FINAL REPORT

EVALUATION OF VIBRATION LIMITS AND MITIGATION TECHNIQUES FOR URBAN CONSTRUCTION

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SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^{o}C

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16. Abstract

The overriding purpose of this research was to develop a comprehensive framework to address vibration issues prior to and during construction, including calculation of anticipated ground vibrations during project design, condition surveys of structures, vibration limits, mitigation strategies to control ground and structural vibrations from construction sources, and recommendations for improvement of current FDOT Specifications. Using the field data specific to Florida as collected and sorted over the course of this research, simple equations were developed to calculate the maximum peak particle velocity (PPV) of expected ground vibrations prior to construction operations. This research also provided a comprehensive review of and guidelines for pre-construction condition surveys, analysis of the effects of different factors on vibration limits, accompanied by a comparison of the criteria from diverse sources, a summary of the existing preventive and counteractive vibration mitigation techniques used by the industry, and a review of effective mitigation measures to decrease vibration effects from roadway and bridge construction operations in Florida. Finally, the relevant findings of this research were compiled under "Recommendations for Improvement of FDOT Specifications." These recommendations cover a broad base, including pile driving operations and their vibration effects, survey of sites and structures, mitigation measures, calculation of PPV prior to construction, and vibration limits.

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EXECUTIVE SUMMARY

Construction activities, such as pile driving, dynamic compaction of loose soils, and operation of heavy construction equipment, induce ground and structure vibrations. Their effects range from a nuisance to the local population and the disturbance of working conditions for sensitive devices, to the diminution of structure serviceability and durability. It is necessary to recognize the different vibration effects of roadway and bridge construction operations on structures, as well as on people and sensitive devices in urban areas.

The overriding purpose of this research was to develop a comprehensive framework to address vibration issues prior to and during construction, including calculation of expected ground vibrations during project design, condition surveys of structures, vibration limits, mitigation strategies to control ground and structural vibrations from construction sources, and recommendations for improvement of current FDOT Specifications.

State highway agencies, as well as consulting, design, and construction companies, have vast experience in managing the vibration problems generated by construction activities. To benefit from this experience and establish the current state-of-the-practice on the subject matter, a questionnaire was administered to relevant entities, including FDOT Districts, other State Departments of Transportation, consulting, design, and construction companies, and vibration consultants. The survey found out that most of the respondent FDOT Districts (75%) have experienced vibration damage caused by construction operations. The major types of construction operations that cause vibration damage included pile driving, sheet pile installation and extraction, and asphalt compaction. The respondents also stated that vibration damage to structures from pile driving or other operations has resulted in various claims against the agency and the contractor.

For practical goals, it is important to assess the anticipated ground vibrations in terms of maximum peak particle velocity (PPV) during project design. Using the field data specific to Florida as collected and sorted over the course of this research, simple equations were developed to calculate the maximum PPV of anticipated ground vibrations during project design. Simple equations were also derived for calculation of anticipated ground vibrations associated with sheet pile driving, drilled shaft casing operations, and vibratory roller operations.

This research also provided a comprehensive review of and guidelines for pre-construction and post-construction condition surveys, analysis of the effects of different factors on vibration limits accompanied by a comparison of the criteria from diverse sources, a summary of the existing preventive and counteractive vibration mitigation techniques used by the industry, and a review of effective mitigation measures to decrease vibration effects from roadway and bridge construction operations in Florida.

Finally, the relevant findings of this research were compiled under “Recommendations for Improvement of FDOT Specifications.” These recommendations cover a broad base, including pile driving operations and their vibration effects, survey of sites and structures, mitigation measures, calculation of PPV during project design, and vibration limits.

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1. INTRODUCTION

1.1 Background

Construction activities, such as blasting, pile driving, dynamic compaction of loose soils, and the operation of heavy construction equipment, induce ground and structure vibrations. Their effects range from a nuisance to the local population and the disturbance of working conditions for sensitive devices to the 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 the appropriate agencies and authorities. Furthermore, the implementation of construction projects in areas adjacent to existing structures creates additional difficulties. In this respect, the disruption of some businesses, possible structural damage, and annoyance to the public are problems that need to be addressed.

The level of ground and structure vibrations depends on the energy level of vibration source; 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 to the dynamic sources. However, substantial structure damage may also occur at long distances from the sources, on account of the dynamic effect of low-frequency ground vibrations. In addition, foundation settlements resulting from soil vibrations in loose soils may happen at various distances from the source.

1.2 Project Objectives

It is necessary to recognize the different vibration effects of roadway and bridge construction operations on structures, as well as on people and sensitive devices in urban areas. Furthermore, there are problems with calculating the anticipated ground vibration in terms of peak particle velocity (PPV) during project design, and limited liability of the vibration limits used by the construction industry. Currently, 0.5 in/s is the general PPV limit in FDOT projects, while 0.2 in/s is used by some districts on entire projects. The 0.2 in/s limit tends to reduce complaints, but does not eliminate them. Vibratory rollers, tandem rollers, and sheet pile installation in particular are a major source of vibration-related complaints in FDOT projects.

In addition to anticipated vibration levels and utilized vibration limits, more work is also needed on different aspects of the subject matter, such as review of proper vibration mitigation techniques, effective use of pre-construction and post-construction surveys, and use of appropriate vibration limits depending on soil deformation and soil-structure interaction.

Based on the problem statement above, the overriding purpose of this research was to develop a comprehensive framework to address vibration issues prior to and during construction, as is to be included in the Standard Specifications. The specific objectives of this research included: i) analysis of the current practice in assessment and control of the vibration effects of construction operations in Florida, ii) development of appropriate equations for the calculation of anticipated maximum ground vibrations prior to the beginning of construction activities, iii) review of condition surveys of structures at different construction stages as an important step in handling vibration effects from construction operations, iv) evaluation of diverse vibration limits of ground and structural vibrations for application to roadway and bridge construction in Florida, v) evaluation of mitigation strategies to control ground and structural vibrations from construction sources, and vi) development of “Recommendations for the Control of Ground and Structural Vibrations from Roadway and Bridge Construction.”

1.3 Methodology

This research study was conducted by following a work plan which consisted of ten tasks.

Task-1: Literature Review

In executing Task-1, the research team obtained, analyzed, and summarized relevant research, documentation, and reports to support the objectives of, and provide tools and data for, this research. The discussion points were grouped under five categories including: (i) effects of construction vibrations on structures, (ii) calculation, prediction, and measurement of ground and structural vibrations, (iii) vibration limits, (iv) relevant experience in Florida, and (v) vibration measurements and the condition surveys of structures.

Task-2: Questionnaire Survey

State highway agencies as well as consulting, design, and construction companies have experience in the managing of vibration problems generated by construction activities. To benefit from this experience, in Task-2 a questionnaire survey was administered to relevant entities located in Florida and the United States. The survey was delivered as an online link embedded in an e-mail cover letter customized for the participant. The survey process was professionally managed by the research team using Qualtrics™, an online survey tool for designing, distributing, and evaluating survey results.

Task-3: Collect and Sort Available Field-measured Data from Construction Operations in Florida

The different vibration effects of construction operations result in different damage modes of nearby existing structures and buried utilities. In order to better understand structure damage due to vibrations from construction sources, a full range of information needs to be monitored during the construction. In Task-3, all such field-measured data and other relevant information available from FDOT and other sources were collected, organized, and displayed using tables, graphs, and charts. This information included but was not limited to: (i) general construction site information and construction records, (ii) geotechnical conditions at the project sites, (iii) information on sources of construction vibrations (e.g., pile driving, dynamic compaction, and heavy equipment), (iv) vibration records made on the ground and structures, (v) results of condition surveys and possible damage to structures, and (vi) vibration effects on sensitive objects. The data collected and sorted in this task was analyzed in the subsequent tasks.

Task-4: Interim Report

In Task-4, an up-to-date summary of progress in each task was presented to FDOT in an interim report.

Task-5: Develop Simple Equations to Calculate PPV of Ground Vibrations

For practical goals, during the design of a project, it is important to assess the anticipated maximum PPV of ground vibrations. In Task-5, using the field data specific to Florida as collected and sorted in Task-3, simple equations were developed to calculate the maximum PPV of expected ground vibrations during project design.

Task-6: Review Criteria and Standardized Procedures for Pre-construction Surveys

A survey of structures before construction operations begin is imperative to determine the condition of structures, including the buildings' susceptibility to vibration effects from construction activities, possible dynamic settlement hazard, and vibration background. Pre-construction and post-construction surveys coupled with surveys during construction provide useful information on structural responses to vibration excitations. In Task-6, the research team developed standardized procedures and criteria for pre-construction and post-construction surveys to be used in FDOT projects.

Task-7: Evaluate Limited Liability of the Existing Vibration Criteria and Develop New Appropriate Vibration Limits for FDOT Projects

The existing vibration criteria provide no distinctions for type, age, or the stress history of structures and do not take into account building configuration. In Task-7, the research team analyzed the information collected on vibration limits in previous tasks, as well as the existing vibration criteria to develop new and more appropriate vibration limits for FDOT's construction projects.

Task-8: Evaluate Mitigation Measures to Control Ground and Structural Vibrations from Roadway and Bridge Construction

In addition to the pre-construction and post-construction surveys and vibration prediction, construction vibrations must be monitored and, if required, proper vibration mitigation measures have to be taken during construction. In Task-8, the research team performed a detailed analysis of the existing preventive and counteractive vibration mitigation techniques used by the industry, and recommended effective mitigation measures to decrease vibration effects from roadway and bridge construction operations in Florida.

Task-9: Develop “Recommendations for the Control of Ground and Structural Vibrations from Roadway and Bridge Construction”

This research provided recommendations for addressing vibration issues prior to and during construction in FDOT projects. The developed recommendations were based on a synthesis of the results of the previous research tasks and cover a broad base including pile driving operations and their vibration effects, survey of sites and structures, mitigation measures, calculation of PPV during project design, and vibration limits.

Task-10: Prepare the Final Report

In Task-10, the final report of the research project was prepared with a demonstration of all findings.

2. LITERATURE REVIEW

2.1 Introduction

Construction activities such as pile-driving, dynamic compaction of loose soils, and the operation of heavy construction equipment induce ground and structure vibrations. Their effects range from a nuisance to the local population and the disturbance of working conditions for sensitive devices, to the 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 the appropriate agencies and authorities. Furthermore, the implementation of construction projects in areas adjacent to existing structures creates additional difficulties. In this respect, disruption of some businesses, possible structural damage, and annoyance to the people are problems that need to be dealt with.

The level of ground and structure vibrations depends on the dynamic construction source, 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 to the dynamic sources. However, substantial structure damage may also occur at long distances from the sources on account of the dynamic effect of low-frequency ground vibrations. In addition, foundation settlements resulting from soil vibrations in loose soils may happen at various distances from the source.

It is necessary to recognize the different vibration effects of roadway and bridge construction operations on structures, as well as on people and sensitive devices in urban areas. Besides, there are problems with calculating the peak particle velocity (PPV) of ground vibrations before the beginning of construction activities and vibration limits used by the construction industry. In addition to anticipated vibration levels and utilized vibration limits, more work is also needed in different aspects of the subject matter, such as identification of proper vibration mitigation techniques, effective use of pre-construction surveys, and the use of correct vibration limits depending of soil deformation and soil-structure interaction.

The discussion points are grouped under five categories including: (i) effects of construction vibrations on structures, (ii) calculation, prediction, and measurement of ground and structural vibrations, (iii) vibration limits, (iv) experience in Florida, and (v) vibration measurements and condition surveys of structures.

2.2 EFFECTS OF CONSTRUCTION VIBRATIONS ON STRUCTURES

Sources of construction vibrations generate body and surface waves in the 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, are transmitted 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 is 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 wave 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 dies away before the next impact occurs. Such vibrations are excited by air, diesel, or steam impact pile drivers, by the dynamic compaction of loose sand and granular fills, and by construction 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 1 and 100 Hz, respectively. 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 ranges from 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. Both double-acting impact hammers operating at relatively high speeds and heavy machinery excite such vibrations. The dominant frequency range the waves generated by this type of equipment is about 7 to 60 Hz.

During dynamic excitation, stress waves propagate in the soil medium and induce soil deformations (ground 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 on adjacent and remote structures. Moreover, vibratory pile driving may trigger resonant soil layer vibrations. Under certain circumstances related to soil deposit and dynamic movement (vibrations or displacements), stress waves can be the cause of plastic soil deformations and dynamic settlement. Soil-structure interaction will be different for soil failure. Thus, the structural response to ground excitation depends on soil deformations that are triggered by waves propagated from the source, as well as soil-structure interaction (Svinkin, 2008).

Assessment of construction vibrations on structures is a complicated problem. There are a considerable diversity of buildings and underground facilities. These structures and their parts, for instance, floors, internal walls etc., have different responses to the same ground vibrations. Besides, subjects of concerns are structure contents such as glass and china in residential houses, computerized systems, instrument cabinets, medical apparatuses and other sensitive devices in offices that also have their own responses to ground vibrations.

For example, spectra of door step, wall, instrument cabinet and ground vibrations from an impact made by a falling weight of 1 tonne dropping from a height of 1 m on the ground near the structure are depicted in Figure 1. It can be seen different ground, structure and instrument cabinet responses to the same impact. Thus, the amplitude of the instrument cabinet response was 2.7 and 12 times larger than the amplitude of ground adjacent to the building and door step vibrations, respectively. The dominant frequency of cabinet vibrations was about 6 times smaller than the frequency of ground adjacent to the building and door step vibrations. It is impossible to correlate structural responses to ground vibrations with the same ground PPV (Svinkin, 2006).

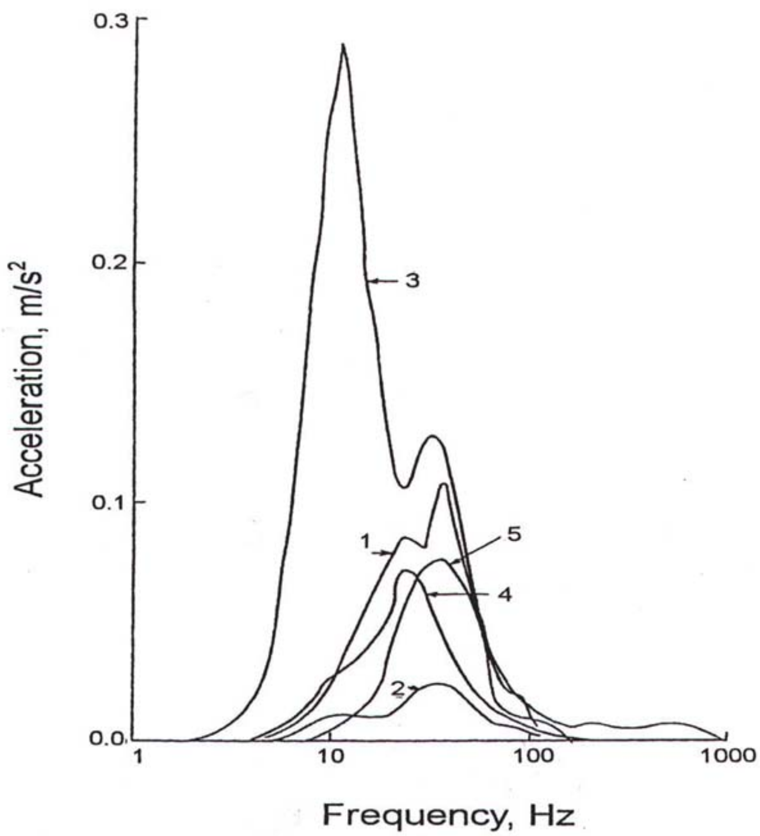


Figure 1: Ground, structure and equipment responses to test weight dropping on ground: 1 – on ground adjacent , 2- on door step, 3 – on instrument cabinet, 4 – on first floor wall, 5 –on ground at some distance from building. Note: source 1 tonne, dropping - 1 m, distance – 9 m from (1), accelerometers all horizontal in same direction. ***From Eldred and Skipp (1998)***

Ground vibrations from pile driving may affect adjacent and remote structures in several different ways as follows. Because elastic and plastic soil deformations cause dissimilar structural responses and damage, diverse thresholds are used for assessment of direct vibration effects, resonant structural vibrations, resonant soil vibrations, and dynamic settlements.

Direct Vibration Effects

Direct damage to structures occurs as a result of soil-structure interaction when the frequencies of ground vibrations do not match the natural frequencies of structures. Such damage may occur within a distance of about one-pile length from the driven pile (Woods 1997). These distances can be substantially larger for susceptible structures. According to data available in Siskind et al. (1980), direct minor and major structural damage to one- to two-story houses without resonant structural responses are observed in the velocity range of 1.3-7.5 in/s for frequencies of 2 to 5 Hz, and in the velocity range of 4-10 in/s for frequencies of 60 to 450 Hz.

Resonant Structure Vibrations

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

For remote structures, the proximity of the low-frequency components of ground vibrations induced by impact hammers to that of a building's natural frequencies may generate the condition of resonance in the building and trigger large horizontal vibrations.

For one- to two-story residential houses, a dynamic magnifying factor at resonance was measured in the limits of 2 to 9. This factor can be much higher for buildings of more than two stories. 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 reducing resonant horizontal building vibrations, but fortunately these vibrations seldom occur.

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

Resonant Soil Vibrations

Matching the dominant frequency of propagated waves to the frequency of a soil layer can create the condition of resonance and generate large soil vibrations. Such amplification of soil vibrations may happen during vibratory pile driving. According to Woods (1997), layers between about 1 and 5 m (3.28-16.4 ft) thick may produce a potential hazard for increasing vibrations when vibrators with operating frequencies between 20 and 30 Hz install piles in soils with shear wave velocities of 120 to 600 m/s (390-1970 ft/s). The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to the accidental soil layer resonant vibrations.

Resonant effects may occur at any point within a layered soil profile. It is possible to consider two locations with the same soil within the same site excited by the same dynamic source, and these locations could respond quite differently because of the nature and dimensions of surrounding soil layers (Davis and Berrill, 1998).

Dynamic Settlements

Different forms of dynamic settlements exist in sand and clay soils. Relatively small ground vibrations can be the cause of dynamic settlement in sandy soils, while horizontal ground displacements, as opposed to vibrations, can be the cause of heave and subsequent settlement in soft and medium clays.

Soil Settlement in Sand Soils

Pile installation in sand may cause soil and structure settlements due to the densification and liquefaction of vulnerable granular soils. Large settlements had been observed in loose to medium dense sands with a relative density of less than 70%. Soil classification and relative density of cohesionless soils can be derived from the results of a cone penetration test (CPT), which has often been employed for the geotechnical investigation of highway projects. Therefore, it is anticipated that a dynamic settlement-prone soil layer might be reasonably identified if the CPT results for construction site soils are available.

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

Soil Settlement in Clay Soils

Pile installation in clay is different from pile driving in sand. Pile penetration into clay produces an increase in lateral stresses, pore pressures, and heaves of the ground surface. During pile driving, the excess pore pressure increases with each driven pile and may reach large values at distances far beyond the pile group area. This excess pore pressure can be much greater 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 the dynamic loading-induced settlement is present at a construction site. Effects of pile driving in soft to medium clay on the surrounding area should be expected at distances from the pile installation equal to about the thickness of the clay layer being penetrated.

Additional Causes of Damage

Soil excavation associated with pile driving and made in close proximity to existing buildings can produce structural damage. Permanent excavation deformations induced in adjacent structures generally exceeded those from pile driving equipment. 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.

2.3 Calculation, Prediction, and Measurement of Ground and Structural Vibrations

Ground vibrations can be calculated or predicted before the beginning of construction activities or measured at the time of construction operations. In practice, Golitsin's and

Wiss' equations are used to calculate the expected PPV of ground vibrations; two more approaches are also presented below.

Golitsin's Equation

About 100 years ago, Golitsin (1912) derived a simple and sensible equation for surface waves generated by earthquakes to calculate a reduction of the maximum displacement of ground vibrations between two points at distances r_1 and r_2 from the source as

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

Where A_1 = peak particle displacement of ground vibrations at a distance r_1 from the source, A_2 = peak particle displacement of ground vibrations at a distance r_2 from the source, and 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 the attenuation of low-frequency Rayleigh waves with large wavelengths 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 the assessment of wave attenuation in soils.

From 1930's, a number of researchers used Equation (1) for preliminary computation of the peak particle velocity of ground vibrations from industrial and construction sources. Such an application of Equation (1) is inaccurate because waves generated by these sources have higher frequencies and smaller wavelengths in comparison with surface waves from earthquakes, and propagate mostly in the upper soil strata close to the ground surface. For such circumstances, the coefficient γ, which is important for the accurate calculation of wave attenuation, changes in the broad range for an arbitrary arrangement of geophones, and it can yield incoherent results of ground vibration measurements because waveforms measured in arbitrary locations at a site might represent different soil layers (Svinkin, 2008).

For the reasons mentioned above, Equation (1) was not chosen for the preliminary calculation of ground vibrations prior to the beginning of construction operations.

Scaled-distance Approach

For the assessment of ground vibration attenuation generated by blasting, pile driving, and other construction sources, any distance D from a source is normalized (scaled) with the applied energy W. The most popular approach is square-root ($D/W^{1/2}$) scaling. Wiss (1981) applied the scaled-distance approach (SD) for construction sources of vibrations and proposed the following scaled-distance equation to calculate the peak particle velocity of ground vibrations:

$$v = k[D/\sqrt{W_t}\,]^{-n} \qquad (2)$$

Where W_t = energy of source, and k = value of velocity at a scaled distance, ($D/W_t^{\,½}$), of one. The value of 'n' yields a slope of amplitude attenuation for all tested soils in the narrow range of 1 to 2 on a log-log chart.

Equation (2) provides very rough assessment of ground vibrations as a function of the source energy and at a horizontal distance, D, 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. However, equation (2), adjusted for site soil conditions and pile types with field pile testing, provides better results than equation (1) for rough assessment of expected PPV of ground vibrations generated by pile driving.

IRFP Method

The Impulse Response Function Prediction (IRFP) method was developed for the prediction of complete time-domain records on existing soils, buildings, and equipment prior to the 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. It 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 in Svinkin (1996), this method can be used to predict ground and structure vibrations from construction sources, such as impact pile driving and dynamic compaction. Wave equation analysis can be used to assign a pile movement, but it is necessary to underline that the pile movement can be also assigned arbitrarily (for example, as a dampened sinusoid) because ground vibrations at some distance from a dynamic source depend only on the dynamic force transmitted on the ground and soil properties (Svinkin, 2002).

The following is a general outline of the IRFP method for the prediction of complete vibration records of soil and structures prior to installation of a dynamic source: (i) at the place chosen for impact dynamic source, impulse loads of known magnitude, which should be no smaller than 10 times less than the dynamic load of the source, are applied on the ground; (ii) 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), and these oscillations are the IRFs of the considered system, which automatically take into account complicated soil conditions; and (iii) convolution integral of IRF and dynamic loads transferred onto the ground is calculated 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 a depth of about 30 ft below the ground surface affects the intensity of ground vibrations. The high soil resistance with deeper pile penetration into the ground slightly affects ground surface vibrations. Therefore, it makes sense to use the IRFP method at sites with stiff upper soil layers and buildings containing sensitive equipment.

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.

Some comments are necessary. (1) 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. (2) Obviously, the effect of pile-soil interaction on ground vibrations and pile capacity depend on hammer energy. There is a typical statement in a number of papers that pile capacity was not mobilized because of the low hammer energy. (3) During pile installation, ground vibrations should be measured, not calculated.

2.4 Vibration Limits

There are no general regulations developed for the assessment of ground and structure vibrations generated by construction operations and equipment. However, there are limits of ground vibrations as the basis for the cosmetic cracking threshold developed in the blasting industry for low-rise residential structures, the ANSI Standard for vibration of buildings from various dynamic sources, and other vibration criteria.

USBM RI8507 Criteria

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

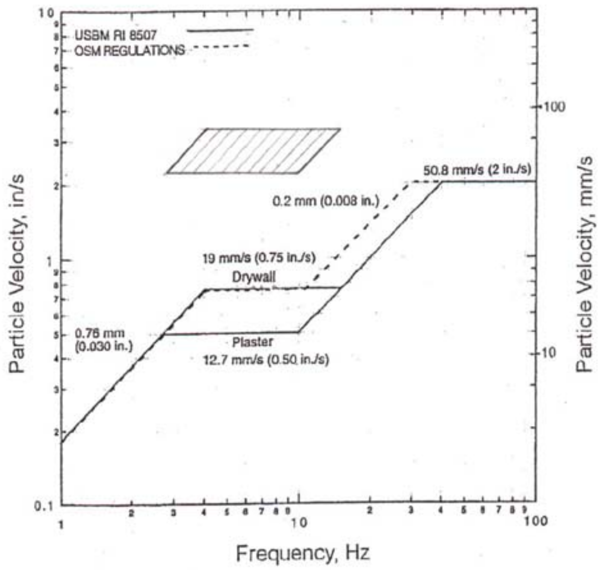


Figure 2: Safe level blasting criteria from USBM RI 8507 and the derivative version (dashed line), the Chart Option from OSM surface coal mine regulations. Shaded area shows maximum velocities of structural vibrations with amplification of 4.5 at resonance. *Data were modified from Siskind (2000) and plot was adapted from Svinkin (2008).*

The USBM vibration limits were developed on the basis of two decades of research studies on the correlation between ground vibrations and observations of cracking damage in one- to two-story houses, the most common structures in urban and rural areas. These limits are applied for ground vibrations as the criteria for the possibility of crack formation in houses (Figure 2). The USBM research study has been recognized as a great achievement that ensures the safety of low-rise residential houses from vibrations generated by surface coal mining blasting. The USBM criteria are, without a doubt, good for the specific blast design, soil conditions, and types of structures for which they were developed, but cannot be automatically used in a number of cases with different blast, construction vibration sources, soil, and structure conditions (Siskind et al., 1980 and Siskind, 2000). For example, the authors of the USBM vibration limits suggested the limit of 0.12 in/s (3 mm/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).

OSM Criteria

The derivative version of the USBM safe limits shown in Figure-2 was included as the Chart Option in the surface coal mine regulations by the Office of Surface Mining (OSM, 1983). The comments above on the USBM limits can also be addressed to the Chart Option. Nevertheless, Siskind (2000) pointed out simple and workable OSM distance-dependent PPV criteria for blasting: 31.8 mm/s (1.25 in/s) for 0 to 92 m (300 ft), 25.4 mm/s (1 in/s) for 92 m (301 ft) to 1525 m (5000 ft), and 19 mm/s (0.75 in/s) for distances greater than 1525 m (5000 ft). These vibration limits were found for low-rise residential houses.

The USBM and OSM vibration limits are irrelevant for the assessment of construction vibrations, but some data from the USBM and OSM studies are beneficial for the research of ground and structure vibrations generated by construction operations and equipment.

Standard ANSI S2.47-1990

ANSI S2.47-1990 is a guide known as the American National Standard: Vibration of Buildings – Guidelines for the Measurement of Vibrations and Evaluation of Their Effects on Buildings.

This standard is the U.S. counterpart of the International Standard ISO 4866-1990. It is intended to establish the basic principles for carrying out vibration measurement and processing data with regards to the evaluation of vibration effects on buildings. The evaluation of the effects of building vibration is primarily directed at structural responses and includes appropriate analytical methods in which the frequency, duration, and amplitude can be defined.

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

Florida DOT Criteria

Currently, 0.5 in/s is the general PPV limit in FDOT projects, while 0.2 in/s is used by some districts on entire projects. The limit of 0.2 in/s tends to reduce complaints, but does not eliminate them. Vibratory rollers, tandem rollers, and sheet pile installation in particular are a major source of vibration-related complaints in FDOT projects.

Russian Criteria

The Russian limits of 30 to 50 mm/s (1.18 to 1.97 in/s) for the vibrations of sound structures were found by the Moscow Institute of Physics of the Earth to assess the safety of structures from the 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 work well for building vibrations excited by different dynamic sources. It is necessary to accompany the direct measurement of structural vibrations with observation of the results of dynamic effects. As such, for residential buildings of more than two stories, commercial, and industrial buildings, the frequency-independent safe limit of 51 mm/s (2 in/s) can be chosen for the PPV of structural, and not ground, vibrations.

It is easy to demonstrate compatibility of this simplified safe criterion with some existing regulations such as the USBM and OSM vibration criteria (Figure 2). 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 2. 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.

Dynamic Settlement

All aforementioned vibration limits have nothing to do with the structural damage caused by plastic soil deformations. There are no federal, state, or local regulations addressing the critical ground vibration levels which may trigger dynamic settlement in soil.

Attempts to use the decreased values of the USBM limits for preventing dynamic settlements have been unsuccessful. For example, the research team experienced a case history of vibration effects on a two-story house from vibratory sheet pile driving. The vibration limit of 5 mm/s (0.2 in/s) was used for ground vibrations. This threshold is 2.5 times less than the smallest value from the USBM limits. However, such decreasing of the vibration limit did not prevent vibration damage to the house. A settlement crack was found in the brick chimney and the house’s driveway was destroyed. Also, vibratory sheet pile driving with a frequency of about 26 Hz triggered resonant vertical vibrations on the second floor, resulting in architectural damage to the house.

There are a couple of publications with information about the critical vibration levels of ground vibrations that may trigger dynamic settlements. Lacy and Gould (1985) analyzed 19 cases of settlements from piles driven mostly by impact hammers in narrowly-graded, single-sized clean sands with a relative density of less than about 50% to 55%. They found that the peak particle velocity of 2.5 mm/s (0.098 in/s) could be considered as the threshold of significant settlements at investigated sand sites. According to Dowding (1996), a pre-construction survey of all buildings has to be performed within a radius of 120 m (400 ft) of future pile driving (construction) activities, or out to a distance at which vibration of 2 mm/s (0.079 in/s) occurs. A peak particle velocity of 2 mm/s (0.079 in/s) is the limit beyond which dynamic settlement may be triggered. Woods (1997) stated that distances as great as 400 m (0.25 mi) may need to be surveyed to identify settlement damage hazard. Also, Woods has concluded that simple methods of estimating settlements in loose to medium dense sand during pile driving do not provide practical solutions. He pointed out that the prudent approach is to always proceed with caution when the condition of settlement is known to exist.

2.5 Experience in Florida

The following examples presented an experience of managing ground vibrations from pile driving in Florida.

