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16. Abstract

The main objective of this project was to update the current Louisiana Department of Transportation and Development (LADOTD) policy on pile driving vibration risk management with a focus on how to determine an appropriate vibration monitoring area. The current best practice of managing the risk of pile driving by federal and state highway agencies was identified by conducting a comprehensive literature review and a questionnaire survey. Ground vibration data were collected from previous pile driving projects in the state of Louisiana, which were statistically analyzed on the basis of the scaled-distance concept to develop regression equations for predicting ground vibration Peak Particle Velocity (PPV) values. A rational procedure for determining an appropriate vibration monitoring distance (VMD) was developed for Louisiana's local conditions based on a 99 percent prediction-level regression equation for predicting PPV values. The findings (the threshold PPV limits and the VMD) obtained from the empirical scaled-distance concept were further verified with dynamic finite element method (FEM) simulations.

The results from this study indicated that the vibration criteria specified in the current Louisiana's special provision are generally too conservative (i.e., a PPV limit of 0.2 in/s for residential buildings and a pre-construction survey distance of 500 ft.) and should be revised. Regarding the threshold PPV limits, the results suggest that 0.5 and 0.1 in/s should be used for a general scenario (neither historic buildings nearby nor loose sandy soil layers present) and for a special scenario (either a historic building or a loose sandy layer existing near pile driving sites), respectively. Consequently, VMDs of 200 and 500 ft. are recommended for general and special scenarios, respectively. The values of VMD in the case of a large pile driving hammer (i.e., its rate energy larger than 100,000 ft-lbf) being used were also recommended. The pre-construction survey distance was suggested to take the same value as the VMD.

A specification draft was developed on the basis of the major findings from this study, which is included in Appendix E and ready to be implemented by LADOTD in future pile driving projects.

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ABSTRACT

The main objective of this project was to update the current Louisiana Department of Transportation and Development (LADOTD) policy on pile driving vibration risk management with a focus on how to determine an appropriate vibration monitoring area. The current best practice of managing the risk of pile driving by federal and state highway agencies was identified by conducting a comprehensive literature review and a questionnaire survey. Ground vibration data were collected from previous pile driving projects in the state of Louisiana, which were statistically analyzed on the basis of the scaled-distance concept to develop regression equations for predicting ground vibration Peak Particle Velocity (PPV) values. A rational procedure for determining an appropriate vibration monitoring distance (VMD) was developed for Louisiana's local conditions based on a 99 percent prediction-level regression equation for predicting PPV values. The findings (the threshold PPV limits and the VMD) obtained from the empirical scaled-distance concept were further verified with dynamic finite element method (FEM) simulations.

The results from this study indicated that the vibration criteria specified in the current Louisiana's special provision are generally too conservative (i.e., a PPV limit of 0.2 in/s for residential buildings and a pre-construction survey distance of 500 ft.) and should be revised. Regarding the threshold PPV limits, the results suggest that 0.5 and 0.1 in/s should be used for a general scenario (neither historic buildings nearby nor loose sandy soil layers present) and for a special scenario (either a historic building or a loose sandy layer existing near pile driving sites), respectively. Consequently, VMDs of 200 and 500 ft. are recommended for general and special scenarios, respectively. The values of VMD in the case of a large pile driving hammer (i.e., its rate energy larger than 100,000 ft-lbf) being used were also recommended. The pre-construction survey distance was suggested to take the same value as the VMD.

A specification draft was developed on the basis of the major findings from this study, which is included in Appendix E and ready to be implemented by LADOTD in future pile driving projects.

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IMPLEMENTATION STATEMENT

Based on statistical analyses on the ground vibration monitoring data collected from previous pile driving projects in Louisiana, this study applied a scaled-distance concept based procedure to approximating a reasonable vibration monitoring distance and pre-construction condition survey distance. The threshold magnitudes of ground vibrations in terms of peak particle velocity were identified and recommended for LADOTD to protect the public safety and manage risk associated with pile installation.

Based on the findings of this research, the following is recommended for implementation. The current threshold PPV limit (0.2 in/s for residential buildings) specified in Louisiana's special provision for limiting structural damage caused by pile driving is overly conservative and should be updated as follows: threshold PPV limits of 0.5 and 0.1 in/s should be used for a general scenario (neither historic/sensitive buildings nearby nor loose sandy soil layers present) and for a special scenario (either a historic/sensitive building or a loose sandy layer existing near pile driving sites), respectively.

The current pre-construction condition survey distance of 500 ft. in the Louisiana's special provision is too conservative and should be revised as follows: (1) for the general scenario, the VMD shall be 200 ft.; and (2) for the special scenario, the VMD shall be 500 ft. for projects with a the rated hammer energy of less than 111,000 ft-lbf. Otherwise, the VMD shall be calculated as $\mathrm{VMD} = 1.6 \times \sqrt{\mathrm{W_r}}$, with W_r being the rate of energy of a pile driving hammer for historic buildings or in the site with a loose sandy soil layer present.

The pre-construction survey distance was suggested to take the same value as the VMD.

The draft specification developed from the findings from this study is provided and is ready to be implemented subject to approval by LADOTD.

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INTRODUCTION

Piles have often been used to transfer heavy loads to stronger soil strata or temporarily retain earth or water in highway and bridge construction. LADOTD spends millions of dollars annually on pile foundations. Despite the advantages of driven piles, its installation processes inevitably cause the surrounding ground to vibrate. The intensity of the vibration depends on the physical properties of the pile (material, weight, length, size, etc.); pile installation method; and the soil (type, density, water content, etc.). Depending on the intensity of ground vibration, it can occasionally cause varying degrees of damage to adjacent buildings and structures or becomes annoying to occupants of the buildings. According to the survey conducted by Woods, 28 Departments of Transportation (DOTs) and 26 pile driving contractors had experience with vibration claims from driving various piles *[1]*. In addition, poor public relations or even litigations often result from pile driving operations. Thus, it is imperative for all parties involved in pile driving to have a rational risk management plan that addresses concerns and problems associated with pile driving vibrations. State DOTs can benefit both financially and technically from a well-planned pile driving risk analysis prior to any pile driving operations–any unnecessarily conservative assumptions will increase construction costs or delay the project.

The extent of structure damage due to pile driving is believed to be related to the magnitude of ground vibration that is often quantified in terms of peak particle velocity (PPV). There are many specifications and provisions that define allowable (or permissible) PPV values *[1-4]*. Nevertheless, there is no consensus on a well-accepted allowable PPV value to prevent vibration-induced damage because the complex interactions between piles, soil conditions, and surrounding buildings. One way to address this problem is to monitor vibrations of the surrounding ground during pile driving. For instance, LADOTD has a special provision that requires the contractor to monitor the ground vibration within of 300 to 500 ft. from any pile driving activities. The specified distances have contributed additional cost to the projects. It is LADOTD's desire to determine reasonable monitoring distances that are technically sound while minimizing risk.

The following aspects of a pile driving risk management plan are needed to address this question: a rational approach to determine the relationship between ground vibration levels, soil conditions, and potential structural damage; a rational approach to approximate peak particle velocity of the ground in relation to pile driving activities; and mitigation measures to reduce ground vibrations if needed. The following sections provide a background to address the above issues.

Mechanisms of Ground Vibrations Caused by Pile Driving

To understand ground vibrations caused by pile driving, it is necessary to consider the following four processes as depicted in Figure 1:

A. Wave propagation of the pile-energy is generated as the pile hammer (1) impacts the pile head (2) that is then transmitted down the pile (3);
B. Interactions between soil-pile interfaces-vibrations are transmitted into the surrounding soil [along the pile shaft (4) and at the pile tip (5)];
C. Wave propagates in the ground; and
D. Dynamic soil-structure interactions.

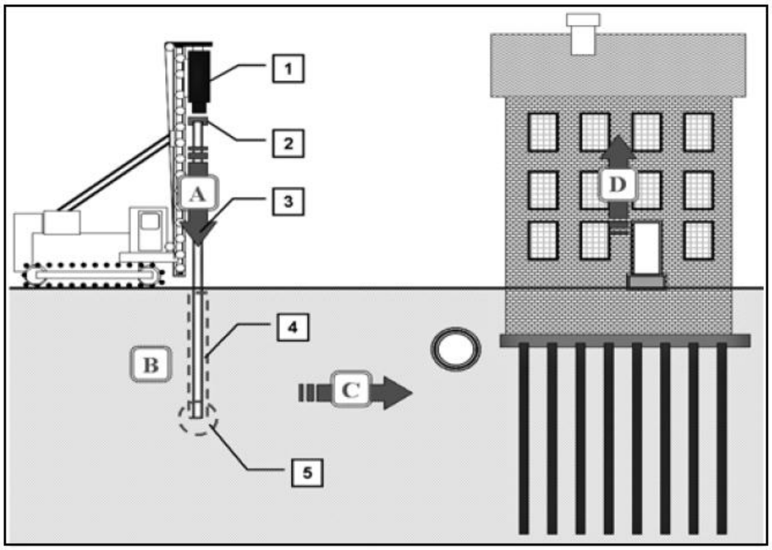


Figure 1
Schematic diagram of an entire process of vibration transmission during pile driving *[2]*

The process of vibration transmissions during pile driving is illustrated in Figure 1, during which a stress wave (i.e., vibration) is created that propagates down the pile, into the soil, and eventually into adjacent buildings and structures as the pile driving hammer impacts the pile head *[2]*. The vibration propagates in the system in terms of two types of body waves: P-waves and S-waves. P-waves, also known as primary, compressional or longitudinal waves, cause compression and rarefaction of the materials through which they pass; and S-waves, also called secondary, shear, or transverse waves, generate shear deformations when they travel through a material. The motion of an individual particle that a P-wave travelling through is parallel to the direction of P-wave travels, but the counterpart of an S-wave travelling through is perpendicular to the direction an S-wave travels *[5]*. As the most important part in the vibration transmission chain, the interactions between soil-pile interfaces include: (1) shear waves generated by relative motion between the surrounding soil and the pile along the pile shaft or skin and (2) both primary and shear waves generated at the pile tip, which are shown schematically in Figure 2. When P- and S-waves encounter the ground surface, part of their energy is converted to surface Rayleigh waves and part is reflected back into the ground as reflected P- and S-waves. It is these waves that transmit vibration (energy) to the surrounding ground during pile driving and cause potential damage to adjacent buildings and annoyance to nearby occupants. Therefore, the dynamic soil-pile interactions, specifically dynamic resistance of the soil surrounding the pile, dictate the portion of the energy and thus the extent of vibration transmitted into the ground from the pile. Impedance of the soil and pile govern the dynamic resistance of the soil during pile driving and therefore constitute the most important factors affecting ground vibrations. Impedance is a measure of how much a structure resists motion when subjected to a given force, which is a function of a structure's material (e.g., density and stiffness) and dimensions *[6]*.

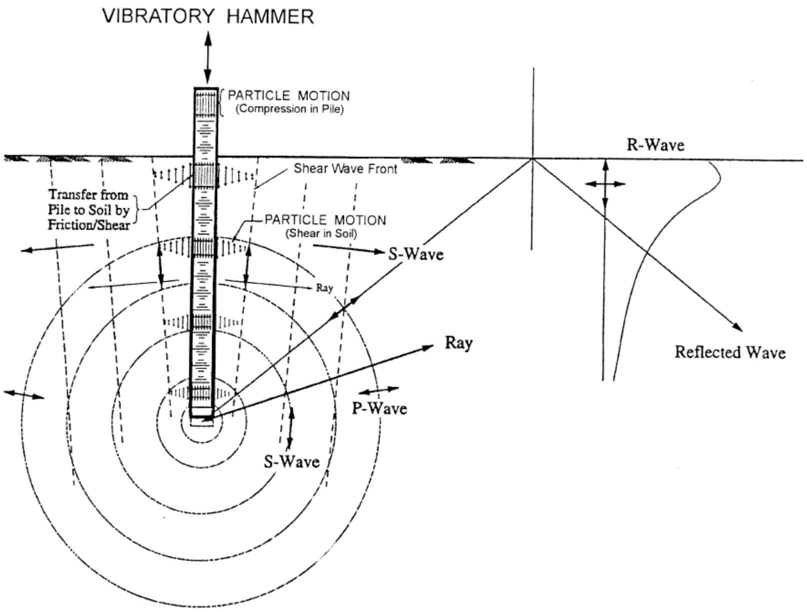


Figure 2
Generation mechanism of seismic waves during
vibratory (or impact) driving of piles in homogeneous soil *[1]*

Approximation of PPV Values of Surrounding Grounds

It has been generally accepted that damage to surrounding structures during pile driving is directly related to the magnitude of ground vibration. It is of great importance for the engineers to have a simple means to predicting PPV values to asses pile driving risk with more confidence. Such a predictive means should consider geotechnical conditions, pile conditions, and pile driving equipment information.

