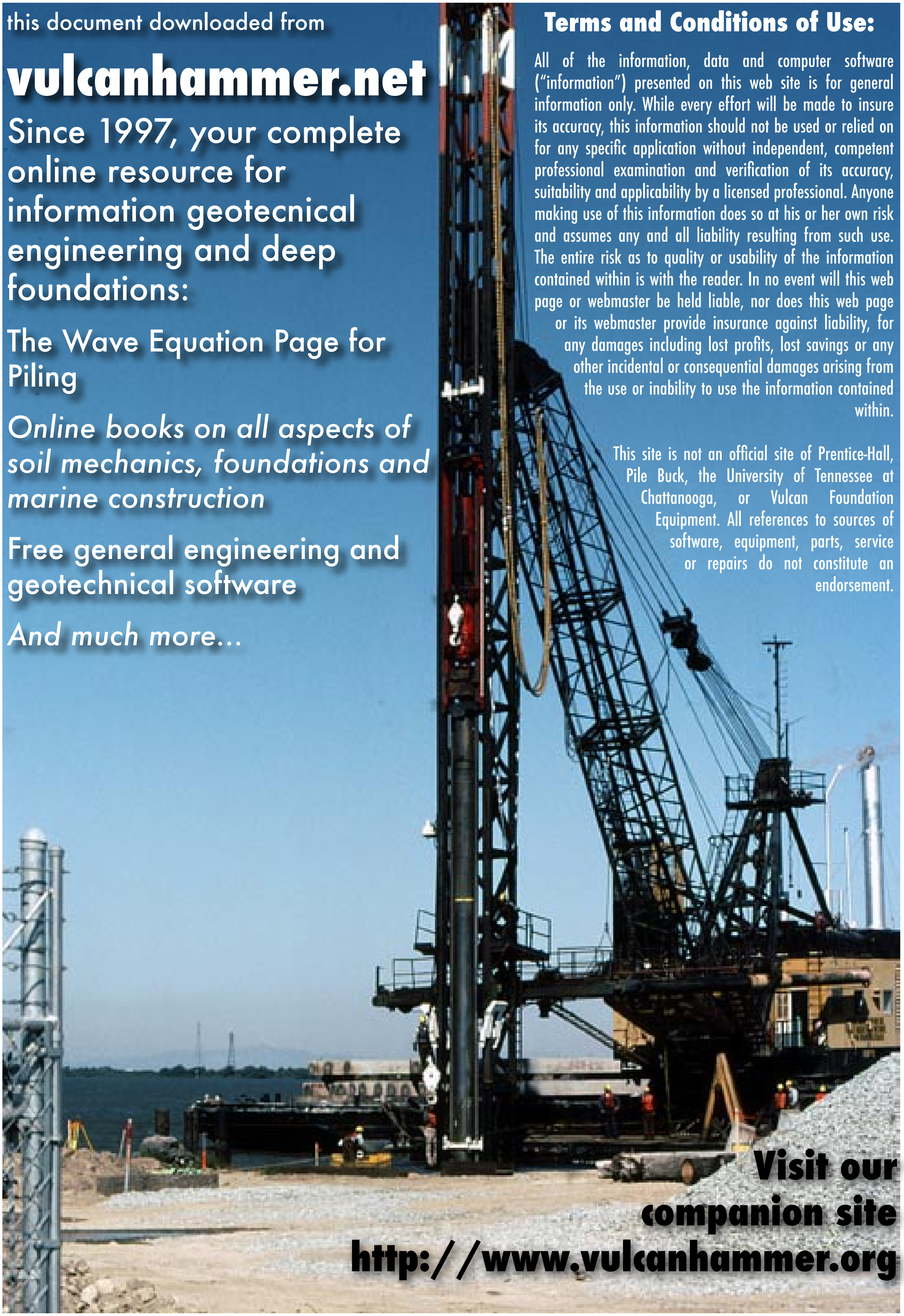

The necessity of condition surveys for structural protection against pile driving effects

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ABSTRACT: Pile driving generates ground and structural vibrations which may detrimentally affect adjacent and remote buildings, houses, people and sensitive devices. Vibration effects on structures depend on numerous factors. Because of uncertainties in the vibration limits available for pile driving operations, condition surveys are very useful for analysis of the causes of the existing damage to structures. Surveys of structures should be performed before, during, and after pile installation. In general, condition surveys can be more important for the safety of structures than calculations of expected ground vibrations and vibration monitoring. Therefore, condition surveys have to be used together with vibration monitoring and control. Mitigation measure should be determined at the time of preconstruction condition surveys of structures.

1 INTRODUCTION

Dynamic effects of pile installation on adjacent and remote structures change in the broad range from devastating structural damage to insignificant vibrations which cannot affect structures. For example, 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 steel H piles in sand with impact and vibratory hammers, but in contrast Kesner et al. (2006) described successful management of structural vibrations of two historic buildings adjacent to a construction site.