Lynch (1960) reported installation of 30 cm (12 in) piles and 36 cm (14 in.) shells to the depth of about 18 to 24 m (60-80 ft) with a 41 kJ Vulcan hammer at Port Everglades. The soil at the site consisted of sand fill, organic silt, loose to medium dense sand, limestone, and compact sand. Telltale measurements of the test piles indicated downdrag loading the pile tip caused by sand compaction that settled previously driven piles up to 17.8 cm (7 in). Hesham et al. (2003) studied how construction-related vibrations impacted existing structures proximate to the areas of a large construction site in Palm Beach County, Florida. Based upon a simplified equation in which PPV depends on a distance and coefficients 'n' and 'k', the conservative allowable vibration level of 5 mm/s (0.2 in/s) was determined at distances between 80-125 m (262-410 ft) for different hammers. Heung et al. (2007) present the results of vibration monitoring studies conducted during pile driving operations on Florida's Turnpike Enterprise projects in central and south Florida. Most of the available data were derived from driving 455 mm (18 in) PPC piles. The study underlined the importance of predrilling to penetrate through a shallow medium dense layer and underlined use of correlations with scaled horizontal distance. Svinkin and Saxena (2004) performed a study of vibration effects of stormwater treatment construction on residential houses and vibration tests at a staging area. During tests, ground vibrations were measured from various vibration sources: driving of two sheet piles in parallel; driving of two perpendicular sheet piles; dropping a heavy weight on the ground; moving vibratory compactor and loader; and moving loader and excavation. It was concluded that environmental forces and aging processes in house materials appear to be the actual causes of the damages to houses.

2.6 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 not for the effects of pile driving. There is no legal basis to use these vibration limits for evaluation of pile driving effects on structures. AASHTO (2004) stated that 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 useful 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. For example, Kesner et al. (2006) successfully controlled vibrations of two historic buildings from construction activities with daily condition surveys of building structures.

The preconstruction survey should include field observations which may indicate existing unstable 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 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. 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.

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 the installation of hundreds of piles near a building with the mainframe 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.

3. QUESTIONNAIRE SURVEY

3.1 Introduction

State highway agencies as well as consulting, design, and construction companies have vast experience in managing the vibration problems generated by construction activities. To benefit from this experience and establish the current state-of-the-practice on the subject matter, a questionnaire survey was administered to relevant entities including FDOT Districts, other Departments of Transportation, consulting, design, and construction companies, and vibration consultants. This chapter presents a comprehensive discussion of the survey effort and an analysis of its results.

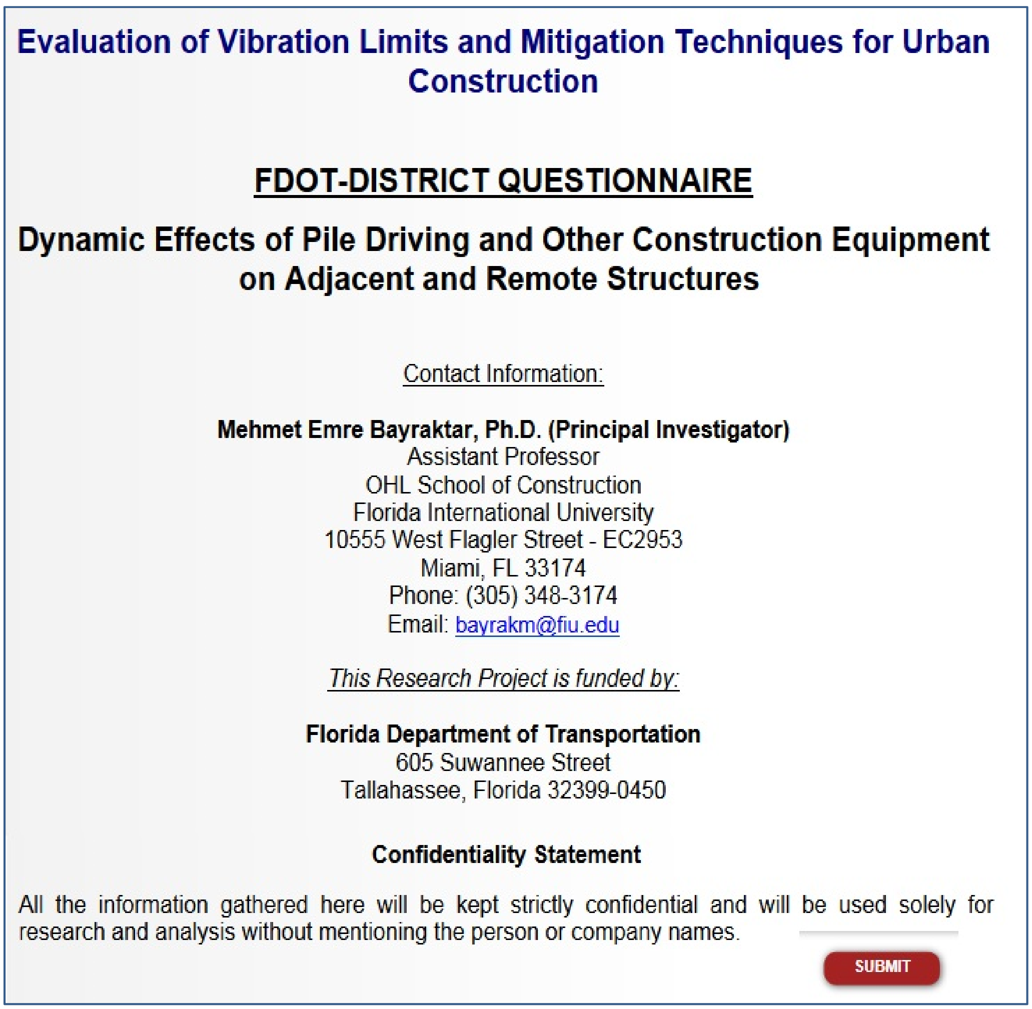
3.2 Survey Design and Administration

Knowledge from a previous questionnaire (Woods, 1997) was used for preparation of the survey questions. The survey was conducted under the title *"Dynamic Effects of Pile Driving and Other Construction Equipment on Adjacent and Remote Structures."* Four (4) versions of the questionnaire were designed, including questionnaires for FDOT Districts, other Departments of Transportations (DOTs), contractors, and vibration measuring firms / vibration consultants. In general, the information elicited through the surveys includes, but is not limited to, the following:

- Variation of soil conditions in Florida;
- Local experience in the implementation of condition survey of structures;
- Vibration limits used for ground vibrations generated by construction activities;
- Engineering measures to mitigate the effects of vibrations from construction operations; and
- State codes, local codes, and ordinances on vibrations.

The different questionnaires were also intended to retrieve some specific information from target respondents as shown in Figure 3.

Figure 3: Information collected from survey respondents



Evaluation of Vibration Limits and Mitigation Techniques for Urban Construction

FDOT-DISTRICT QUESTIONNAIRE

Dynamic Effects of Pile Driving and Other Construction Equipment on Adjacent and Remote Structures

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This Research Project is funded by:

Florida Department of Transportation
605 Suwannee Street
Tallahassee, Florida 32399-0450

Confidentiality Statement

All the information gathered here will be kept strictly confidential and will be used solely for research and analysis without mentioning the person or company names.

SUBMIT

Figure 4: Online survey cover page

The survey was delivered as an online link embedded in an e-mail cover letter customized for the participant. The survey process was professionally managed by the research team using Qualtrics™, an online survey tool for designing, distributing, and evaluating survey results. The snapshot of the cover page for the FDOT District questionnaire is shown in Figure 4.

3.3 Response Characteristics

Table 1 provides a summary of target respondents and information on their participation in the survey.

Table 1: Information on target respondents and survey participation

Questionnaire Type	Target Respondents	Number of Survey Invitations Sent	Number of Responses Received
FDOT District	District Geotechnical Engineers, Geotechnical Specialist, Construction Project Manager, etc.	All seven (7) FDOT districts plus Florida's Turnpike	Four (4)
Other State DOT	District Geotechnical Engineers, Geotechnical Specialist, Geotechnical Project Manager, etc.	All State DOTs throughout the United States	Eight (8)
Vibration measuring firm and/or vibration consultant	Regional/Area managers, Principal Engineers, Project Managers, etc.	Fourteen (14)	Four (4)
Contractor	Project Managers, Construction Engineers, and Bridge Project Administrators, etc. of different contractors working on transportation projects in Florida.	Fifteen (15)	One (1)
		Total Number of Responses	Seventeen (17)

The following sections summarize the results obtained from the survey for all four questionnaires including FDOT Districts, other State DOTs, contractors, and vibration measuring firms / vibration consultants. However, it should be noted that the findings of the survey are based on the information received from participating respondents and, therefore, should not be construed as applying to the whole country.

3.4 FDOT Districts

The objective of the FDOT District survey was to gather general information related to (1) Occurrence and Causes of Vibration Damage; (2) Effects of Soil Conditions; (3) Condition Surveys; (4) Vibration Monitoring; (5) Local Criteria and Procedures for Vibration-caused Problems; and (6) Preventive Measures to Decrease Vibration Effects.

Occurrence and Causes of Vibration Damage

Most of the respondent districts (75%) have experienced vibration damage caused by construction operations, as shown in Figure 5. The major types of construction operations that cause vibration damage include pile driving, sheet pile installation and extraction, and asphalt compaction. The four responding districts stated that vibration damage to structures from pile driving or other operations have resulted in various claims against state DOT and the contractor.

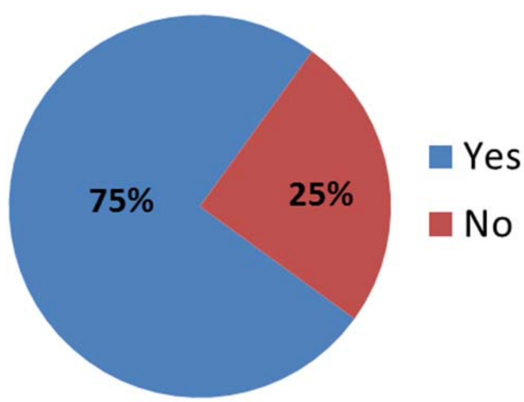

Figure 5: FDOT District experience with vibration damages

There were three (3) main reasons identified as the cause of damage to structures during pile driving and other construction operations. These are as follows:

- Planned operations were too close to the facility using the specific equipment and operation mode.
- Design plan did not provide restrictions or caution the contractor regarding the potential impact to existing structures.
- Sometimes, minor stucco cracking from pile driving and movement of Mechanically Stabilized Earth (MSE) wall panels from sheet pile driving/extraction were also found to be the cause of damage.

Effects of Soil Conditions

According to the respondents, soil conditions have also contributed to the vibration issues caused by construction operations. There are specific geological profiles or other soil conditions in some of the FDOT Districts that exacerbate or have exacerbated pile driving and other construction problems related to vibration. Loose sand has typically been mentioned as the cause of vibration-induced settlements. This is particularly true with loose sands of low blow counts; i.e., less than about 10 blows per foot (bpf). The problem is found to be quite common to Central and South Florida. For instance, one of the district respondents stated that certain damage was caused during sheet pile installation and extraction, and when asphalt compaction were performed in loose sand. MSE panel settlement sometimes occurs due to the extraction of adjacent sheet piles.

Condition Surveys

Half of the respondents replied that condition surveys before and after construction are required at all times, while the remaining half said that it is required only sometimes. Almost all of the respondent districts performed videotaping and photography in these condition surveys, in addition to taking inspection notes. Crack gauges are also utilized by two-thirds of the districts (Figure 6).

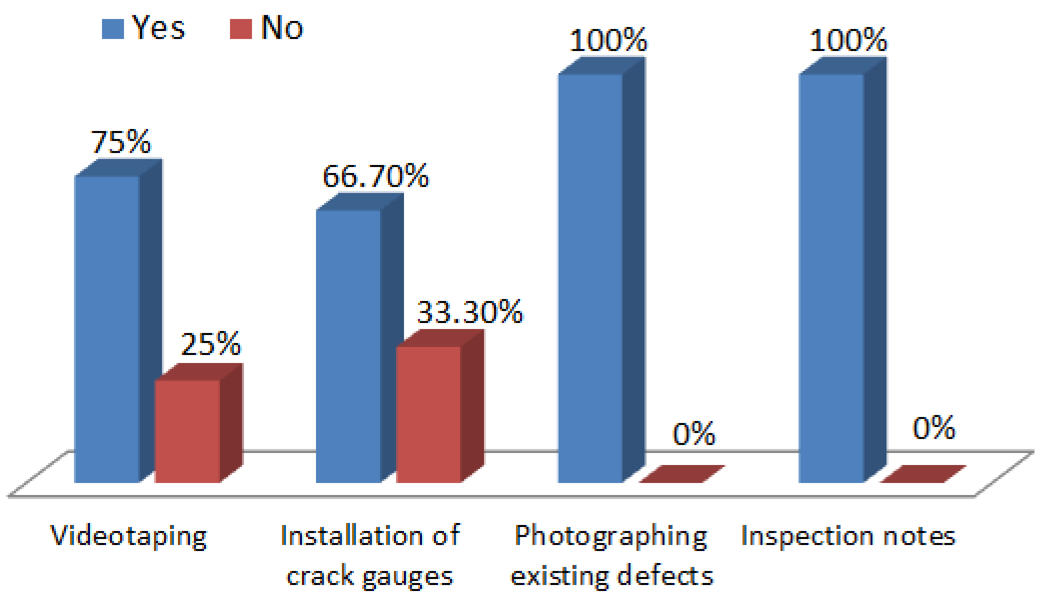

Figure 6: Methods used in condition surveys (FDOT Districts)

The condition survey records are maintained by the contractor, construction office, and consultants performing the survey. The project department responsible also gets a copy of the survey's findings.

The distance/radius for a pre-construction condition survey of structures in case of pile driving operations is determined from the FDOT Standard Specifications for Road and Bridge Construction - Section 455-1.1. However, respondents mentioned that there is no specific distance for some construction activities, such as paving operations. The contract plans will sometimes list the structures which require condition survey. At other times, hammer energy and the condition of existing buildings is also found to be a valuable indicator for determining the radius of the pre-construction condition survey.

Vibration Monitoring

Half of the respondents stated that vibration monitoring is required at all times while the remaining half said that it is required only sometimes. In general, the reported data includes, but is not limited to, the following:

- Site location plan (general location)
- Monitoring locations and relative distances to the vibration source

- Vibration event report (histogram mode)
- Summary of maximum peak particle velocity
- Calibration certification of the vibration equipment used
- Operation mode of the vibration equipment
- Geophone set up and construction equipment photos (if possible)

A majority of the respondents (75%) stated that specification or plan note require either the continuous monitoring of ground vibrations during pile driving or intermittent monitoring (i.e., not for the entire duration of pile driving); the method chosen depends on the scenario, with each method having its own set of drawbacks. For instance, in the case of Turnpike projects, if a plan note indicates that the Turnpike will be responsible for vibration monitoring for driven piles, typically the test piles are monitored and geophones are setup at a distance representing the closest distance between any pile and existing structures for the site. After that, monitoring of the production piles closest to the existing buildings is sometimes performed. If plan note requires the contractor to monitor vibration, this monitoring is performed whenever there is pile driving. Usually, this is reserved for the most critical cases in which geotechnical engineers anticipate future complaints..

For sheet pile, continuous monitoring at different locations is warranted. For vibration compaction, the vibration source is moving and continuous monitoring is not required. Respondents reported that there were projects where baselines were established on the first day of operation to find out whether the attenuation of peak particle velocity (PPV) with distance using the vibratory rollers and the vibratory mode to be used. At least one geophone is typically setup at a distance representing the closest distance between the roller and the existing structure (determined through aerial photos on Google map, etc.). In this way, geotechnical engineers establish the baseline data.

A majority of the respondents (75%) indicated that they require the vibration monitoring data to be submitted at a certain time interval. In case of Turnpike projects, if the contractor is responsible for performing vibration monitoring work, they are usually required to submit these data (Event Report) within seven (7) days, and a final signed and sealed report is required when all construction activities are completed. If the consultants engaged by the Turnpike are responsible for the work, the same data can be made available within one or two days, as needed.

Local Criteria and Procedures for Vibration-caused Problems

Some of the Districts have developed unique criteria or procedures to address pile driving vibration problems for certain local conditions. For instance, one of the respondents mentioned that, to protect existing utilities buried at a shallow depth and close to the pile, preformed pile holes are used such that pile driving will start at an elevation slightly below the utility of concern. Different vibration limit values for pile driving, sheet pile installation, and roadway compaction have been indicated as being used by different Districts. Pile driving usually follows Section 455-1.1 (0.5 in/s), with exceptions based on the condition of structures or the sensitive nature of the surroundings (e.g., distressed building or medical facility nearby). In the case of sheet pile installation and roadway compaction, a respondent indicated use of a typical PPV range of 0.2 to 0.3 in/s to minimize complaints.

Preventive Measures to Decrease Vibration Effects

All of the respondent Districts use preventive measures to decrease the vibration effects of pile driving and other construction operations. The major preventive measures adopted, are the following:

- Limitin vibrations during pile driving based on the Standard Specifications;
- Monitoring the site and performing surveys to a distance determined based on the hammer's rated energy and distance to the structure;
- Fuel setting adjustments of pile hammer;
- Pre-drilling/Preforming;
- Use low displacement piles (H-piles or open ended pipe piles);
- Vibration monitoring and reduce energy when vibration limits are approached; and
- Static compaction

3.5 Other State DOTs

The objective of this survey was to gather relevant information from other State DOTs in the United States related to (1) Occurrence and Causes of Vibration Damage; (2) Effects of Soil Conditions; (3) Condition Surveys; (4) Vibration Monitoring; (5) Local Criteria and Procedures for Vibration-caused Problems; and (6) Preventive Measures to Decrease Vibration Effects.

Occurrence and Causes of Vibration Damage

Most of the respondent State DOTs (75%) have experienced vibration damage caused by construction operations. According to the responses, the major types of construction operations that cause vibration damage include pile driving, micro-pile installation, earthwork compaction, rock blasting, sheet pile installation/removal, soil/aggregate compaction, asphalt compaction, and sometimes the vibration of drilled shaft casings into place and/or removal of casing.

Some of the prominent reasons identified as the cause of damage to structures during pile driving and other construction operations are as follows:

- Being too close to the threshold limits set by the vibration consultant;
- Induction of pile hammer vibration in saturated, loose, and moderate to high silt content granular soils;
- Problems with micro-piles in areas of highly fractured rock;
- Poor construction practices which lead to micro-pile induced settlement; and
- Existence of prior (minor) damages to the structure.

Effects of Soil Conditions

Most of the respondent State DOTs (75%) indicated that they have not experienced settlements caused by vibrations from pile driving or other construction operations. However, 88% of the respondents have experienced specific geological profiles or other soil conditions that exacerbate or have exacerbated pile driving and other construction problems related to vibration. Some of them experienced settlement during pile driving and drilled shaft casing advancement through shale layers and also through layers of sand/stone/cobbles. One of the respondents experienced settlements due to the combination of soil condition and existing structure, and stated that, *"We drove 48-inch open-ended piles into a 200' plus thick sand layer to set a bridge on friction piles. A couple of the piles were near a very old railroad foundation. The sand firmed up with all of the vibration from the hammer and we had to set the fuel on the hammer at its lightest setting to stay within the thresholds of vibration."* Other such soil conditions, as mentioned by the respondents, include but are not limited to saturated; presence of loose, moderate to high silt content granular soils and lake bottom sediments; etc.

Condition Surveys

A majority of the respondent State DOTs (88%) stated that condition surveys before and after construction are sometimes required, while the remaining States (12%) said that it is required at all times. Similar to the results obtained from the FDOT District survey, all of the respondents mentioned taking photographs and inspection notes for the purposes of such surveys (Figure 7).

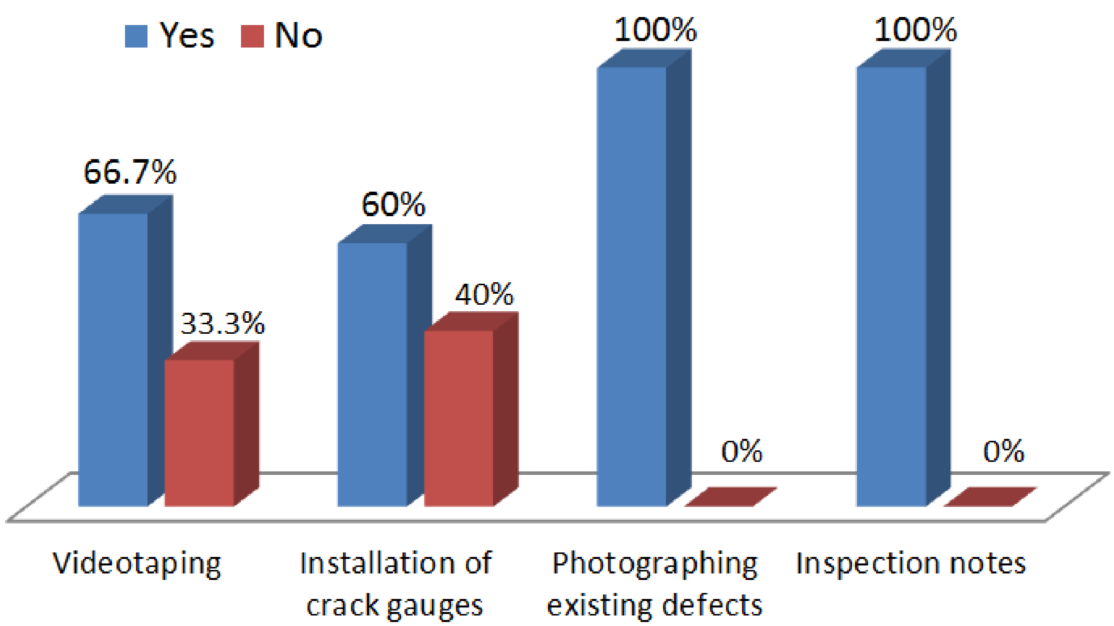

Figure 7: Methods used in condition surveys (Other State DOTs)

The distance/radius for the pre-construction condition survey of structures is determined from the specifications. However, various respondent State DOTs stated that they use engineering judgment, past experience, and/or rely on the vibration specialist to recommend to the Contractor how far out they should test, taking into account the different job types and conditions. A 50-foot radius is also used as a “good estimated range” by some of the State DOTs. One of the respondents stated that, “*We use charts developed by Wiss to estimate the distance, combined with a pre-construction building survey. The distance is adjusted based on the actual condition of the buildings, and whether or not they are classified as 'historical'."*

<u>Vibration Monitoring</u>

A majority of the respondent State DOTs (76%) stated that vibration monitoring is only “sometimes” required during construction, while 12% said that it is required at all times. The remaining 12% do not require vibration monitoring. In general, the reported data includes readouts from seismographs or vibration readings. Most of the time these requirements seem to be varied by the type and criticality of the construction work. The period and frequency of monitoring depends upon the type of construction work as well. For instance, one of the respondents stated that *“it might be that the first couple of piles driven (the closer one is to the adjacent structure) must be monitored with a seismograph. If blasting is the activity of concern, all blasting may have to be monitored.”*

In most of the cases (75%), the respondent State DOTs stated that specifications or a plan note was used to specify locations where ground vibrations should be measured. The reported distances were within 1500 feet of the site or to the nearest structure and up to a half-mile radius. In other cases, it was determined by an independent vibration consultant.

Furthermore, a majority of the districts stated that continuous vibration monitoring is required either at all times (38%) or sometimes (38%). In some cases, monitoring of the beginning of pile driving is performed when the pile tip is not deep. Again, the needs are site-specific. As vibrations from pile driving attenuate with distance, as the pile tip is driven deeper, the effect is reduced.

In general, the specifications or plans require the data to be submitted daily during vibration-related construction activities, and after each blast in the case of blasting activities.

Local Criteria and Procedures for Vibration Caused Problems

Most of the respondent districts (75%) have not developed any unique criteria or procedures to address pile driving vibration problems for certain local conditions. However, peak particle velocity (PPV) is the agreed upon vibration parameter, based on the survey results as represented in Figure 8. As far as limits are concerned, typically 1 in/s for impact/blasting and 0.1 in/s for steady state, 2 in/s typically for pile driving, 0.1 in/s for historical or critical structures, and 0.2 in/s for vibratory rollers are used as the threshold limits. Some of the States also use Siskind's curve to determine the limits. In general, 0.5 in/s is the limit for PPV. However, the respondents do understand that a sliding scale should be used for PPV limits.

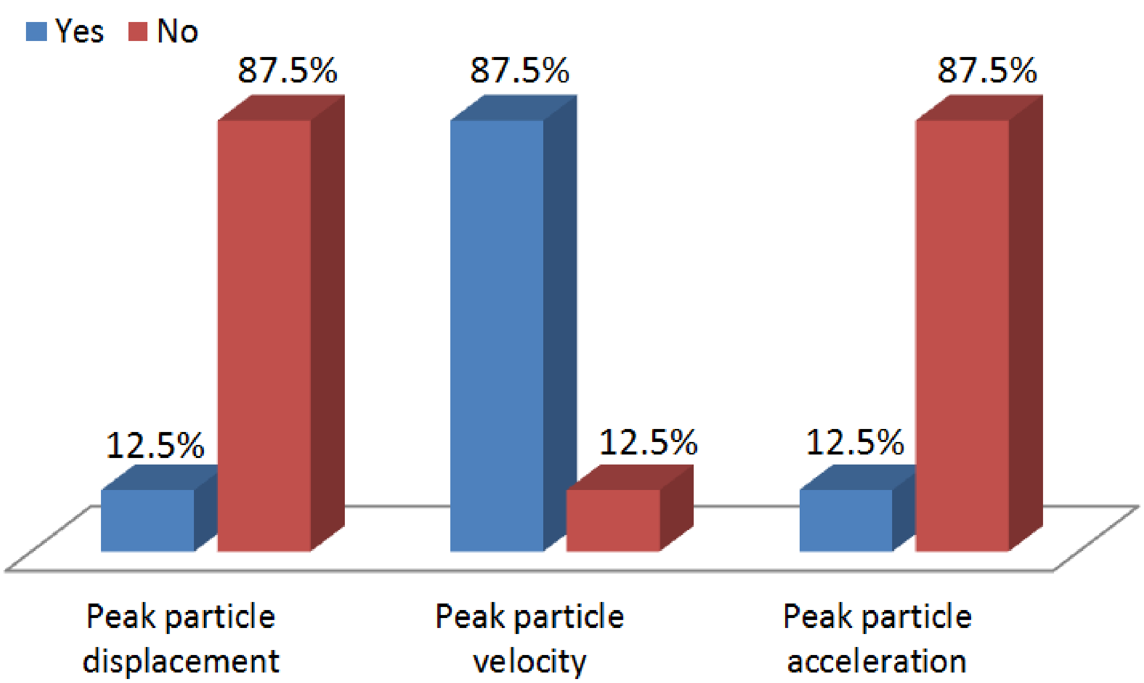

Figure 8: Measured parameter in vibration monitoring (Other State DOTs)

Preventive Measures to Decrease Vibration Effects

The majority of the respondent State DOTs (88%) use preventive measures to decrease the vibration effects of pile driving and other construction operations. The major preventive measures adopted, as mentioned, include:

- Deployment of continuous vibration monitors at site;

- Defining special provisions to limit vibrations of critical structures;
- Using drilled-shaft and micro-pile foundations where possible;
- Restricting use of vibratory drivers;
- Leaving sheet piling material in place;
- Using pre-augering techniques; and
- Mandating pre-boring of the initial 15 to 20 ft. prior to pile driving to limit ground vibrations.

3.6 Vibration Monitoring Consultants

The objective of this survey was to gather relevant information from vibration monitoring consultants regarding the general practices of these firms with respect to vibration monitoring. A summary of the survey findings are provided below.

The survey concluded that, in general, vibration consultants do perform analysis to determine the possible causes of existing damage to the structures near vibration-related construction activity. The majority of them also identify potential mitigation measures for pile driving, as well as other construction equipment effects on structures. They also estimate ground vibrations prior to pile driving, and measure background vibrations. The consultants engage with several stakeholders while performing vibration measurement, including: owner of the construction, prime contractor, victim of alleged vibration damage, insurance company, district engineer, etc.

As relates to best practices to avoid or mitigate effects of vibrations-related construction operations, the vibration consultants agree that nearby residents should be educated in advance and that this information should also be communicated effectively. Pre-construction surveys with plenty of photos and video also tend to minimize vibration related complaints.

Another aspect as agreed upon by respondent consultants is that a site-specific vibration monitoring program should always be in place whenever vibratory equipment is utilized, to develop a baseline and an understanding of PPVs at radial distances from the energy source. One of the consultants stressed the stated need by saying that, *"Vibration measurement and inspection requirements need to be specifically established for projects adjacent to structures, including residences, commercial facilities, and in some cases, utilities. The limits need to be established by vibration consultants familiar with the standards. Also, there needs to be standardization of limitations that are realistic--not what is currently used by FDOT. Measurement and inspections need to be conducted by qualified vibration firms and employees."* As far as distance or radius where vibration monitoring should be performed is concerned, monitoring at the edge of project right-of-way (vibrations leaving the site) appears to have been beneficial in controlling construction activities.

3.7 Contractors

As previously presented in Table 1, only one contractor response was received to the survey request. Since the received response was not significant to the objectives of the project, it was not included in the summary of responses.

4. OVERVIEW OF PROJECT DATA COLLECTION

4.1 Introduction

According to Section 455-1.1 “Protection of Existing Structures” in FDOT’s Standard Specifications for Road and Bridge Construction, vibration levels during the driving of casings, piling, sheeting, or blasting operations shall be monitored and recorded when shown in the Contract Documents. Based on this requirement, the underlying premise of the methodology adopted for this research was to collect all such field-measured vibration data and other relevant project information with the help of FDOT, contractors, and vibration consultants to be analyzed in the subsequent research tasks.

This chapter provides a review of the project data collection effort conducted by the research team to support the objectives of this study. The review is divided into three categories including: (i) data sources, (ii) data types, and (iii) summary of the data collected.

4.2 Data Sources

To collect the required data, the research team started by contacting FDOT’s Geotechnical Engineering District offices and the Turnpike Enterprise via telephone, followed by an e-mail. All District Geotechnical Engineers, Assistant District Geotechnical Engineers, Geotechnical Construction Engineers, Geotechnical Project Managers, and if applicable, Geotechnical Assistants, were contacted. Also, additional contacts and information provided by the Central Office Geotechnical Engineering group was utilized in the early phases of data collection.

With the assistance provided by the FDOT staff, some of the initial data collected was directly received from the agency’s Geotechnical Engineering Offices. Once all of the aforementioned sources were exhausted, the research team shifted its focus to FDOT’s Construction Offices. Similar to what was done with the Geotechnical Engineering Program, the State Construction Office and all the District Offices were contacted. With the involvement of the Construction Offices, the research team also started to get data from contractors (Figure 9).

Although the data collection effort was a very tedious and time-consuming process due to the scattered nature of different data pieces and long lead times, in the end, our team was able to collect vibration-related data from more than 100 construction projects in Florida. This would not have been possible without the great support and understanding of the FDOT personnel and contractors doing business in Florida.