Energy-based Empirical Prediction Models

As illustrated in Figure 2, stress waves are emanated at the soil-pile interfaces and attenuate while they propagate away in the ground. Two main factors contributing to the attenuation include: (1) geometric damping associated with the enlargement of the wave front as the distance from the vibration source increases and (2) material damping by the soil. In most of energy-based empirical models, the intensity of ground vibration is quantified by peak particle velocity that is often approximated by a function of the distance from the vibration source and the vibration energy. One of the widely referenced models is a so-called scaled-distance equation (also referred to as the pseudo-attenuation approach) proposed by Wiss *[7]*:

$$v = k\left(\frac{D}{\sqrt{E}}\right)^{-n} \tag{1}$$

where,
v = peak particle velocity (inches per second);
k = intercept value of ground vibration amplitude in velocity (inches/s) at a "scaled distance" of $D/\sqrt{E}$ [ft/ (ft-lb)$^{1/2}$];
n = slope or attenuation rate;
D = distance from the vibration source (ft.); and
E = energy input at source (in ft.-lbs).

Wiss provides neither guidance on how the distance (D) should be chosen when a pile is driven into the ground, nor a definition of the driving energy (E) *[7]*. On the basis of the model proposed by Wiss and gathered data from field construction projects with known or estimated vibratory energy, Woods and Jedele generated Figure 3 for estimating peak particle velocity, with energy magnitudes of common vibration sources provided in Figure 5 *[7] [8]*. The parameter n in equation (1) represents the slope of vibration amplitude attenuation in a log-log space, with values ranging from 1.0 to 2.0. Woods and Jedele also correlated the value of the attenuation rate (n) with soil types: with a slope of n = 1.5 for soil class II and a slope of n = 1.1 for soil class III, and soil ground types used by Woods and Jedele are summarized in Table 1 *[8]*. The scaled-distance equations, such as the one developed by Woods and Jedele, provide a simple and quick means to estimate ground vibration velocity *[8]*. However, their empirical nature limits a general application to project sites with soil and/or pile conditions different from those on which they were originally developed, and their applicability under Louisiana conditions remains to be evaluated.

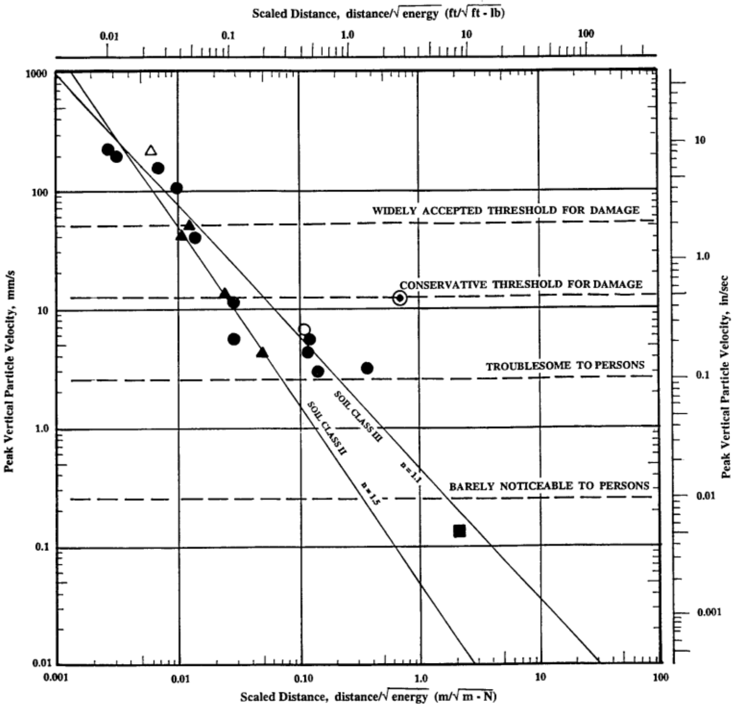


Figure 3

Peak particle velocity versus scaled distance for soil class II and III, Woods and Jedele *[8]*

Table 1

The soil classification by Woods and Jedele *[8]*

Class	Description of Material
I	Weak or Soft Soils-loessy soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, topsoil. (shovel penetrates easily) (N<5)
II	Competent Soil-most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel) (5<N<15)
III	Hard Soils-dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, need pick to break up) (15<N<50)
IV	Hard, Competent Rock-bedrock, freshly exposed hard rock. (difficult to break with hammer) (N>50)

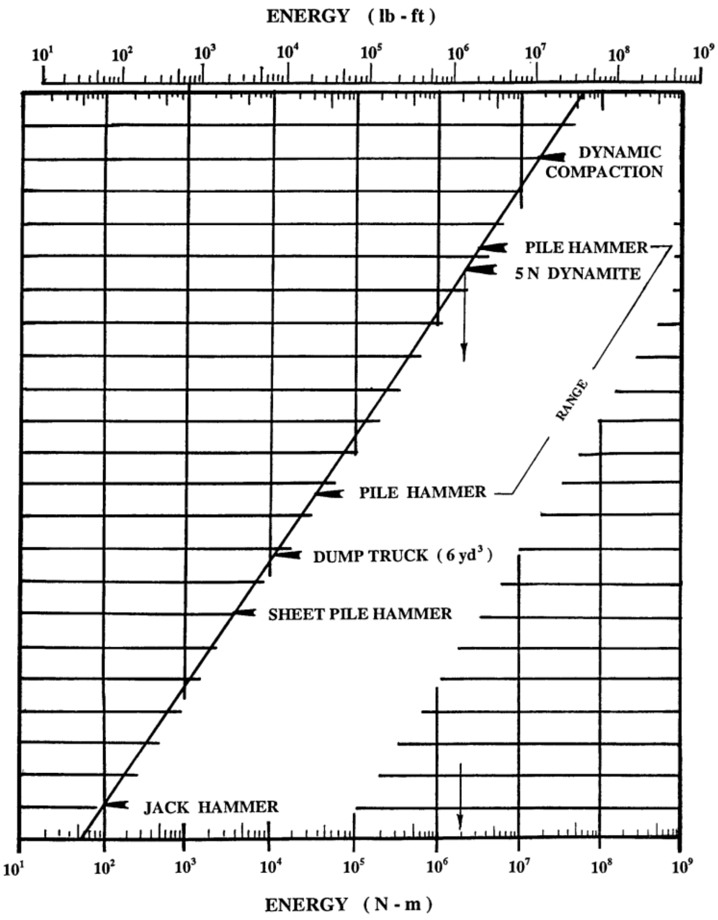


Figure 4

Relative energy of various vibration sources *[1]*

Dynamic Finite Element Analyses

The major drawback of the current empirical predicative models lies in the lack of considering dynamic interactions of soil-pile-pile driving system–vibrations transmitted from the driving hammer to the pile and vibrations transmitted through dynamic soil-pile interactions, although these aspects are the most important information for understanding pile driving-induced ground vibrations. Massarsch and Fellenius proposed a method that takes the aforementioned dynamic interaction into account *[2]*. However, the proposed method requires very detailed hammer information that is not available for most projects during the design stage. To fully understand the cause of pile driving-induced ground vibration, it is necessary to consider the whole process of vibration transmission from the pile hammer, along the pile shaft, to the pile toe, and to the surrounding soil layers, as illustrated previously in Figure 2. The processes of how the vibration energy is emanated from dynamic interactions along soil-pile shaft and soil-pile toe interfaces are well understood qualitatively, but these processes are too complex to have analytical solutions. Therefore, simulations with the aid of the commercial software Plaxis Dynamics were performed in this study to shed light on the complex processes involved in wave propagation and attenuation during pile driving and to verify the results obtained from the empirical scaled-distance concept.

Correlations between Ground Vibrations and Structural Damage

To conduct a risk analysis of pile-driving-induced ground vibrations, it was necessary to first understand the mechanisms of damage to surrounding buildings. There are generally two different damage mechanisms–damage due to vibration directly and damage due to vibration-induced settlement (or densification).

Because the damage depends on the velocity and frequency of ground vibrations, an apparent mitigation measure is to limit peak particle velocity caused by pile driving. This is also the basis on which many existing specifications addressing pile driving concerns were developed. Some common vibration limiting criteria in literature were critically reviewed and are discussed in the Methodology section.

While there are many specifications that limit the peak particle vibration velocity in order to prevent potential damage to surrounding structures, there is relatively little guidance available in literature regarding vibration-induced settlement. According to Woods, most vibration settlement is from sheetpile installation *[1]*. Settlement-related damage can be a major concern during pile driving if loose cohesionless soils are present in the vicinity of a project site. For example, significant settlement up to 3 in. at the ground 5 to 30 ft. away from the driven piles was reported to be caused by peak particle velocity as low as 0.1 in/sec (2.5 mm/sec); that is much lower than the damaging vibration levels *[9]*. A procedure proposed by Massasch provides a simple means to approximating critical vibration values under which vibration-induced settlement is less likely to occur *[10]*. This procedure is based on the critical shear strain concept that shear strain is the primary factor causing densification/settlement of granular soils, which is discussed in more detail in the Methodology section.

Preconstruction Survey

A preconstruction survey should be carried out prior to any pile driving activities, including a testing pile program, to ensure safety and serviceability of adjacent structures. The survey aims to determine buildings' susceptibility to pile driving vibrations and to document preconstruction status of buildings surrounding the pile driving site. The main targets are existing cracks that will be marked and documented during the survey. The information gathered from the pre-construction survey will help design engineers in the evaluation of the suitability of the pile driving method and ground vibration monitoring plan.

Before conducting the pre-construction survey, a proper survey coverage area should be determined within every structure that should be examined. However, there is no consensus on this issue in literature. For example, Dowding suggested a radius of 394 ft. of construction activities or out to a distance at which vibrations of 0.08 in/s occur *[11]*. Woods considered distances of as much as 1,312 ft. to be surveyed to identify settlement damage hazards *[1]*. Since the pre-construction survey area used in many previous pile driving projects varies widely and depends upon many project specific factors (e.g., conditions of surrounding structures, types of piles, site soil conditions, etc.), a rational procedure to determine an appropriate preconstruction survey distance is required for LADOTD and was one of the main research objectives of this research project.

Ground Vibration Monitoring

Ground vibration monitoring is an essential component of an effective vibration risk management plan for pile driving because it can help engineers determine whether potential structure damage is likely to occur and whether mitigation measures are necessary. The vibration magnitude, either of ground or of structure, at a specific distance from the driven pile should be monitored during pile driving and checked against the threshold vibration magnitude (i.e., the threshold PPV value). A ground vibration monitoring program consists of the following components: (1) an appropriate ground vibration monitoring distance; (2) vibration parameters to be monitored and recorded during pile driving; and (3) vibration monitoring apparatus and installation. Each of these vibration monitoring components is briefly discussed in the paragraphs below.

Vibration Monitoring Distance

The vibration monitoring area is one of the most important parameters to manage vibration risk during pile driving because too large a monitoring area will be costly, but too small a monitoring area will leave the surrounding structures susceptible to vibration induced claims of damage, which negate the intent of monitoring. The vibration monitoring area can be quantified in terms of the VMD, which is defined as a distance beyond the magnitude of ground vibrations that is small enough to not cause damage to the structures. There is no consensus on how large this distance should be, and most specifications about this issue are of empirical nature at best. For example, monitoring distances of 100, 200, or 400 ft. from the driven piles are used by several state DOTs regardless of site specific conditions *[1]*. This research study aimed to determine an appropriate VMD for LADOTD by taking into account local conditions, based on the results of this study, and detailed in the Methodology section.

Vibration Parameters to be Measured During Pile Driving

The vibration parameters used to describe the characteristics of ground vibrations usually include the frequency, the duration, and the amplitude of the vibrations. Since structure damage caused by pile driving is mainly dependent upon the magnitude of vibrations, the magnitude parameters are the most relevant, including the peak acceleration, peak velocity, and/or peak displacement. In practice, only one of these three parameters is needed and the others can be calculated from measurement either by integration or differentiation.

Typically, the acceleration-sensitive region usually corresponds to high frequency vibrations (e.g., seismic excitations); the velocity-sensitive region is associated with intermediate frequency vibrations, and the displacement-sensitive region is associated with relatively low frequency vibrations. It is evident in the tripartite plot shown in Figure 5 *[11]*. In the frequency range of 5-70 Hz, which is the dominant frequency range of ground vibrations induced by pile driving, the structural response is more related to ground velocity than to either ground acceleration or displacement. Therefore, PPV has been used for quantifying the magnitude of ground vibrations induced by pile driving.