Vibration effects on structures depend on a number of factors such as dynamic sources, the soil medium where waves propagate, soil conditions at location of structures, soil-structure interaction, and susceptibility of structures to vibrations. Also, there are serious problems in vibration protection of sensitive equipment and operations in buildings from pile driving.

Preventive measures for diminishing of vibration effects should be used before the beginning and during pile driving. Calculations of expected ground vibrations prior to pile installation and vibration monitoring during pile driving are implemented for decreasing or elimination of the pile driving effects on structures. The obtained results might be good or bad depending on a number of factors. Independently of measured vibrations and vibration limits, condition surveys performed before, during, and after pile driving operations could be the best indications of structural responses and damage to dynamic excitation from pile installation. It is very important for determining the actual causes of damage to structures.

2 VIBRATION EFFECTS ON STRUCTURES

Impact hammers or vibratory drivers are commonly used for installation of driven piles. Vibratory pile driving mostly affects soil and adjacent structures. Impact pile driving may be the cause of soil deformations and damage to adjacent and remote structures.

The maximum rated energy of the most commonly used impact hammers varies from 5 to 300 kJ/blow. Impact pile driving generates longitudinal pile oscillations and ground vibrations with the dominant frequency in the 7-30 Hz range with predominance at the lower values. The measured maximum pile velocity and displacement values vary per blow from 0.9 to 4.6 m/s and 12 to 35 mm, respectively. Both parameters depend on the pile type, the hammer energy transferred to a pile, and soil resistance to pile penetration (Svinkin 1992).

Vibratory drivers for driving limited displacement piles usually have low to moderate force amplitude and operating frequencies between 20-30 Hz. Displacement piles are driven by vibratory drivers with frequencies of about 10 Hz and much higher force. The soil resistance to pile penetration and the seismic effect of vibratory driven piles depend on the soil conditions, the pile type and the vibratory driver model.

Dynamic loads force piles to vibrate and penetrate into the ground and trigger elastic waves which propagate in the soil medium and induce elastic soil displacements and vibrations at various levels depending on the intensity of propagated waves. The structural responses to ground vibrations depend on soil-structure interaction. Ground vibrations can produce direct vibration effects on structures and trigger resonant structural vibrations of adjacent and remote structures.

Under certain circumstances related to soil deposit and dynamic movement (vibrations or displacements) elastic waves can be the cause of plastic soil deformations and dynamic settlement. Soil-structure interaction will be different for soil failure. Thus, the structural responses to ground excitation depend on soil deformations triggered by waves propagated from the source and soil-structure interaction (Svinkin 2004, Svinkin 2008).

2.1 Direct vibration effects.

Direct damage to structures occurs as a result of soil-structure interaction when frequencies of ground vibrations do not match natural frequencies of structures. Such damage can be expected within a distance of about one pile length from a driven pile. These distances can be substantially larger for susceptible structures. According to an available experience in the blasting industry (Siskind, 2000), direct minor and major structural damage to 1-2 story residential houses without resonant structural responses are observed in the velocity range of 33-191 mm/s for frequencies of 2 to 5 Hz and in the velocity range of 102-254 mm/s for frequencies from 60 to 450 Hz.

2.2 Resonant structural vibrations

The proximity of the dominant frequency of ground vibrations to one of building’s natural frequency can amplify structural vibrations and even generate the condition of resonance. If ground vibrations have only a few cycles with the dominant frequency equal to one of building’s natural frequency, resonant vibrations do not develop. The resonant structural vibrations are independent of the structure stiffness being limited only by damping.

Vibratory drivers with various operating frequencies may produce resonant floor vibrations because the natural frequencies of vertical floor vibrations range between 8-30 Hz. These vibrations may affect precise and sensitive devices installed on the floors.

For remote structures, the proximity of the low-frequency components of ground vibrations induced by impact hammers to building’s horizontal natural frequencies may generate the condition of resonance in the building and trigger large horizontal vibrations. For one or two-story residential houses, a dynamic magnifying factor at resonance was measured in the limits of 2-9. This factor can be much higher for multi-story buildings. The natural frequencies range from 2 to 12 Hz for horizontal building vibrations and from 12 to 20 Hz for horizontal wall vibrations. There are no readily apparent means for reduction of resonant horizontal building vibrations, but fortunately, these vibrations seldom occur.

2.3 Resonant soil layer 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. According to Woods (1997), 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 between 120 and 600 m/s. The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to accidental augmentation of ground vibrations.

2.4 Dynamic settlement

Different natures of dynamic settlements exist 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 clays (Svinkin 2006).

2.4.1 Soil settlement in sand soil

Pile installation in sand may cause soil and structure settlements due to densification and liquefaction of vulnerable granular soils. Large settlements are usually observed in loose to medium dense sands with relative density less than 70 %. Soil classification and relative density of cohesionless soils can be derived from the results of cone penetration test (CPT).