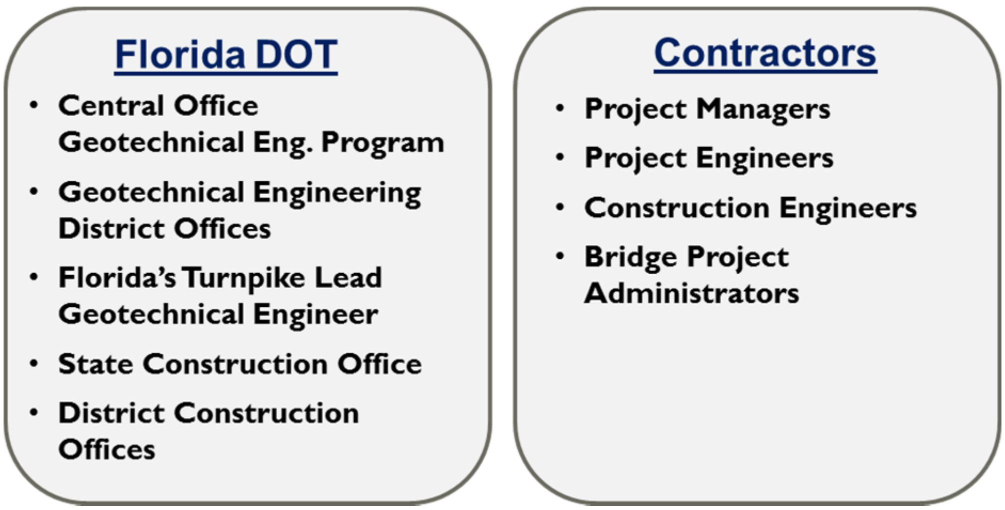

Figure 9: Sources Contacted for Project Data

4.3 Data Types

Based on the feedback received from FDOT, the research team focused on three major types of construction activity as a source of ground vibrations in Florida: (i) pile driving, (ii) sheet pile installation/extraction, and (iii) road compaction.

In addition to the ground vibration measurement results, the following supporting data were collected for each project (as much as available):

- General construction site information and construction records
- Geotechnical conditions at the project site
- Specific information related to the equipment inducing construction vibrations
- Piles: material, length, cross-section (in case of driven piles)

- Results of condition surveys and possible damage to structures
- Pile driving logs

4.4 Summary of the Data Collected

The data collection effort conducted by the research team resulted in a database with 109 projects from various parts of Florida. Figure 10 provides a breakdown of these projects by type of vibration source followed by Figure 11 presenting a more detailed breakdown by FDOT Districts on a Florida map.

The following chapter provides the analysis of data conducted to develop simple equations to calculate the PPV of expected ground vibrations prior to construction operations. However, it is important to note that not all of the data collected by the research team was utilized in the analysis as for some projects the supporting data was not available.

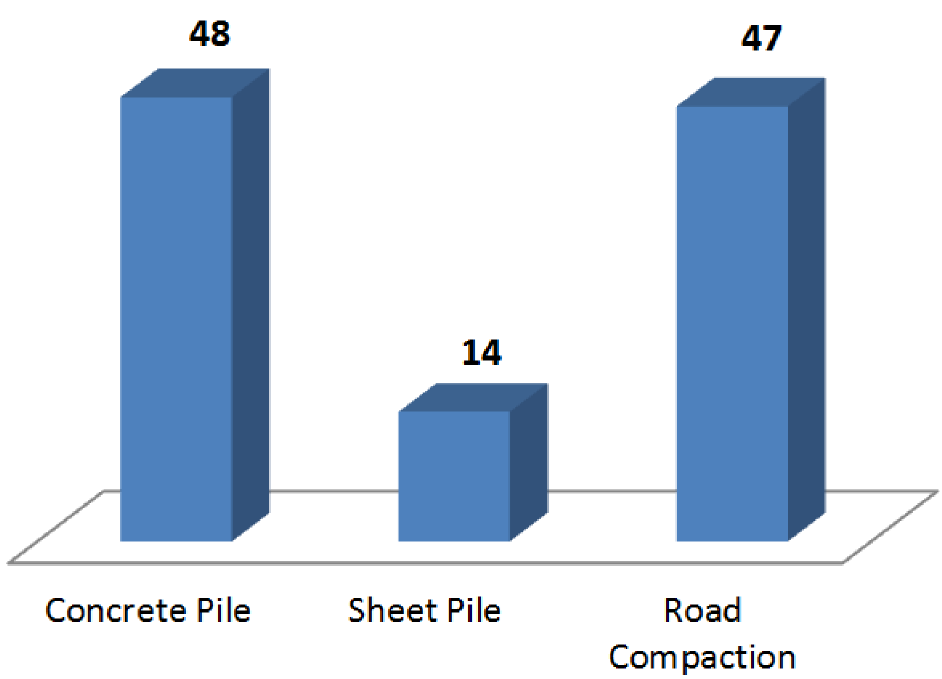

Figure 10: Number of projects by type of vibration source

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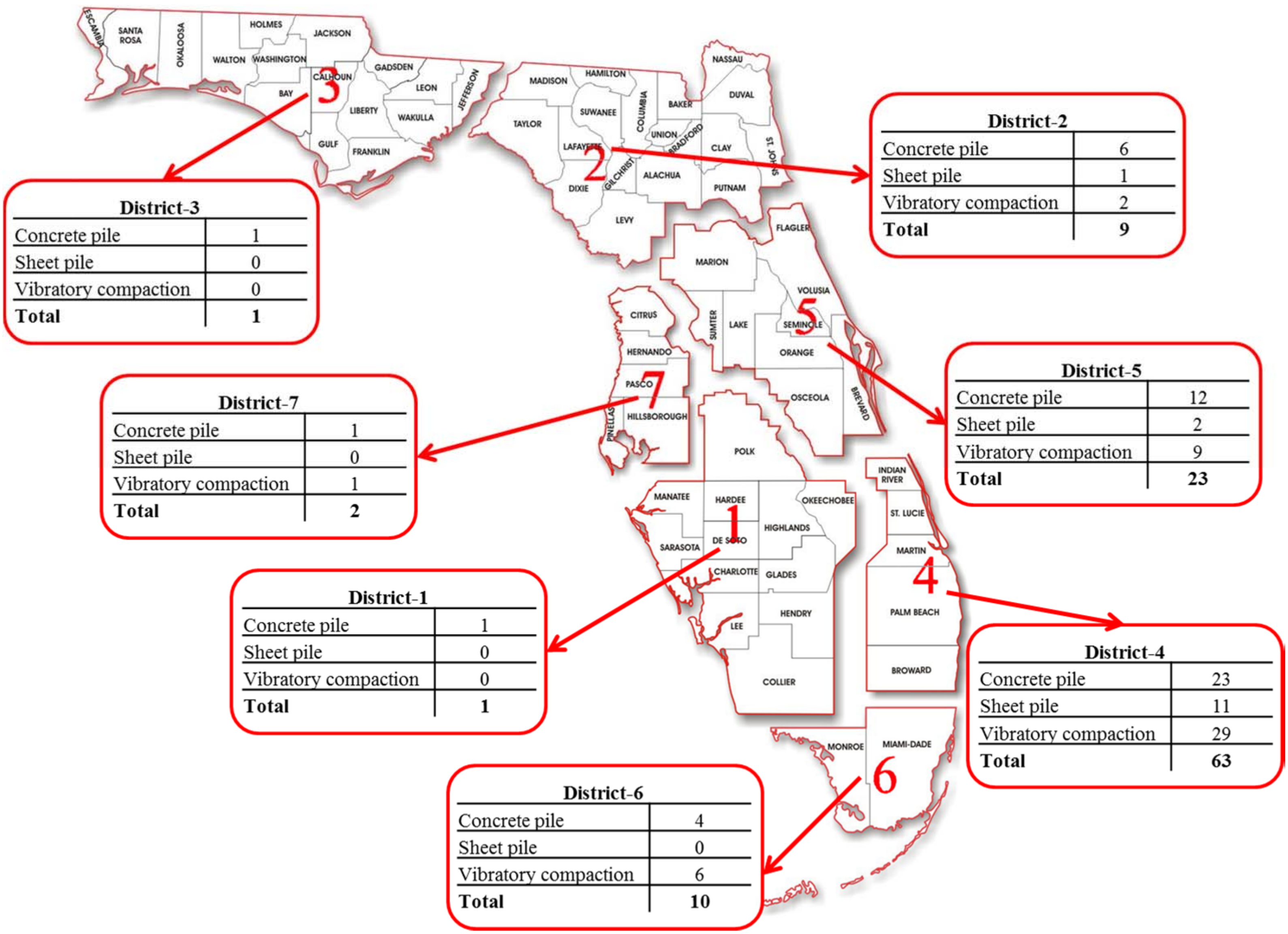

District-3

Concrete pile	1
Sheet pile	0
Vibratory compaction	0
Total	**1**

District-2

Concrete pile	6
Sheet pile	1
Vibratory compaction	2
Total	**9**

District-7

Concrete pile	1
Sheet pile	0
Vibratory compaction	1
Total	**2**

District-5

Concrete pile	12
Sheet pile	2
Vibratory compaction	9
Total	**23**

District-1

Concrete pile	1
Sheet pile	0
Vibratory compaction	0
Total	**1**

District-4

Concrete pile	23
Sheet pile	11
Vibratory compaction	29
Total	**63**

District-6

Concrete pile	4
Sheet pile	0
Vibratory compaction	6
Total	**10**

Figure 11: Breakdown of projects by type of vibration source and physical location

5. SIMPLE EQUATIONS TO CALCULATE PPV OF GROUND VIBRATIONS

5.1 Introduction

For practical goals, prior to the beginning of construction operations, it is important to assess the maximum PPV of ground vibrations expected during construction operations. In Task-5, using the field data specific to Florida, as collected and sorted in Task-3, simple equations were developed to calculate the PPV of expected ground vibrations prior to construction operations. This chapter provides the results of Task-5.

5.2 Methodology

It is a complicated problem to calculate expected ground vibrations from diverse construction sources at various distances from sources. There are diverse empirical equations applied for calculation of ground vibrations, but a scaled-distance approach is an appropriate way to calculate the upper limits of ground vibrations before the beginning of pile driving.

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

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

Where W_r = energy of source or rated energy of impact hammer, k = value of velocity at one unit of scaled distance, $(D/W_r^{½})$. The value of 'n' yields a slope of amplitude attenuation for all tested soils in the narrow range of 1 to 2 on a log-log chart.

Woods and Jedele (1985), Woods (1997) confirmed the soundness of this approach with gathered data from field construction projects conducted in Michigan and North Carolina and they 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. 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).

According to Svinkin (2013), equation (1) provides very rough assessment of ground vibrations as a function of the source energy and distance from the source. Also, equation (1) 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 no connections with calculations of structural vibrations or dynamic settlements and assessment of vibration effects on sensitive equipment. However, equation (1) adjusted for site soil conditions and pile types with field pile testing provides relatively better calculation results than other empirical equations for assessment of the upper limits of expected ground vibrations. To reach such results, certain requirements should be applied to variables of equation (1) to assure good results.

1. Horizontal distances should be used in calculations.
2. For pile driving during design, the energy transferred to piles, W_t, is calculated as the product of the rated energy and transfer efficiency. Hydraulic hammers usually have higher transfer efficiencies than diesel hammers. Hammer transfer efficiency can be determined as the result of pile testing at a site or estimated from previous experience.
3. Upper values of expected PPV can be calculated with lower attenuation of ground vibrations. The coefficient ‘n’ represents the attenuation rate (slope) of ground vibrations, and n=1 means lower attenuation and consequently higher PPV of ground vibrations. It means that the coefficient n=1 should be used.
4. Local experience is the best way to determine a value of “k”. For example, the value of “k” can be evaluated from pile testing performed at a site.

It is known that equation (1) is used for calculation of PPV of expected ground vibrations generated by dynamic sources with impact loads. Svinkin (2008) applied equation (1) for calculation of PPV of ground vibrations from vibratory drivers.

During this research, available field data were analyzed to derive simple equations for calculation of PPV of ground vibrations before the beginning of pile driving. For measured PPV and energy transferred to piles received from the PDA data, back analysis was utilized to calculate the coefficient ‘k’. In some cases, when the PDA data was not available, the transfer energy was based on previous experience with the hammer. Simple equations were also derived for calculation of PPVs prior to sheet pile driving, drilled shaft casing operations, and vibratory roller operations. A transfer efficiency of 25% was assumed for all vibratory drivers included in this research.

Table 2: The coefficient “k” determined from field data by using the transfer energy

No.	District	County	Number of piles or vibratory rollers	Range of coefficient “k”	Comments
Pile Driving					
1	2	Clay	1	5.5	
2	4	Palm Beach	2	5.2 - 5.4	
3	4	Broward	36	1.8 - 7.0	
4	5	Orange	4	1.3 - 3.4	
5	5	Osceola	10	2.8 - 8.0	
6	5	Seminole	1	5.0	
7	6	Miami-Dade	6	0.7 - 1.7	Low value due to pile being in a canal
Sheet Pile Driving					
1	4	Palm Beach	N/A	19.0	Vibratory pile driving
2	5	Flagler	N/A	6.4	Impact pile driving
3	5	Flagler	N/A	14.9	Vibratory pile driving
Casing Installation and Removal					
1	2	Duval	6	0.7 - 3.3	
Vibratory Rollers					
1	Turnpike Projects		40	3.5*	

* *Based on horizontal distance and attenuation rate of 0.6 without scaling with the energy of the vibratory roller (see Section 5.6 of this report).*

The results were obtained for 60 driven piles, a number of sheet piles, 6 casing installation and removal, and 40 vibratory rollers. Obtained results are shown in Table 2 for different FDOT Districts and Counties.

Over the course of this research, charts were developed for driven piles, sheet piles, and casing installation and removal by using the transfer energy as well as the rated energy. The charts based on transfer energy are presented in Sections 5.3, 5.4, and 5.5, respectively. This report also provides two charts which were developed by using the rated energy including Figure 12 presenting the overall data for driven piles and Figure 13 presenting the overall data for sheet piles.

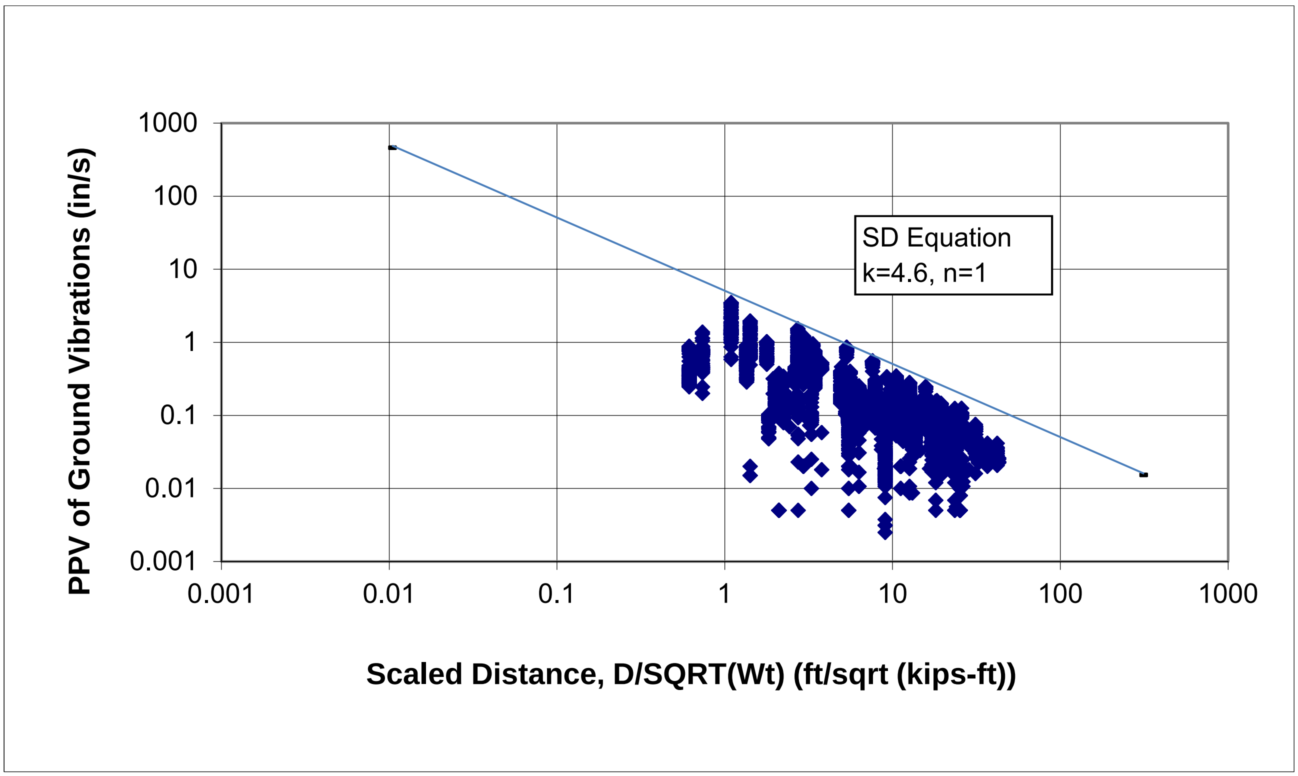

Figure 12: The coefficient “k” for driven piles determined from field data by using the rated energy

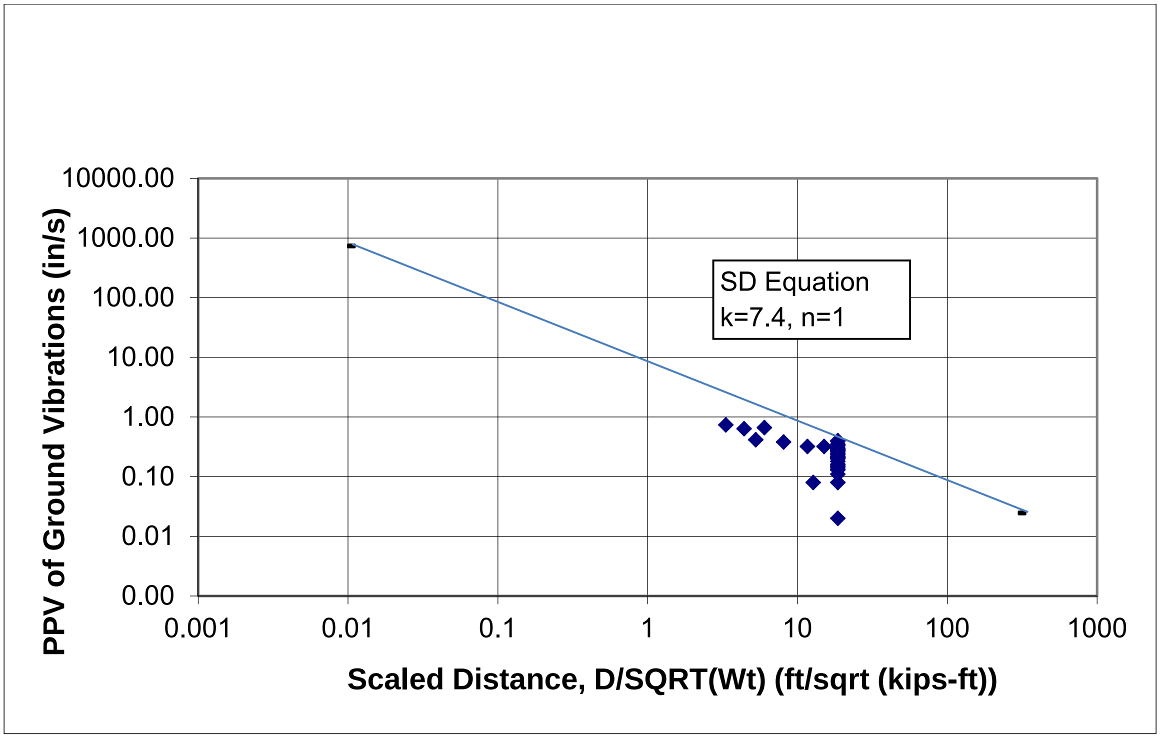

Figure 13: The coefficient "k" for sheet piles determined from field data by using the rated energy

5.3 Scaled Distance Equations for Driven Piles

Clay County

SR 15 (US 17) Widening Doctors Inlet Bridge and Approaches

A Berminghammer B5505 diesel hammer with a rated energy of 105.9 kip-ft was used to install 18-in and 24-in square PSC piles for Bents and Piers, respectively. The results of PDA monitoring of a driven piles performed on 18-in PSC pile on April 7, 2009 and on 24-in PSC pile on June 12, 2009 were available. The average energy transferred to 18-in square piles was 16.2 kip-ft. The transfer energy of 24.7 kip-ft was used for assessment of vibrations from driving of a 24-in square pile. A soil profile is not available, but there is information that soil at a site consisted of sandy layers with a small percentage of organic content. The results of ground vibrations are available in 12 locations measured from installation of 18-in square PSC piles and in one location measured during driving of one 24-in square PSC pile. A SD equation was derived on the basis of field data. The coefficient k=5.5 was determined for the considered pile using the transfer energy.

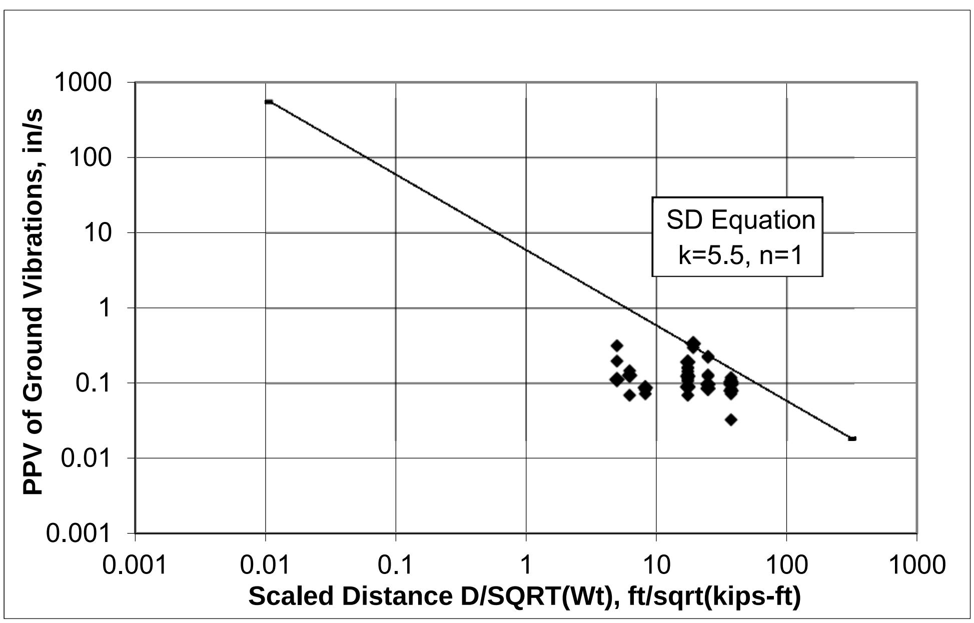

Figure 14: SR 15 (US 17) Pier 5

Palm Beach County

Turnpike over L-30 Canal

An ICE 80-S diesel hammer with a rated energy of 80 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 4 to16.7 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand (SP, SP-SM). A SD equation was derived on the basis of field data. The coefficient k=5.4 was determined for the considered pile using the transfer energy.

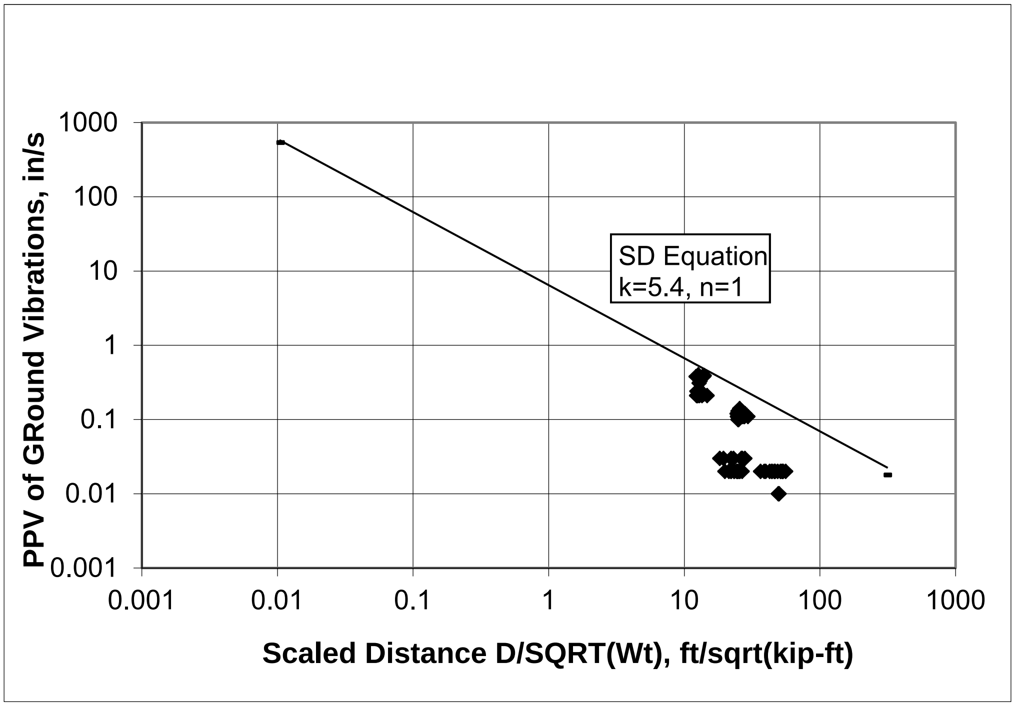

Figure 15: Turnpike over L-30 Canal Bent 2, Pile 4

Palm Beach County

Atlantic Boulevard Interchange

A Delmag D36-32 diesel hammer with a rated energy of 90.56 kip-ft was used to install 18-in square PSC piles. The transfer energy during pile driving assumed to be 24.1 kip-ft using a transfer efficiency of 0.266.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand (SP, SP-SM). A SD equation was derived on the basis of field data. The coefficient k=5.2 was determined for the considered pile using the transfer energy.

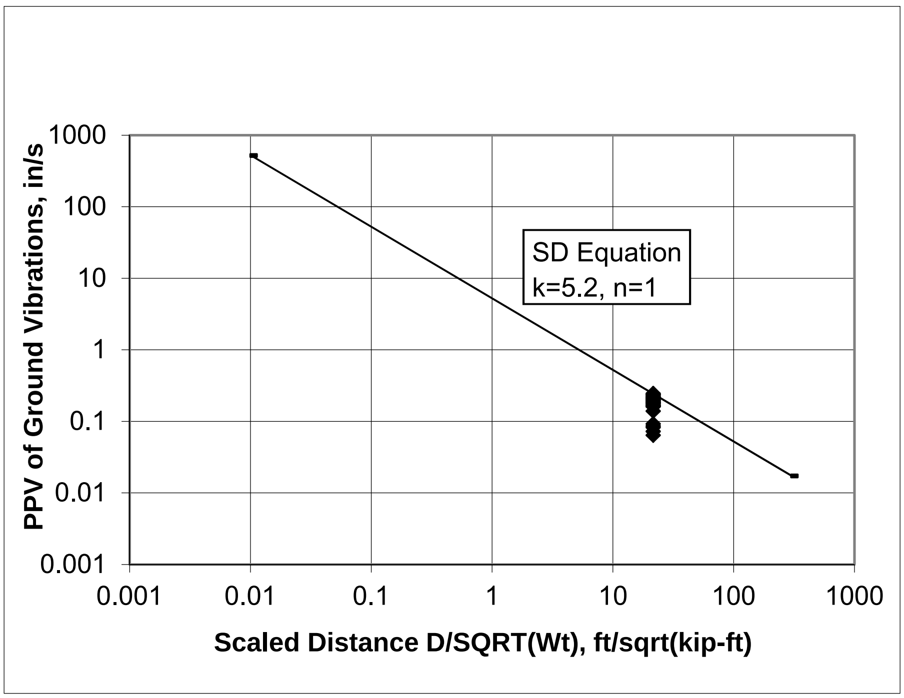

Figure 16: Atlantic Avenue, Ramp D, EB 1, P3

Broward County

Sawgrass Expressway over Coral Ridge Drive

An APE D36-32 diesel hammer with the rated energy of 90.56 kip-ft was used to install 18-in square PSC piles. The maximum transfer energy during pile driving was assumed 26.9 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP, LS). A SD equation was derived on the basis of field data. The coefficient k=5.3 was determined for the considered pile using the transfer energy. For other three piles, the coefficient k equals 3.5, 7.0 and 3.5.

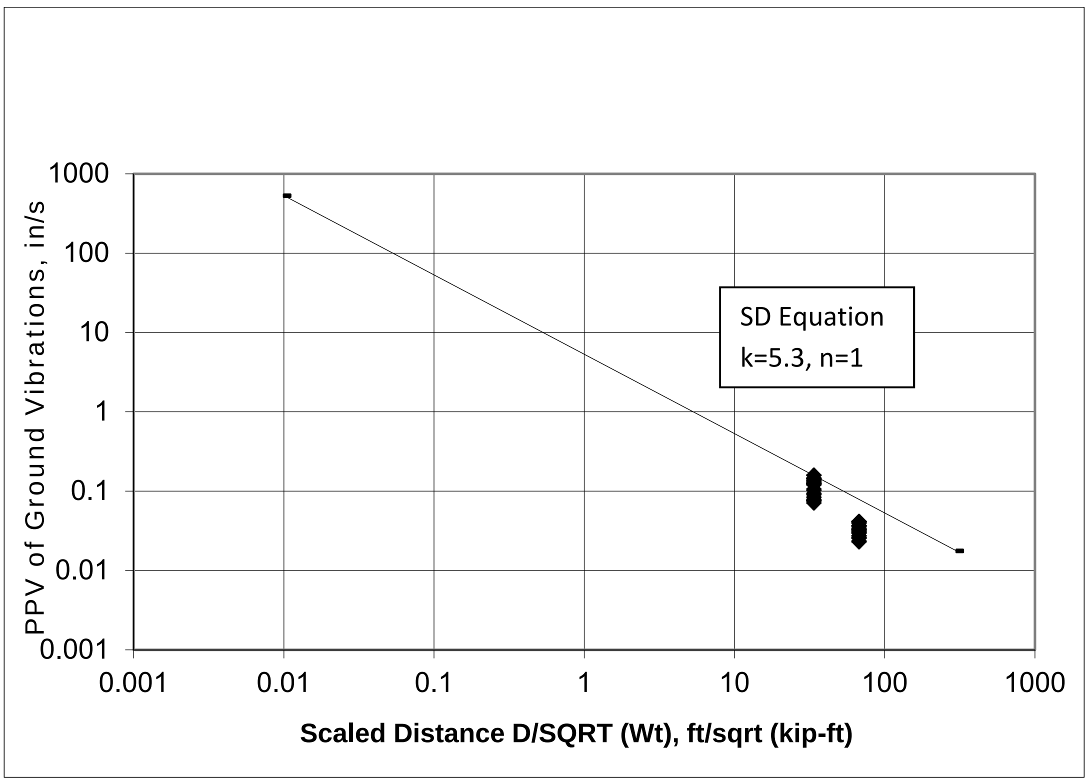

Figure 17: Sawgrass Expressway over Coral Ridge Drive Pile 5

Broward County

Sawgrass Expressway over Coral Spring Drive

An APE D36-32 diesel hammer with a rated energy of 90.56 kip-ft was used to install 18-in square PSC piles. The maximum transfer energy during pile driving was assumed to be 26.9 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP, LS). The coefficient k=3.5 was determined for the considered pile using the transfer energy. For other seven piles, the coefficient k equals 3.5, 2.8, 2.8, 2.4, 2.2, 2.7 and 1.9.