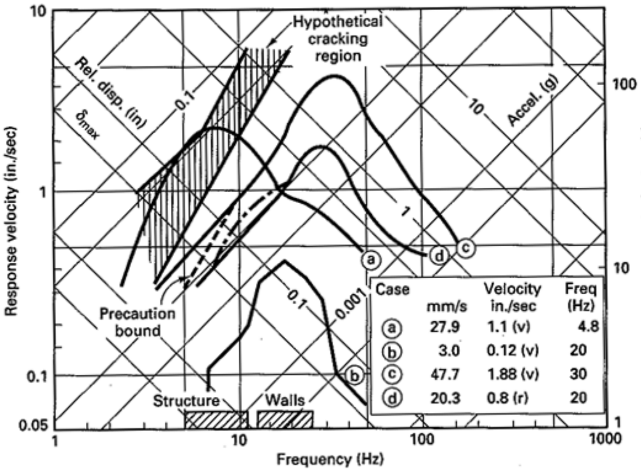


Figure 5

Response spectra of pile-driving ground motion recorded close-in to driving.
Case a: 19.7 ft. (6 m) from Franki pile driving in peat.
Case b: same pile, bulbing at depth.
Case c: 11.5 ft. (3.5 m) from Franki pile driving in silt.
Case d: 4.9 ft. (1.5 m) from H pile driving in fill *[11]*

Vibration Monitoring Apparatus and Records

A proper vibration monitoring apparatus should be selected and carefully mounted to the ground surface or the structures to measure the faithful vibrations resulting from pile driving. In most pile driving projects, the ground motion frequency is in the range of 0 – 100 Hz, associated with the amplitude range of 0 to 0.51 in. for which a velocity transducer is usually chosen *[1]*. When the weight of the transducer is sufficient to couple itself to the ground, a three-leg support is recommended. The transducer can also be glued or bolted to the ground surface or buried underground. When its weight is relatively light, sand bags should be draped over the transducer to assist fastening it to the ground *[1]*.

Three components (i.e., transverse, vertical, and horizontal) of particle velocity are usually recorded by a velocity transducer during pile driving. The PPV is often used to quantify the magnitude of ground vibrations, which can be either: (1) the maximum value of the three velocity component maxima, or (2) the vector sum of the three velocity component maxima. The vector sum of measured individual component maxima is overly conservative because three individual maxima of a velocity signal rarely occur simultaneously. Therefore, the first expression of PPV is used in this study.

Engineering Measures to Mitigating Pile-Driving Induced Ground Vibrations

When it is physically impossible to eliminate vibrations from pile driving, some mitigation measures, often associated with pile installation methods, are often employed to manage pile driving operations such that the induced vibrations do not cause structural damage. Below is a list of typical engineering measures used for this purpose *[1]*:

- Jetting uses water, compressed air, or the combination of both to loosen the soil in front of the pile so that a pile can be advanced into the designed depth with reduced ground vibrations. Jetting is more effective in granular soils than in clays.
- Predrilling involves drilling a vertical hole to a certain depth into which a pile is driven so that some troublesome soil layers (e.g., shallow harder layers that can generate high levels of ground vibrations) can be bypassed.
- Non-displacement piles like H-piles in lieu of displacement piles may be considered for the purpose of reducing the volume of the soil being displaced during pile driving, thus reducing the level of ground vibrations.
- A fresh and absorbing cushion should be used for impact-type hammers because a much larger impulse, accompanied with a higher level of ground vibrations, will otherwise be resulted from a worn cushion.

- Svinkin also suggested that pile driving should be proceeded in such a sequence that directing away from existing structures that ground vibrations can be reduced *[4]*,*[12]*.

Mitigation measures that are suitable for a given pile driving project often depend on specific project conditions.

OBJECTIVE

The objective of this study was to update the current LADOTD policy on pile driving vibration risk management with a focus on the determination of an appropriate vibration monitoring area. The research study also aimed to provide recommendations on the components of a risk management plan for pile driving, including the permissible peak particle velocity of ground vibrations to prevent damage to surrounding structures, and the pre-construction survey area.

SCOPE

This research study carried out an extensive literature review and a questionnaire survey of state DOTs and consulting companies to identify the best practice on the issues pertinent to vibration risk management during pile driving. Based on the current best practice of pile driving risk management, the threshold magnitudes of ground vibrations in terms PPV were selected for different types of buildings and project soils conditions in Louisiana. Ground vibration data were collected for 10 pile driving projects in the state of Louisiana, which were analyzed on the basis of the scaled-distance concept and from which the ground vibration monitoring distances were determined statistically for different scenarios. The results from the scaled-distance concept, including the threshold PPV and vibration monitoring distance, were further verified with dynamic FEM simulations that are capable of considering other important factors (e.g., ground-structure interactions), which were ignored by the current practice of pile driving risk management.

METHODOLOGY

The main objective of this research study is to update the current LADOTD policy on vibration risk management during pile driving, with the best current practice and with a focus on how to determine an appropriate vibration monitoring distance for Louisiana's local conditions. The current best practice of managing vibration risk associated with pile driving employed by federal and other state highway agencies was identified from conducting a survey and performing a comprehensive literature review. The flowchart of Figure 6 shows the procedure used in this study to determine an appropriate vibration monitoring distance (VMD). The details of each step are presented in this section.

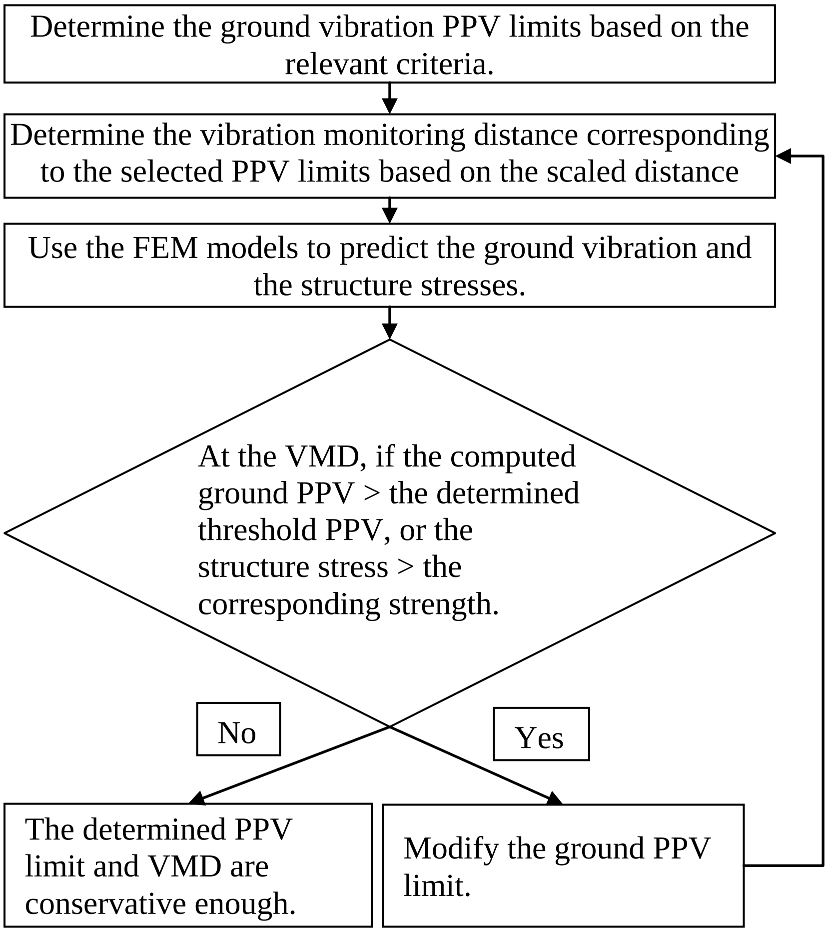


Figure 6
Flowchart illustrating the procedure of determining ground vibration PPV limits and vibration monitoring distance

Questionnaire Survey

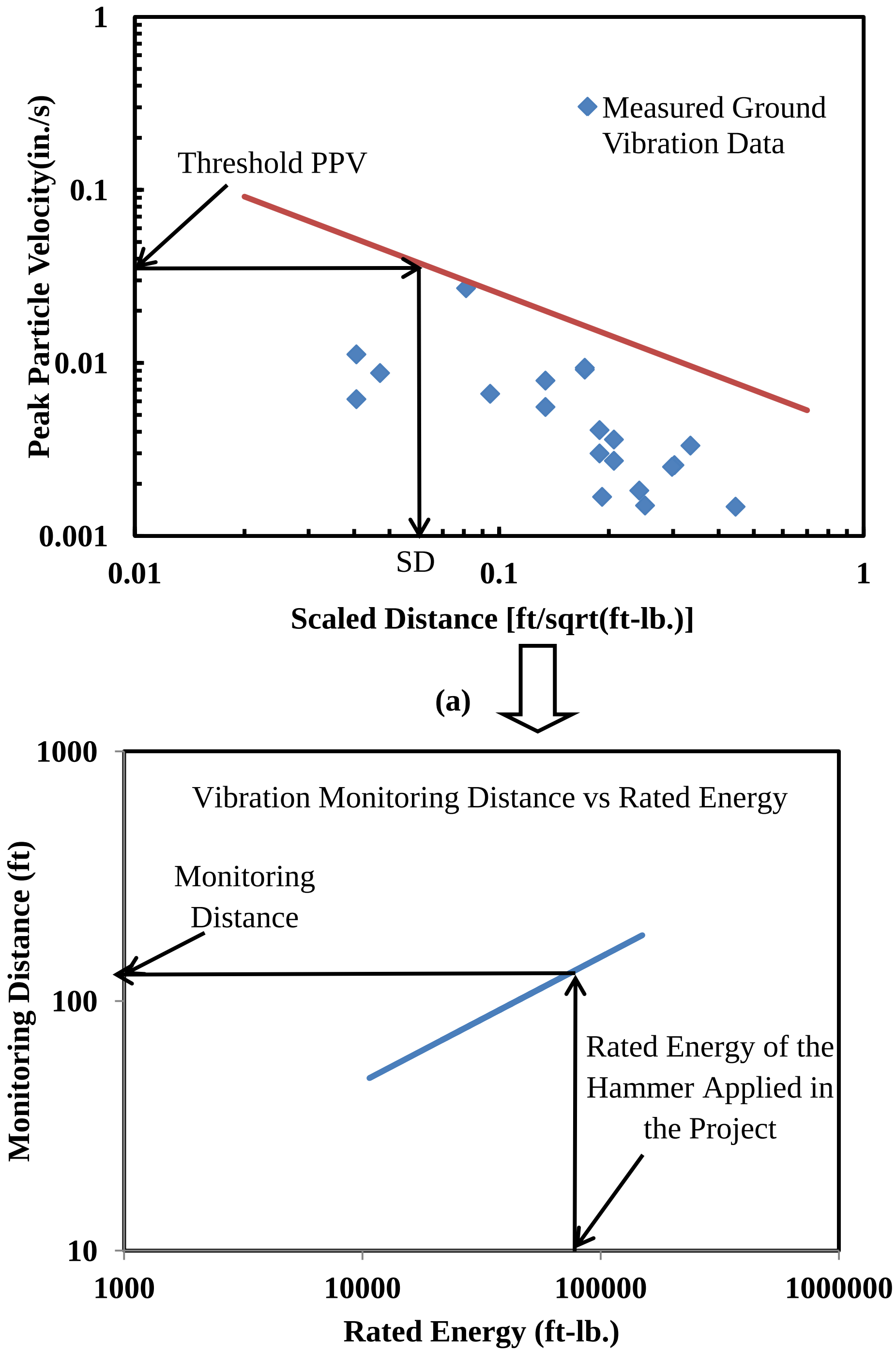
Besides a comprehensive literature review on the issues pertinent to pile driving, there are many useful existing data in the files of state DOTs, individual consultants, and contractors that are not readily accessible to the outsiders. To capitalize on these invaluable data and to identify the best current practice of piling driving vibration monitoring and risk management, a questionnaire survey was conducted of state DOTs, pile driving contractors, and consultants to get different perspectives. The questionnaire survey forms were developed to include the following important issues related to pile driving risk management:

- The threshold vibration limits at which damage to adjacent structures is expected to occur;
- A procedure to approximate peak particle velocity;
- A procedure to approximate a reasonable vibration monitoring distance;
- Procedures and means for assessing pre-driving conditions of neighboring structures and buildings; and
- Engineering measures to mitigating ground and structure vibrations due to pile driving.

Appendix A contains the questionnaire survey form, which is divided into three parts, A-1, A-2, and A-3, for DOTs, contractors, and consultants, respectively.

Determination of Vibration Monitoring Distance

The method of determining an appropriate VMD based on the scaled-distance concept for managing vibration risk associated with pile driving is illustrated schematically in Figure 7 which involves the following steps: (1) to select threshold PPV limits that refer to the magnitude of ground vibrations over which damage to a surrounding structure is likely to occur during pile driving; (2) to develop a scaled-distance based approach to approximate PPV values of ground vibrations during pile driving; and (3) to verify the vibration monitoring distance obtained from the empirical scaled-distance concept with the aid of dynamic finite element method. Each of the above steps is detailed in the following sections.



(a)

(b)

Figure 7

A schematic illustrating the procedure of determining the ground VMD: (a) determination of the scaled distance (SD) corresponding to the chosen threshold PPV; and (b) determination of VMD from the rated energy of hammers

Determination of Threshold PPV Values

General Scenarios. The available criteria on the vibration limits were critically reviewed to evaluate their suitability for Louisiana conditions. General scenarios herein refer to pile driving projects where neither historic/sensitive buildings nor loose sandy layers are present, while special situations refer to the projects where either historic buildings or loose sandy layers are of concern.