It is possible to drive piles in sand soils without structural damage to adjacent and remote buildings because sand soils have different responses to dynamic excitations and some sand soils do not develop settlement under dynamic loading. Also, preventive measures can be used against dynamic settlement.

According to Woods (1997), simple methods to estimate settlements in loose to medium dense sand during pile driving do not provide practical solutions. Therefore, the prudent approach is to always proceed with caution when the condition of settlement is known to exist.

2.4.2 *Soil settlement in clay soil*

Pile installation in clay is different from pile driving in sand. Pile penetration into clay produces an increase in lateral stress and pore pressure and also trigger heave of the ground surface. During pile driving, the excess pore pressure increases with each driven pile and may reach big values at large distances beyond the pile group area. This excess pore pressure can be much larger than the initial effective overburden stress. After the completion of pile driving and the dissipation of the excess pore pressure, the soil reconsolidates and ground surface settles. The soil settlement is usually greater than the heave during pile driving because soil compressibility is significantly increased by soil remolding after pile installation (D'Appolonia 1971).

Movements of adjacent buildings during pile installation can be an important problem if clay susceptible to dynamic loading-induced settlement is present on a construction site. Effects of pile driving in soft to medium clay on the surrounding area should be expected at distances from pile installation equal to about the thickness of the clay layer being penetrated.

2.5 *Additional causes of damage*

It is necessary to take into account the accumulated effect of repeated dynamic loads from production pile driving. This approach is especially important for historic and old buildings.

3 CONDITION SURVEYS OF STRUCTURES

A preconstruction condition survey is the important step in the control of construction vibrations to ensure safety and serviceability of adjacent and remote houses, buildings and facilities. The preconstruction survey should be undertaken after the accomplishment of dewatering and excavation at a construction site and prior to the start of any other activities on the site, including the test pile program. The survey will include all buildings within a radius of about 60 m of the pile driving activities. The distance of 60 m was determined on the basis of analysis of ground vibrations measured at a number of construction sites from pile driving, the existing experience of pile driving effects of structures, and common sense. This distance has to be mostly used for assessment of direct vibration effects on structures. The condition survey should be selectively performed for historic buildings at the area with a radius of 400 m.

The objective of this survey is to determine the condition of structures including the buildings' susceptibility to vibration effects from pile driving, possible dynamic settlement hazard, and vibration background. This survey can detect possible disruption of businesses from pile driving vibrations which includes impact on sensitive equipment and operations, as well as cosmetic cracking and effects on surrounding houses and buildings.

3.1 *Goals of condition surveys*

3.1.1 *Document the existing cracks and other damage*

This survey should include observation and documentation of the existing condition of foundations, exterior and interior walls, ceiling, floors, roof and utilities. Cracks and other damage should be detailed by videotapes and photographs. Notes and sketches should be made to highlight, supplement, or enhance the photographic evidences. It is beneficial to make similar documentation for areas of buildings without damage for future comparisons after the completion of pile driving operations. The condition survey report should summarize the condition of each building and define areas of concern. 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.

3.1.2 *Analyze possible causes of existing damage*

A pre-pile driving condition survey of structures is imperative to determine causation of the exiting damage because environmental forces, geotechnical hazards, and dynamic forces from pile driving can be the causes of similar structural damage which can exist before the beginning of pile driving. Such analysis is important to predict lengthening and widening of old cracks under the vibration effects of construction activities. First of all verification of a dynamic settlement risk should be done because dynamic settlement is the major cause of damage to structures from pile driving. Most settlement cracks have stairs shapes, and they can be easily recognized.

Geotechnical natural danger at various distances from construction sites such as heave, settlement, and sliding may damage structures prior to construction, during and after construction. Environmental stresses may be generated by forces either within the house or outside the house. Some of the larger stresses in the construction materials or the structures are developed by such factors as changes in temperature, changes in moisture, drying and curing of such materials as lumber, plaster, mortar, grout, concrete, brick and other masonry products, different application of internal heat, aging, and other factors.

3.1.3 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). Historic buildings usually have high susceptibility rating.

3.1.4 Determine mitigation measures of pile driving effects on structures

Reduction measures for decreasing of vibration effects of pile driving depend on soil deformation and soil-structure interaction, and they should be considered before the beginning of pile driving. The separate lists of measures to mitigate direct vibration effects on structures, dynamic settlement in sand soil, and dynamic settlement in clay soils are presented in Svinkin (2006).

3.2 Condition survey during and after construction

Condition surveys during pile installation and after the completion of pile driving are significant 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 important. If crack widths increase without increasing of crack lengths, it is not dangerous for structures.

Historic and old buildings require special attention during a preconstruction survey and surveys performed at the time of pile installation and also after the completion of pile driving. Daily inspections should be performed for historic and old buildings.

