. Geotech. Eng. Div., Am. Soc. Civ. Eng.*, 107(2), 167–181.

Woods, R. D. (1997). *Dynamic effects of pile installations on adjacent structures, NCHRP Synthesis 253*, Transportation Research Board National Research Council, Washington, D.C.