The following vibration limit criteria reported in literature were evaluated for their suitability under Louisiana conditions, and the most appropriate one was recommended to LADOTD for adoption and implementation:

1. *USBM criteria [13]*: The vibration criteria proposed by the U.S. Bureau of Mines (USBM) were developed from an extensive study on damage to residential buildings from surface mine blasting, which has been widely used for assessing structural damage potential caused by pile driving. PPV is used in the USBM criteria for its effectiveness in correlating cosmetic damage (e.g., cracking) and simplicity, and its frequency-dependent limiting values are shown in Figure 8. Note that the lower PPV limits (i.e., 0.5 in/s for the plaster and 0.75 in/s for the drywall) are recommended at frequencies less than 40 Hz in order to take into account the fact that the structural and mid-wall resonant frequencies are usually within this range for residential structures. The vibration limit of 0.5 in/s suggested in the USBM criteria has been proven to be conservative based on the results from studies conducted in homes from Nevada to Connecticut and from Wisconsin to Florida, which indicated that environmental factors (e.g., changes in humidity) are more influential than vibratory effects at 0.5 in/s in triggering or widening cosmetic cracks *[14]*.

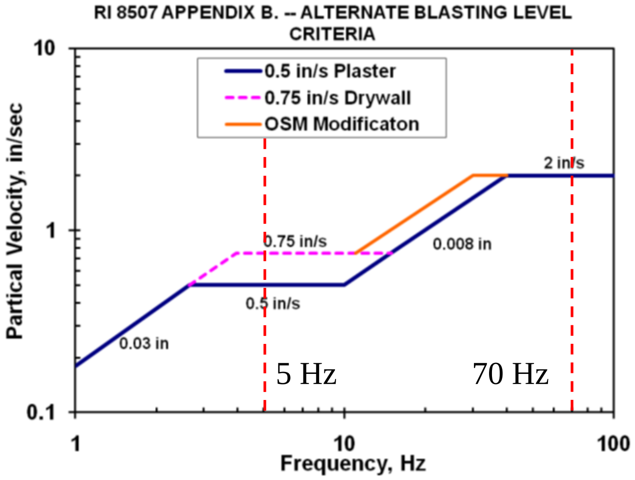


Figure 8

Safe level blasting criteria from USBM Ri 8507 and the derivative version (the chart option from OSM surface coal mine regulations) ***[13]***

2. *German criteria- DIN 4150 [1]*: The German criteria-DIN 4150 are presented in Figure 9, along with those recommended by the Office of Surface Mining Reclamation and Enforcement (OSM) that are largely similar to the USBM criteria. Note that the German criteria also include lower limiting PPV values (i.e., 0.2 in/s at frequency lower than 10 Hz and linearly increasing from 0.2 in/s at 10 Hz to 0.8 in/s at 100 Hz), as indicated by the "R" dash-dotted line in Figure 9, which are based on the residents' response to pile driving induced vibrations rather than structural damage potential.

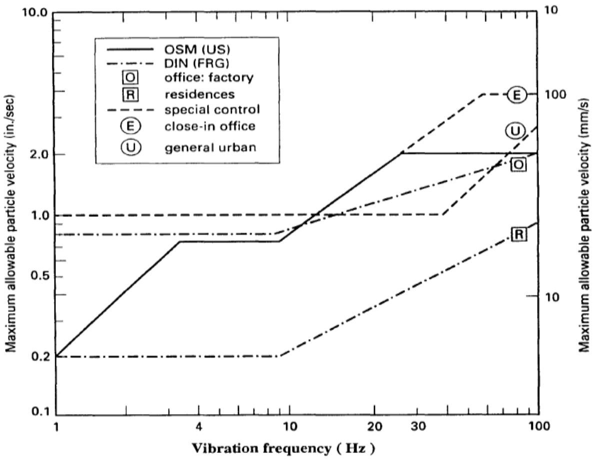


Figure 9

Frequency-dependent PPV limits provided by U.S. Office of Surface Mining and German Standard Office

3. *The Swedish Standard [2]*: The Swedish Standard SS 02 542 11 (SIS 1999) on permissible PPV values was also evaluated, which takes into account foundation conditions (i.e., the type of foundation soils and construction material of foundations), the type of structures, and the type of building materials. This criterion specifies the allowable vertical vibration velocity at the base level of buildings, which can be approximated by equation (2):

$$v = v_0 F_b F_m F_g \quad (2)$$

where,

v = allowable vertical component of vibration velocity (mm/s),
v_0 = vibration velocity based on soil type (mm/s),
F_b = building factor,
F_m = material factor, and
F_g = foundation factor.

The recommended values for v_0, F_b, F_m, and F_g are given in Table 2 to Table 5, respectively. With typical values provided in Table 2 to Table 5, PPV values were calculated for both residential and industrial buildings to determine the corresponding ground vibration limits and assess the viability of using this standard in Louisiana.

Table 2
Acceptable vibration velocity for different soil types, v_0 (mm/sec)

Soil type	Piling, sheet piling, or excavation	Compaction work
Clay, silt, sand or gravel	9	6
Glacial till	12	9
Bedrock	15	12

Table 3

Building factor, F_b

Class	Type of structure	Building factor
1	Heavy structures such as bridges, quay walls, defense structures etc.	1.70
2	Industrial or office buildings	1.20
3	Normal residential buildings	1.00
4	Especially susceptible buildings and buildings with high value or structural elements with wide spans, e.g., church or museum	0.65
5	Historic buildings in a sensitive state as well as certain sensitive ruins	0.50

Table 4

Material factor, F_m

Class	Type of building material	Material factor
1	Reinforced concrete, steel, or wood	1.20
2	Unreinforced concrete, bricks, concrete blocks with voids, light-weight concrete elements, masonry	1.00
3	Light concrete blocks and plaster	0.75
4	Limestone	0.65

Table 5

Foundation factor, F_g

Class	Type of foundation	Foundation factor
1	Spread footings, raft foundations	0.60
2	Buildings founded on shaft-bearing piles	0.80
3	Buildings founded on toe-bearing piles	1.00

As an example, take a residential building on clayey soil layers using the Swedish standard, the values yielded from equation (2) provide a maximum acceptable ("allowable") vertical vibration velocity, v, of 0.16 in/sec (4.1 mm/s), with v_0 = 9 mm/s (soil type: clay, silt, sand, and gravel); F_b = 1.00 (normal residential building); F_m = 0.75 (light concrete blocks and plaster); and F_g = 0.60 (spread footings, raft foundations). The Swedish standard is too conservative for the purpose of preventing damage to surrounding buildings during pile driving because its allowable vertical vibration velocity is smaller than that in German criteria- DIN 4150 for addressing residents' response to the vibrations caused by pile driving.

4. *Maximum PPV independent of frequency proposed by Woods [11]*: To control the magnitude of ground vibrations during pile driving and thus to prevent damage to surrounding structures, Woods suggested that the peak particle velocity shall be less than a specific control limit at the nearest structure. The type of structure and distance between this structure and the nearest pile will dictate the allowable value as described in Table 6. Particle velocity shall be recorded in three mutually perpendicular axes.

Table 6

Frequency independent limiting particle velocity

Structure and Condition	Limiting Particle Velocity (in/s)
Historic and some old structures	0.5
Residential structures	0.5
New residential structures	1.0
Industrial building	2.0
Bridges	2.0

5. *LADOTD special provision*: The limits of ground vibrations are set as 0.25 in/s and 0.1 in/s nearby non-historic and historic structures, respectively, in the current LADOTD special provision for pile driving monitoring and risk management.

Special Scenario. Some special scenarios, including historic buildings, loose sand, or buildings housing sensitive equipment warrant special considerations for ground vibration limits because they are less tolerable to ground vibrations caused by pile driving. The following section describes how the limits of ground vibrations in terms of PPV for these situations should be determined.

Dynamic settlements in sand and clay. It is well known that the nature of settlements in sand and clay are different, but both can be evaluated using the same procedure developed initially for dynamic settlements in loose to medium dense sand by Massarch *[10]*. This method is based on the critical shear strain concept that shear strain is the primary factor causing densification/settlement of granular soils. The critical shear strain is defined as the value of cyclic shear strain under which loose dry granular soils will not experience any densification or no pore pressure will build up in saturated cohesive soils, as illustrated in

Figure 10 *[15]*. With the following equation, the shear strain of a soil (γ) can be estimated, provided that its shear wave velocity (c_s) and vertical particle vibration velocity (v) are known.

$$\gamma = \frac{v}{c_s} \tag{3}$$

Note that shear wave velocity of a soil layer can be measured directly at the field or approximated from a seismic cone penetration test (CPT) or MiniCPT testing that can be conducted at driven pile project sites in Louisiana.

The procedure for assessing the likelihood of triggering dynamic settlement in a loose sandy layer by pile driving is illustrated by the flowchart of Figure 10, which is modified from the one proposed by Massarsch *[10]*.

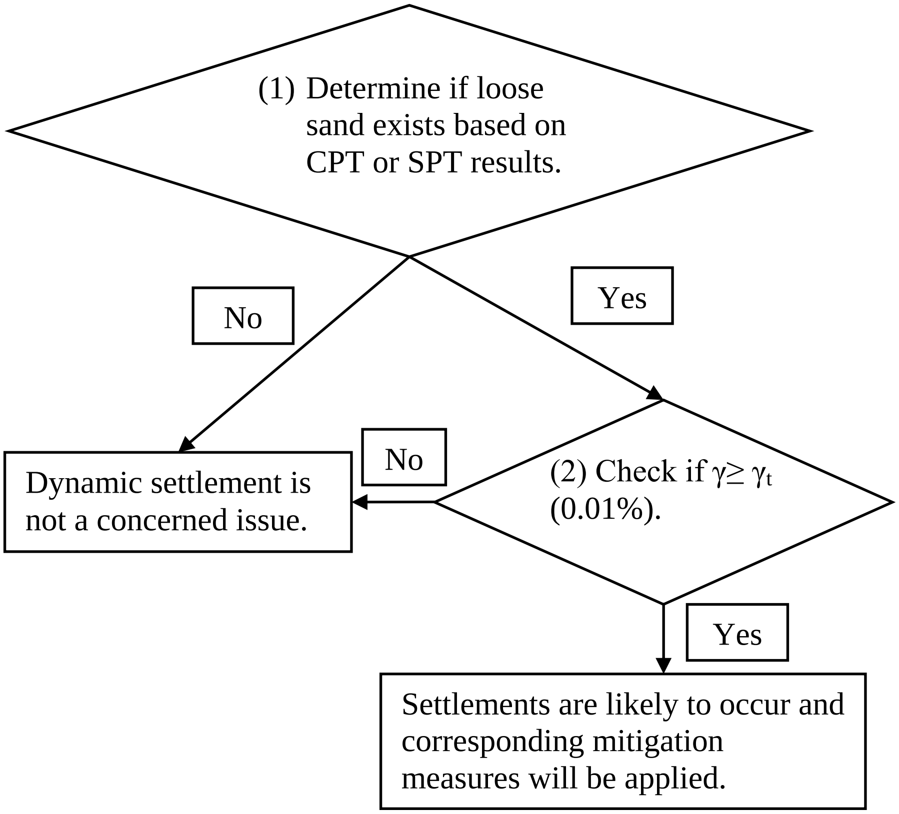


Figure 10
Procedure of determining the likelihood of triggering dynamic settlement in a loose sandy layer by pile driving

If loose sands exist at a pile driving site, based on its relative density (e.g., sands with a relative density less than 40 percent generally viewed as loose soils) that can be correlated from CPT and/or standard penetration tests (SPT) results, the shear strain of the soil caused by pile driving can be approximated with equation (3) and compared to the critical (or threshold) shear strain (0.01 percent for most of sand). The critical shear strain is defined as the value of cyclic shear strain under which loose dry granular soil will not experience any densification or no pore pressure will build up in saturated cohesive soil, as illustrated in Figure 11 *[16]*.