3.3 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. 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 in buildings, construction vibrations may create conditions for complaints about disturbance and malfunctioning of sensitive equipment. 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, dropping of boxes with computer paper and other footfall events.

Inducing of concrete floor slab movements, footfalls often produce relatively large vertical floor vibrations with the dominant frequency in the range from 5 to 32 Hz, but noticeable levels of peak particle velocity recorded from heavy footfalls may yield unrealistic guidelines regarding permissible values of ambient vibrations for computer systems. However, footfall events constitute a regular environment at rooms for computer systems and a measured vibration background can be at least considered as the survival limit for computer hardware. Sensitive equipment or operations in nearby buildings require measurement of structural vibrations at their locations.

4 CALCULATIONS OF GROUND VIBRATIONS

In practice, two equations are usually used for approximate calculations of the expected peak particle velocity (PPV) of ground vibrations at various distances from driven piles. These equations provide assessment of PPV attenuation between two points on the ground surface. A relationship between pile and ground vibrations is also presented. Besides, two more approaches will be discussed.

4.1 Golitsin's equation

Golitsin's equation takes into account geometric and material damping (Golitsin 1912)

$$A_2 = A_1 \sqrt{r_1 / r_2}\, e^{-\gamma(r_2 - r_1)} \quad (1)$$

where A_1 = peak particle displacement of vibrations at distance r_1 from source, A_2 = peak particle displacement of vibrations at distance r_2 from source, γ = attenuation coefficient. The term $(r_1/r_2)^{0.5}$ indicates the radiation or geometric damping and the term $\exp[-\gamma(r_2-r_1)]$ indicates the material or hysteretic damping of wave attenuation between two points.

Equation (1) was originally obtained to estimate attenuation of low frequency Rayleigh waves with large wavelengths generated by earthquakes for which the coefficient γ depends very slightly on the properties of upper soil layers. For such conditions, the coefficient γ changes reasonably in narrow limits for assessment of wave attenuation in soils. However, construction and industrial sources generate waves with higher frequencies and smaller wavelengths in comparison with surface waves from earthquakes and these waves propagate mostly in the upper soil strata close to the ground surface.

The coefficient γ is important for accurate calculation of wave attenuation. Collected experimental data indicate that for the same site and the same dynamic source, soil stratification significantly affects the coefficient γ. Measured data show that for various pairs of widely separated points on the ground surface, values of γ can vary more than an order of magnitude and even change sign. Thus, the coefficient γ acceptable for small distances may be inadequate for long distances. Due to wave reflection and refraction from boundaries of diverse soil layers, an arbitrary arrangement of geophones at a site can yield incoherent results of ground vibration measurements because waveforms measured at arbitrary locations at a site might represent different boundaries of soil layers (Svinkin 2008).

For correct application of Equation (1), it is necessary to use a seismograph array similar to one utilized in seismic analysis of seismic waves (SASW).

4.2 *Scaled-distance equation*

Wiss (1981) applied the scaled-distance (SD) approach for construction sources and proposed the following equation to calculate attenuation of the peak particle velocity of ground vibrations

$$v = k[D/\sqrt{W_r}]^{-n} \tag{2}$$

where D = distance from source, W_r = energy of source or rated energy of impact hammer, k = value of velocity at one unit of distance. A distance from the source is normalized (scaled) with the source energy. The attenuation rate represented by the coefficient ‘n’ is a conventional combination of mostly material damping and partially geometric one. This is a so-called pseudo-attenuation coefficient. The value of 'n' yields a slope of PPV attenuation for all tested soils in the 1-2 narrow range on a log-log chart, and this coefficient is independent of the soil type, the source energy, and the energy level. Coefficient n=1 means lower attenuation of ground vibrations and consequently higher PPV of ground vibrations. Woods (1997) confirmed a soundness of this approach with gathered data from field construction projects and developed a scaled distance chart correlated with ground types. Most of those data correlated with a slope of n=1.5 for Soil Class II and some of the data presented in that study showed n=1.1 for Soil Class III. From Woods (1997), Soil Class II is *Competent Soils* - most sands, sandy clays, silty clays, gravel, silts, weathered rock (can dig with shovel and 5<N<50); Soil Class III is *Hard Soils* – dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock (cannot dig with shovel, must use pick to break up and 15<N<50).

Equation (2) provides very rough assessment of ground vibrations as a function of the source energy and a distance from the source. Also, Equation (2) does not take into account the soil conditions, the pile penetration depth, the soil resistance to pile penetration, the soil heterogeneity and uncertainty, the soil-structure interaction, and has nothing to do with structural vibrations, dynamic settlements, and vibration effects on sensitive equipment.

Nevertheless, Equation (2), adjusted for site soil conditions and pile types with field pile testing, provides relatively better results than equation (1) for rough assessment of expected PPV of ground vibrations generated by pile driving.