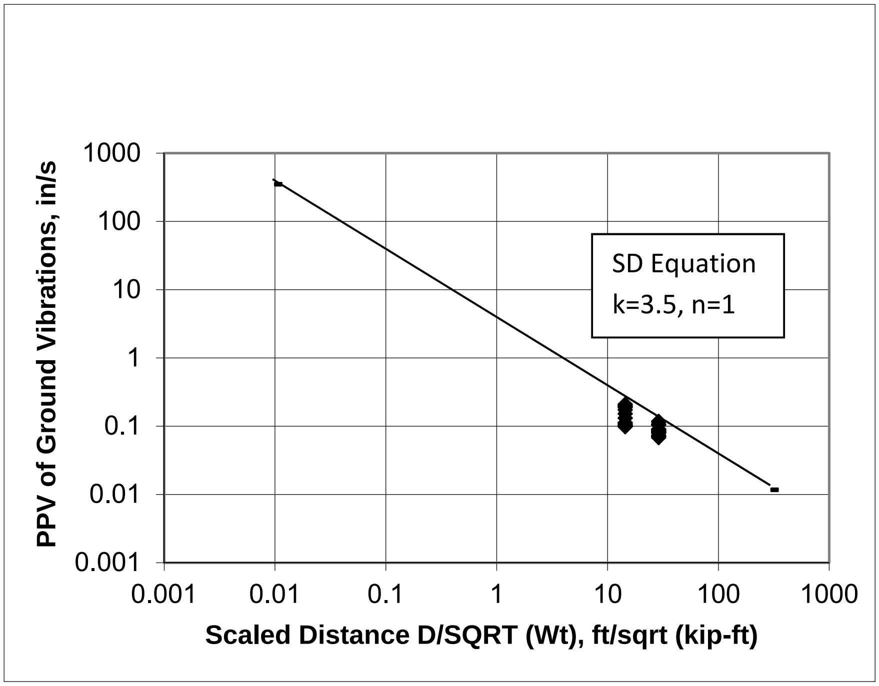

Figure 18: Sawgrass Expressway over Coral Springs Drive Pile 5

Broward County

Sawgrass Expressway over University Drive

An APE D36-32 diesel hammer with a rated energy of 90.56 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 17.3-29.0 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP, LS). A SD equation was derived on the basis of field data. The coefficient k=2.3 was determined for the considered pile using the transfer energy. For other two piles, the coefficient k also equals 2.3.

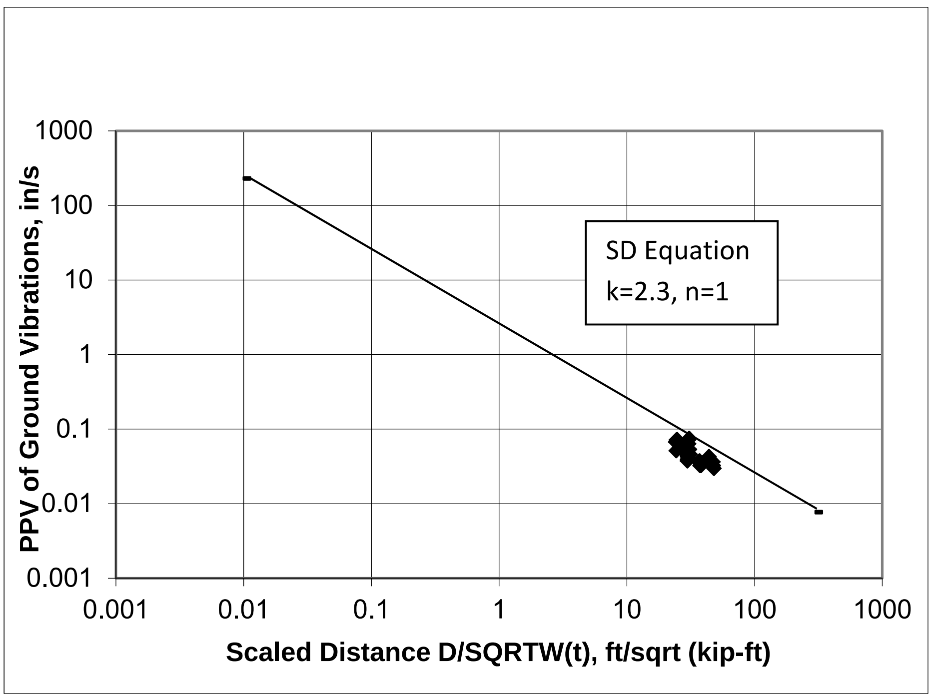

Figure 19: Sawgrass Expressway over University Drive Right Bridge Deck, Pier 2, Pile 6

Broward County

Sawgrass Expressway over Riverside Drive

An APE D36-32 diesel hammer with a rated energy of 90.56 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 16.3-25.1 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP, LS). A SD equation was derived on the basis of field data. The coefficient k=4.2 was determined for the considered pile. For other five piles, the coefficient k equals 3.1, 3.1, 4.0, 3.1 and 6.1.

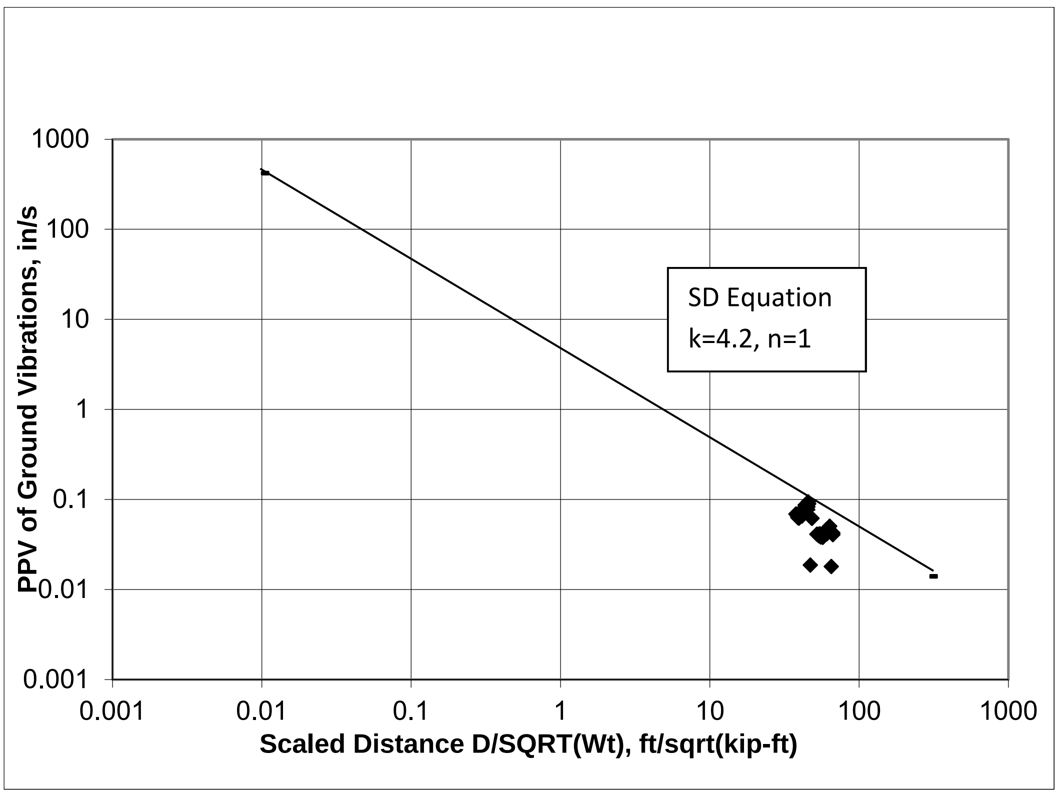

Figure 20: Riverside Drive Bridge Widening LBD, Pier 2, Pile 5

Broward County

Sawgrass Expressway over Lyons Road

An APE D36-32 diesel hammer with a rated energy of 90.56kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 18.3-27.4 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP, SC, LS). A SD equation was derived on the basis of field data. The coefficient k=6.7 was determined for the considered pile using the transfer energy. For other six piles, the coefficient k equals 3.9, 4.5, 3.9, 3.9, 7.0 and 4.0.

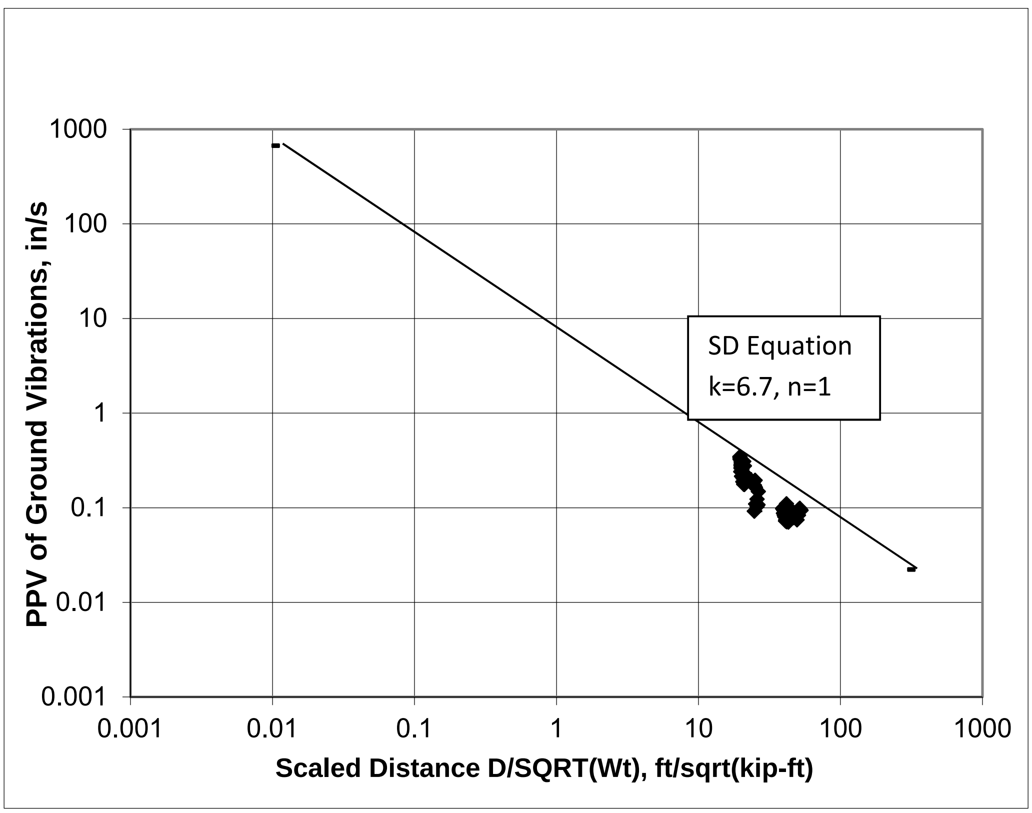

Figure 21: Sawgrass Expressway over Lyons Road RBD, Pier 2, Pile 1

Broward County

Turnpike over SR 7

A D30-02 diesel hammer with a rated energy of 66.3 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 8.0-25.5 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP-SM, LS). A SD equation was derived on the basis of field data. The coefficient k=5.6 was determined for the considered pile using the transfer energy.

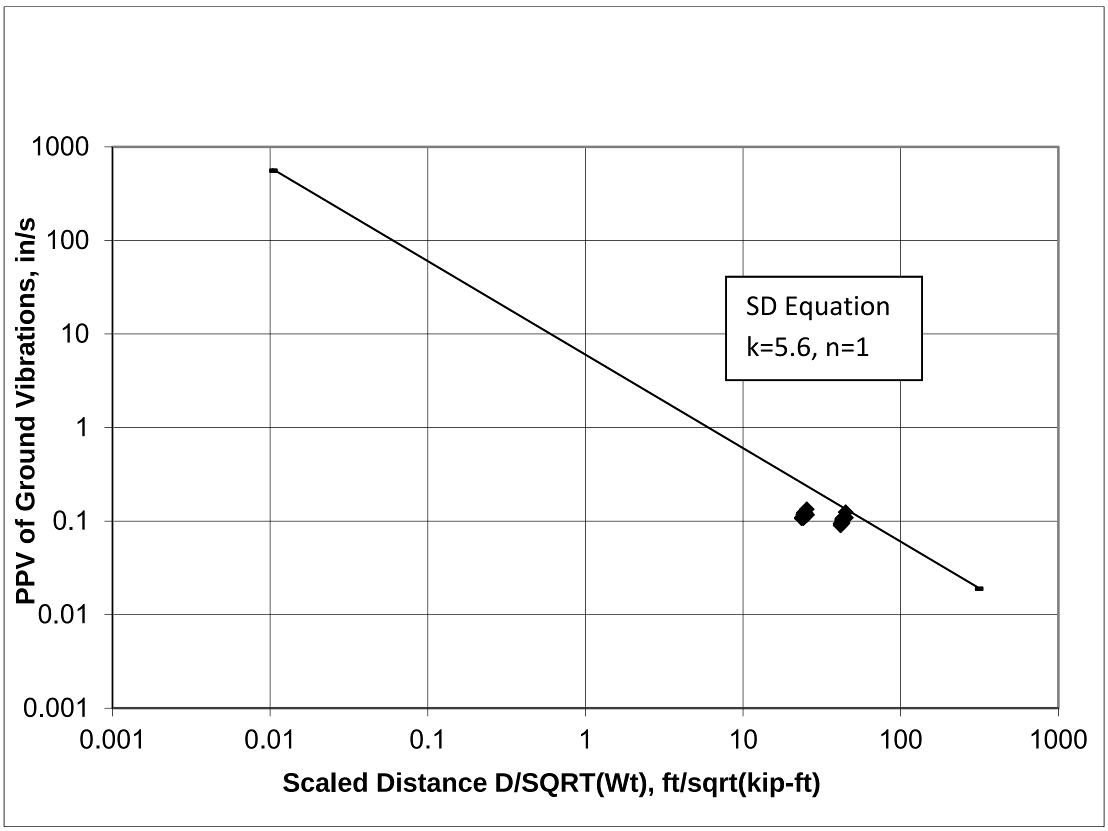

Figure 22: Turnpike over SR 7 Right Deck, Pier 2, Pile 7

Broward County

Commercial Boulevard over Turnpike

A D30-02 diesel hammer with a rated energy of 66.3 kip-ft was used to install 18-in square PSC piles. The maximum transfer energy during pile driving was assumed 25.5 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, limestone (SP, SP-SM, LS). A SD equation was derived on the basis of field data. The coefficient k=5.6 was determined for the considered pile using the transfer energy. For other five piles, the coefficient k equals 2.2, 4.7, 1.9, 3.3 and 1.8.

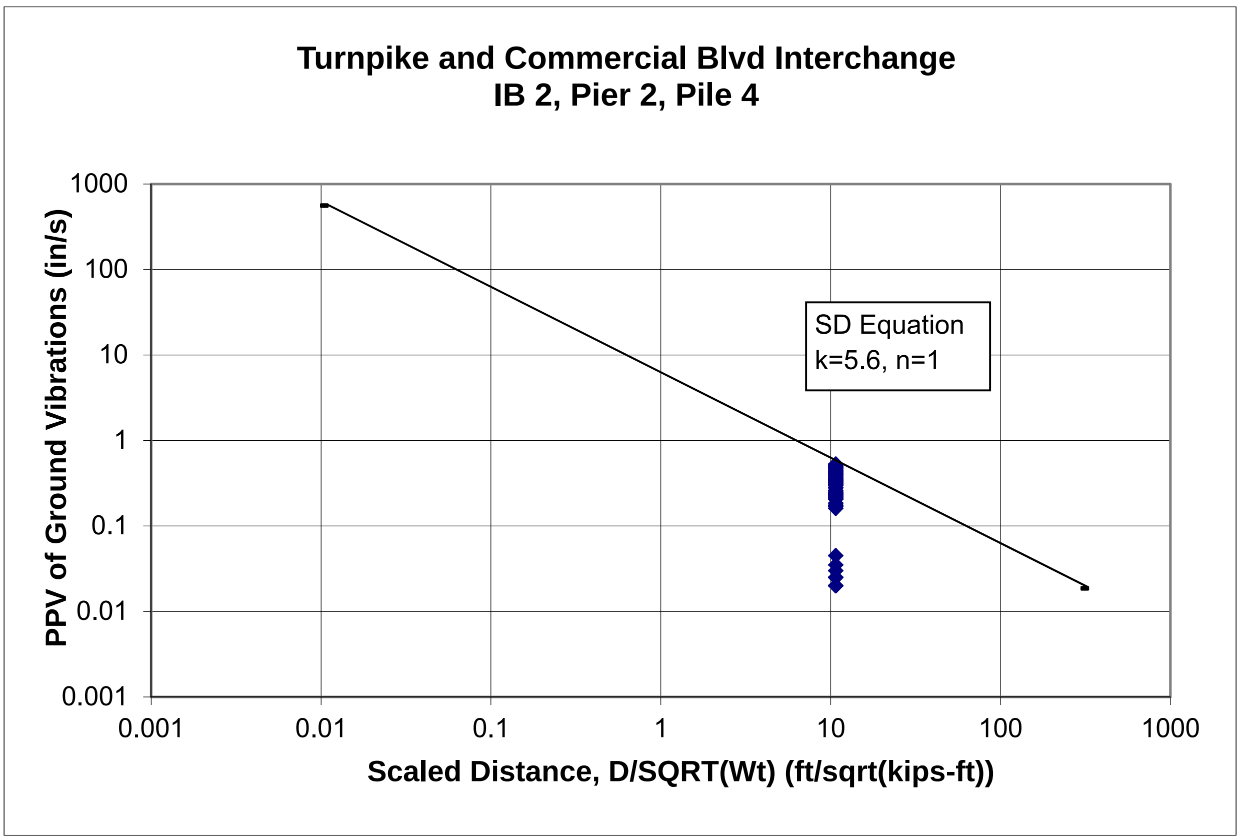

Figure 23: Turnpike and Commercial Boulevard Interchange IB 2, Pier 2, Pile 4

Broward County

Turnpike over C-13 Canal

A D30-02 diesel hammer with a rated energy of 66.3 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 4.1-11.3 kip-ft. The maximum transfer energy during pile driving was assumed 11.3 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand (SP, SP-SM). A SD equation was derived on the basis of field data. The coefficient k=3.5 was determined for the considered pile using the transfer energy.

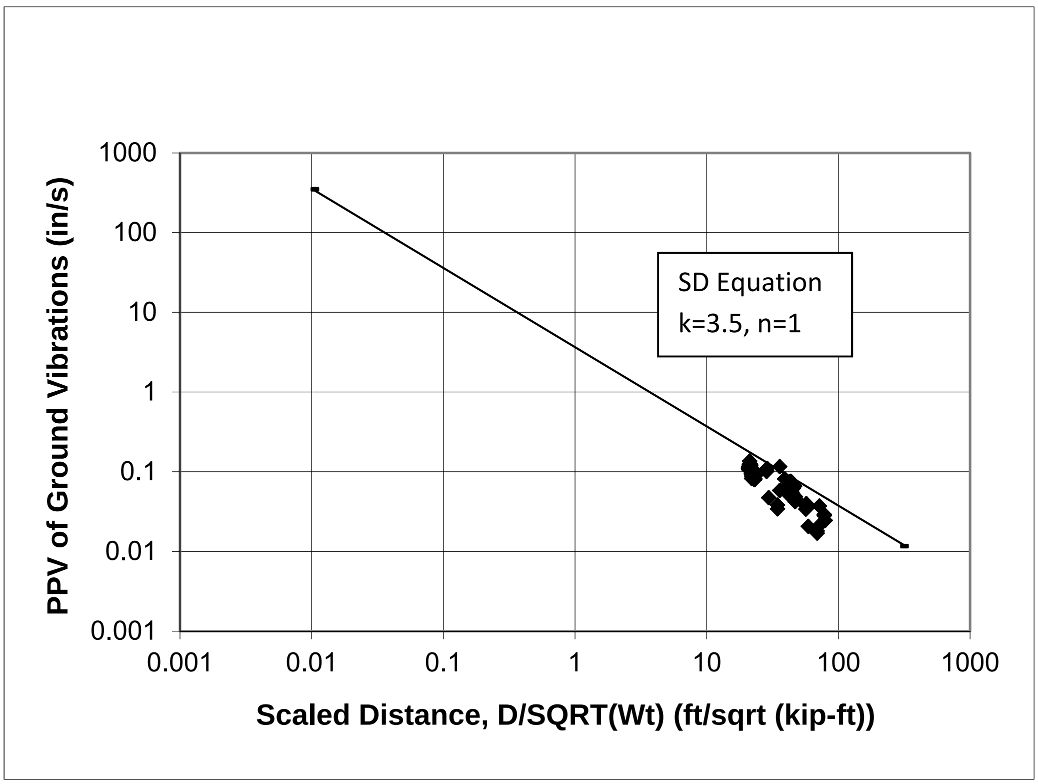

Figure 24: Turnpike over C-13 Canal

Orange County

Turnpike over Shingle Creek

An APE D62-22 diesel hammer with a rated energy of 161.5 kip-ft was used to install 24-in square PSC piles. During pile driving, the transfer energy changed in the limits of 7.9-25.6 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, clay (SP, SP-SM, CL, ML). A SD equation was derived on the basis of field data. The coefficient k=1.4 was determined for the considered pile using the transfer energy.

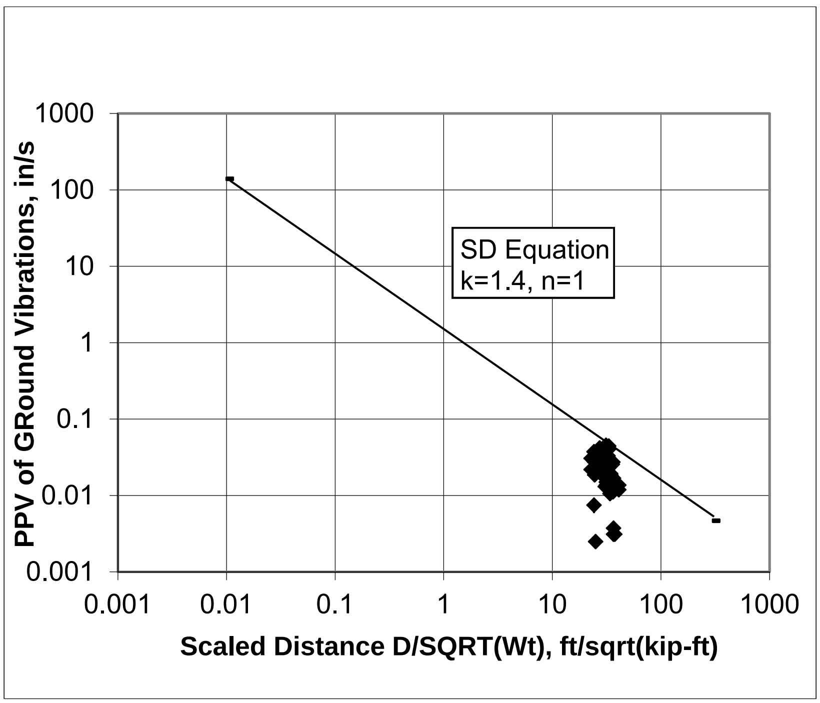

Figure 25: Turnpike over Shingle Creek Bent 3, Pile 8

Orange County

Sand Lake Road over Turnpike

An ICE 100-S diesel hammer with a rated energy of 100.0 kip-ft was used to install 18-in square PSC piles. The maximum transfer energy during pile driving was assumed 18.0 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, clay (SP, SP-SM, CL, ML). A SD equation was derived on the basis of field data. The coefficient k=1.3 was determined for the considered pile using the transfer energy.

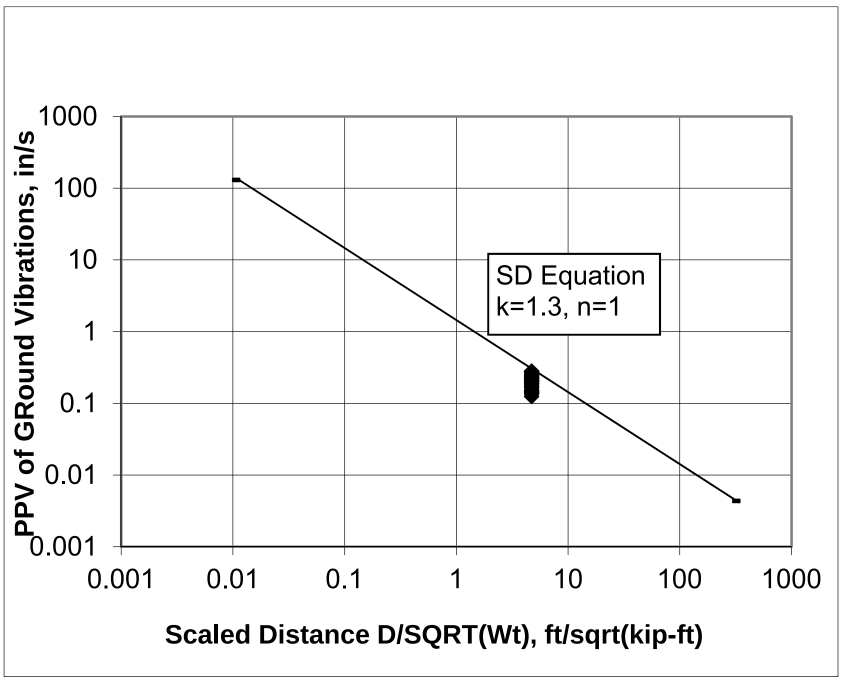

Figure 26: Sand Lake Road over Turnpike Pier 2, Pile 17

Orange County

SR 528 over Turnpike

An ICE 80-S diesel hammer with a rated energy of 80 kip-ft was used to install HP 14x89 steel piles. During pile driving, the transfer energy changed in the limits of 11.8-30.6 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, clay (SP, SP-SM, CL, ML). A SD equation was derived on the basis of field data. The coefficient k=3.4 was determined for the considered pile.

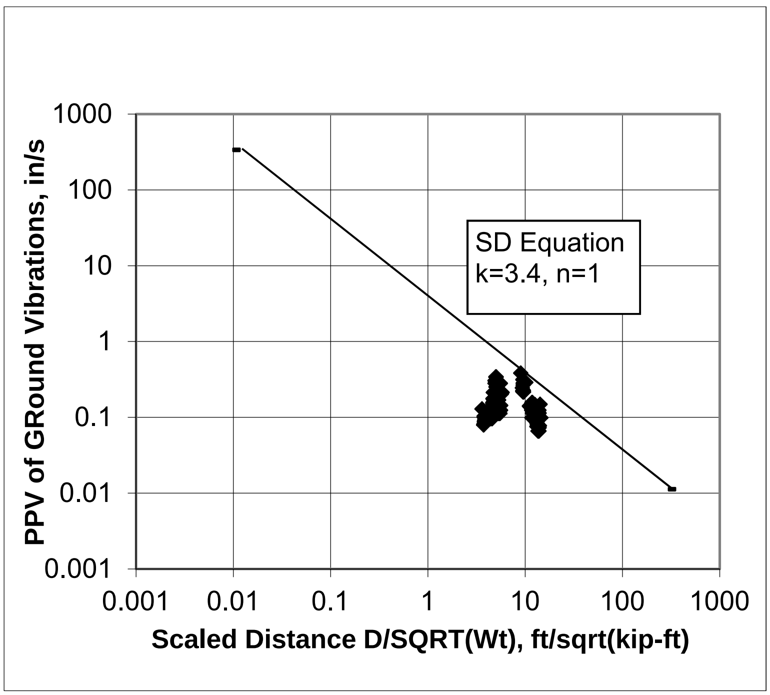

Figure 27: SR 528 over Turnpike Bent 7, Pile 2

Orange County

Turnpike over US 441

An ICE 100-S diesel hammer with a rated energy of 100.0 kip-ft was used to install 24-in square PSC piles. During pile driving, the transfer energy varied between 12.4-21.2 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, clay (SP, SP-SM, CL, ML). A SD equation was derived on the basis of field data. The coefficient k=1.3 was determined for the considered pile using the transfer energy.

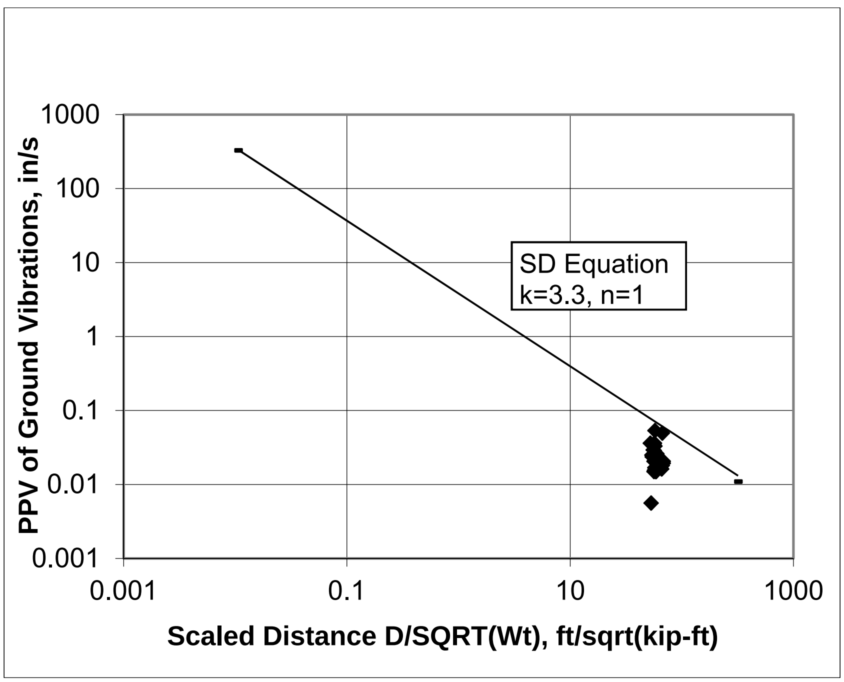

Figure 28: Turnpike over US 441 Bent 2, Pile 14

Osceola County

Kissimmee Park Road over Turnpike

An APE D36-32 diesel hammer with a rated energy of 84.06 kip-ft was used to install 18-in square PSC piles. The maximum transfer energy during pile driving was assumed 26.9 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand, clay (SP, SM, SP-SM, CH, ML). A SD equation was derived on the basis of field data. The coefficient k=6.7 was determined for the considered pile using the transfer energy. For other three piles, the coefficient k equals 3.5, 2.8 and 3.5.