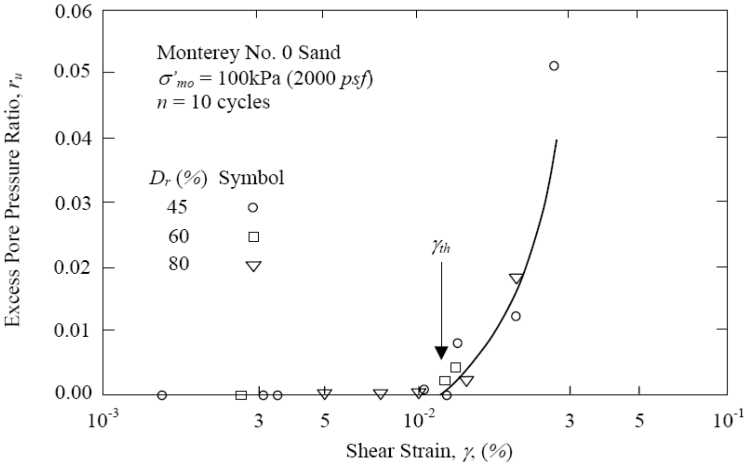


Figure 11

Correlation between the shear strain and the excess pore pressure of sand *[15]*

Consequently, the threshold PPV value to prevent dynamic settlement from occurring in a loose sand layer is limited by such a magnitude that the induced shear strain does not exceed the critical shear strain (0.01 percent). To adopt this approach for preventing the occurrence of dynamic settlement in loose sand during pile driving, the PPV of ground vibrations was used in lieu of the vertical particle velocity in equation (3) since it is more conservative and convenient to be obtained. Then, equation (3) can be rearranged as a function of the critical shear strain and shear wave velocity of a soil layer, with which the threshold PPV corresponding to dynamic settlement potential in loose sand can readily be approximated.

$$\mathrm{PPV_s} = \gamma_t c_s \tag{4}$$

where,
$\mathrm{PPV_s}$ = the threshold PPV for preventing dynamic settlements in loose sand caused by pile driving.

Historic or sensitive buildings. The historic and old buildings are more vulnerable to ground vibrations induced by pile driving. Therefore, lower PPV limits for historic buildings are specified in different criteria. For the Swedish standard, with v_0=9 mm/s (0.35 in/s) (soil type: clay, silt, sand, and gravel); $F_b = 0.50$ (historic buildings in a sensitive state as well as certain sensitive ruins); $F_m = 0.75$ (light concrete blocks and plaster); and $F_g = 0.60$ (spread footings, raft foundations), v = 9 × 0.50 × 0.75 × 0.60 = 2.02 mm/s (0.08 in/s) is rendered. For frequency-independent PPV limits proposed by Woods: the PPV limit of 0.5 in/s is recommended for historic and some old buildings. The PPV limit adopted by the current LADOTD special provision is 0.1 in/s, which is close to that in the Swedish standard.

Develop a Scaled–distance Based Approach to Approximate PPV Values

In order to link the threshold PPV values to the vibration monitoring distance for vibration risk management purposes, it is necessary to develop a simple means to predict the PPV values of ground vibrations caused by pile driving. To this end, the scaled-distance concept that was described previously was used in this study. For the ease of discussion, the scaled-distance equation proposed by Wiss is given herein again *[7]*:

$$v = k\left(\frac{D}{\sqrt{E}}\right)^{-n} \tag{5}$$

The ground vibration data collected from previous pile driving projects in Louisiana were analyzed statistically with the aid of the regression analysis tools provided in MATLAB®, from which the k and n values in equation(s) were determined. As observed in some previous studies, there is generally large data scattering between the PPV and the SD *[8]*. Thus, both regression equations associated with the confidence interval and the prediction interval were also developed, in addition to the best fit line for the relationship between the PPV and SD.

The Best Fit Line and Woods and Jedele's Equation. If a strong correlation exists between the PPV and the SD for the data collected for this project, the best fit line can be directly used to determine the vibration monitoring distance for a chosen threshold PPV value. The viability of applying the scaled-distance equations developed by Woods and Jedele to the ground vibration data collected from the state of Louisiana, as shown earlier in Figure 3, was also examined *[8]*.

The Upper Line of Confidence Interval and Prediction Interval. Statistically speaking, a confidence interval represents a range of values around the sample mean that include the true mean of the population, which generates a lower and upper limit for the mean with a degree of certainty (i.e., a confidence level). For example, a 95 percent confidence interval in the case of ground vibration magnitude (i.e., PPV) means that 95 times out 100, the mean of the collected ground vibration dataset would fall within this interval if ground vibrations are measured many times. The higher the confidence level is, the wider the confidence interval is, and the higher probability, the more likely the mean PPV falls into the confidence interval. The upper and lower limits of a confidence interval can be calculated from the following equation *[17],[18]*.

$$x \pm \frac{t_{r,\alpha/2} \times s}{\sqrt{N}} \tag{6}$$

where,

x = sample mean of ground vibration data,

$t_{r,\alpha/2}$ = upper $(1/2)\alpha \times 100$ percent point of the t distribution with r degree of freedom,

α = probability of the mean PPV value will not fall into the confidence interval,

s = estimate of the variance of the PPV data relative to the computed mean, and

N = the size of the current selected ground vibration dataset *[18]*.

The above formula indicates that as *N* increases, the confidence interval gets narrower from the $\sqrt{N}$ term and that noisy data (i.e., data with a large standard deviation) generate wider confidence intervals than data with a smaller standard deviation.

The prediction interval is an estimate of an interval within which the next measurement of the sample will fall *[17],[18]*. Taking the example of measured PPV values of ground vibrations during pile driving, a 95 percent prediction interval means that 95 times out 100, the PPV of any next collected ground vibration would fall within this interval. Similar to a confidence interval, a prediction interval also generates an upper and lower prediction limit with a degree of certainty (i.e., a prediction level). The upper and lower limits of a prediction interval can be calculated as follows:

$$x \pm \frac{t_{r,\alpha/2} \times s}{\sqrt{1+\frac{1}{N}}} \tag{7}$$

Once the threshold PPV value and a predictive equation for PPV are established, it is straightforward to determine a VMD as follows:

$$SD = \left(\frac{PPV}{k}\right)^{-\frac{1}{n}} \tag{8}$$

$$\mathrm{VMD} = \mathrm{SD} \times \sqrt{\mathrm{W}} = \mathrm{SD} \times \sqrt{\varepsilon \mathrm{W}_r} \tag{9}$$

where,
ε = the energy transfer efficiency of a pile driving hammer, and
W_r = the rated energy of the hammer, ft-lbf.

As illustrated in equation (9), the transferred energy from a pile driving hammer to a pile is equal to the product of the rated energy of the driving hammer and its energy transfer efficiency, εW_r.

Pre-construction Survey Distance (PSD)

Because a pre-construction survey is an essential component for effectively managing vibration risk associated with pile driving, it should be performed prior to any pile driving activities. A reasonable PSD should be determined, but there is currently no consensus on how large a PSD should be in the literature. The research team recommends that a PSD the same as the VMD should be used, as illustrated by Figure 12. The rationale behind such a recommendation is that the SDs determined based on the above procedures are quite conservative, therefore the PSD = VMD should be adequate. Any structure within the PSD should be surveyed prior to any pile driving activities to document their pre-existing conditions; ground vibration monitoring should be set up at one location at least along the perimeter of the VMD and at the ground near the building closest to the driven pile within the VMD if it is relevant, and the measured PPV values can serve as the basis for not surveying or monitoring any building beyond the VMD; if any complaint or claim is filed during or after pile driving, a post-construction survey should be conducted on these buildings such that a comparison of the cracks before and after the construction can be made, which can help LADOTD engineers assess whether any damage has been caused from the pile driving.

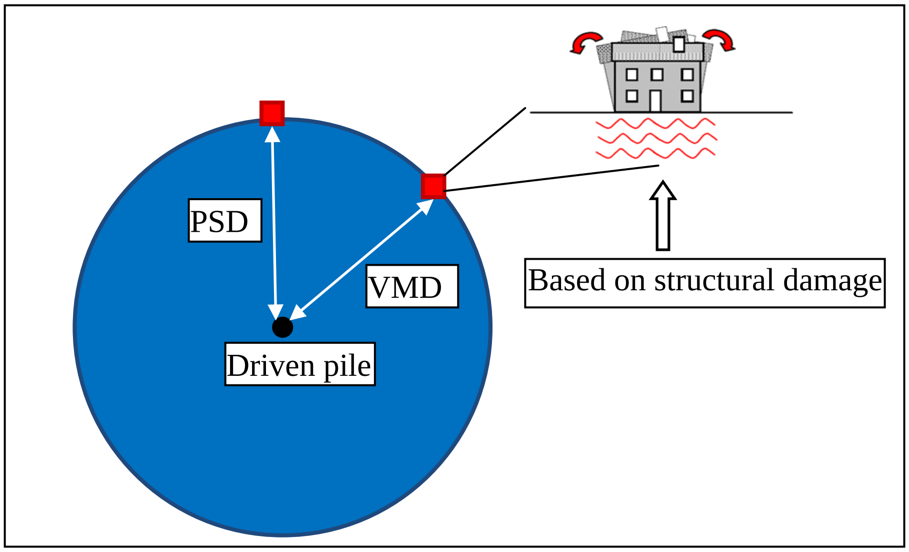


Figure 12
Schematic diagram illustrating the pre-construction survey distance and vibration monitoring distance

Validation of the Scaled-distanced based VMD with Dynamic FEM Simulations

Because inherent limitations exist in the empirical scaled-distance concept (e.g., incapable of considering ground-structure interactions during pile driving), the VMD, determined from the scaled-distance based procedure, warrants further validation. To this end, dynamic FEM simulations were performed with the aid of the FEM software PLAXIS 2D.

Dynamic FEM Simulations

A simplified axisymmetric model was set up to simulate the pile driving process, with a typical Plaxis 2-D model shown in Figure 13. The properties of the soil profiles at the previous pile driving projects investigated in this study were considered when the input soil parameters were chosen. A plate element was used to simulate a driven pile in the model, with an interface element used between the pile and soils for modeling the interfacial behavior. A simplified structure consisting of beam elements was set up at the VMD determined from the procedure previously discussed. The standard fixities were added to the model, and the absorbent boundaries were used at the bottom and the right side of the soils to avoid the spurious reflection *[19]*.

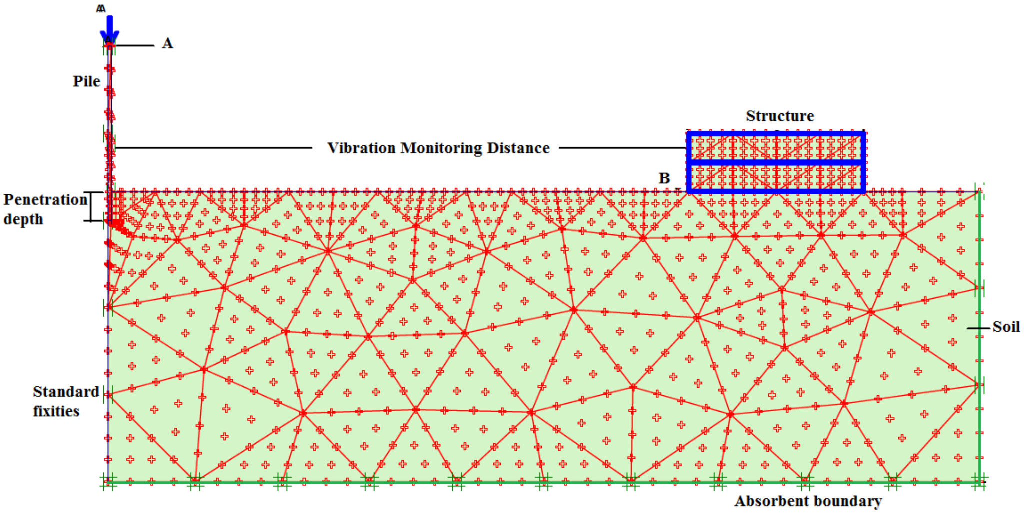


Figure 13

Schematic geometry of the model with single soil layer used in FEM simulations

The hammer loading was simulated by one pulse of distributed harmonic loading at the top of the pile, expressed as:

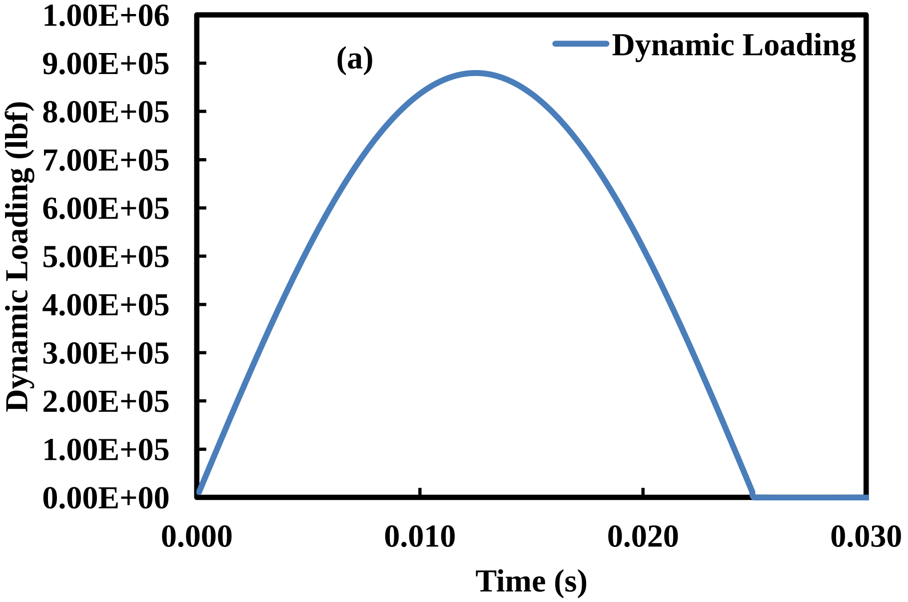
$$F = A \times \sin(2\pi f t + \varphi) \qquad (10)$$

where,
A = the amplitude of the loading, lb.,
f = the frequency of the loading, Hz,
t = the instant time, in second, and
φ = the phase angle of the loading, degree (°).