4.3 *New scaled-distance equation*

The traditional scaled-distance equation requires the knowledge of a velocity value at some distance from the source for calculating of a ground vibration reduction. The initial velocity is usually unknown. At the same time, the peak particle velocity of pile vibrations can be calculated prior to pile installation.

A new approach in application of a scaled-distance equation for pile driving was presented by Svinkin (2008). The new equation uses the scaled-distance relationship between pile and ground velocities as

$$v_g = a v_p \frac{\sqrt{Wt}}{D} \tag{3}$$

where a = coefficient related to dimensions, v_p = PPV of pile vibrations at the pile head, v_g = PPV of ground vibrations, Wt = energy transferred to pile that can be determined as the product of rated energy and efficiency. The value of n=1 was chosen to obtain the upper limit of PPV with the lower value of the attenuation rate. The maximum PPV measured at the pile head ranges between 900 and 4600 mm/s.

Values of v_p (mm/s) can be calculated using the following equation

$$v_p = 0.000263\sqrt{2\frac{c}{ZL}W_t} \tag{4}$$

where c = velocity of wave propagation in pile, Z = ES/c is pile impedance, E = modulus of elasticity of pile material, S = pile cross-sectional area, L = pile length. The coefficients for dimension adjustments were not included in Equations (4) and (5) in Svinkin (2008).

Substitution of Equation (4) into Equation (3) gives

$$v_g = 0.00037\frac{W_t}{D}\sqrt{\frac{c}{ZL}} \tag{5}$$

Equation (5) provides an opportunity to calculate the PPV of ground vibrations prior to the beginning of pile driving because PPV is a function of known pile parameters. This development of the scaled-distance approach eliminates the need to know in advance the factor k and increases the accuracy of calculated ground velocity before pile installation. Equation (5) can be adjusted for site soil conditions and pile types with field pile testing similarly to Equation (2)

In contrast to other empirical equations, Equations (3) and (5) can be used to assess ground vibrations from vibratory drivers (Svinkin 2008). Two ways can be used to determine the PPV of vibratory driven piles. First, the PPV of vibratory driven pile is the product of the maximum pile displacement available in the vibrator specification and the angular frequency of pile vibrations. Second, the maximum energy transferred to a vibratory driven pile per a cycle of driving is the product of the maximum power, the period of pile vibrations and the efficiency. Then the PPV of a vibratory driven pile can be computed using Equation (4).

There are two approaches to choose a distance for the SD equation. Horizontal distance is a distance on the ground surface between the driven pile and the seismograph. Seismic or slope distance is a distance from the driven pile tip to the seismograph. Obviously, the use of slope distances yields smaller PPV of ground vibrations. However, actual measured surface ground vibrations at some locations can be larger than calculated PPV for either distance choice. Therefore, it makes sense to use horizontal distances for practical goals to calculate the upper vibration limits.

4.4 Impulse response functions approach

An Impulse Response Function Prediction (IRFP) method was developed for predicting of complete time-domain records on existing soils, buildings, and equipment prior to installation of impact machine foundations (Svinkin 2002). The method is founded on the utilization of the impulse response function (IRF) technique that does not require soil boring, sampling, or testing at the site, eliminates the need to use mathematical models of soil profiles, foundations and structures in practical application, and provides the flexibility of implicitly considering the heterogeneity and variety of soil and structure properties. There are no assumptions about soil conditions and structural properties. As it was shown by Svinkin (1996), this method can be used to predict ground and structure vibrations from construction sources such as impact pile driving. Wave equation analysis was used to assign a pile movement, but it necessary to underline that the pile movement can be assigned arbitrarily, for example as a damped sinusoid, because ground vibrations at some distance from a dynamic source depend only on the dynamic force transmitted onto the ground and soil properties (Svinkin 2002).

The following is a general outline of the IRFP method for prediction of complete vibration records of soil and structures prior to installation of a dynamic source. 1. At the place chosen for impact dynamic source, impulse loads of known magnitude, which should be not smaller than 10 times less of the dynamic load of the source, are applied on the ground. 2. At the moment of impact on the ground, vibrations are recorded at the points of interest, for example, at the locations of instruments and devices sensitive to vibrations. These oscillations are impulse response functions of the considered dynamic system which automatically take into account complicated soil conditions and soil-structure interaction. 3. Calculation of convolution integrals of impulse response functions and dynamic loads transferred onto the ground to obtain the complete records of soil and structure vibrations. The predicted soil vibrations demonstrate a close fit to the measured data.

It is common that the high resistance of upper soil layers at depth about 10 m below the ground surface affects intensity of ground vibrations. The high soil resistance with deeper pile penetration into the ground much slightly affects surface ground vibrations. Therefore, it makes sense to use the IRFP method at sites with stiff upper soil layers and buildings containing sensitive equipment.