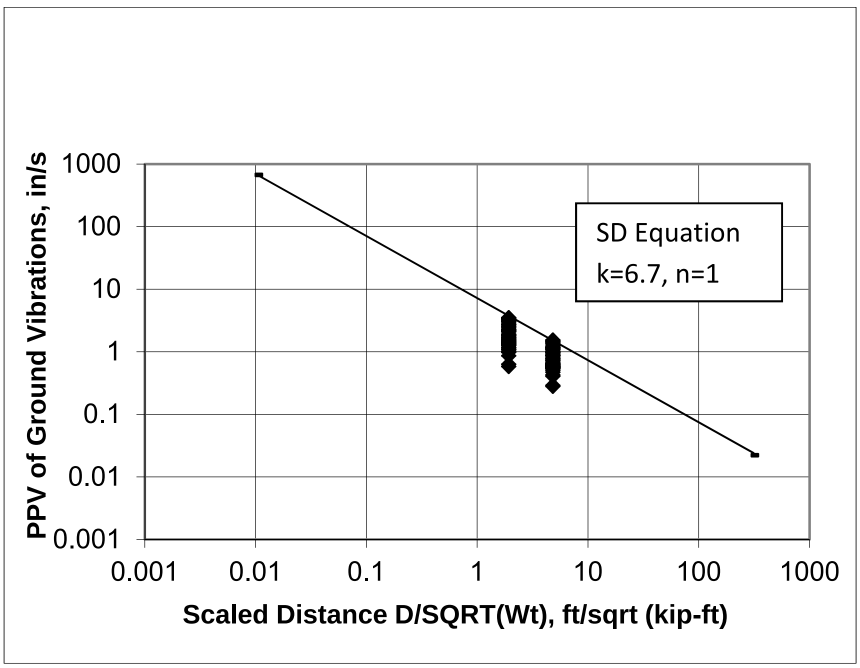

Figure 29: Kissimmee Park Road over SR 91 Bent 3, Pile 9

Osceola County

SR 429 Ramp B over I-4 and Ramp C

An ICE I-19 single diesel hammer with a rated energy of 43.2 kip-ft at 10.8 ft stroke was used to install HP14x89 steel piles. During pile driving, the transfer energy changed in the limits of 10.7-15.5 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix (SP). A SD equation was derived on the basis of field data. The coefficient k=7.6 was determined for the considered pile using the transfer energy. For another pile, the coefficient k equals 6.1.

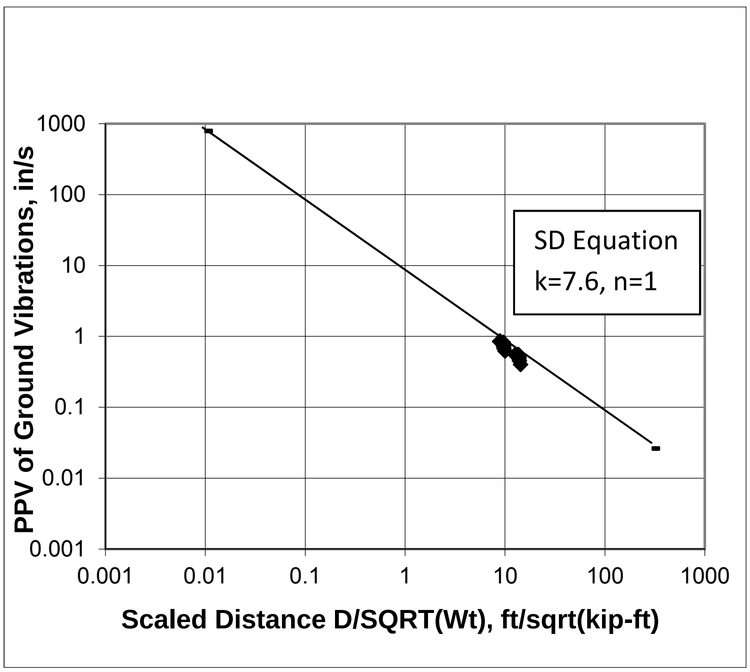

Figure 30: SR 429 Ramp B over I-4 and Ramp C Pier 3, Pile H-16

Osceola County

SR 429 Ramp B over Dreamer's Drive

A Delmag D46-32 diesel hammer with a rated energy of 122.2 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 6.0-31.6 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand (SP, SP-SM). A SD equation was derived on the basis of field data. The coefficient k=8.0 was determined for the considered pile using the transfer energy. For other two piles, the coefficient k equals 7.1 and 6.8.

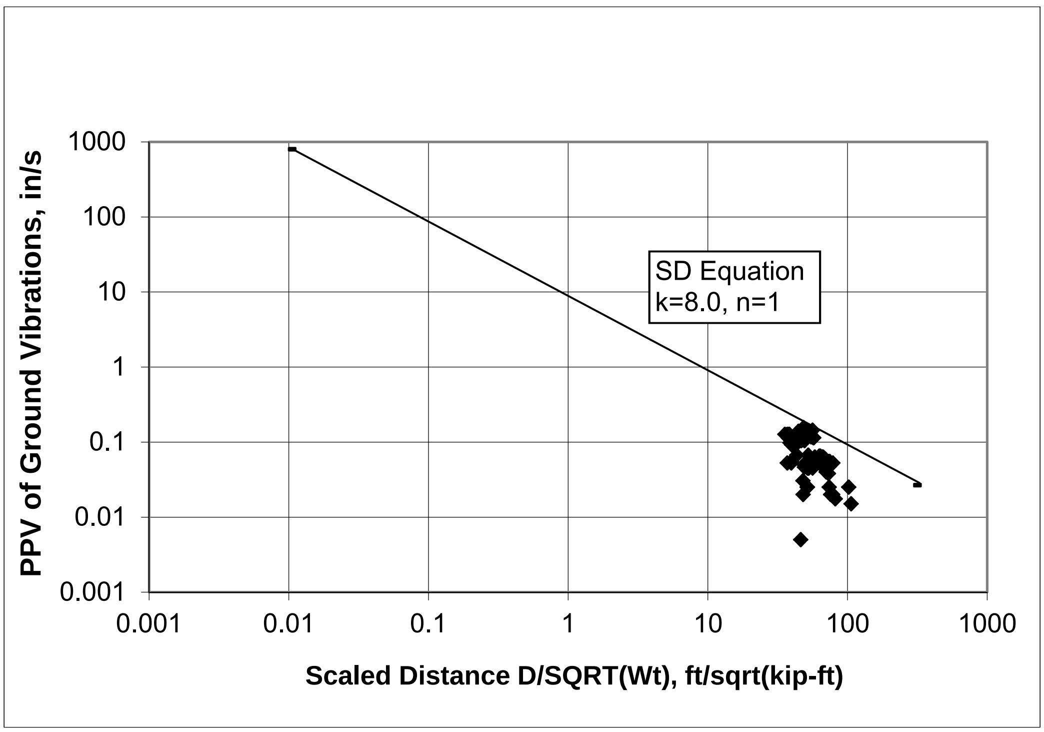

Figure 31: SR 429 over Dreamer's Drive Pier 2, Pile 1

Osceola County

SR 429 over Funie Steed Road

A Delmag D46-32 diesel hammer with a rated energy of 122.2 kip-ft was used to install 24-in square PSC piles. During pile driving, the transfer energy changed in the limits of 11.01-27.05 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand (SP, SP-SM). A SD equation was derived on the basis of field data. The coefficient k=7.5 was determined for the considered pile using the transfer energy.

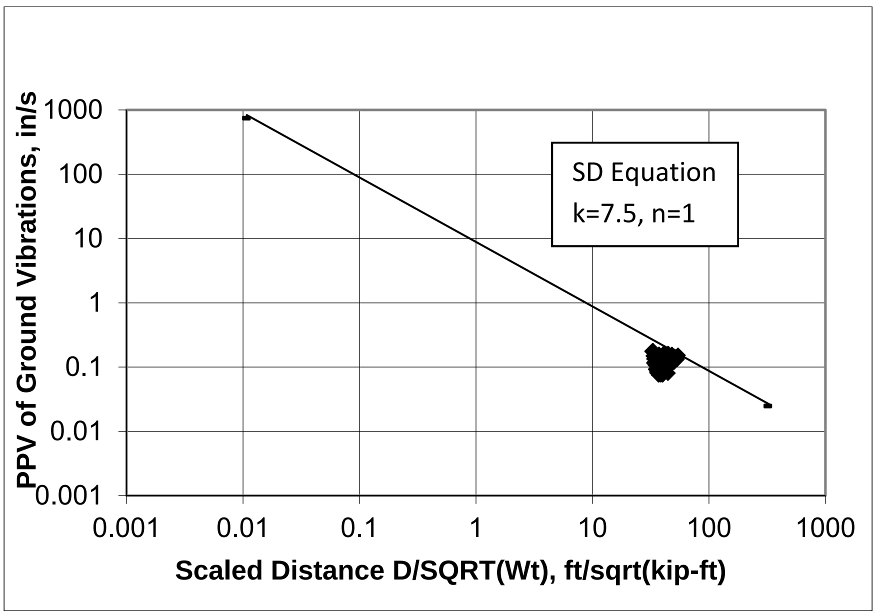

Figure 32: SR 429 over Funie Steed Road End Bent 1L, Pile 12

Seminole County

SR 417

An APE D46-32 diesel hammer with a rated energy of 101.52 kip-ft (setting 2) was used to install 24-in square PSC piles. The maximum transfer energy during pile driving was assumed 20.3 kip-ft on the basis of previous pile installation with the same impact hammer.

Soil conditions are mostly various sands: sand, sand with silt, and sand with clay (SP, SM). A SD equation was derived on the basis of field data. The coefficient k=5.0 was determined for the considered pile using the transfer energy.

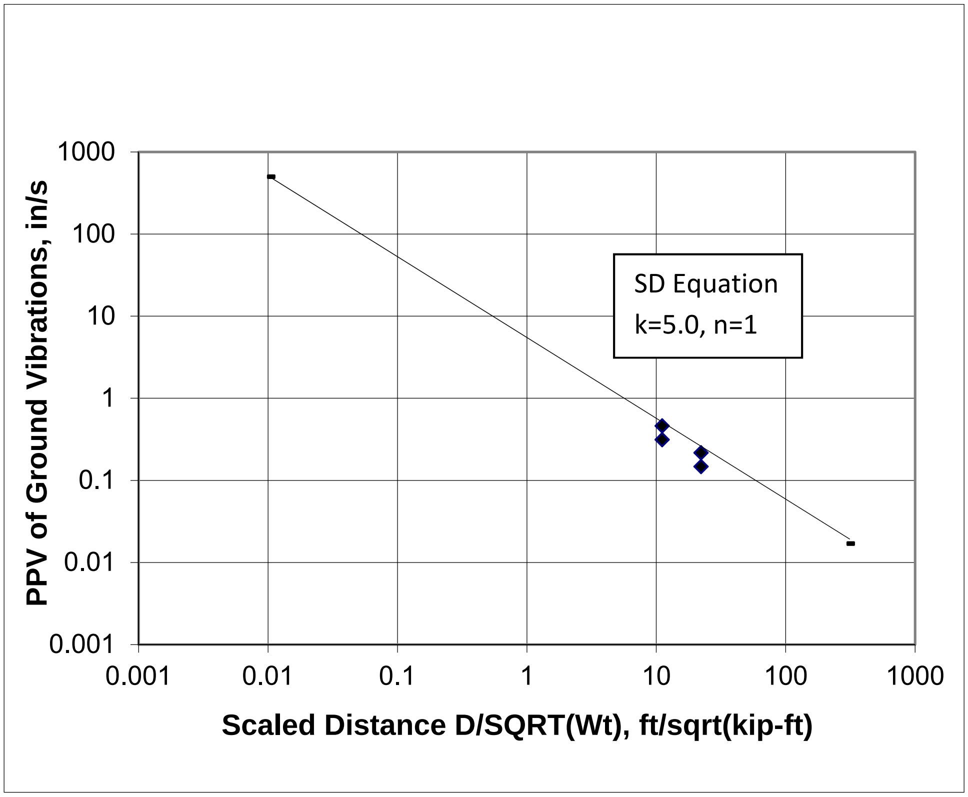

Figure 33: SR 417 End Bent 1, Pile 14

Miami-Dade County

Ramp A over Snapper Creek Canal

An ICE 120-S diesel hammer with a rated energy of 120.0 kip-ft was used to install 30-in square PSC piles. During pile driving, the transfer energy changed in the limits of 5.4-25.2 kip-ft.

Soil conditions: limestone (LS). A SD equation was derived on the basis of field data. The coefficient k=1.3 was determined for the considered pile using the transfer energy.

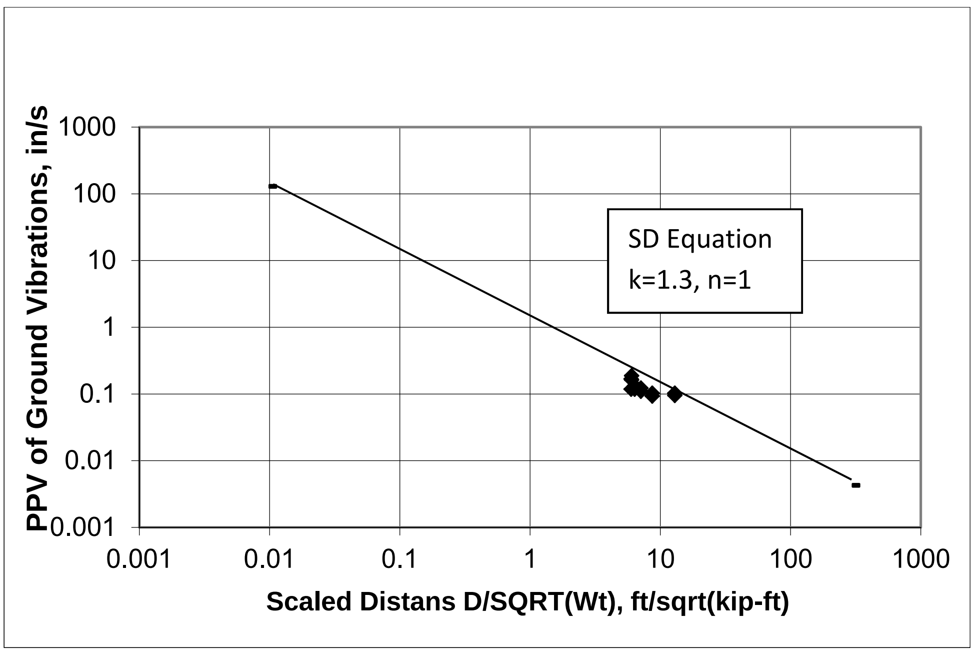

Figure 34: Ramp A over Snapper Creek Canal End Bent 4, Pile 5

Miami-Dade County

Ramp B over Snapper Creek Canal

An ICE 120-S diesel hammer with a rated energy of 120.0 kip-ft was used to install 30-in square PSC piles. During pile driving, the transfer energy changed in the limits of 9.9-22.4 kip-ft.

Soil conditions: limestone (LS). A SD equation was derived on the basis of field data. The coefficient k=1.7 was determined for the considered pile using the transfer energy. For another piles, the coefficient k equals 1.2, 0.7 and 1.1.

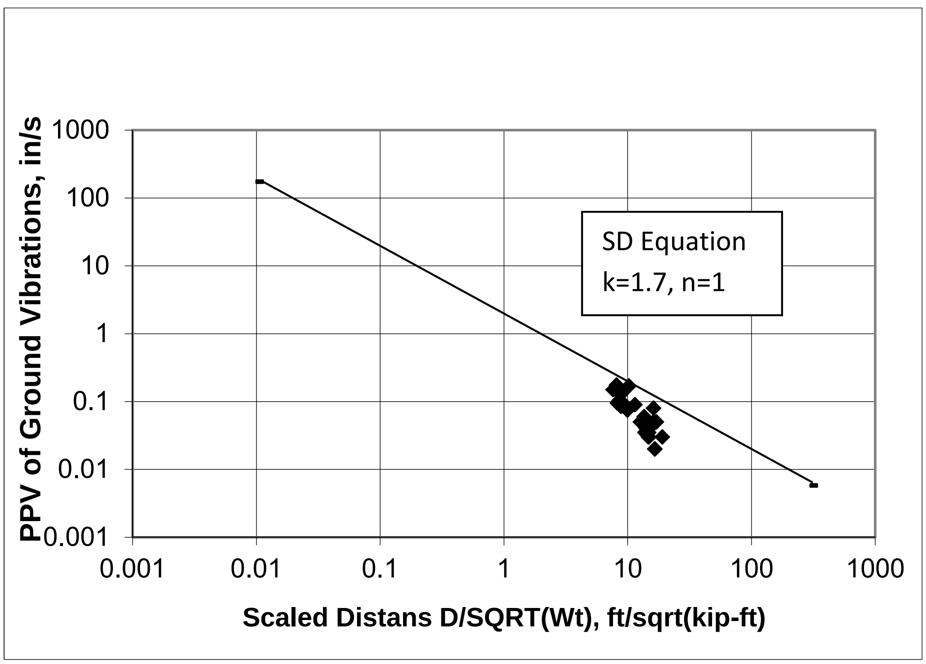

Figure 35: Ramp B over Snapper Creek Canal Bent 4, Pile 2

Miami-Dade County

Ramp C over Snapper Creek Canal

A Delmag D36-32 diesel hammer with the rated energy of 90.56 kip-ft was used to install 18-in square PSC piles. During pile driving, the transfer energy changed in the limits of 10.5-17.6 kip-ft.

Soil conditions: limestone (LS). A SD equation was derived on the basis of field data. The coefficient k=1.7 was determined for the considered pile using the transfer energy.

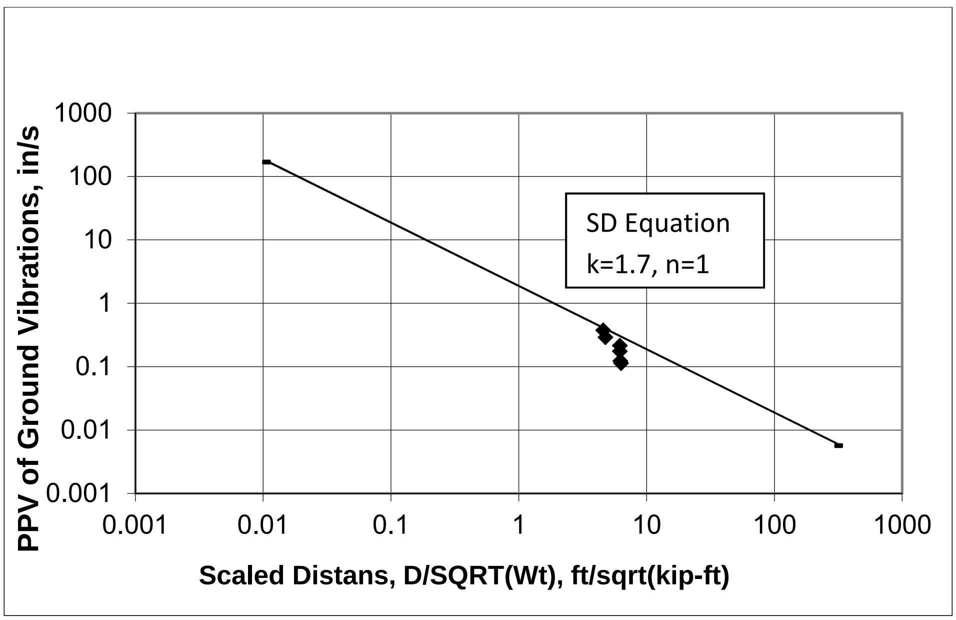

Figure 36: Ramp C over Snapper Creek Canal End Bent 1, Pile 5

5.4 Scaled Distance Equations for Sheet Piles

Flagler County

SR A1A

The vibratory driver used in the installation of the seawall was an HPSI Model 450. The vibratory driver used in the installation of the anchor wall was an HPSI Model 250. The operating frequency of both vibratory drivers is 1600 rpm. On January 3, 2006, the vibratory driver was changed to Hammer & Steel HPH 2400 hydraulic impact hammer. The transfer energy was assumed 3.06 kip-ft and 15.6 kip-ft from the vibratory driver and impact hammer, respectively. The soil profile approximately consists of a dry well-graded sand with shell, including intermittent zones of hard, cemented shell and sand (coquina) below depth of 20 feet below grade. A SD equation was derived on the basis of field data. The coefficients k=6.4 for impact hammer and k=14.9 for vibratory driver were determined for sheet piles using the transfer energy.

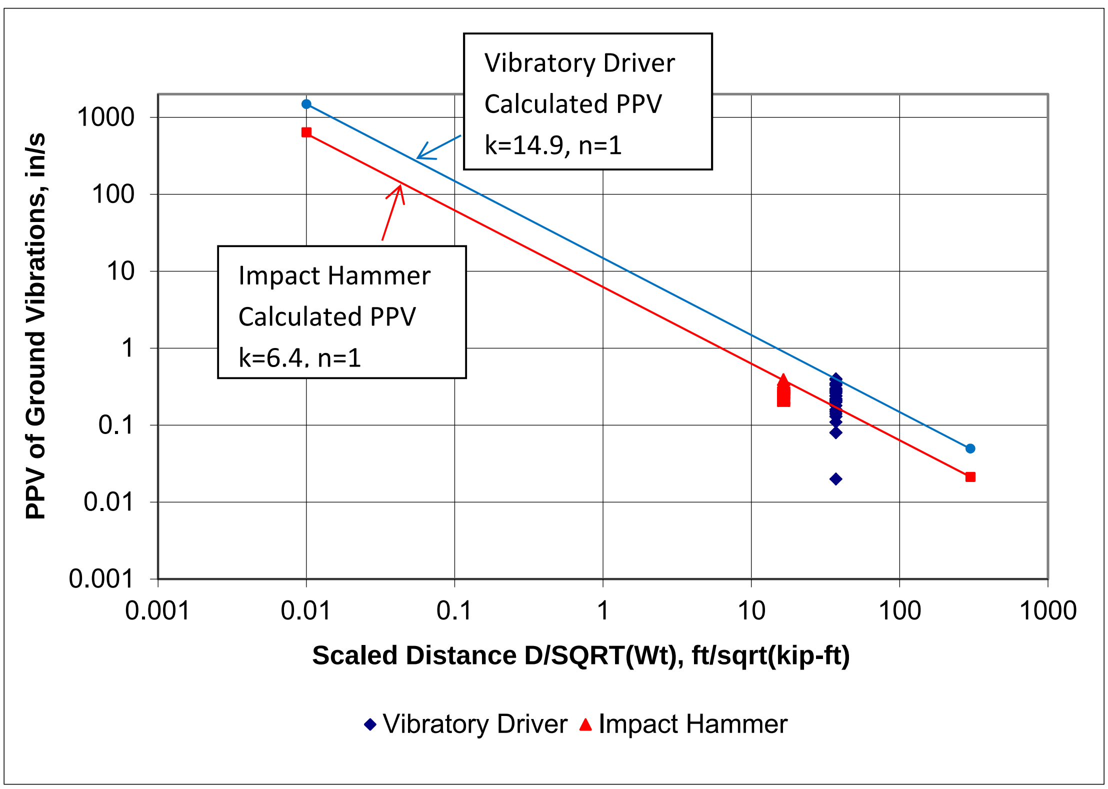

Figure 37: Sheet Pile Driving at SR A1A

Palm Beach County

Atlantic Boulevard Interchange

A pile section consisting of two interlocked ball and socket-type, “Z” shaped sheet piles (AZ-18), preassembled with tack welds at the interlock were simultaneously extracted or driven with the vibratory driver and crane assembly.

ICE 416 and J&M 44B vibratory drivers were used to install sheet piles. ICE 416 driver has the following characteristics: power of 150 Kw and frequency of 26.67 Hz. The energy (E) of vibratory drivers is equal to power/frequency. Thus, the rated energy of the vibratory driver was calculated as E = 150 / 26.67 = 5.62 kip-ft. Assuming a transfer efficiency of 25% for all vibratory drivers in this study, the transfer energy was calculated as 5.62 x 0.25 = 1.41 kip-ft.

Soil conditions: different layers of clean fine sand, sand-gravel mix and silty sand (SP, SP-SM). A SD equation was derived on the basis of field data. The coefficient k=19.0 was determined for the considered sheet piles using the transfer energy.

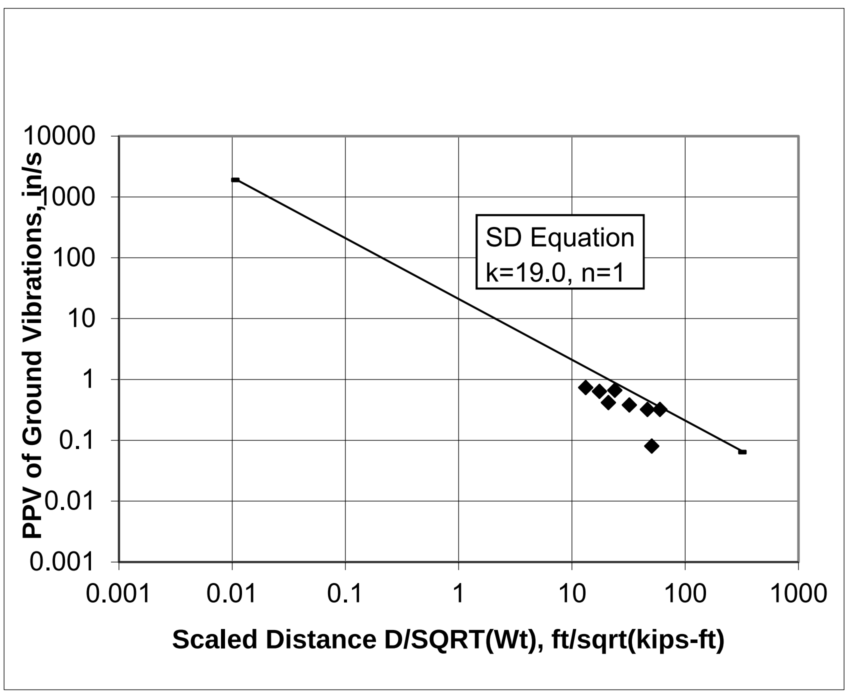

Figure 38: Atlantic Boulevard Interchange Sheet Piles

5.5 Scaled Distance Equations for Casing Operations

Duval County

Beaver Street Viaduct

The data used to prepare Figures 39 to 44 are from an ICE Model 812 vibratory driver with assumed maximum transfer energy of 14 kip-ft.