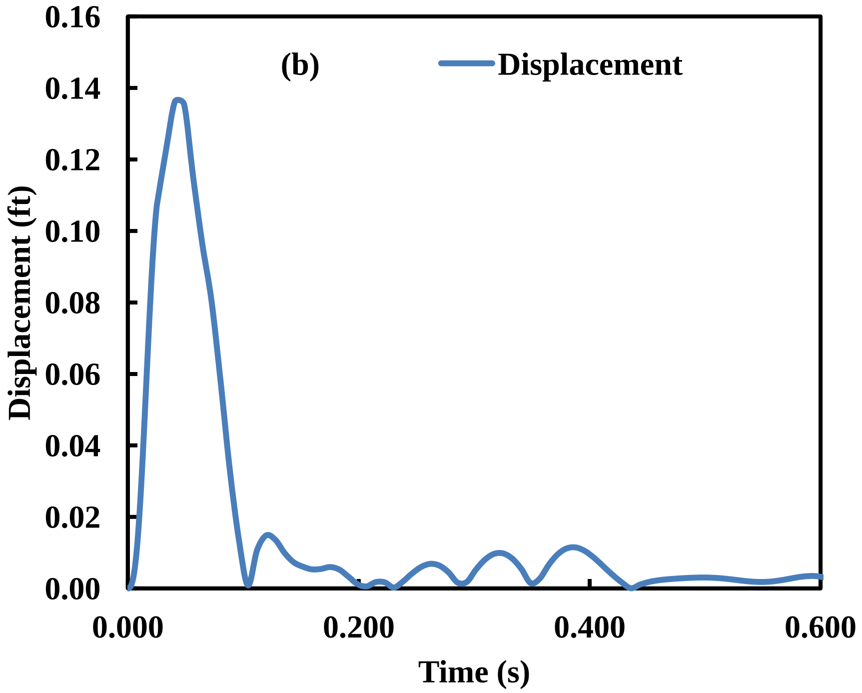
One loading pulse curve is depicted in Figure 14(a) as well as the resulting displacement curve at the top of the pile in Figure 14(b). The frequency of this dynamic loading is 20 Hz. By calculating the area enveloped by the dynamic loading-displacement curve at the top of the pile, as shown in Figure 14(c), the energy transferred to the pile from the hammer was obtained. A trial-and-error process was used to select appropriate amounts of dynamic loading applied to the top of a pile so that the energy transferred from the hammer to the pile falls within a reasonable range (i.e., from 1×10^4 to 7.5×10^5 lb-ft, which is based on a typical rated energy range of 2×10^4 to 1.5×10^6 lb-ft for pile driving hammers and a 50 percent energy transfer efficiency ratio).

To verify whether this FEM model is capable of simulating ground vibrations induced by pile driving, a dynamic load with an amplitude of 104,461 lb/ft^2 was applied on the top of the pile. The peak particle velocity of ground vibrations at different distances from the driven pile were predicted from the FEM simulations and plotted against the corresponding scaled distances, as shown in Figure 15. Because of their wide use in pile driving, Woods and Jedele's equations for soil class II and III were compared with the predicted relationship between PPV and SD obtained from the FEM simulations. Figure 15 indicates that the FEM simulation results are in excellent agreement with that of Woods and Jedele's equations if appropriate soil parameters are used and thus dynamic FEM simulations can be employed to model ground vibrations induced by pile driving.

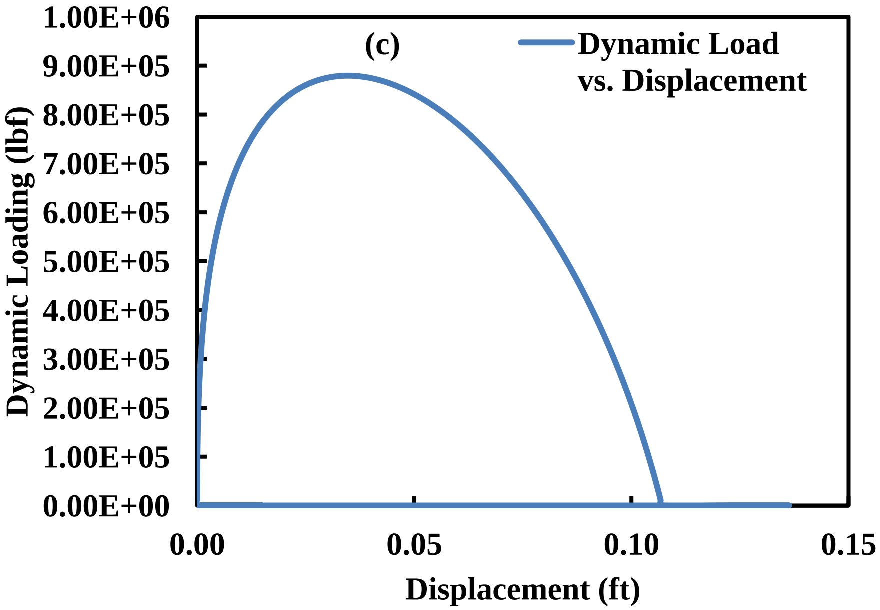
From the results of dynamic FEM simulations, both the vibrations at the ground near the building and the responses of the building to the dynamic loading applied to the pile can be obtained. Subsequently, the structural responses in terms of normal and shear stresses were compared to the corresponding strengths to assess whether the VMD chosen from the scaled-distance approach is adequate to prevent structural damage. If the predicted ground PPV exceeds the threshold value or if any of the predicted stresses in the structure is larger than the corresponding strength, the threshold PPV limits should be reduced and the VMD should be enlarged accordingly.



(a)



(b)



(c)

Figure 14

(a) Dynamic loading applied to the top of the pile; (b) displacement developed at the top of the pile induced by the dynamic loading; and (c) displacement vs. the dynamic loading at the top of the pile from FEM simulations

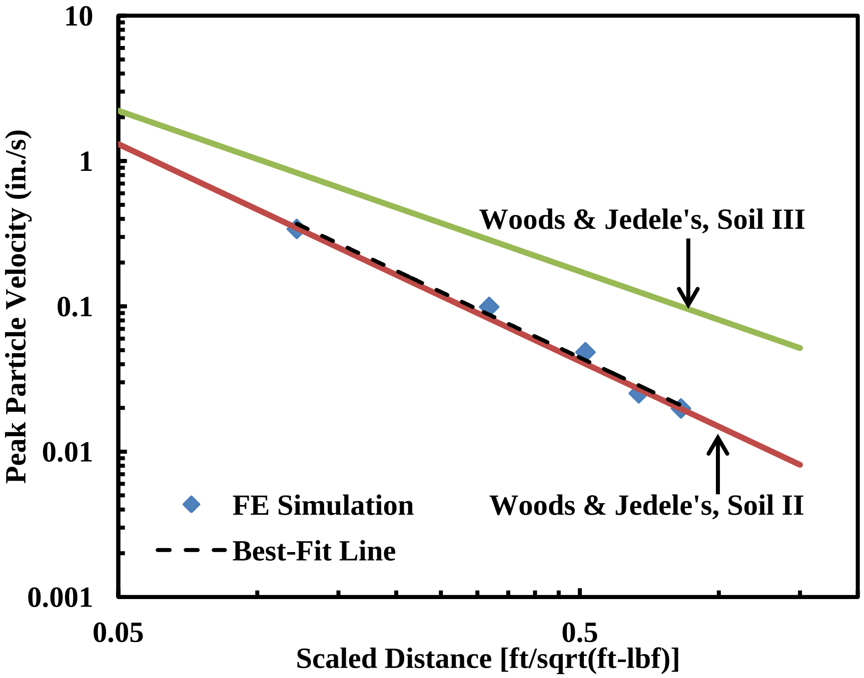


Figure 15
Verification of dynamic FEM simulations by comparing to the PPV vs. SD relationships predicted from Woods and Jedele’s equations

Collecting Vibration Monitoring Data from Previous Pile Driving Projects in Louisiana

With the help of LADOTD’s and LTRC’s Pavement and Geotechnical Section, ground vibration data were collected from 10 pile driving projects in the state of Louisiana. The information of these pile driving projects investigated in this study is summarized in Table 7 with the locations of these projects shown in the map in Figure 16.

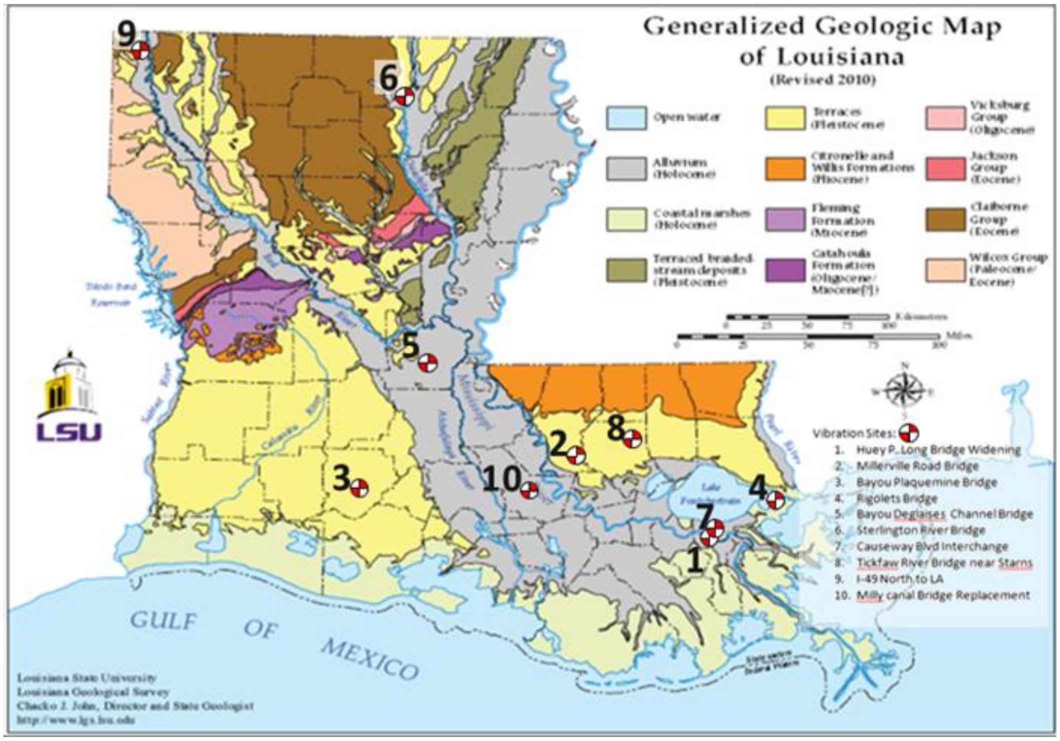


Figure 16

Approximate locations of the investigated pile driving projects (courtesy of LTRC, LSU)

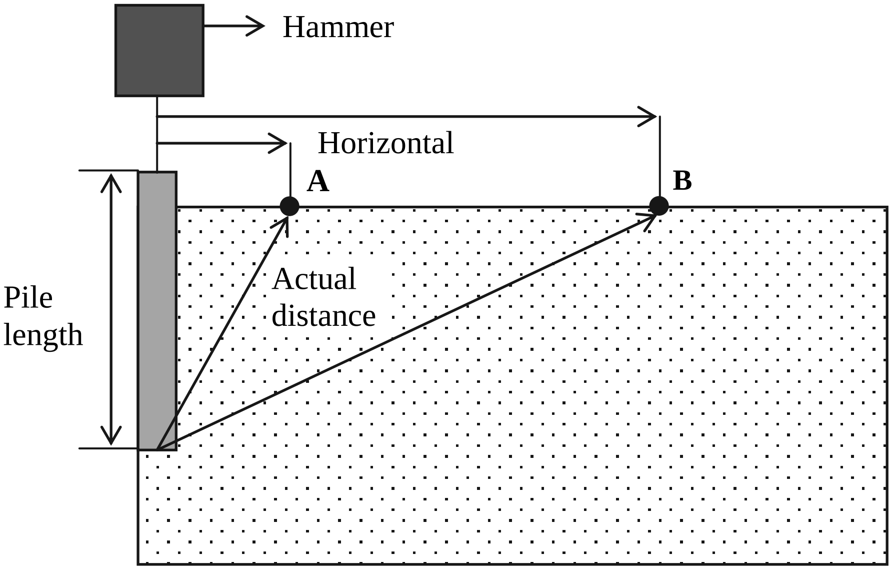


Figure 17

Schematic diagram illustrating the influence of pile penetration depth on ground vibration at two different locations, points A and B *[2]*

Precast prestressed concrete (PPC), concrete, and steel piles were used in these bridge projects, with side dimensions ranging from 14 to 30 in. in the case of PPC or concrete piles. The lengths of the piles used in these projects ranged from 57 to 161 ft. The hammers used in these projects include: single acting air hammers and single acting diesel hammers, with rated energies ranging from 35,000 to 149,600 ft-lb. The soils encountered in the projects under investigation include: sand, silt, and clay, with most of the soil strata not being homogeneous and often consisting of multi-layers. The major strata of the soil profiles in these projects are depicted schematically from Figure 27, Figure 29, Figure 31, and Figure 33 to Figure 39 in Appendix C with some minor soil layers being merged into the adjacent major layers.