4.5 Pile capacity and ground vibrations

Some authors, for example Hajduk and Adams (2008), found that ground vibrations can be correlated with pile capacity determined during pile driving, and they believe that pile-soil interaction, not energy, is the major influence in the generation of ground vibrations from driven piles. Obtained conclusions are not accurate because ground vibrations and pile capacity are outcomes of the same pile driving process and only an accidental correlation between them is possible.

Some comments are necessary. First, during pile driving, the static pile capacity is determined by signal matching software on the basis of force and velocity measurements at the pile head. Unfortunately, different software produces different results. Second, obviously, the effect of pile-soil interaction on ground vibrations and pile capacity depend on the hammer energy. There is a typical statement in a number of papers that pile capacity was not mobilized because of the low hammer energy. Third, during pile installation, ground vibrations should be measured not calculated because possible detrimental effects of pile driving operations predetermine the necessity of ground vibration measurements. Fourth, measured ground vibrations are more reliable than calculated ones.

5 VIBRATION LIMITS

5.1 USBM RI 8507 criteria

The frequency-based safe limits for cosmetic cracking threshold were originated for 1-2 story residential houses by the U.S. Bureau of Mines, Siskind et al. (1980). The limits depicted in Figure 1 have the following displacement and velocity values for the four ranges of the dominant frequency: 0.76 mm (0.03 in) for 1-4 Hz, 19 mm/s (0.75 in/s) for 4-15 Hz, 0.2 mm (0.008 in) for 15-40 Hz, and 50.8 mm/s (2.0 in/s) for 40-100 Hz. The limit of 19 mm/s (0.75 in/s) for 4-15 Hz is used for drywall while the limit of 13 mm/s (0.5 in/s) for 2.5-10 Hz is applied for plaster.

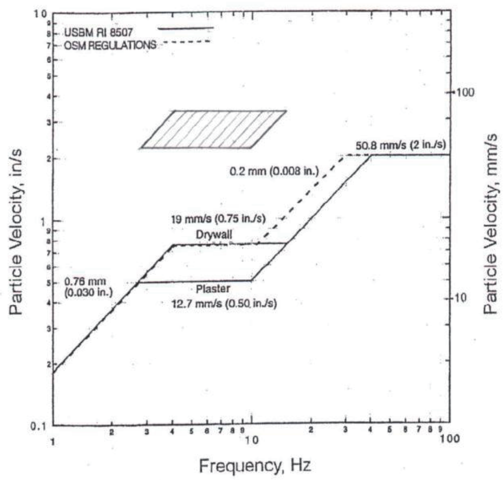

Figure 1. Safe level blasting criteria from USBM RI 8507 and the derivative version (dashed line), the Chart Option from OSM surface coal mine regulations. Shaded area shows maximum velocities of structural vibrations with amplification of 4.5 at resonance. Data were modified from Siskind (2000) and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

The USBM vibration limits 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 which are most typical structures in urban and rural areas, and these limits are applied for ground vibrations as the criteria of the possible crack formation in houses. The USBM research study has been recognized as the great achievement which provides the safety of low-rise residential houses from vibrations generated by surface coal mining blasting. The USBM criteria without doubt are good for the specific blast design, soil conditions and the types of structures they were developed for, but they cannot be automatically used in a number of cases with different blast, soil and structure conditions (Siskind et al. 1980, Siskind 2000). For example, the authors of the USBM vibration limits suggested the limit of 3 mm/s (0.12 in/s), which is four time less than the lowest limit of the USBM criteria, for a soil stratification with a high water table and low wave attenuation in Florida, (Siskind and Stagg 2000). A brief description of that report can be found in Svinkin (2005).

The existing regulations are conservative for assessment of direct blasting vibration effects on structures in the non-resonant frequency zones of structural vibrations when ground vibrations do not trigger plastic soil deformations under structures, but they cannot protect low-rise structures from appearance of cosmetic cracks by amplification of ground vibrations higher than 4.5x (the maximum amplification of ground vibrations used in the USBM RI 8507) and beyond the 4-12 Hz frequency range, and also from dynamic settlement. Furthermore, the application of these limits to different super and underground structure is incorrect. AASHTO Designation: R 8-96 (2004) stated the application of the USBM limits to markedly different types of structures is common and inaccurate. Siskind (2000) mentioned that the USBM criteria do not cover nonresidential cases: concrete, power poles, pipelines, bridges, etc.

5.2 Standard ANSI S2.47-1990

ANSI S2.47-1990 is 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 evaluating vibration effects on buildings. The evaluation of the effects of building vibration is primary directed at structural response, and includes appropriate analytical methods where the frequency, duration and amplitude can be defined.

According to the Standard, measurement of vibration in buildings is carried out for a variety of purposes such as problem recognition, control monitoring, documentation, and diagnosis. Diverse source-related factors are considered: characteristics of vibration responses in buildings (deterministic and random); duration (continuous and transient); frequency; and range of vibration severity. Building-related factors are also considered: type and condition of buildings; natural frequency and damping; building base dimensions; soil structure interaction; soil compaction with notes of importance of dynamic settlements in evaluating vibration severity and diagnosing vibration-related damage, but this assessment is beyond the scope of the Standard; and quantity to be measured.