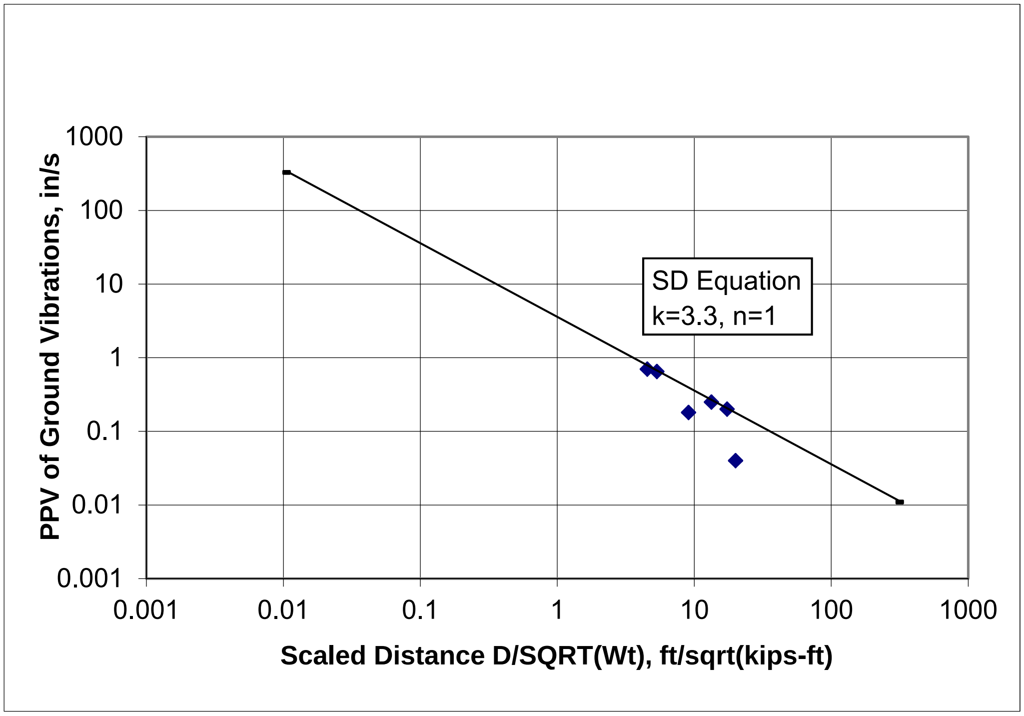

Figure 39: Casing removal, Bent 7, Shaft 3

Scaled-distance equation for vibratory removal of 49.5 inch (O.D.) casing during concrete placement

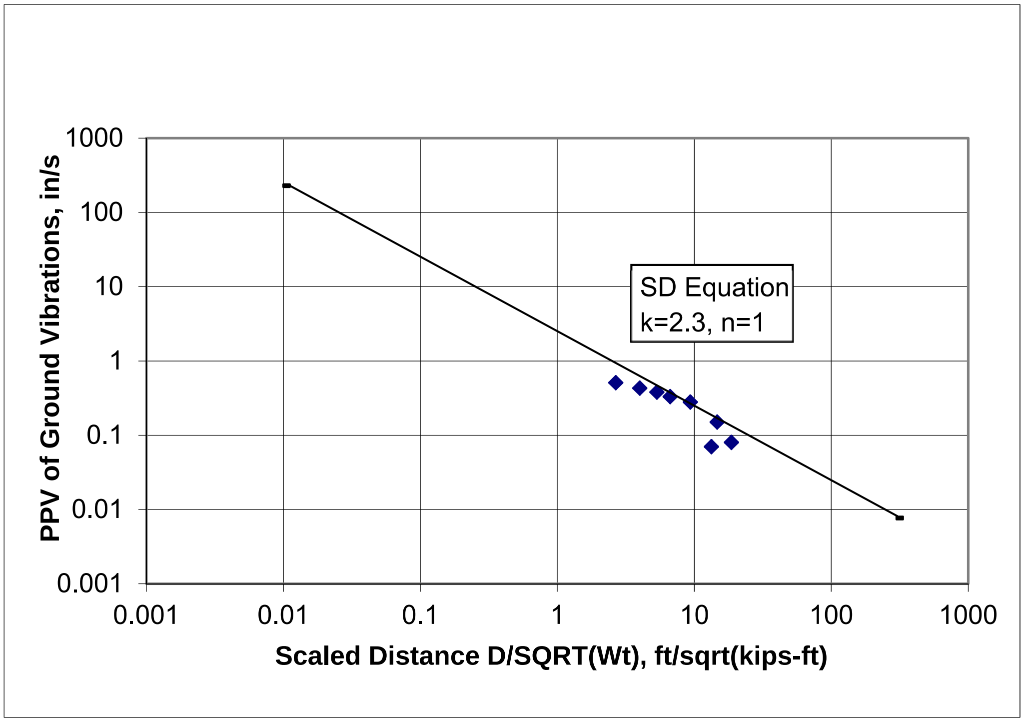

Figure 40: Casing installation, Bent 6, Shaft 4

Scaled-distance equation for vibratory installation of 49.5 inch (O.D.) casing

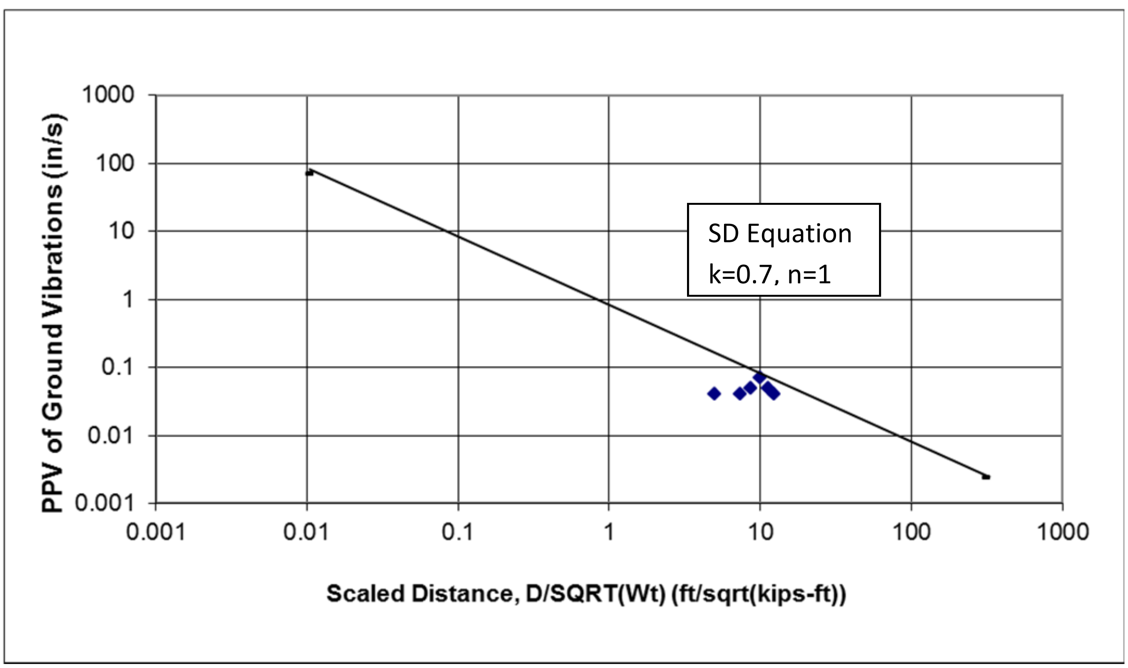

Figure 41: Casing installation, Bent 2, Shaft 5

Scaled-distance equation for vibratory installation of 49.5 inch (O.D.) casing

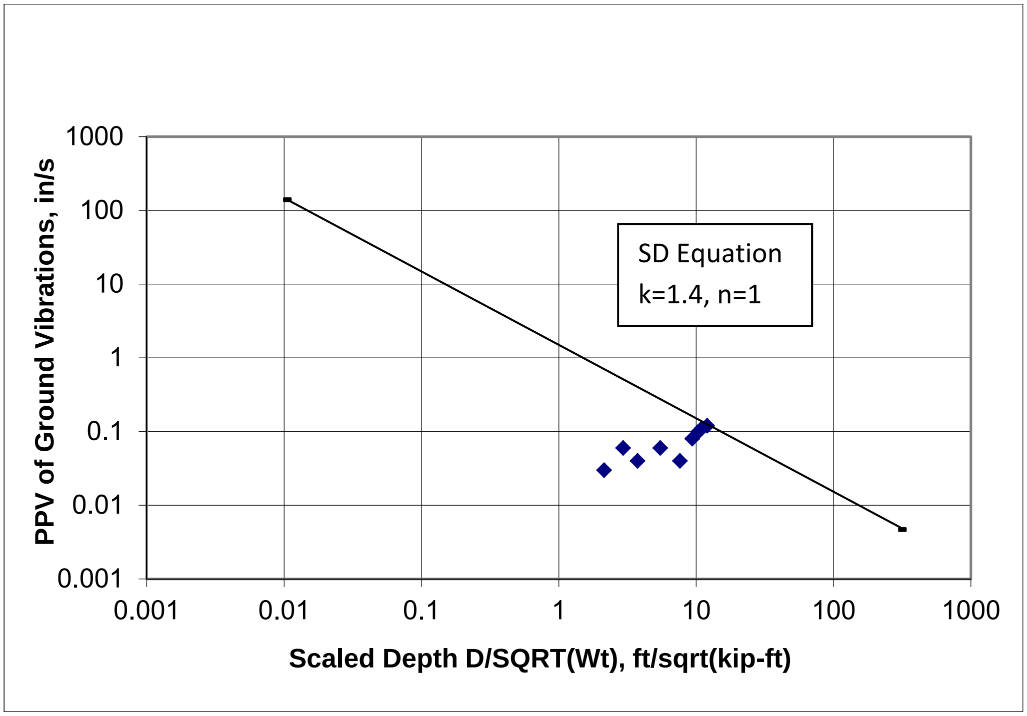

Figure 42: Casing installation, Bent 2, Shaft 4

Scaled-depth equation for vibratory installation of 49.5 inch (O.D.) casing

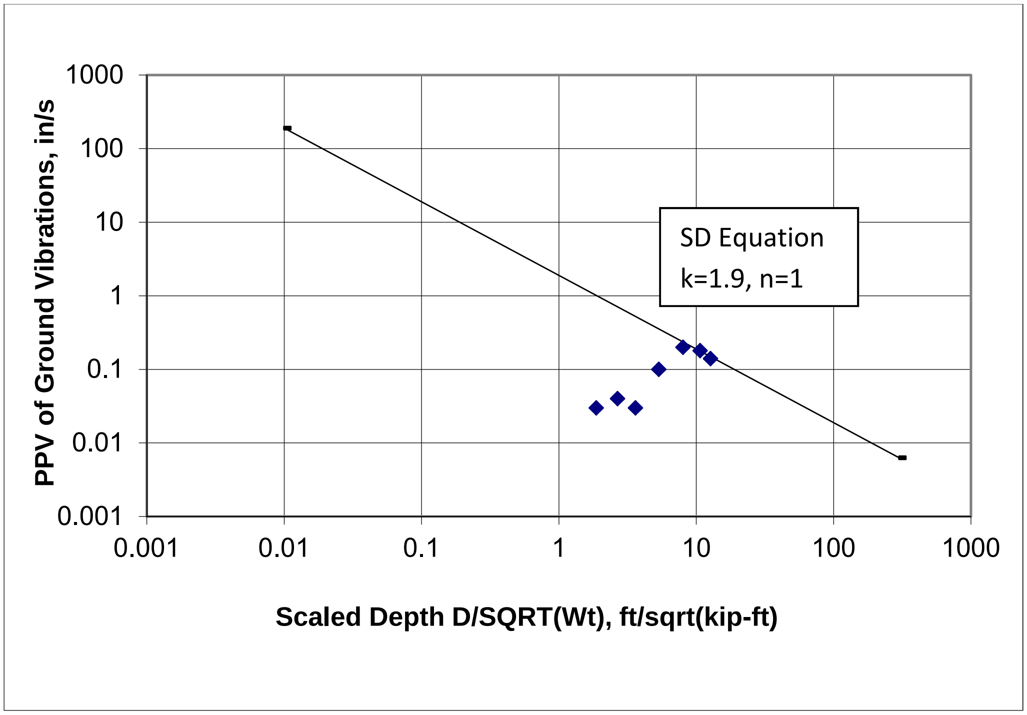

Figure 43: Casing installation, Bent 2, Shaft 3

Scaled-depth equation for vibratory installation of 49.5 inch (O.D.) casing

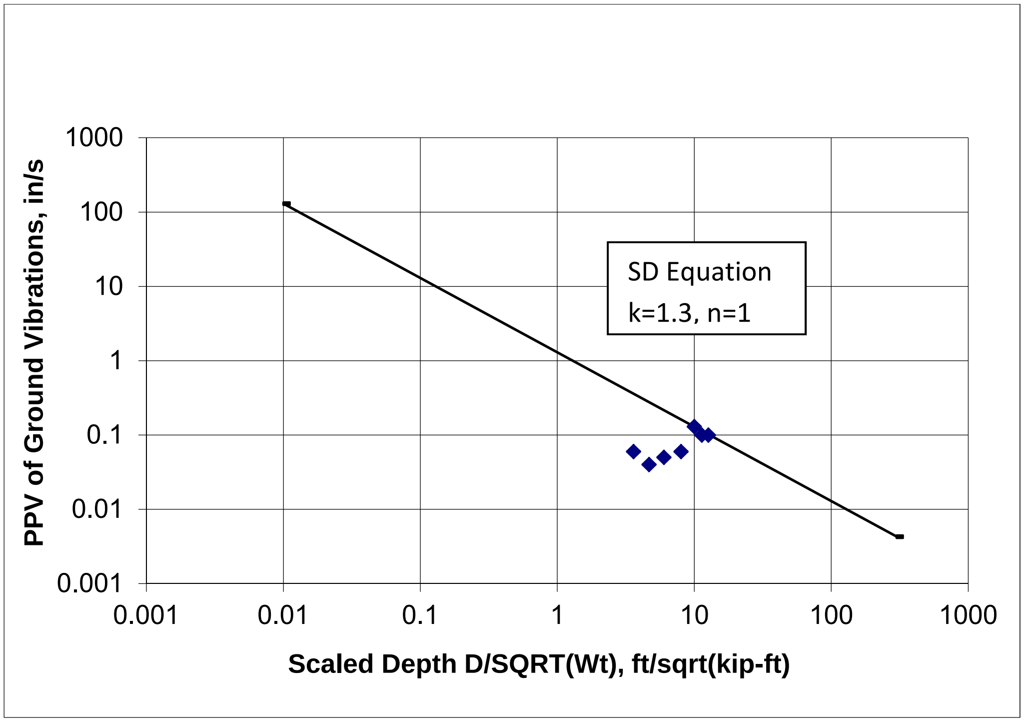

Figure 44: Casing installation, Bent 4, Shaft 3

Scaled-depth equation for vibratory installation of 49.5 inch (O.D.) casing

5.6 Equation for PPV of Ground Vibrations from Vibratory Rollers

The data presented in Figure 45 was provided by Mr. Wing Heung, Turnpike Lead Geotechnical Engineer, from an on-going effort to collect and analyze vibration data in Turnpike projects. The figure includes vibratory roller data compiled from 40 different vibration monitoring reports including over 170 data points over various compaction materials. Vibration measurements were plotted on a log-log plot to show peak particle velocities as a function of horizontal distance and develop the attenuation relationship.

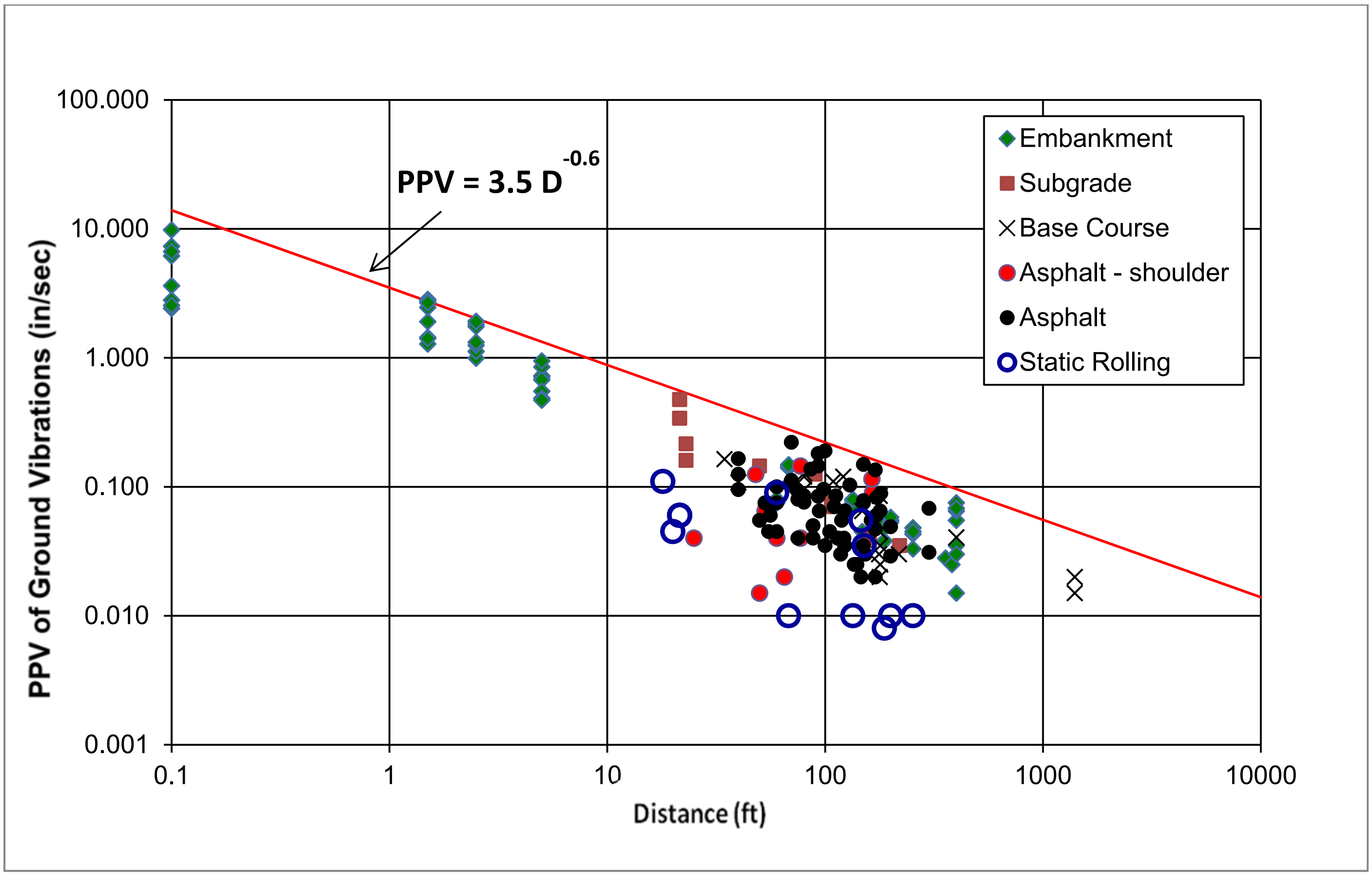

Figure 45: PPV of ground vibrations as a function of horizontal distance, (D)

6. CONDITION SURVEY OF STRUCTURES

6.1 Introduction

A pre-construction condition survey is an important step in the control of construction vibrations to ensure safety and serviceability of adjacent and remote houses, buildings, and facilities. A pre-construction condition survey should also be conducted after the dewatering and excavation and before the beginning of the test pile program. Pre-construction surveys coupled with surveys during construction provide useful information on structural responses to vibration excitations.

This chapter provides a comprehensive review of and guidelines for condition surveys under four categories including: (i) existing practice, (ii) the goals of condition surveys, (iii) condition surveys during and after construction, (iv) measurement of background vibrations and sensitive equipment, and (v) appropriate distances for condition surveys.

6.2 Existing Practice

Based on the responses to the survey discussed in Chapter 3, the necessity of a pre-construction condition survey of structures is recognized by the majority of respondents. A pre-construction condition survey is usually conducted to document the existing cracks and other damage, assess the condition of structures, and determine mitigation measures for potential effects of pile driving on structures. Pre-driving surveys generally include the video recording and inspection of structures, photographs of the existing flaws and damage, installation of crack gages, and inspection notes. Most survey responses indicated use of condition surveys for nearby structures within a certain range, such as 100 ft., 200 ft., or a distance determined on a project-by-project basis.

Florida DOT Practice

FDOT Soils and Foundations Handbook and the Standard Specifications for Road and Bridge Construction underline the importance of: (i) condition surveys, (ii) the analysis of possible vibration effects on structures, and (iii) the need to apply mitigation measures to decrease vibration effects. Relevant sections are quoted below.

FDOT - Soils and Foundations Handbook 2011

9.2.4 Existing Structures Survey and Evaluation

Structures in close proximity to construction activities should be evaluated for potential damage caused by these activities. The usage of the structures should also be included in this evaluation. This needs to happen early in the design process. Vibration, settlement, noise and other damaging results of these construction activities should be considered in evaluation. When warranted, the recommendations should include possible means of reducing the damaging effects of the construction activity, such as time restrains on certain operations, underpinning, monitoring, or even purchasing of the property. Table 14 shows what is needed in a report. Table 15 and the notes that follow are examples of what may be shown on the plan sheets.

Where there is a potential impact on existing structures in the surrounding area, the report should include the structure's address, type of construction, the estimated vibration level that may cause damage, the usage (storage building, hospital, etc.), what the potential problem may be and what actions should be taken to minimize the impact.

Vibration: The contractor shall provide surveys and settlement/vibration monitoring of the existing structures listed, as per FDOT Standard Specifications.

10 Construction and Post-Construction

Where existing structures may be sensitive to vibrations or movement, preconstruction and post-construction surveys of structures should be performed. Mitigation action shall be taken to reduce the impact. It may also be desirable to monitor construction-induced vibrations, groundwater level changes, and/or settlement or heave of structures.

FDOT - Standard Specifications for Road and Bridge Construction 2013

455-1.1 Protection of Existing Structures

When the Plans require excavation or foundation construction operations in close proximity to existing structures, take all reasonable precautions to prevent damage to such structures. The requirements described herein apply to all types of structures (on or off the right-of-way) that may be adversely affected by foundation construction operations (including phase construction) due to vibrations, ground loss, ground heave, or dewatering. Protect utilities as described in the applicable provisions of Section 7.

Survey and monitor structures for settlement in a manner approved by the Engineer, recording elevations to 0.001 foot. Employ a qualified Specialty Engineer to inspect and document the condition of structures prior to and after construction of excavations and foundation construction. Inspect and monitor the following structures:

(1) as shown in the Plans,
(2) within a distance of ten shaft diameters or the estimated depth of drilled shaft excavation, whichever is greater,
(3) within a distance of three times the depth of other excavations,
(4) within 200 feet of sheet pile installation and extraction operations,
(5) for projects with pile driving operations, inspect and document the condition of all structures within a distance, in feet, of pile driving operations equal to 0.25 times the square root of the impact hammer energy, in foot-pounds. Survey and monitor for settlement all structures within a distance, in feet, of pile driving operations equal to 0.5 times the square root of the impact hammer energy, in foot-pounds.

Obtain the Engineer’s approval of the number and location of monitoring points. Record elevations:

(1) before beginning construction,
(2) daily during the driving of any casings, piling, or sheeting,
(3) weekly for two weeks after stopping pile driving,
(4) during excavation,
(5) during blasting,
(6) or as directed by the Engineer.

Notify the Engineer of any movements detected and immediately take any remedial measures required to prevent damage to the existing structures.

The Department will make the necessary arrangements to provide right of way entry to the existing structures.

Adequately document the condition of the structures and all existing cracks with descriptions and pictures. Prepare two reports documenting the condition of the structures: one report before beginning foundation construction operations and a second report after completing foundation construction operations. The Department will take ownership of both reports. Do not perform pre-driving and post-driving surveys of the condition of bridges owned by the Department except when shown in the Contract Documents.

6.3 Goals of Condition Surveys

A pre-construction survey is the first step in the control of construction vibrations to ensure safety and serviceability of adjacent and remote houses, buildings, and facilities. This survey can detect possible disruption of businesses from pile driving vibrations, which includes the vibrations' impact on sensitive equipment and operations, as well as cosmetic cracking and the effects it will have on surrounding houses and buildings.

The initial step is to get access permission into a property in performing the condition surveys. It is recommended that requests to access the property in performing condition surveys be sent through certified letter or similar delivery which has a return receipt. Based on past experience, many recipients will not respond. The receipt of the certified mail will provide documentation that pre-construction survey could not take place beyond the control of the project. This may become a considered factor if a damage claim is submitted for the same property owner in the future.

There are four goals of a preconstruction condition survey (Svinkin, 2012):

1. Document the existing cracks and other damage.
2. Analyze the possible causes of the existing damage.
3. Assess susceptibility rating of structures.
4. Determine mitigation measures of pile driving effects on structures.

The existing practice takes into account the first, and partially the fourth goal; all goals, however, are important for a successful condition survey.

1. Document the Existing Cracks and other Damage

A preconstruction condition survey must be conducted with care, ensuring that all observable defects are documented. A poor inspection in which defects are omitted will be meaningless to a pile driving contractor (Dowding, 1996). A condition survey of structures should therefore be conducted by an engineer or experienced technician.

This survey should include observation and documentation of the existing condition of exterior and interior walls, ceiling, floors, roof, utilities, and foundation, if possible. Cracks and other damage should be detailed by video and photography. Notes and sketches should be made to highlight, supplement, or enhance the photographic evidence. It is also beneficial to document those areas of buildings without damage for future comparisons after the completion of pile driving operations.

It is necessary to distinguish the different types of cracking in structures, as follows: cosmetic cracking, architectural or minor damage, and structural cracking, which may result in the serious weakening of buildings. Therefore, the most attention should be paid to cracks in the structures themselves. A survey for estimating the preconstruction status of houses, buildings, and facilities is usually accompanied by instrumentation on structures. The targets of instrumentation should be the existing cracks in structures. It is necessary to analyze crack movements from everyday activities and environmental changes before the beginning of construction activities.

The condition survey report should summarize the condition of each building and define areas of concern.

2. Analyze Possible Causes of Existing Damage

A pre-pile-driving condition survey of structures is imperative to determine causation of the existing damage. Environmental forces, geotechnical hazards, and dynamic forces from pile driving and the dynamic compaction of weak soils can be the causes of similar structural damage, and such damage can exist before the beginning of construction operations (Svinkin, 2008).

It is necessary to point out that there are many non-vibratory environmental forces which act on structures to generate cracks and other defects. These forces begin exerting their influence before the time of construction begins, and some of them will continue to act over the lifetime of the structures.

Environmental stresses may be generated by forces either within or outside the structure or outside the house. Some of the larger stresses in the construction materials or the structure are developed by factors such as: changes in temperature; changes in moisture (relative humidity as well as liquid water); curing, shrinking or warping of lumber; drying and curing of such materials as plaster, mortar, grout, concrete, brick and other masonry products, and adobe; internal heating of the structure; aging, involving both chemical and physical deterioration; loss of friction; loss of elasticity; gravitational loads induced by the weight of the structure itself and all of the furnishings, supplies, and persons inside the home; and other factors.

Also, there are many important exterior factors, including site development: cut and fill profiles, type of underlying material; changes in soil conditions: addition or loss of water (rainfall or applied by owner), drainage and the condition of drainage facilities; weather changes; wind; vegetation, especially the influence of roots; yard maintenance; aging and deterioration of exterior materials and structural components; natural disasters; and other factors.

In all cases, it is necessary to pay attention to the quality of materials, workmanship, and maintenance. There are many reasons for the various cracks that form in structures and in the adjacent driveways, sidewalks, patios, garden walls, planters, and similar items that are frequently mentioned in vibration damage claims. Most materials used in residential construction undergo some shrinkage or warping during their curing stages, and will continue to suffer additional deterioration for the lifetime of the structure. The older the structure, the more cracks we expect to find. This means that some cracks are normal, not abnormal.

It is particularly important to analyze the geotechnical natural hazards at various distances from construction sites, such as heave, settlement, stability, sliding, and failure, which may cause damage to structures prior to, during, and after construction. There are case histories that show the major effects of geotechnical causes and environmental forces on crack formation and structural damage in spite of pile driving in the proximity of structures. Properly performed surveys provide the reliable arguments for protecting the pile driving contractors in possible litigations.

3. Classify Susceptibility Rating of Structures

Inspected houses and buildings should be classified into three different categories, as a function of the building's susceptibility to cracking during pile driving: high, moderate, or low susceptibility (Dowding, 1996). Cracking is the threshold of cosmetic cracking.

Buildings identified as having high susceptibility have already experienced a significant amount of degradation to their primary structural and/or nonstructural systems. Construction vibrations may result in further degradation of these elements. Buildings with loose or unstable elements, such as loose bricks or architectural details, or buildings with significant quantities of fragile and unstable contents, are considered to fall into this category. Historic buildings usually have a high susceptibility rating.

Buildings identified as having moderate susceptibility have not yet experienced significant degradation to their primary structural and/or nonstructural systems. Buildings with small-to-moderate quantities of fragile, potentially unstable contents, which may be damaging during construction, are included in this category.

Buildings identified as having low susceptibility are not expected to experience cosmetic cracking when subjected to construction vibrations.

4. Determine Mitigation Measures of Pile Driving Effects on Structures

Reduction measures for decreasing the vibration effects of pile driving depend on soil deformation and soil-structure interaction, and 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 Chapter 8.

6.4 Condition Survey During and After Construction

Condition surveys during pile installation and after the completion of pile driving are significant in determining the potential causes of damage to structures. Each construction site is unique; sites with similar soil deposits do not always have the same dynamic settlement response. As such, the physical evidence of damage to structures from dynamic sources is very important. If crack widths increase without increasing of crack lengths, it is not dangerous for structures.

One of the research team members experienced a case history with substantial building damage in which pre- and post-construction surveys found no evidence of dynamic settlement. Damage in a building was identified before the beginning of pile driving, and damage increased during and after construction was completed. In general, dynamic effects of construction operations can develop only at the time of pile driving. The process of the building damage began prior to the start of pile driving operations at the adjacent construction site, continued during the construction, and became more intense after the completion of the construction project. Given the evidence, the cause of damage to the structure was later determined to be slope sliding.

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

6.5 Measurement of Background Vibrations and Sensitive Equipment

As a part of the preconstruction survey, a measurement of the existing vibration background should be taken to obtain information regarding the effects of existing vibration sources. This is because the presence of sensitive devices and/or operations, such as electronics, medical facilities, and optical and computerized systems usually placed on floors, requires the measurement of floor vibrations. For relatively flexible floor systems in buildings, construction vibrations may create conditions for complaints about the 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, the dropping of boxes with computer paper, and other footfall events.

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

6.6 Distances for Pre-construction Condition Survey

Diverse approaches are analyzed below to determine the acceptable distance for condition surveys.

General Considerations

There is no single opinion regarding the maximum radius of a preconstruction survey area with houses and buildings surrounding a construction site. In addition to the information provided in Chapter 3, it is necessary to underline some of the general approaches used to determine the distances for condition surveys.

Dowding (1996) suggested a radius of 400 ft. of construction activities, or out to a distance at which vibrations of 0.08 in/s occur. The low vibration limit is connected with the dynamic settlement triggered by pile driving, and probably 400 ft. is a distance where settlement may not be expected. This limit is acceptable for a number of sites, but not all of them. For example, Kaminetzky (1991) mentioned an interesting case in which building settlement developed at a distance of about 1000 ft. away from a pile driving site. The foundations of the buildings were underpinned on piles down to the tip elevation of the new driven piles to prevent building settlements. Apparently, this case history affected Woods' (1997) conclusions, as he considered distances of as much as 1,300 feet to identify settlement damage hazards.

Distances for Surveys as a Function of the Hammer Energy

In this section, distances for condition surveys are considered as a function of the hammer energy transfer to driven piles. In a deterministic formulation for the known transfer energy and vibration limits, a distance can be obtained from back analysis of a scaled-distance equation.

Choice of Appropriate Distances for Condition Surveys

An appropriate distance has to be chosen on the basis of factors for inducing ground and structural vibrations. Three groups of factors can affect a choice of distances for condition surveys.

- <u>Soil Conditions</u>: Soil around driven piles; soil at construction sites; soil beyond construction sites where waves propagate to structures; soil heterogeneity and uncertainty.
- <u>Pile Driving System</u>: The type of piles (displacement or non-displacement piles); the pile penetration depth; the hammer energy transferred to a pile; the resistance to pile penetration into the ground.
- <u>Vibration Receivers</u>: Soil elastic and plastic deformations with possible dynamic settlement; resonant soil vibrations; soil-structure interaction (direct vibration effects and resonant structural vibrations).

It is practically impossible to find a mathematical relationship for survey distances as a function of all three groups of factors. However, the vibration records of ground vibrations generated by pile driving can help to make a choice of appropriate distances for condition surveys because measured ground vibrations are site responses which automatically take into account a pile type, the hammer energy, and the resistance to pile penetration; the soil medium effects on ground vibrations from driven piles to locations of vibration measurements where elastic or plastic deformations can be detected. Therefore, PPV of ground vibrations measured at a construction site, together with general site information, are the basis for a determination of the appropriate distance for condition surveys.

A preliminary solution based on the research team's knowledge and experience is the following. The survey will include all buildings within a radius of about 40 to 80 m (approximately 130 to 260 ft). of the pile driving activities, depending on local conditions.

The mentioned above was determined based on an analysis of the ground vibrations from pile driving measured at a number of construction sites, the past experience of pile driving effects on structures, and common sense. This distance is mostly used to assess the direct vibration effects on structures. The condition survey should be selectively performed for areas within a 400 m (approximately 1300 ft). radius of historic buildings, as well as for areas with soils in which there is possible dynamic settlement.