Ground vibrations were monitored in transverse, vertical, and horizontal directions in these projects, during the course of driving testing piles and/or production piles. The layouts of the monitoring sites in these projects, including their distances from the driven piles and relative orientations with respect to the driven piles, are schematically shown in Figure 26, Figure 28, Figure 30, and Figure 32 in Appendix C.

The details regarding the pile driving processes (e.g., the settings of pile driving hammers, pile driving records with penetrations in the course of pile driving, blow counts, and dynamic pile testing results) vary considerably from project to project. The recorded ground vibrations in terms of PPV from these projects were summarized in Table 15 included in Appendix C, along with the SD values that were calculated from the rated energy of the pile driving hammers and the horizontal distances between the driven piles and the monitoring sites. In this study, the horizontal distance was used to calculate the scaled distance for the following considerations:

- As illustrated in the diagram shown in Figure 17, the vibration magnitude will be overestimated at such a location as Point A that is close to the pile by using the horizontal distance that neglects the gradually increasing pile penetration length. Such an overestimation and ensuing conservativeness associated with the use of horizontal distance are acceptable because the focus of this research study is to determine a reasonable vibration monitoring distance rather than to accurately predict ground vibration magnitude.
- The influence of using the horizontal distance becomes much smaller for a monitoring point (e.g., Point B) at a distance ranging from one to two pile lengths from the driven pile, which is likely to be the range for a reasonable ground vibration distance.

- The information about the penetration depth of driven piles is not always available or recorded synchronically with the ground vibration measurements during pile driving, which makes it practically difficult to calculate the radial distance between the monitoring point on the ground and the pile tip).

Table 7
Information of soil, hammers, and piles used in the pile driving projects of LADOTD

Project	Pile	Hammer Model	Rated Energy (ft-lbf)	Subsurface Condition
Bayou Plaquemine Bridge Replacement	24" PCC	DELMAG D46-23, Diesel Hammer	105000	Alternative clay and sand
Millerville Road over Honey Cut Bayou	14" PCC	PILECO, D19-42, Diesel Hammer	21510(Setting 1)	Clay
			28035(Setting 2)	
			35260(Setting 3)	
			42480(Setting 4)	
Huey P. Long Bridge Widening	HP 12x102 steel piles	Boh/Vulcan 08	24000	Alternative clay and sand
		Boh/Vulcan 09	27000	
		Boh/Vulcan 010	32500	
The Rigolets Pass Bridge	30" PCC	Conmaco 300E5,Air Hammer	149600	Alternative clay and sand
	66 inch O.D			
Bayou Desglaises Channel Bridge	14" Concrete	I.C.E 42-S,Single-Acting Diesel	42000	
		I.C.E 60S, Single-Acting Diesel	60000	
	30" Concrete	I.C.E I-46v2, Single-Acting Diesel	10700	
Causeway Blvd.	16’’ PCC	APE D30-42	37824(Setting 1)	Clay and sand
			55315(Setting 2)	
			67274(Setting 3)	
			74750(Setting 4)	
Tickfaw Bridge	PPC	I.C.E I-30 diesel hammer	35385(min)	Alternative sand and silt in the shallow layer, clay in the bottom
			71700(max)	
Amite River Relief Bridge	24" PCC	APE D46-32	122000	Clay
I49 North	24" PCC	D 46-32	107484	Clay and sand
Milly Canal	16" PCC	ICE I-30	75477	Alternative sand and silt in the shallow layer, clay in the bottom

Notes: 1)The information of soil was not provided in Bayou Desglaises Channel Bridge project, but the soil condition of this site is similar to the others. 2)PCC = Precast Prestressed Concrete.

DISCUSSION OF RESULTS

Summary of the Questionnaire Survey

Sixty-eight survey responses were received from 44 state DOTs, 10 pile driving contractors, and 13 consultants. Appendix B contains the summary of the questionnaire survey responses, which is divided into three parts, B-1, B-2, and B-3, for DOTs, contractors, and consultants, respectively.

Preconstruction Survey

State agencies, contractors, or consultants consider the preconstruction survey a necessary action for assessing the conditions of existing structures and soil at project sites and for determining appropriate engineering measures to reduce the damage risk caused by pile driving. Pre-driving surveys generally consist of performing inspection, photographing the existing damage and defects, videotaping the existing damage and defects, installing crack gages, taking inspection notes and so on. However, there is no consensus on how to determine the preconstruction condition survey area, and it is usually done on a project by project basis. Typical preconstruction survey distances used by some state DOTs are: 100 ft., 200 ft., or 400 ft.

Vibration Monitoring

Various vibration parameters are used by state DOTs for assessing vibration effects from pile driving, such as peak particle acceleration, peak particle displacement, and/or PPV, but most agencies agree that PPV is the most appropriate measure of motions associated with pile driving. No consensus exists on the range of a vibration monitoring distance during pile driving, with 100 or 200 ft. from the driven pile used by several state DOTs. If there is no specification on the vibration monitoring area, consultants often control the monitoring area within 200 ft. from the driven pile.

Threshold PPV Values

A number of state DOTs and consultants use the frequency-based PPV limits recommended by the USBM (United States Bureau of Mines) for controlling cosmetic cracking while others adopt the OSM (Office of Surface Mining) frequency independent vibration criteria between 0.75 and 1.25 in/s. Nevertheless, higher PPV values up to 2 in/s and lower PPV values down to 0.1 in/s are also employed by some DOTs and consultants.

Recommended Threshold PPV Limits for LADOTD

General Scenario

As described in the Methodology section, some commonly used vibration criteria were critically evaluated. Consequently, a frequency independent threshold PPV limit of 0.5 in/s is recommended to LADOTD for the following reasons: (1) a threshold PPV limit that is independent of frequency and has a reasonable extent of conservativeness is desirable because of its simplicity and the ease of implementation; (2) a PPV limit of 0.5 in/s is conservative enough for preventing or minimizing potential damage to surrounding buildings during pile driving based on the observations reported in literature that vibrations at a PPV of 0.5 in/s resulted in smaller changes in crack width than those produced by average weekly weather fluctuations; and (3) a PPV of 0.2 in/s as included in German DIN 4105 criteria is too conservative because it aimed at addressing nearby residents' response to vibrations rather than controlling cosmic damage in a structure during pile driving *[14]*. The threshold PPV limit of 0.5 in/s was also further verified with the dynamic FEM simulations that are presented in a later section.

Special Scenario

The threshold PPV limits of ground vibrations for pile driving projects where soil layers prone to dynamic settlements exist (e.g., loose sands) or nearby historic/sensitive structures are discussed in this section.

Threshold PPV Limit in Loose Sandy Soils. As stated previously in the Methodology section, the threshold PPV limit for loose sand prone to dynamic settlements can be calculated with equation (4) if shear wave velocity of the soil layer is known. For sand, a typical shear wave velocity is in the range of 300-500 ft/s and for clay, a typical shear wave velocity is around 500 ft/s *[20]*. A critical shear strain of 0.01 percent is usually assumed for sand. With the lower shear wave velocity value of 300 ft/s used for sand, the threshold PPV value above which the critical shear strain (i.e., dynamic settlement) is likely to be triggered is 0.36 in/s. This indicates that some existing PPV limits (e.g., 0.1 and 0.17 in/s) are very conservative in terms of preventing structural damage associated with dynamic settlements in loose sandy layers *[9]*,*[21]*. To be on the safe side, a threshold PPV limit of 0.1 in/s is adopted herein.

Threshold PPV Limit for Historic Buildings. From the discussions in the Methodology section, the PPV of 0.1 in/s used by the current LADOTD practice is a conservative criterion to prevent the damage to the historic/sensitive buildings near pile driving sites.

In summary, a threshold PPV limit of 0.1 in/s is recommended for the special scenario for the sake of ease of implementation and being conservative.

Determination of Vibration Monitoring Distance

Scaled-distance based PPV Prediction Lines

A total of 188 individual PPV values at different distances from the driven piles were obtained for this study, with each of these data points representing the maximum of PPV values measured at a given monitoring site, which are plotted in a log-log chart, as shown in Figure 18. Note that the PPV values plotted in the following figures are the maximum of three measured individual component maxima (longitudinal, transverse, and vertical) rather than the vector sum of all three components. The vector sum of measured individual PPV component maxima will be overly conservative because three individual maxima of velocity rarely occur simultaneously.

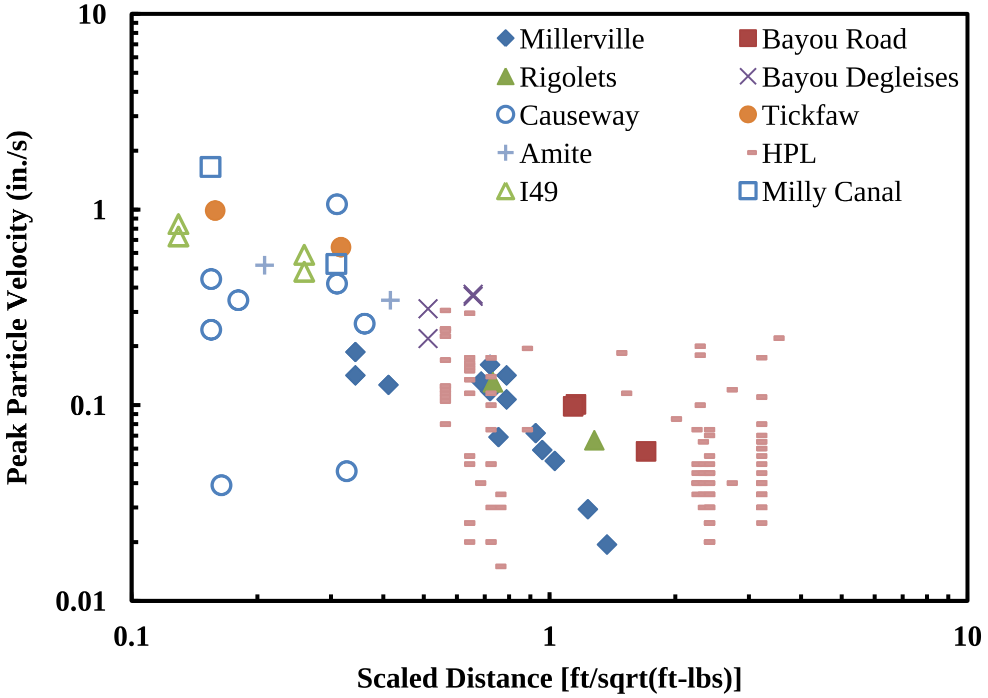


Figure 18

Ground PPV data collected from different pile driving projects in Louisiana

The Best Fit Line and Woods' and Jedele's Equation. Figure 19 shows all the 188 PPV data, along with various scaled-distance based regression equations including the best-fit line of these data and Woods' and Jedele's equation for soil class II and III. The MATLAB code developed in this research study for performing the nonlinear regression analyses is provided in Appendix D. Note that although different symbols in Figure 19 are used to represent the data collected from different pile driving projects, the regression analyses were performed on the whole data set (i.e., all 188 data points were treated as one sample set).