The Standard presents preferred measuring quantities for different sources of vibrations. For example, toward blasting ground-borne vibrations, there is the 1-300 Hz frequency range and 0.2-500 mm/s (0.008-20 in/s) velocity range; toward pile driving ground-borne vibrations, there is the 1-100 Hz frequency range and 0.2-50 mm/s (0.008-2 in/s) velocity range. It is necessary to point out that the upper velocity limit of structural vibrations from pile driving is underestimated because structural vibrations with PPV of 50 mm/s (2 in/s) cannot usually damage structures. Nevertheless, a procedure available in the Standard can be used for evaluation of any measured structural vibrations generated by pile driving.

Obviously, ANSI S2.2.47-1990 is not used in the construction industry because of involvement of structural dynamics in measurement of structural vibrations and assessment of vibration effects on structures, but in complicated situations, this Standard should be used for evaluation of pile installation effects on adjacent and remote structures.

5.3 *Russian criteria*

The Russian limits of 30-50 mm/s (1.18-1.97 in/s) for vibrations of sound structures were found by the Moscow Institute of Physics of the Earth to assess the safety of structures from explosive effects of various blasts in the air, on the ground, and under the ground at the time of the Second World War (Sadovskii 1946). These vibration limits well work for building vibrations exited by different dynamic sources. It is necessary to perform direct measurement of structural vibrations accompanied by observation of the results of dynamic effects. Thus, for multi-story residential, commercial and industrial buildings, the frequency-independent safe limit of 51 mm/s (2 in/s) can be chosen for PPV of structural, not ground, vibrations. Under the condition of elastic soil deformations, this criterion automatically takes into account soil-structure interaction for the whole building frequency range. In the support of this criterion, it is necessary to underline that according to the USBM study, the PPV of 51 mm/s (2 in/s) is the highest vibration level generated inside houses by walking, jumping, slamming doors, etc. (Siskind 2000). Besides, this vibration limit is compatible with the European Standards, and it does not exclude higher allowable vibration levels (Svinkin 2008).

It is easy to demonstrate compatibility of this simplified safe criterion with some existing regulations such as the USBM and OSM vibration criteria (Figure 1). To evaluate tolerable structural vibrations, the smallest vibration limits of 13 mm/s (0.5 in/s) and 19 mm/s (0.75 in/s) from the USBM vibration criteria have to be multiplied by 4.5 (the maximum amplification of ground vibrations by structures used in these regulations), and their products of 57 mm/s (2.25 in/s) and 85.5 mm/s (3.37 in/s) are higher than the simplified criterion of 51 mm/s (2 in/s), Figure 1. It is important that the limit of 51 mm/s (2 in/s) for structural vibrations can be applied for assessment of vibration effects on 1-2 story houses as well.

5.4 *Criteria for dynamic settlement*

There are no regulations of the critical levels of ground vibrations which may trigger dynamic settlements beyond the densification zone. However, there are a few publications with information about the vibration levels of ground vibrations which may trigger dynamic settlements. Dowding (1996) used the limit of 2 mm/s (0.08 in/s) to determine a distance for preconstruction survey. Lacy and Gould (1985) analyzed 19 cases of settlements from piles driven by mostly impact hammers in narrowly-graded, single-sized clean sands with relative density less than about 50 to 55 %. They 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. Clough and Chameau (1980) revealed that acceleration higher than 0.05 g can trigger dynamic settlement in loose sands with rubble and broken rock. This criterion is adequate to the peak particle velocity of 4.3 mm/s (0.17 in/s) for the frequency of 18 Hz of ground vibrations from the vibratory driver.

5.5 *Criteria for structures with sensitive equipment*

Vibration limits for sensitive equipment and operation should be received from manufacturers. For example, Grose and Kaye (1986) obtained data from the computer manufacturer regarding the acceptable intensity of floor vibrations for installation of almost 400 driven piles on a site bounded by two vibration sensitive structures.

Boyle (1990) accumulated information from computer manufacturers such as IBM, ICL, Hewlett Packard and NCR which determined the following tolerable vibrations of mainframe disk drives. Constant amplitude vibration limits over the frequency range of 5 to 500 Hz: functional limits are between 0.2 g and 0.25 g and survival limits can be 0.5 g. Impact vibration limits: functional limits for the impact with maximum 11 ms duration are about 3 g. This value is commented as a slightly conservative estimate because disk drives have still functioned at vibration levels up to 4 g at the ground under earthquake simulation tests.

5.6 *Comparison of measured PPV with vibration limits*

It is common to compare the maximum single PPV of three components of measured ground vibrations with the vibration limits. Sometimes, the instantaneous vector sum is used. However, consideration of such a vector makes sense when the frequency contents of three components are the same, but it happens very seldom.