7. STRUCTURAL RESPONSE AS THE BASIS FOR DETERMINING VIBRATION LIMITS

Elastic waves travel from dynamic sources and induce elastic soil deformations (ground vibrations) which vary in magnitude 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. However, under certain circumstances such as a combination of non-cohesive soil deposits and ground vibrations, elastic waves can be the cause of plastic soil deformations, e.g. liquefaction, densification and soil settlements. Soil-structure interaction will be different when plastic soil deformation occurs. The structural response to ground excitation depends on the soil response to waves propagated from the source and soil-structure interaction, Svinkin (2008).

7.1 Direct Vibration Effects

Direct damage to structures is a result of soil-structure interaction when frequencies of ground vibrations do not match natural frequencies of structures. Such damage may occur within a distance of about one pile length from the driven pile. These distances can be substantially larger for susceptible structures. The critical velocity values of ground vibrations, which may trigger crack formation and other structural damage, can be determined from analysis of vibrations from blasts because blasting produces the most intensive ground and structure vibrations. The U.S. Bureau of Mines (USBM) accumulated results of structural responses and damage produced by ground vibrations from surface mine blasting are shown in Figure 46 which was modified from Siskind (2000). 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 even exceeding 51 mm/s (2 in/s). These data indicate different vibration effects on structures in the three zones of PPV versus dominant ground vibration frequency.

Analysis of these data indicates different vibration effects on structures depending on the dominant frequency and the peak particle velocity of ground vibrations. According to Figure 46, direct minor and major structural damage were observed in the velocity range of 33-191 mm/s (1.3-7.5 in./s) for frequencies of 2 to 5 Hz and in the velocity range of 102-254 mm/s (4-10 in./s) for frequencies of 60 to 450 Hz. The levels of these vibrations are substantially higher than the USBM and OSM (the Office of Surface Mining) vibration limits.

In general, the blasting energy is 50 to 1000 times higher than the energy transferred to piles during driving, but in proximity of driven piles, ground vibrations are similar to those from blasting. For example a Linkbelt 440 Diesel Hammer with energy of 24.6 kJ (18.14 ft-kips) induced ground vibrations with a PPV of 152 mm/s (6 in/s) at a distance of 0.7 m (2.3 ft) from a driven pile and 117 mm/s (4.6 in/s) were measured at a distance of 0.3 m from a Drop Weight with the energy of 8.1 kJ (5.97 ft-kips), Woods (1997).

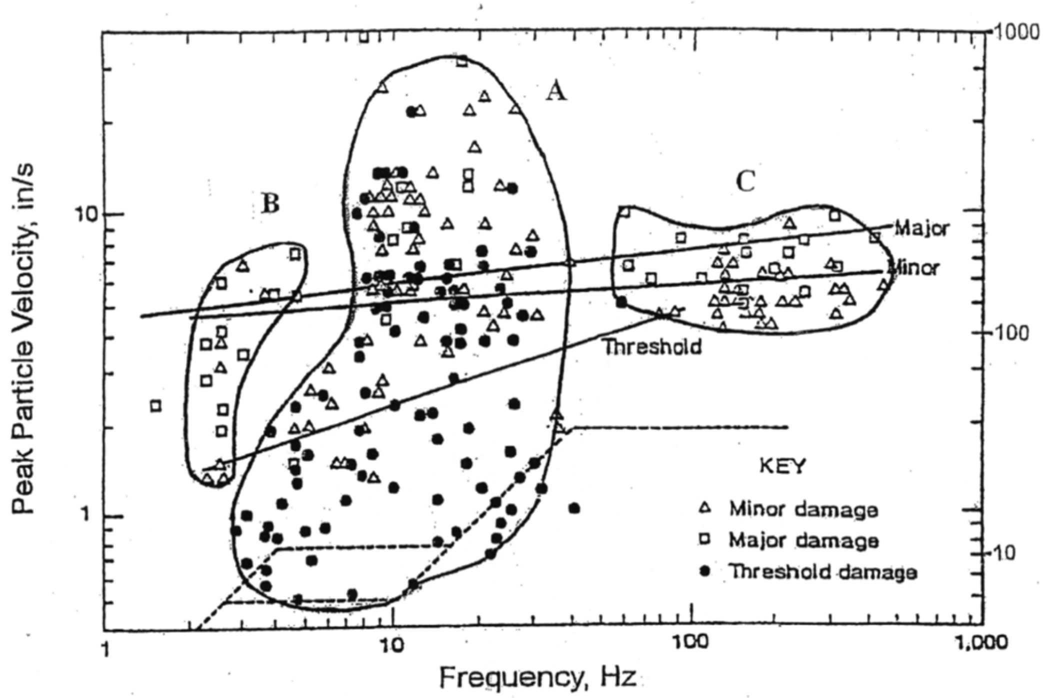

Figure 46: Three zones with closely grouped structure responses and damage summary from ground vibrations generated by blasting, and USBM recommended safe limits-dashed lines. *Data were modified from Siskind (2000) and plot was adapted from Svinkin (2006a).*

7.2 Resonant Structure Vibrations

The proximity of the dominant frequency of ground vibrations to a 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 the building's natural frequency, resonant vibrations do not develop. The resonant structural vibrations are independent of the structure's stiffness, being limited only by damping.

Similarly to blasting, the proximity of the low-frequency components of ground vibrations induced by impact hammers to building's natural frequencies may generate the condition of resonance in the building at remote locations and trigger large horizontal vibrations. For one- and two-story residential houses, a dynamic magnifying factor at resonance was measured in the range of 2 to 9 during blasting operations. This factor can be much higher for buildings of more than two stories. The natural frequencies range from 2 to 12 Hz for horizontal building vibrations and from 12 to 20 Hz for horizontal wall vibrations. Nevertheless, because pile driving is a much less powerful source of vibrations than blasting, the probability of triggering resonant structural vibrations by impact hammer driving is very small. There are only two known case histories of resonant structural vibrations at distances of 200 and 500 m (656 and 1640 ft) triggered by forge hammers, which are similar to impact hammer used for pile driving (Svinkin, 2004). To the best of the writer's knowledge, there are no case histories of generation of resonant structural vibrations at large distances from impact pile driving. It is reasonable to not consider such effects in practice.

Vibratory drivers with various operating frequencies may produce resonant floor vibrations because the natural frequencies of vertical floor vibrations range from 8 to 30 Hz. These vibrations may affect precise and sensitive devices installed on the floors. Svinkin (2008) described a case history of vibratory sheet pile driving with the frequency of about 26 Hz. Vibratory sheet pile driving generated ground vibrations below 5 mm/s (0.2 in/s) and vertical floor vibrations higher than 50 mm/s (2.0 in/s) in a two-story house. These vibrations induced architectural damage to the house which experienced dynamic settlement as well.

7.3 Resonant Soil Vibrations

Resonance of soil layers is one more manifestation of harmful effects of construction vibrations (Svinkin, 2008). Matching the dominant frequency of propagated waves to the frequency of a soil layer can create the condition of resonance and generate large soil vibrations. Such amplification of soil vibrations may happen during vibratory pile driving. Woods (1997) noted that layers between about 1-5 m thick may produce a potential hazard for increasing vibrations when vibrators with operating frequencies between 20 and 30 Hz install piles in soils with shear wave velocities of 120 to 600 m/s (390 to 1970 ft/s). The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to accidental soil layer resonant vibration.

Transient soil vibrations can be affected by resonance of soil layers in diverse ways. Waves from blasting and dynamic sources with impact loads travel through the soil medium in all directions forming a series of quasi-harmonic waves, and they can be amplified as a result of resonant vibrations of soil strata. In most cases, analysis of site responses is focused on the motion at the free ground surface. However, resonant effects may occur at any point within a layered soil profile. It is possible to consider two locations with the same soil within the same site excited by the same dynamic source, and these locations could respond quite differently because of the nature and dimensions of surrounding soil layers (Davis and Berrill, 1998).

A bright example of strong ground and structure vibrations due to resonance of a soil layer was reported by Bodare and Erlingsson (1993). At the time of a rock concert held in the Nya Ullevi Stadium in Gothenburg (Sweden), a good half of the audience was in the stands on both sides of the soccer field and more than twenty-five thousand people were standing on the field close to the stage. During the concert, the audience jumped in time to the music. In this way, the audience excited vibrations of a clay layer 25 m (82 ft) thick from the surface. The layer had the same natural frequency of about 2.4 Hz as the beat of the rock music. The song lasted for several minutes and build up a high vibration level. Resonance of the clay deposit amplified ground vibrations and excited violent vibrations of stadium structures. Also, residential buildings 400 m (1312 ft) away experienced vibrations.

7.4 Dynamic Settlements

Dynamic forces transmitted from construction impact and vibratory sources to the soil medium can be the cause of soil failure that becomes apparent in soil liquefaction, densification and soil settlements beyond the potential densification zone.

Liquefaction can occur in saturated or dry sand. Different criteria are used for assessment of possible liquefaction at construction sites. For consistency with the vibration limits applied for ground vibrations generated by blasting, PPV values are employed as the vibration threshold for liquefaction in sand. Analysis of known publications shows that the limit of 10 cm/s (4 in/s) would be appropriate for assessment of liquefaction hazard in sands, Svinkin (2008). Unlike blasting, other sources of construction vibrations usually generate considerably smaller ground vibrations which are below the liquefaction threshold.

Pile driving and dynamic compaction can densify weak soils. Densification of sands is expected at short distances from blasting and such densification is used for improving loose and saturated sands to receive satisfied soil conditions. Dynamic loads force piles to vibrate and penetrate into the ground that result in densification and vibrations of soil surrounding a pile. The soil movements may produce heave, settlement and lateral displacement toward the existing nearby foundations and induce vibrations of adjacent structures. Dynamic compaction is used for densification and improvement of loose sands and granular fills.

Differential ground and foundation dynamic settlements can be triggered by relatively small ground vibrations in sand and by soil displacements in clay. Such settlements may happen beyond the potential densification zone at various distances from construction and industrial dynamic sources. According to Woods (1997), distances as great as 400 m may need to be surveyed to identify settlement damage hazard in sandy soils during pile driving.

Diverse forms of dynamic settlements exist in sand and clay soils. For example, relatively small ground vibrations can be the cause of dynamic settlement in sand, while horizontal ground displacements, as opposed to vibrations, can be the cause of heave and following settlement in soft and medium clays, (D'Appolonia, 1971; Svinkin, 2006b).

Soil Settlement in Sand Soils

Pile driving in loose to medium uniform saturated sands may cause differential soil and structure settlements. Relative density less than 70% is inferred as loose and medium dense sands. Also, large settlements have been reported for sites where piles were driven into diverse sands: denser, calcareous, silty, and sand with gravel and rubble. In addition to soil deposit, other factors could be also accountable for dynamic settlement such as the type of piles (low or high displacement piles), pile spacing, the method of pile installation (impact or vibratory driver), the sequence of pile driving, and the number of driven piles (Svinkin 2006a and Svinkin 2008).

The damages to structures range from small settlements (fractions of an inch) to the destruction of surrounding buildings. Examples of harmful effects on structures from settlements induced by pile driving are presented in a number of publications. Swiger (1948) described a case where driving H piles through about 30 m (100 ft) of saturated loose fine silty sand caused subsidence of the foundation area with a maximum settlement of 45 cm (1.5 ft), and installation of a few piles in the immediate proximity of an adjacent building founded on deep piles resulted in 0.6-1.2 cm (0.25-0.5 in) settlement of the building exterior wall. Lynch (1960) reported installation of 30 cm (12 in.) piles and 36 cm (14 in.) shells to the depth of about 18 to 24 m (60-80 ft) with a 41 kJ Vulcan hammer. The soil at a site consisted of sand fill, organic silt, loose to medium dense sand, limestone, and compact sand. Telltale measurements of the test piles indicated down-drag loading the pile tip caused by sand compaction that settled previously driven piles up to 17.8 cm (7 in). In a field study described by Horn (1966), pile driving in sand caused settlement of 15 cm (5.9 in) within the driving area and ground settlements at distances to 23 m (75 ft) from driven piles. Feld and Carper (1997) reported a case of significant settlements and severe damage to adjacent structures including one 19-story building caused by installation of H piles in sand with impact and vibratory drivers. The soil consisted of uniform medium dense sand.

Considerable settlements can occur at distances within approximately 30 m (98.4 ft) from the driven pile. Ground vibrations generated by pile driving are a major cause of ground settlements. Though dynamic settlement can mostly be expected in the close proximity of driven piles, such soil deformations may also occur at remote locations as well. For example, Kaminetzky (1991) mentioned an interesting case of building settlement developed at a distance of about 305 m (1000 ft) away from a pile driving site. Foundations of the buildings were underpinned on piles down to the tip elevation of the new driven piles to prevent building settlements.

It is possible to drive piles in sand without structural damage to adjacent and remote buildings because sand have different responses to dynamic excitations and some sand do not develop settlement under dynamic loading (Ashraf et. al 2002 and Svinkin 2008). Also, preventive measures can be used against dynamic settlement.

Soil Settlement in Clay Soils

Pile installation in clay is different from pile driving in sand. Pile penetration into clay produces an increase in lateral stresses, pore pressures, and heaves of the ground surface. During pile driving, the excess pore pressure increases with each driven pile and may reach large values at distances far beyond the pile group area. This excess pore pressure can be much greater 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 critical if clay susceptible to dynamic load-induced settlement is present at a construction site. Effects of pile driving in soft to medium clay on the surrounding area should be expected at distances from the pile installation equal to about the thickness of the clay layer being penetrated.

Movements of adjacent buildings during pile installation are an important problem. Four case histories were reviewed to compare the role of several factors to mitigate effects of pile driving in soft to medium clay on adjacent buildings.

Case 1 (from D'Appolonia, 1971). End bearing pipe piles were driven for the foundations of the new MIT buildings in Boston. The soil consisted of about 6 m (19.5 ft) of miscellaneous fill, organic silt and peat followed by about 4 m (13 ft) of sand and gravel underlain by about 25 m (82 ft) of soft to medium blue clay deposited on dense sandy till and Cambridge shale. Piles were driven into preaugered holes drilled with a slightly oversized auger [34.3 cm (14 in) auger versus 31.4 cm (12 in) pile diameter] to within 4.6 to 9.2 m (15.1 ft to 30.2 ft) of the bottom of the soft clay. Preaugering was performed for approximately 75 to 87 % of the piles' final embedment depths. During pile driving the adjacent structures heaved up 0.9 cm (0.4 in). Subsequently, these structures settled. The maximum settlements were up to 3.8 cm (1.5 in) in two to five years after the end of construction. Measurable settlement occurred at distances greater than 30 m (98.4 ft). Two mitigation measures were used at the sites: pipe piles were driven into slightly oversized preaugered holes and the average pile density (defined as the number of piles per unit foundation area) in the test area was 0.086 and 0.172 piles/m^2 (0.008 and 0.016 piles/ft^2).

<u>Case 2 (from Casagrande and Avery, 1959)</u>. Non-displacement steel H piles were driven without preaugered holes near the site of the John Hancock Building in Boston. The soil profile is essentially the same as that described in case 1. Installation of H piles produced 2-3 times larger settlements at distances 15-45 m (49.2-147.6 ft) from the driven pile than driving displacement pipe piles into predrilled holes. In case 2, the pile density of 0.269 piles/m^2 (0.025 piles/ft^2) was 1.6-3.1 times higher than those in case 1. Perhaps this is one more cause of larger settlements developed from driving H piles.

<u>Case 3 (from Hokugo, 1964)</u>. Concrete piles with diameter of 51 cm (19.9 in) were driven through 30 m (98.4 ft) of soft to firm clay near buildings supported on short friction piles and railroad tracks. The average pile density was 0.484 piles/m^2 (0.045 piles/ft^2). Surface settlement markers and horizontal displacement devices were installed around the foundation area. Observation of soil movements were made during pile driving. After driving a small portion of the total number of production piles, it was found that the heave was 9.1 and 5.1 cm (3.6 and 2 in) at distances 3.8 and 10 m (12.5 and 32.8 ft), respectively, and the lateral displacement reached about 11 cm (4.3 in) at distances of 3 to 8 m (9.8 to 26.2 ft). The engineers concluded that driving some of the remaining piles would cause substantial damage to adjacent buildings and the railroad tracks. Therefore, many of proposed piles were replaced with drilled piers.

<u>Case 4 (from Bradshaw et al., 2005)</u>. 350 precast prestressed concrete piles were driven to support the highway structure. The piles were 41 cm (16 in) wide square. The soil consisted of about 6 m (19.7 ft) of fill followed by 4 m (13.1 ft) of organic silt and sand followed by 33 m (108.2 ft) of soft marine clay followed by 7 m (23 ft) of very dense glacial silt and sand underlain by bedrock. The piles were designed as end bearing piles to be driven into the dense glacial soils. Pile driving operations were organized in two phases. Piles were driven in the direction toward the building. Minimum distances between the building and driven piles were 27 m (88.6 ft) in the first phase and 16 m (52.5 ft) in the second phase. The average pile density was 0.161 piles/m^2 (0.015 piles/ft^2. The heave measured at the perimeter of the building increased steadily to 4.4 cm (1.7 in) as pile driving continued in the direction toward the building. Since heave exceeded the maximum specified value of 2.54 cm (1 in) at three locations, mitigation measures were implemented for the second phase of work. In particular, these measures included installation of wick drains, between the building and the pile driving field, for reducing pore pressure beneath the building and preaugering the holes for pile driving. The latter was done with a 41 cm (16 in) diameter auger to a depth of 26 m (85.3 ft), roughly 50 to 60 % of the pile's final embedment depth. The cross-sectional area of the auger was about 21 % less than the pile cross-sectional area. Heave continued to increase even after pile installation in the preaugered holes.

7.5 Additional Causes of Damage

Soil excavation associated with pile driving made in close proximity to existing buildings can produce structural damage. Permanent excavation deformations induced in adjacent structures generally exceeded those from pile driving equipment. Also, 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.

8. CHOICE OF APPROPRIATE VIBRATION LIMITS

8.1 Introduction

This chapter provides an analysis of the effects of different factors on vibration limits accompanied by a comparison of the criteria from diverse sources.

8.2 Direct Vibration Effects

From the USBM experience of ground vibration measurement from blasting shown in Figure 2, Chapter 2, it can be seen that ground vibrations may cause direct damage to structures in two frequency zones where excitation frequencies do not match the natural frequencies of structures. Direct minor and major structural damage without resonant structural responses were observed in the velocity 33-191 mm/s (1.3-7.52 in/s) range for frequencies of 2 to 5 Hz and in the velocity 102-254 mm/s (4-10 in/s) range for frequencies of 60 to 450 Hz. In both frequency zones, PPV of ground vibrations were higher than 25.4 mm/s (1.0 in/s).

Woods (1997) determined the vibration limits specifically for pile driving operations. The following criteria were suggested for PPV independent of frequency: for residential structures, 12 mm/s (0.5 in/s); for new residential structures, 25 mm/s (1.0 in/s); and for industrial buildings, 50 mm/s (2 in/s). Other approaches used for PPV vary with frequency. 25.4 mm/s (1.0 in/s) was suggested for all distances of more than 25 m (82 ft). For distances of less than 25 m (82 ft), different sources yield vibration limits from 19 to 25.4 mm/s (0.75 to 1.0 in/s) range. The minimum reasonable limit is 19 mm/s (0.75 in/s).

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

8.3 Resonant Structural and Soil Vibrations

It was mentioned in Chapter 7 that pile driving is a much less powerful source of vibration than blasting and, consequently, the probability of triggering resonant structural vibrations by impact hammer driving is very low. To the best of the research team's knowledge, there are no case histories of resonant structural vibrations being generated at large distances from impact pile driving. Therefore, it is reasonable to not consider such effects for practical goals. In particular, it is a confirmation that the USBM vibration limits are not applicable for pile driving.

Nevertheless, vibratory pile driving may produce resonant floor vibrations and also resonant vibrations of soil layers. There are no readily apparent means for reducing resonant structural vibrations and resonant soil layer vibrations. The best way to mitigate these effects is to use vibratory drivers with variable force and frequency. If resonant vibrations continue to occur, it is necessary to stop pile driving and change the frequency.

The application of a 51 mm/s (2 in/s) limit for measured structural vibrations can help to determine unacceptable vibrations of various structures.

8.4 Dynamic Settlement

Ground and foundation settlements as a result of relatively small ground vibrations in diverse sandy soils may occur at various distances from the source. This phenomenon is quite different from liquefaction because liquefaction can be triggered by relatively high ground vibrations with PPV of about 100 mm/s (4 in/s) (Svinkin, 2009), but ground vibrations with PPV 20 to 40 times smaller may be the cause of dynamic settlement in vulnerable granular soils. Although dynamic settlement can mostly be expected in close proximity to driven piles, such soil deformations may also occur at remote locations as well.

Lacy and Gould (1985) found that the peak particle velocity of 2.5 mm/s (0.1 in/s) could be considered as the threshold of possible significant settlements at vulnerable sites. Woods (1997) pointed out that the prudent approach is to always proceed with caution when the condition of settlement is known to be present.

8.5 Additional Causes of Structural Damage

Excavation and dewatering at construction sites may damage adjacent, and sometimes remote, structures. As these construction operations are performed before the beginning of pile driving, it is necessary to separate damage to structures from construction operations and from construction activities with the application of dynamic forces. Because of that, the pre-driving condition survey has to take place once excavating and dewatering have been completed at the site.

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

8.6 Historic and Old Structures

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

8.7 Equipment and Devices Sensitive to Vibrations

If medical or computerized equipment and devices are found on the floors of buildings, it is necessary to measure structural vibrations at the floors and use vibration limits specified for sensitive equipment and devices (Svinkin, 2012). The vibration limits for sensitive equipment and operations should be obtained 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 was then used to determine the following tolerable vibrations of mainframe disk drives: Constant amplitude vibration limits over the frequency range of 5 to 500 Hz, where functional limits are between 0.2 g and 0.25 g and survival limits can be 0.5 g; and impact vibration limits, where functional limits for the impact with maximum 11 ms duration are about 3 g. This value is a slightly conservative estimate because disk drives have still functioned at vibration levels of up to 4 g (at the ground) under earthquake simulation tests.

8.8 Final Comments

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

9. MITIGATION MEASURES TO DECREASE VIBRATION EFFECTS

As it was shown in Chapter 7, there are no specific regulations of soil and structural vibrations generated by pile driving and other construction equipment. The existing limits of construction vibrations do not cover a wide range of structures. Nevertheless, there is experience of managing vibrations from pile driving to eliminate or decrease cracks and other structural damage. There are certain rules for mitigating vibration effects on structures from construction sources, e.g. D'Appolonia (1971), Wiss (1981), Dowding (1996), Woods (1997), Jones and Stokes (2004), Svinkin (2006a and 2006b) and others.

This chapter provides a summary of the existing preventive and counteractive vibration mitigation techniques used by the industry, and recommends effective mitigation measures to decrease vibration effects from roadway and bridge construction operations in Florida.

A proactive environmental approach has to be used to ensure that no cracking and damage to structures will be originated from construction vibrations and for reducing possible complaints. Every construction site is unique and preliminary assessment of expected vibrations should be made prior to the beginning of construction operations.

Reduction measures for decreasing of vibration effects of pile driving and other construction equipment depend on elastic or plastic soil deformation, and soil-structure interaction. They should be considered before the beginning of pile driving operations (Svinkin, 2006b). The separate lists of measures to mitigate direct vibration effects on structures, resonant soil and structure vibrations, dynamic settlement in sand, and dynamic settlement in clay are presented below.

9.1 Direct Vibration Effects

For mitigation of direct vibration effects of ground vibrations on structures from installation of driven piles, a few factors should be considered (Woods 1997 and Svinkin 2006b). First, installation of low soil displacement piles, e.g. H-piles, instead of high soil displacement piles, e.g. concrete piles, can reduce ground and structure vibrations. Second, hard pile driving to a depth about 10 m from the ground surface may increase ground vibrations, but hard pile driving at a greater penetration depth induce less ground vibrations. Predrilling and jetting may be helpful for overcoming the high penetration resistance in upper soil layers, but both operations in sands should be done with caution. Third, substantial decrease of the hammer energy can be helpful; however, slight reduction of the hammer energy will have a small effect because PPV of ground vibrations depends on the square root of the hammer energy. Fourth, according to D'Appolonia (1971), pile driving operations should start nearby the existing structures and continue away from the structures because previously driven piles act as a shield and soil movements are greater in the direction away from the stiffer zone around the driven piles.

9.2 Resonant Soil and Structural Vibrations

Vibratory drivers may trigger resonant vibrations of soil layers and structures, but vibratory drivers with variable frequency can eliminate these phenomena (Woods, 1997).

Similar to blasting, low-frequency transient ground vibrations may appear at some distances from pile driving and such ground vibrations may trigger resonant soil layer and structure vibrations at remote distances from driven piles. However, in evaluation of pile driving vibration effects, there is no case history of resonant structural vibrations triggered by low-frequency ground vibrations from pile driving. It is good because there are no readily apparent means for reducing resonant structural vibrations induced by low-frequency ground vibrations with an exception of a pile driving halt.

9.3 Dynamic Settlement

It is known that relatively small ground vibrations can be the cause of dynamic settlement in sand. Horizontal ground displacements, not vibrations, can be the cause of heave and the subsequent settlement in soft and medium clays (D'Appolonia 1971 and Svinkin 2006a). Because of the different nature of dynamic settlements in sandy and clay soils, somewhat different mitigation measures are used in sands and clays to reduce the effects of dynamic settlement.

Dynamic Settlement in Sands

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

Dynamic Settlement in Clays

Effects of pile driving in soft to medium clays on the surrounding area should be expected at distances from pile installation equal to about the thickness of the clay layer being penetrated (D'Appolonia, 1971). Several factors can affect the induced pore pressure and movements. First, the chosen pile type is very important. Low soil displacement piles reduce the volume of soil displaced during pile driving. Second, predrilled holes improve conditions for using displacement piles. The cross-section of the auger and the drilled depth can strongly affect the volume of soil movements. Third, the spacing of the piles characterized by the average pile density per unit foundation area affects soil movements: the higher the density the larger the movement. Fourth, the sequence of pile driving operations should be directed away from the existing structures.

Mitigation measures together with criteria for vibration monitoring and control should be included in pile driving specifications. Examples of such specifications are available in Dowding (1996) and Woods (1997).

9.4 Alternative Construction Techniques

Improved construction techniques and alternative construction methods can also help to minimize the vibration impacts of construction activities. The major mitigation approach is the proper selection of pile installation methods to help minimize the vibration-caused issues at construction sites. Different techniques have been used as various alternatives to pile driving methods to help reduce vibration in one manner or another. The methods used and its reasons for selection are presented below.

Cast-in-place Piles

This technique is suitable where there is not a high pile capacity requirement. The use of cast-in-place or auger cast piles eliminates impact driving and limits vibration generation to the small amount produced by drilling, which is negligible (Woods 1997 and Jones & Stokes 2004).

FDOT uses drilled shaft which is also a type of cast-in-place piles or bored piles. It has the drawback if a vibratory driver is used to install the temporary casing. Some larger rigs have the capability of twisting or oscillating the casing in place without the use of vibratory drivers.

Low Soil Displacement Piles

Installation of low soil displacement piles, e.g. H-piles, minimizes vibration problems because load carrying capacity is expected in the end bearing, and large friction transfer along the shaft is not expected. Such piles reduce the volume of soil displaced during pile driving (D'Appolonia 1971 and Woods 1997).

Press-in Pile Installation

Several proprietary pile driving systems designed specifically to reduce impact-induced vibration by using torque and down-pressure or hydraulic static loading. The applicability of these methods depends in part on the type of soil. For example, the Gikon press-in pile system has the capability to drill through harder layers as it presses the pile sections in place. Some other examples are the Fundex Tubex piling system, Still Worker, etc. (White et al. 2002 and Jones & Stokes 2004).

Wave Barriers

The barriers absorb or reflect wave energy, thereby reducing the propagation of energy between a source and a receiver. Wave barrier is typically a trench or a thin wall made of sheet piles or similar structural members. The depth and width of a wave barrier must be proportioned to the wavelength of the wave intended for screening. They must be very deep and long to be effective. However, they are not cost effective for temporary applications, such as pile driving vibration mitigation (Woods, 1997).

10. RECOMMENDATIONS FOR IMPROVEMENT OF FDOT SPECIFICATIONS

10.1 Introduction

These recommendations have been prepared for management and control of ground and structure vibrations mostly from various pile driving operations conducted by impact and vibratory installation of piles, sheet piles and drilled shaft casings. However, the developed simple equations and vibration limits can also be applied for ground vibrations generated by vibratory rollers during soil compaction and paving. Recommendations are intended to establish controls of construction activities mentioned above in the interest of life, health, and safety of employees and the public, as well as the protection of nearby structures, property, and soils that remain in place. All of the contractor's responsibilities apply equally to any subcontractor involved in pile driving activities. Pile driving shall be allowed only during specific periods of time, as determined by the engineer on a site, according to locally applicable codes and necessary operational restrictions.

Recommendations consist of pile driving as a source of vibrations, pile driving effects on structures, various surveys of structures, determination of distances for condition surveys, calculations of expected PPV of ground vibrations, vibration monitoring of ground and structural vibrations during pile driving, vibration limits of ground and structural vibrations, and mitigation measures to decrease vibrations from pile installation.

10.2 Pile Driving – Source of Vibrations

Impact hammers or vibratory drivers are used for installation of driven piles. Dynamic loads force piles to vibrate and penetrate into the ground that result in displacements and vibrations of soil surrounding driven piles.

Maximum rated energy of the most commonly used impact hammers for construction on the land can be up to 221 kip-ft per blow. It is common that only 30-50 % of this energy is usually transferred to driven piles. 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 maximum pile velocity and displacement measured at the head of steel, concrete and timber piles range from 2.5 to 16.0 ft/s and between 0.47 to 1.38 in, respectively. Both parameters depend on the pile type, the hammer energy transferred to a pile, and the soil resistance to pile penetration. The transfer efficiency of sheet pile driving is below 25 % because of clutch friction between two sheet piles.

Vibratory drivers for driving non-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 soil conditions, the pile type and the vibratory driver model.

10.3 Pile Driving Effects on Structures

During pile driving, elastic waves propagate in the soil medium and induce elastic soil deformations (ground vibrations) at levels depending on the intensity of propagated waves. The structural responses to ground vibrations in turn depend on soil-structure interaction. Ground vibrations can produce direct vibration effects on structures and trigger resonant structural vibrations of adjacent and remote structures. Moreover, vibratory pile driving may trigger resonant soil layer vibrations.

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 when plastic soil deformation occurs. Thus, the structural response to ground excitation depends on soil deformations triggered by waves propagated from the source and soil-structure interaction.