6 VIBRATION MEASUREMENTS AND CONDITION SURVEYS OF STRUCTURES

It is common to calculate and measure ground vibrations from pile driving for assessment of vibration effects on structures and compare them with the USBM vibration limits. However, these criteria were developed for protection of 1-2 story houses from surface coal mining blasts, and these criteria have nothing to do with ground and structural vibrations generated by pile driving. There is no legal basis to use these vibration limits for evaluation of pile driving effects on structures. As it was mentioned before, the application of the USBM limits to markedly different types of structures is common and inaccurate.

Approximate calculation of expected ground vibrations and even vibration monitoring yield relative information on vibration effects on structures, and these results could be inconclusive. Moreover, there is uncertainty in application of the existing vibration limits for assessment of pile driving effects on soils and structures. Therefore, it is necessary to perform condition surveys of structures before, during and after pile installation which provide complete information on structural responses to vibration excitations. Obtained information can be much beneficial than vibration assessment and measurements for analysis of causes of damage to structures.

It is reasonable to use the results of condition surveys to judge vibration contributions to structural damage. The following are three examples from a writer experience.

First case history (California). Dynamic compaction was conducted near the existing residential houses built on peat. All houses and their driveways had previous damage from peat deformations. It was difficult to determine what additional damage was done by dynamic compaction. Nevertheless, one home owner completely repaired his house and driveway before the beginning of dynamic compaction, and a preconstruction condition survey was made for this house. Therefore, new damage to this house triggered by dynamic compaction was easily recognized.

Second case history (Vermont). Blasting and pile driving were conducted at distances of 9-15 m (30-50 ft) from one story administrative building which received serious damage. The results of vibration measurements were inconclusive. Due to condition surveys performed before, during, and after construction, it was found that a geotechnical hazard, slow slope sliding, was the cause of damage to the building. Blasting and pile driving did not produce damage to that building.

Third case history (Michigan). Vibratory and impact sheet pile driving made damage to a new two story house. The vibration limit of 5 mm/s (0.2 in/s) was used. However, such decreasing of the vibration limit in a comparison with the USBM criteria 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. Then a vibratory driver was replaced with an impact hammer which completely destroyed a driveway of the house. Conditions surveys of this house were performed before, during, and after construction.

One more representation from Kesner et al. (2006) who successfully controlled vibrations of two historic buildings from construction activities with daily condition surveys of building structures.

It is important in the preconstruction survey to check the stability of the soils surrounding the pile driving site. Densification of loose material and slope movement can occur during pile driving vibrations, and this possibility must be considered when establishing of the control limits for ground motions. At sites with possible dynamic settlement, the distance for preconstruction survey shall be increased.

There is the criterion of 60 m which could be good for a number of sites but not for all of them. For example, there is an interesting case with building settlement developed at a distance of about 305 m (1000 ft) away from a pile driving site, Kaminetzky (1991). Foundations of the buildings were underpinned on piles down to the tip elevation of the new driven piles to prevent building settlements. Possible dynamic settlement was not detected at the time of a preconstruction survey because condition surveys at such large distances are unpractical and will mostly waste time and money. However, the pile driving contractor immediately responded to the sign of dynamic settlement and prevented building damage. The prudent approach is to always proceed with caution when the condition of settlement is known to exist. The contractor must provide a fast response to complaint on structural damage due to vibrations from pile driving.

There are a considerable diversity of buildings and their structures. For instance, floors, external and internal walls, roofs, etc., have different responses to the same ground vibrations. Besides, subjects of concerns are structure contents such as computerized systems, instrument cabinets, medical apparatuses and other sensitive devices in office buildings and glass and china in residential houses that also have their own responses to ground vibrations. It is imperative to measure structural vibrations for correct assessment of vibration effects on structures in accordance with Standard ANSI S2.47-1990 which is the U.S. counterpart of the International Standard ISO 4866-1990.

It is important to underline that only measurement of floor vibrations at locations with sensitive equipment and their comparison with vibration limits can prevent damage to such equipment. Grose and Kaye (1986) described installation of hundreds piles in close proximity to two vibration sensitive structures with the main-frame computer. During pile testing, pile driving parameters were adjusted to keep floor vibrations measured near the computer below the vibration limits allowable for the computer.

7 CONCLUSIONS

Approximate calculations of expected ground vibrations and even vibration monitoring yield relative information about vibration effects on structures, and these results could be inconclusive. Moreover, there is uncertainty in application of the existing vibration limits for assessment of pile driving effects on soils and structures. At the same time, condition surveys of structures before, during, and after pile installation provide complete information on structural responses and damage from vibration excitations and these acquired facts can be much beneficial for analysis of the causes of damage to structures than vibration assessment and measurements. Therefore, condition surveys have to be used together with vibration monitoring and control.

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