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 may occur within a distance of about one pile length from the driven pile. These distances can be substantially larger for susceptible structures. According to an available experience, direct minor and major structural damage to 1-2 story houses without resonant structural responses are observed in the velocity range of 1.3-7.5 in/s for frequencies between 2 and 5 Hz and in the velocity range of 4-10 in/s for frequencies between 60 and 450 Hz.

Resonant Structure 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.

From an experience of blasting effects on structures, the proximity of the low-frequency components of ground vibrations induced by impact hammers to building's natural frequencies may generate horizontal resonant vibrations in building at remote distances. However, pile driving is much less powerful source of ground vibration than blasting. Obviously because of that, there are no case histories which demonstrate resonant structural vibrations triggered by low-frequency ground vibrations from impact pile driving.

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

Resonant Soil Vibrations

Matching the dominant frequency of propagated waves to the frequency of a soil layer can create the condition of resonance and generate large soil vibrations. Such amplification of soil vibrations may happen during vibratory pile driving. Layers between about 3-16 ft thick may produce a potential hazard for increasing vibrations when vibrators with operating frequencies between 20 and 30 Hz install piles in soils with shear wave velocities of 390 to 1970 ft/s. The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to accidental augmentation of ground vibrations.

Dynamic Settlements

Different natures of dynamic settlements exist in sandy and clay soils. Relatively small ground vibrations can be the cause of dynamic settlement in sand. Horizontal ground displacements, not vibrations, can be the cause of heave and the subsequent settlement in soft and medium clays.

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 CPT (cone penetration test) that has often been employed for geotechnical investigation of highway projects. Also, preconstruction surveys may reveal structural damage triggered by soil settlement.

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

It is known that simple methods of estimating 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.

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, an increase in pore pressure and a heave of the ground surface. During pile driving, the excess pore pressure increases with each driven pile and may reach high 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 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.

Movements of adjacent buildings during pile installation can be critical if clay susceptible to dynamic load-induced settlement is present at 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.

Additional Causes of Damage

Soil excavation associated with pile driving and made in close proximity to existing building can produce structural damage. Permanent excavation deformations induced in adjacent structure generally exceeded those from pile driving equipment.

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.

10.4 Surveys of Sites and Structures

Different surveys have to be performed before, during and after construction. However, it is necessary to establish friendly public relations with residents and businesses in the pile driving affected areas prior to implementation of any survey.

Public Awareness

The contractor is required to have both letter and personal contact with residents, institutional operators, and business establishments that are within the construction area and near enough for ground and structural vibrations from pile driving to be easily perceptible. This contact shall be made prior to the beginning of any pile driving activity. The contractor is required to furnish the engineer with a list of those contacted prior to the pile driving operations, and include on that list all pertinent information as approved by the engineer.

Permanent Displacement

A line (location) and grade (elevation) survey will be performed by a surveyor licensed by the state in which the construction occurs. It will establish guidelines to detect movements along the exterior faces of the buildings. This survey will be conducted on all buildings within an 83-ft (25 m) radius of the construction site and all historic buildings or structures within a 417-ft (125 m) radius. Reports shall be delivered to both engineer and contractor on a regular basis based on the sensitive nature of the project. All control lines and grades shall be referenced to existing benchmarks, which shall be established far enough from the construction site to be preserved for all surveys. Reference points are generally taken at a distance greater than 750 ft (225 m) from the site so they are well beyond the reach of pile driving operations. The precision required can vary, but in general should be accurate to 0.06 inches (1.5 mm).

Tilting of the nearest walls of structures will be established by measurement with a portable tilt-meter or other suitable method. Buildings included in this survey are those that could experience permanent deformation because of their proximity to the pile driving. The amount of deformation expected therefore needs to be quantified, so measurements shall be made at intervals determined by the engineer, but at least once a month.

Measurements of permanent displacement are mostly needed at sites with expected dynamic settlement and subsidence of structure foundations. Therefore, the engineer has to make a decision about the necessity to perform such measurements.

Preconstruction Survey

A preconstruction survey shall 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 200 ft of the pile driving activities. This distance was determined on the basis of analysis of ground vibrations measured at 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 shall be undertaken for all historic buildings or structures within 1300 ft. Condition surveys at different construction phases is an important step in the control of construction vibrations to ensure safety and serviceability of adjacent and remote houses, buildings and facilities.

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 from pile driving vibrations which includes impact on sensitive equipment and operations, as well as cosmetic cracking and effects on surrounding geological and/or geotechnical materials.

There are four goals of a preconstruction condition survey:

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

All goals are important for successful condition survey of structures.

Document the Existing Cracks and other Damage

A preconstruction condition survey has to be conducted with care, ensuring that all observable defects are documented. Therefore, a condition survey of structures should be conducted by engineer or experienced technician.

This survey should include observation and documentation of the existing condition of exterior and interior walls, ceiling, floors, roof, utilities, and foundation, if possible. 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.

It is necessary to distinguish the different types of cracking in structures, such as cosmetic cracking, architectural or minor damage, and structural cracking, any of which may result in serious weakening of buildings. Therefore, most attention should be paid to cracks in the structures themselves. A survey for estimating the preconstruction status of houses, buildings and facilities is usually accompanied by instrumentation on structures. The targets for instrumentation should be existing cracks in structures. It is necessary to analyze crack movements from everyday activities and environmental changes before the beginning of construction activities.

Analyze the Possible Causes of the Existing Damage

A pre-pile driving condition survey of structures is imperative to determine causation of the existing damage because environmental forces, geotechnical hazards, and dynamic forces from pile driving and dynamic compaction of weak soils can be the causes of similar structural damage, and such damage can exist before the beginning of construction operations.

It is necessary to point out that there are many non-vibratory environmental forces which act on houses to generate cracks and other defects. These forces begin exerting their influence before the time of construction begins, and some of them will continue to act for the lifetime of the structures.

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 structure are developed by such factors: changes in temperature; changes in moisture (relative humidity as well as liquid water); curing, shrinking or warping of lumber; drying and curing of such materials as plaster, mortar, grout, concrete, brick and other masonry products; different application of internal heat; aging, involving both chemical and physical deterioration; loss of friction; loss of elasticity; gravitational loads induced by the weight of the structure itself and all of the furnishings, supplies and persons inside the home; other factors.

Also, there are many important exterior factors including such things at site development: cut and fill profiles, type of underlying material; changes in soil conditions: addition or loss of water (rainfall or applied by owner), drainage and the condition of drainage facilities; weather changes; wind; vegetation, especially the influence of roots; yard maintenance; aging and deterioration of exterior materials and structural components; natural disasters; other factors.

In all cases, it is necessary to pay attention to the quality of materials, workmanship and maintenance. There are many reasons for the various cracks that form in structures and in the adjacent driveways, sidewalks, patios, garden walls, planters, and similar items that are frequently mentioned in vibration damage claims. Most materials used in residential construction undergo some shrinkage or warping during their curing stages, and will continue to suffer additional deterioration for the lifetime of the structure. The older the house, the more cracks we expect to find. This means that some cracks are normal, not abnormal.

It is particularly important to analyze the geotechnical natural hazards at various distances from construction sites such as heave, settlement, stability, sliding and failure which may damage structures prior to construction, during and after construction. There are case histories which show the major effects of geotechnical causes and environmental forces on crack formation and structural damage in spite of pile driving in the proximity of structures. Properly performed surveys provide the reliable arguments for protecting the pile driving contractors in possible litigations.

Assess 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. Cracking is the threshold of cosmetic cracking.

Buildings identified as having high susceptibility have already experienced a significant amount of degradation to their primary structural and/or nonstructural systems. Construction vibrations may results in further degradation of these elements. Buildings with loose or unstable elements, such as loose bricks or architectural details or buildings with significant quantities of fragile and unstable contents are considered to fall into this category.

Buildings identified as having moderate susceptibility have not yet experienced significant degradation to their primary structural and/or nonstructural systems which occurred prior to the beginning of construction. Buildings with small to moderate quantities of fragile, potentially unstable contents which may be damaging during construction are included in this category.

Buildings identified as having low susceptibility are not expected to experience cosmetic cracking when subjected to construction vibrations.

Historic buildings usually have high susceptibility. Such buildings require special attention during a preconstruction survey, at the time of pile installation, and after the completion of pile driving.

Determine Mitigation Measures of Pile Driving Effects on Structures

Reduction measures depend on soil deformation and soil-structure interaction and they are shown below under "Mitigation Measures of Pile Driving Effects on Structures."

Assessment of Possible Dynamic Settlement

One of the objectives of the preconstruction survey is to check for stability of the soils surrounding the pile driving site. Densification of loose material and slope movement can occur during pile driving, and this possibility must be considered for establishing control limits of ground motions. At sites with possible dynamic settlement, the distance for preconstruction survey shall be increased. There is the criterion of 400 ft which could be good for a number of sites but not for all of them. 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.

Vibration Background and Sensitive Equipment

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

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; sites with similar soil deposits do not always have the same dynamic settlement response. 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.

Mitigation Measures of Pile Driving Effects on Structures

Reduction measures for decreasing of vibration effects of pile driving and other construction equipment depend on soil elastic or plastic deformation, and soil-structure interaction. They should be considered before the beginning of pile driving operations. The separate lists of measures to mitigate direct vibration effects on structures, resonant soil and structure vibrations, dynamic settlement in sand, and dynamic settlement in clay are presented below.

Direct Vibration Effects

For mitigation of direct vibration effects of ground vibrations on structures from installation of driven piles, a few factors should be considered. First, installation of low soil displacement piles, e.g. H-piles, instead of high soil displacement piles, e.g. concrete piles, can reduce ground and structure vibrations. Second, hard pile driving to a depth about 10 m from the ground surface may increase ground vibrations, but hard pile driving at a greater penetration depth induce less ground vibrations. Predrilling and jetting may be helpful for overcoming the high penetration resistance in upper soil layers, but both operations in sands should be done with caution. Third, substantial decrease of the hammer energy can be helpful; however, slight reduction of the hammer energy will have a small effect because PPV of ground vibrations depends on the square root of the hammer energy. Fourth, pile driving operations should start nearby the existing structures and continue away from the structures because previously driven piles act as a shield and soil movements are greater in the direction away from the stiffer zone around the driven piles.

Resonant Soil and Structural Vibrations

Vibratory drivers may trigger resonant vibrations of soil layers and structures, but vibratory drivers with variable frequency can eliminate these phenomena.

Dynamic Settlement in Sands

The following measures can be provided for diminishing pile driving effects on settlements in sandy soils. First, reduce the level of ground vibrations as much as possible. Second, use predrilling holes for pile installation or use jetting to install piles, but predrilling or jetting in sand should be done with caution. Jetting reduced blow count about three times in comparison with pile installation without jetting. Third, choose a small pile hammer which is adequate for pile installation. Fourth, monitor and control vibrations and structure settlements at a site. Fifth, underpinning of adjacent buildings supported by shallow foundations can prevent building settlements. However, if pile driving triggered settlements of adjacent buildings supported by pile foundations, the technology of pile installation should be changed.

Dynamic Settlement in Clays

Effects of pile driving in soft to medium clays on the surrounding area should be expected at distances from pile installation equal to about the thickness of the clay layer being penetrated. Several factors can affect the induced pore pressure and movements. First, the chosen pile type is very important. Low soil displacement piles reduce the volume of soil displaced during pile driving. Second, predrilled holes improve conditions for using displacement piles. The cross-section of the auger and the drilled depth can strongly affect the volume of soil movements. Third, the spacing of the piles, characterized by the average pile density per unit foundation area, affects soil movements: the higher the density the larger the movement. Fourth, the sequence of pile driving operations should be directed away from the existing structures.

10.5 Calculation of Peak Particle Velocities of Ground Vibrations prior to Pile Driving

For practical goals prior to pile driving, it is important to assess the expected maximum PPV of ground vibrations during project design. A scaled-distance approach is an appropriate way to calculate the upper limits of ground vibrations before the beginning of pile driving.

For assessment of ground vibration attenuation generated by pile driving, any distance D from a source is normalized (scaled) with the hammer energy W. The most popular approach is square-root ($D/W^{1/2}$) scaling. The hammer energy is the major cause of ground vibrations generated by pile installation. However, PPV of ground vibrations varied at the same places on the same site and under the same energy transferred to piles. It happened because the depth of pile penetration into the ground and the soil resistance to pile driving can affect intensity of surface ground vibrations. The weaker soil resistance and the deeper pile penetration into the ground, the lower surface ground vibrations. Soil conditions on the site and distances from driven piles can amplify or weaken such influence.

The SD approach is applied for construction sources of vibrations with the following scaled-distance equation to calculate the peak particle velocity of ground vibrations

$$v = k[D/\sqrt{W_t}]^{-n} \tag{1}$$

Where W_t = energy of impact hammer transferred to piles, k = value of velocity at one unit of scaled distance, $(D/W_t^{1/2})$. The value of 'n' yields a slope of amplitude attenuation for all tested soils in the narrow range of 1 to 2 on a log-log chart. PPV of ground vibrations depends on the distance from a driven pile, the rated hammer energy, and the coefficients ‘n’ and ‘k’.

It is necessary to make a choice of the coefficients ‘n’ and ‘k’ to complete the development of simple calculation models for assessment of the upper limits of the expected maximum ground vibrations. A slope of n =1 corresponds to lower attenuation of ground vibrations and consequently to higher peak particle velocity. Therefore, n =1 was chosen for determining the upper limit for PPV of ground vibrations.

The results presented in Table 2 were obtained for 60 driven piles, a number of sheet piles, 6 casing installation and removal, and 40 vibratory rollers.

10.6 Vibration Limits for the Control of Ground and Structural Vibrations

The suggested flexible vibration limits for Florida soil conditions were chosen on the basis of numerous evidences of soil deformations and soil-structure interaction effects on damage to structures under various soil conditions and also on the basis of analysis and selection from the existing criteria.

Criteria of Dynamic Settlement

Vibration limits of settlement are **0.04 in/s** in loess and **0.10 in/s** in sands. There are no criteria of settlement in clays. Mitigation measures shall be used to prevent or decrease dynamic settlements in loess, sand and clay soils.

Criteria of Direct Vibration Effects

The vibration limit of **0.75 in/s of ground vibrations** is suggested for assessment of direct vibration effects on 1-2 story houses. This criterion can be corrected after accumulation of field data of measured ground vibrations and corresponding structural damage. Meanwhile, the application of **2 in/s limit for measured structural vibrations** (at window sills and floors) can help to determine unacceptable vibrations of various structures, especially of structures with more than two stories.

Assessment of the Resonance Condition

The use of vibratory drivers with variable frequency and force amplitude may minimize damage due to accidental soil layer resonant vibrations and resonant floor vibrations.

Historic and Old Structures

The vibration limit of **0.1 in/s** is an appropriate criterion for at historic structures. In addition to this criterion, daily inspection of structures shall be provided.

10.7 Monitoring of Vibrations

Recorded Data

Peak Particle Velocity - All three components (longitudinal, transverse, vertical) of particle velocity will be measured on the ground at the location of the nearest and other strategic structures and/or at any locations the engineer deems necessary for any particular pile driving operations. These measurements shall be made on the ground adjacent to these structures or on structures during pile driving as determined by the engineer.

Pile Driving Log - The contractor shall maintain a pile driving log and shall submit daily reports to the engineer on piles driven and vibrations measured. These logs shall be in the form specified in the Driving Plan.

Instrumentation

The contractor shall provide the instrumentation agreed to in the pile driving plan to monitor the pile driving vibrations and permanent deformation of the strategic structures. On-site measurements will be made by the engineer. The engineer will provide any other additional instrumentation not defined herein.

Vibration Monitors-(Seismographs) Vibrations in the form of particle velocities shall be monitored by Type I and/or Type II monitors.

- Type I is a waveform recorder. It provides a particle velocity wave form or time history of the recorded event, sometimes in conjunction with peak event information. Independent chart recorders with separate motion transducers can be used in place of "stand-alone" monitors like seismographs when approved by the engineer.
- Type II is known as a continuous peak particle velocity recorder and it provides no waveform and therefore no frequency information.

Transducer Attachment (Coupling)

It is essential to have good ground coupling between the transducer and the measured medium. When the measurement surface consists of rock, steel (or other metal), asphalt, or concrete, the transducers shall be bolted to the measurement surface or bonded with high strength adhesive. On other surfaces the mass of the seismograph and/or transducer package (spikes) may be sufficient for good coupling with low vibration level. For significant accelerations (greater than I.0 g), adhesive or bolts shall be used on all solid surfaces. All transducers on vertical surfaces shall be bolted in place. In some locations burying the transducers will minimize air borne noise, while in other situations, sand bags over the transducers can aid with coupling and reducing air borne noise. Care should be taken to maintain firm contact between the sand bag and the surrounding ground to avoid inducing rocking motion to the transducer.

Number and Location

The number of instruments required is dependent on the specific site. However there shall be, as a minimum, two monitors of type I. One monitor will be used on site, while the second is held in reserve or used at a specific complaint or potential complaint site.

Archiving

The contractor will provide the engineer with all data necessary for record-keeping purposes. These data shall be kept by both parties for at least 3 years after project completion, and shall include, as a minimum, the following information:

- All monthly surveys conducted for vibration control purposes, including the preconstruction survey.
- The original driving plan, as well as any adjustments made to it during the course of the construction activities.
- All monitored data, relative to each and every pile installed. These driving records shall contain all information as required and approved in the pile driving plan, including all information concerning the type and characteristics of the monitoring instruments used, their locations and orientations.
- All driving records correlated with monitored data.
- All weather conditions occurring during the driving activities.

10.8 Pile Driving

Driving Plan

No less than three weeks prior to commencing the test pile program, or at the preconstruction conference (whichever is earliest), or at any time the contractor proposes to change the driving method, the contractor shall submit a driving plan to the engineer for review. The driving plan shall contain: (1) all information required under the general piling specifications, and (2) all information related to vibrations and vibration controls, as described in the following sections.

Pile-Driving Equipment

Two types of equipment can be used: impact hammers or vibratory drivers. The contractor shall be aware of the fact that ground vibrations induced by these machines are of different nature, and therefore utmost care shall be taken in the selection of the equipment and driving method.

Test Pile Program

Definition of Responsible Party

The contractor shall provide any necessary cooperation with the engineer for conducting a test pile program. While the engineer will take the lead role in this program, the contractor shall concur in the intent, design, and process of the testing. This program shall be performed prior to the start of any production piling activities. It shall be performed to show how the vibrations decrease with increasing wave travel path distances from the pile and vary with the type of pile used. This program is intended to provide subsequent guidance for the choice of pile placement technique for this particular project, and not to define any envelope or relationship to be used as a control.

Monitoring

The number, type and location of the seismographs used to monitor the test pile program shall be determined by the engineer.

Analyses

Statistical analysis of the test data will be performed by the engineer. The results of these analyses will be transmitted to the contractor within three weeks after the completion of the test pile program. Three analyses are to be performed: an attenuation analysis, a frequency analysis, and a response spectrum analysis.

11. CONCLUSIONS

11.1 Summary

Construction activities, such as pile driving, dynamic compaction of loose soils, and operation of heavy construction equipment, induce ground and structure vibrations. Their effects range from a nuisance to the local population and the disturbance of working conditions for sensitive devices, to the diminution of structure serviceability and durability. It is necessary to recognize the different vibration effects of roadway and bridge construction operations on structures, as well as, on people and sensitive devices in urban areas.

The overriding purpose of this research was to develop a comprehensive framework to address vibration issues prior to and during construction including calculation of expected ground vibrations prior to the beginning of construction activities, condition surveys of structures, vibration limits, mitigation strategies to control ground and structural vibrations from construction sources, and recommendations for improvement of current FDOT Specifications.

State highway agencies as well as consulting, design, and construction companies have vast experience in managing the vibration problems generated by construction activities. To benefit from this experience and establish the current state-of-the-practice on the subject matter, a questionnaire survey was administered to relevant entities including FDOT Districts, other State Departments of Transportation, consulting, design, and construction companies, and vibration consultants. The survey found out that most of the respondent FDOT Districts (75%) have experienced vibration damage caused by construction operations. The major types of construction operations that cause vibration damage included pile driving, sheet pile installation and extraction, and asphalt compaction. The respondents also stated that vibration damage to structures from pile driving or other operations have resulted in various claims against the agency and the contractor.

For practical goals, prior to the beginning of construction operations, it is important to assess the expected maximum peak particle velocity (PPV) of ground vibrations during construction operations. Using the field data specific to Florida as collected and sorted over the course of this research, simple equations were developed to calculate the PPV of expected ground vibrations prior to construction operations. Available field data were mostly analyzed to derive simple equations for calculation of ground vibration PPV before the beginning of pile driving. Simple equations were also derived for calculation of ground vibration PPV prior to sheet pile driving, drilled shaft casing operations and vibratory roller operations.

This research also provided a comprehensive review of and guidelines for pre-construction condition surveys, analysis of the effects of different factors on vibration limits accompanied by a comparison of the criteria from diverse sources, a summary of the existing preventive and counteractive vibration mitigation techniques used by the industry, and a review of effective mitigation measures to decrease vibration effects from roadway and bridge construction operations in Florida.

Finally, the relevant findings of this research were compiled under “Recommendations for Improvement of FDOT Specifications.” These recommendations cover a broad base including pile driving operations and their vibration effects, survey of sites and structures, mitigation measures, calculation of PPV prior to construction, and vibration limits.

11.2 Recommendations for Future Research

The data collection effort for the purposes of this research was a very tedious and time-consuming process due to the scattered nature of different data pieces and long lead times.

It would be beneficial for FDOT to implement an online statewide data depository to collect and maintain only vibration related project data to be used for analysis, research and benchmarking purposes. Future research can focus on developing and implementing such an online system.

REFERENCES

AASHTO (1996). *Standard Recommended Practice for Evaluation of Transportation-Related Earthborne Vibrations* (R 8-96.), AASHTO, Washington, D.C.

AASHTO Designation: R 8-96. [2004]. *Standard Recommended Practice for Evaluation of Transportation-Related Earthborne Vibrations*, AASHTO, Washington.

ANSI (1990). *American National Standard. Vibration of Buildings – Guidelines for the Measurement of Vibrations and Evaluation of Their Effects on Buildings*, Accredited Standards Committee S2, Mechanical Shock and Vibration, (S2.47), Standard Secretariat c/o Acoustical Society of America, New York.

Ashraf, S., Jayakumaran, S., and Chen, L. (2002). "Case history: pile driving and vibration monitoring for Avenue P Bridge in Brooklyn, New York." *Deep Foundations 2002, Geotechnical Special Publication No. 116*, ASCE, New York, Vol. (1), pp. 500-509.

Bodare, A. and S. Erlingsson (1993). "Rock music induced damage at Nya Ullevi Stadium", *Proceedings of Third Intern. Conference on Case Histories in Geotechnical Engineering*, UMR, Vol. (1), pp. 671-675.

Boyle, S. (1990). "The effect of piling operations in the vicinity of computing systems." *Ground Engineering*, June, pp. 23-27.

Bradshaw, A.S., Baxter, C.D.P., and Osborn, P. (2005). "Lessons learned from pile driving at the Central Artery/Tunnel project." *Proceeding of Geo-Frontiers 2005* (CD-ROM), ASCE, Reston, V.A.

Casagrande, A. and Avery, S.B. (1959). *Report to Metcalf and Eddy upon investigation of building settlements in Back Bay area*. Pierce Hall.

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, pp. 305-320.

D'Appolonia, D.J. (1971). "Effects of foundation construction on nearby structures". *Proceedings of 4th Pan-American Conference on Soil Mechanics and Foundation Engineering*, Puerto Rico, ASCE, New York, Vol. (2), pp. 189-235.

Davis, R.O. and Berrill, J.B. 1998. "Site-specific prediction of liquefaction." *Geotechnique*, V. 48, No. 2, pp. 289-293.

Dowding, C.H. (1996). *Construction Vibrations*. Prentice Hall, Upper Saddle River.

Eldred, P.J.L. and Skipp, B.O., 1998, "Vibration on impact", 'Ground Dynamics and Man Made Processes', Bryan O. Skipp, Editor, Tomas Telford, pp 5-27.

Feld, J. and Carper, K.L. (1997). *Construction Failure*. John Wiley and Sons, New York.

Golitsin B.B. (1912). "On dispersion and attenuation of seismic surface waves". *Russian Academy of Science News*, V. 6, No. 2 (in German).

Grose, W.J. and Kaye, D. (1986). "Driving piles adjacent to vibration sensitive structures." *Ground Engineering*, May, pp. 23-31.

Hajduk, E.L. and Adams, J.C. (2008). "Examination of ground vibrations and dynamic pile measurement during driven pile installation," *Proceedings of the 8th International Conference on the Application of Stress Wave Theory to Piles*; Science, Technology and Practice, Lisbon, Portugal, IOS Press, pp. 715-722.

Hendriks, R. (2002). *Transportation Related Earthborne Vibrations*. California Department of Transportation, Division of Environmental Analysis, Office of Noise, Air Quality, and Hazardous Waste Management, Sacramento, California.

Hesham, A., Castellanos, J., Hart, D., and Nukunya, B. (2003). "Real-time measurement of the impact of pile driving vibrations on adjacent property during construction." *TRB 2003 Annual Meeting*, CD-ROM.

Heung, W. Morgan, K, Yoon, Y.H., Gobin, R., Gollamudi, S. (2007). “Vibration due to driving concrete piles using open-ended Diesel hammer in Central and South Florida.” *Proceedings of the Seventh International Symposium on Field Measurement in Geomechanics*, Boston, Massachusetts, CD-ROM.

Hokugo, H. (1964). “Observation of soil movement due to pile driving.” *Building Engineering News*, Nippon Telegraph and Telephone Public Corporation (in Japanese).

Horn, H.M. (1966). “Influence of pile driving and pile characteristics on pile foundation performance.” *Lecture Notes*, New York Metropolitan Section, ASCE, Soil Mechanics and Foundation Group.

Jones and Stokes (2004). *Transportation- and Construction-Induced Vibration Guidance Manual*. California Department of Transportation, Environmental Program, Environmental Engineering, Noise, Vibration, and Hazardous Waste Management Office, Sacramento, California.

Kaminetzky, D. (1991). *Design and Construction Failures – Lessons from Forensic Investigations*, McGraw-Hill, Inc., New York.

Kesner, K., Hammarberg, E. and Trelstad, D. (2006). “90 Feet – The difference an avenue makes: protection of existing historic structures during adjacent construction”, *Proceedings of 4th Forensic Congress*, ASCE, pp. 399-413.

Lacy, H.S. and J.P. Gould (1985). “Settlement from pile driving in sand”, *Proceedings of Symposium on Vibration Problems in Geotechnical Engineering* (G. Gazetas and E.T. Selig, eds.), ASCE, New York, pp. 152-173.

Lucas, R. G., and Gill, S. A. (1992). “Ground movement from piling vibrations.” *Piling – European Practice and Worldwide Trends, Proc., Conf., of Institution of Civil Engineers*, Thomas Telford, London,163–169.

Lynch, T.J. (1960). “Pile driving experience at Port Everglades.” *J. Soil Mechanics and Foundation Division*, 85(SM2), pp. 41-62.

Office of Surface Mining Reclamation and Enforcement-OSM (1983). *Surface Coal Mining and Reclamation Operations; Initial and Permanent Regulatory Programs; Use of Explosives*. Federal Register, V. 48, No. 46, March 8, pp. 9788-9811.

Sadovskii, M.A. (1946). *The Simplest Methods of Determining Seismic Hazard Due to Massive Blasts*. Academy of Science, USSR, Moscow (in Russian).

Siskind, D.E. (2000). *Vibration from Blasting*. International Society of Explosives Engineers, Cleveland, Ohio.

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

Siskind, D. and M. Stagg, M. (2000). *The Co-Report*. *Blast Vibration Damage Assessment Study and Report,* Miami-Dade County, C3TS Project No.: 1322-01.

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

Svinkin, M.R. (2002). “Predicting soil and structure vibrations from impact machines”, *Journal of Geotechnical and Geo-environmental Engineering*, 128(7), pp. 602-612.

Svinkin, M. R. (2004). “Minimizing construction vibration effects”, *Practice Periodical on Structural Design and Construction*, ASCE, V. 9, No. 2, pp. 108-115.

Svinkin, M.R. (2005). “Closure to ‘Minimizing construction vibration effects’ by Mark R. Svinkin”, Practice Periodical on Structural Design and Construction, ASCE, Vol. (10), No. (3), pp. 202-204.

Svinkin, M.R. (2006a). “Mitigation of soil movements from pile driving”, *Practice Periodical on Structural Design and Construction*, ASCE, Vol. 11, No. 2, 2006, pp. 80-85.

Svinkin, M.R. (2006b). “Regulations of construction vibrations”. *Proceedings of the 31st Annual Conference on Deep Foundations*, DFI, Hawthorne, New Jersey, pp. 559-571.

Svinkin, M.R. (2008). “Soil and structure vibrations from construction and industrial sources”, OSP8, *Proceedings of the Sixth International Conference on Case Histories in Geotechnical Engineering,* Omni Press, Arlington, Virginia, pp. 1-14.

Svinkin, M.R. (2012). The necessity of condition surveys for structural protection against pile driving effects. Proceedings of the 9th International Conference on Testing and Design Methods for Deep Foundations, IS-Kanazawa 2012, T. Matsumoto (Ed.), Kanazawa University, Japan, 429-439.

Svinkin, M.R. (2013). “Forensic engineering of construction vibrations”. *Forensic Engineering*, ICE, 166 (2), pp. 81-93.

Svinkin, M.R. and Saxena, D.S. (2004). Vibration Monitoring, Data Evaluation, and Engineering Consultation Services Report, Conducted on: Existing Residences of 20 Claimants Seville Drive Stormwater Treatment/Enhancement Project (Clark Site), Pensacola, Escambia County, Florida.

Swiger, W.F. (1948). “Effect of vibration on piles in loose sand.” *Proc., 2nd International Conference on Soil mechanics and Foundation Engineering,* V. II, Rotterdam.

White, D., Finlay, T. and Bolton, M. (2002). “Press-in piling: Ground vibrations and noise during pile installation”. *Proceedings of the International Deep Foundation Congress*, Orlando, USA, ASCE GSP 116, pp. 363-371.

Wiss, J.F. (1981). “Construction vibrations: State-of-the-art”, *Journal of Geotechnical Engineering Div.,* ASCE, 107 (2), pp. 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.

Woods, R.D. and Jedele, L.P. (1985). “*Energy-Attenuation Relationships from Construction Vibrations.*” Vibration Problems in Geotechnical Engineering, Proceedings of a Symposium Sponsored by the Geotechnical Engineering Division, ASCE, Detroit, Michigan, October 1985. 229-246.