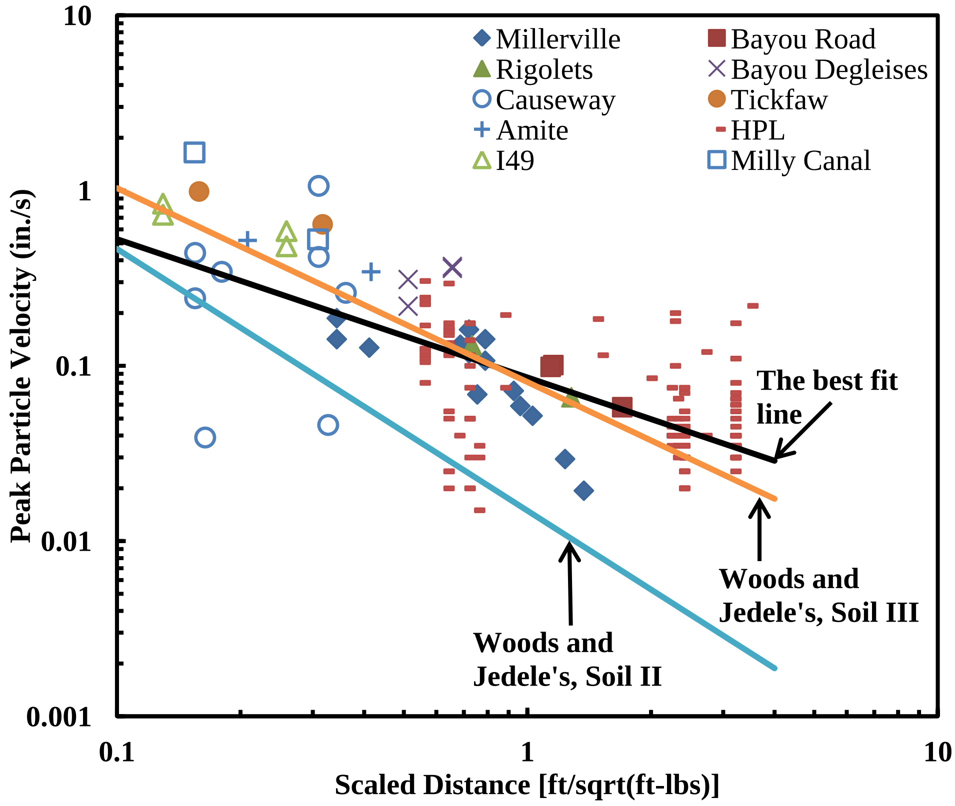


Figure 19

Collected ground vibration data from previous Louisiana pile driving projects and various scaled-distance based approximation relationships [PPV = $0.015\times(SD)^{-1.106}$ for soil II Woods and Jedele's equation; PPV = $0.081\times(SD)^{-1.494}$ for soil III Woods and Jedele's equation; and PPV = $0.086\times(SD)^{-0.789}$ for the best fit line]

As it can be seen in Figure 19, the data points are so scattered that there is no strong correlation between the PPV and the SD for the entire data set and even the individual projects. This is not unexpected considering the fact that complex processes are involved in wave propagation during pile driving; other important factors (e.g., impedance of piles and soils) are not included in the scaled distance approach; and accurate hammer energy efficiency is not always available *[10]*. Although the Woods and Jedele equation for soil class III and the best-fit equation have slightly better predictions compared with the one for soil class II, there are still more than half of the data points falling above these regression lines–as they should be since regression is the mean value line. None of these regression equations seem appropriate for the purpose of determining a reasonable vibration monitoring distance that requires an adequate level of conservativeness.

The Upper Limit Lines of Confidence Interval and Prediction Interval. In principle, the Confidence Interval and the Prediction Interval provide wider ranges of values for the PPV, and thus they were also applied to examine if they are more suitable for the determination of the VMD. The typical range of the *n* value in the scaled distance equation is 1 ~ 2, which was suggested by Woods and Jedele and was also confirmed with an FEM parametric study by the authors *[8]*,*[22]*. In the FEM simulations, the pile driving process was modeled in sand and clay, with the theoretically lower and upper values being used for their respective damping ratios *[23]*. The obtained relationships between *n* values and damping ratios from the FEM simulations are shown in Figure 20.   The smaller the *n* is, the lower the wave attenuation rate is and the more conservative a PPV predictive equation is. Also an unrealistically low value for *n* (i.e., $n = 0.222$ for the upper prediction interval line) was yielded from nonlinear regression analyses probably due to the fact that the horizontal distance measurements instead of those from the vibration source either at the pile tip or along the pile shaft to the ground were used. Therefore, a fixed *n* value of 1 was used to develop confidence and prediction level regression equations. The upper limit lines of 99 percent confidence interval and 99 percent prediction interval were developed based on the data collected from the projects described previously, which are plotted in Figure 21. The values of *k* and *n* corresponding to these upper limit lines are also provided in the figure.

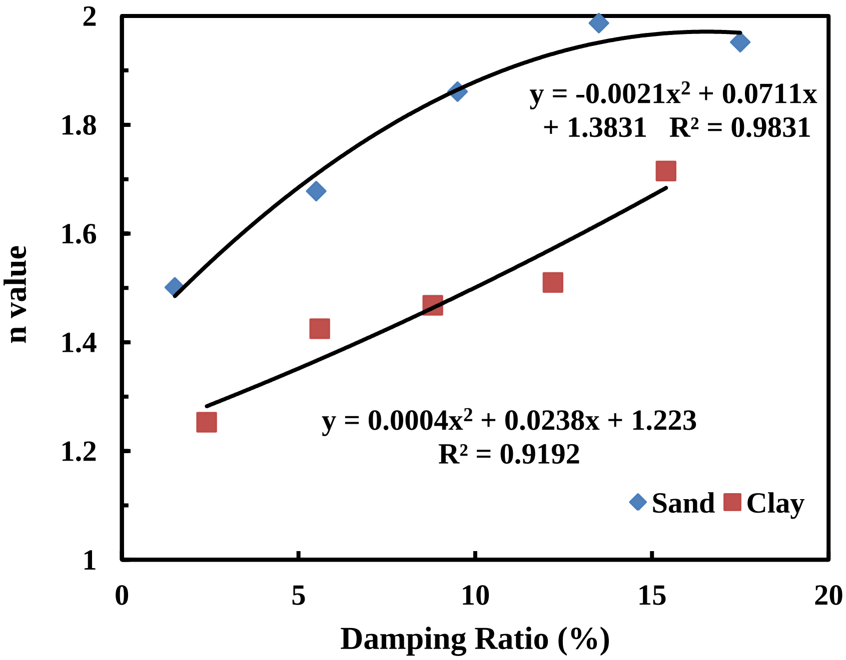


Figure 20

The relationship between *n* values and damping ratios for sand and clay obtained from a parametric FEM study *[22]*

As expected, the upper line of a 99 percent prediction interval provides a wider PPV value range and covers almost all the collected data points. Given the fact that the purpose of this research study is to determine a ground vibration monitoring distance, which entails some degree of conservativeness, the upper line of the 99 percent prediction interval is more appropriate than the confidence interval counterpart. The *k* value is 0.224 for the 99 percent upper prediction level equation, and the corresponding scaled distance can be calculated with the following equation if the threshold PPV is known, according to equation (8).

$$\mathrm{SD} = \left(\frac{\mathrm{PPV}}{0.224}\right)^{-1} \tag{11}$$

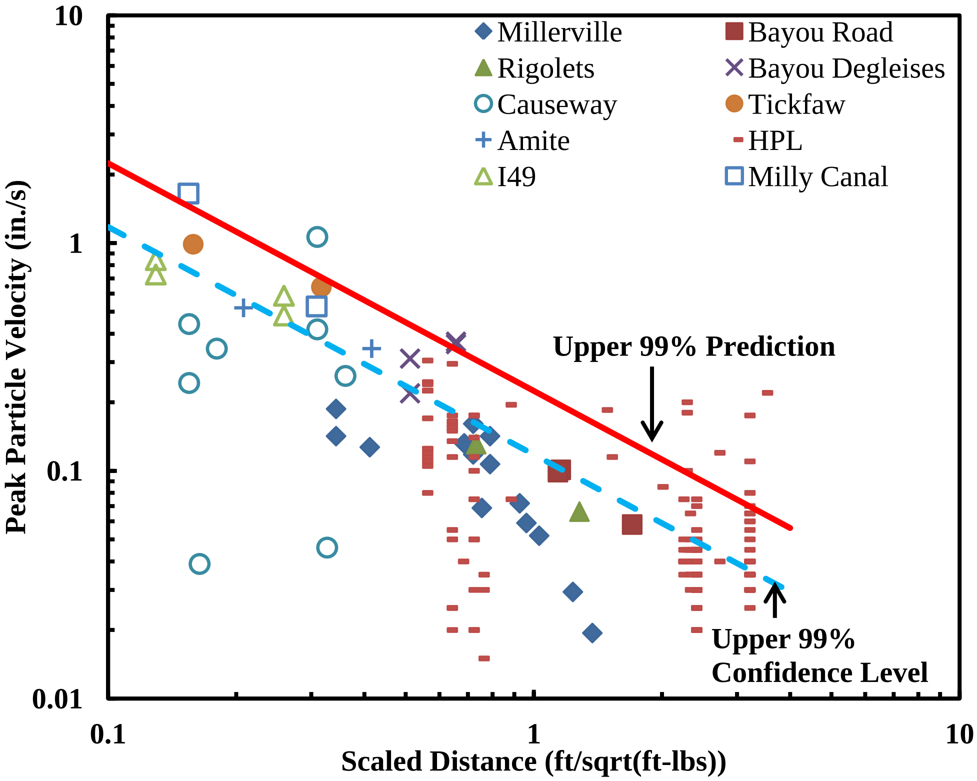


Figure 21

Upper lines of 99 percent confidence interval and 99 percent prediction interval [PPV = $0.224\times(SD)^{-1}$ for upper 99 percent prediction level; and PPV = $0.118\times(SD)^{-1}$ for upper 99 percent confidence level]

General Scenario. Substituting the selected threshold PPV, 0.5 in./s, for the general scenarios into equation (11), the corresponding scaled distance is calculated as 0.450 $\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}}$. With the definition of the scaled distance, the VMD can be calculated as:

$$D = 0.32 \times \sqrt{W_r} \tag{12}$$

Note that 50 percent was used for the hammer energy transfer efficiency when more accurate information is unknown or unavailable. The relationships between the VMD and the rated energy of a hammer are plotted in Figure 22. Compared with the VMD used by Florida DOT, equation (12) provides more conservative VMD values. The VMD values corresponding to 200,000 ft-lbf calculated with both of these two equations are less than 200 ft., and far less than 500 ft. that is currently used in the Louisiana special provision. Therefore, it is suggested that the vibration monitoring distance should be 200 ft. to account for the potential use of larger hammer sizes.

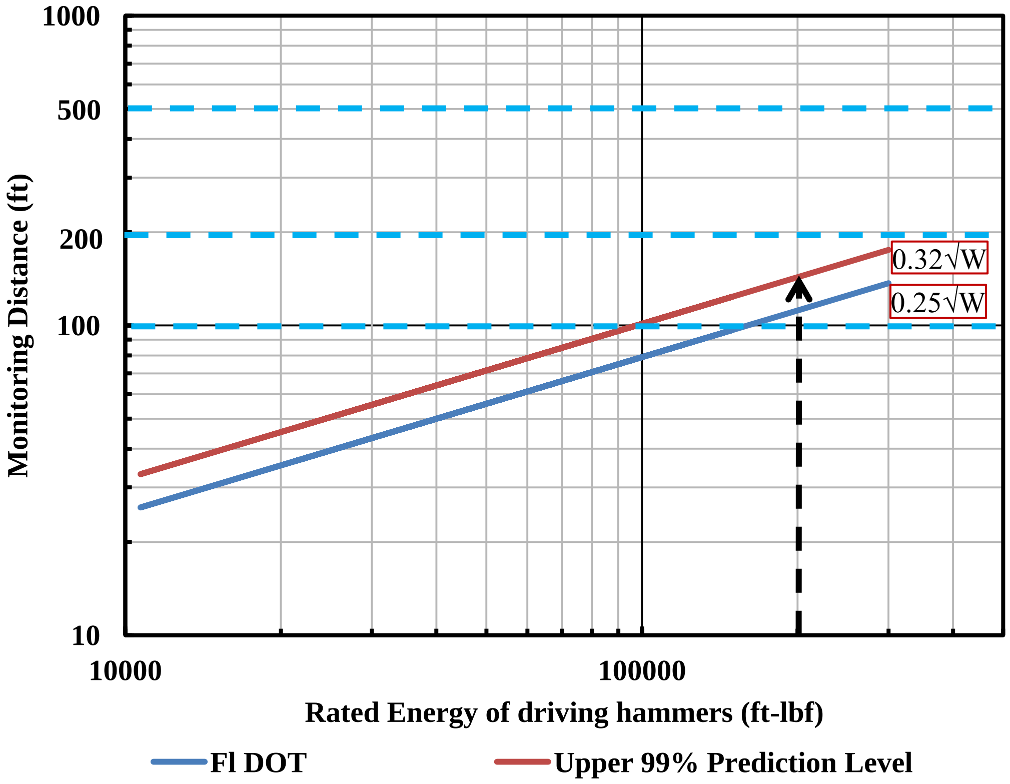


Figure 22
Vibration monitoring distance as a function of the rated hammer energy obtained with different methods for the general case (the threshold PPV = 0.5 in./s)

Special Scenario. Similar to the general cases, the VMD estimation equation was also developed for the special scenario. A larger scaled distance was obtained as 2.244 $\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}}$ corresponding to 0.1 in/s. Accordingly, the VMD is determined with the aid of equation (9) as follows, with an assumed energy transfer efficiency ratio of 50 percent.

$$D = 1.6 \times \sqrt{W_r} \qquad (13)$$

This relationship between the VMD and the rated energy of pile driving hammers for the special scenario is illustrated in Figure 23.

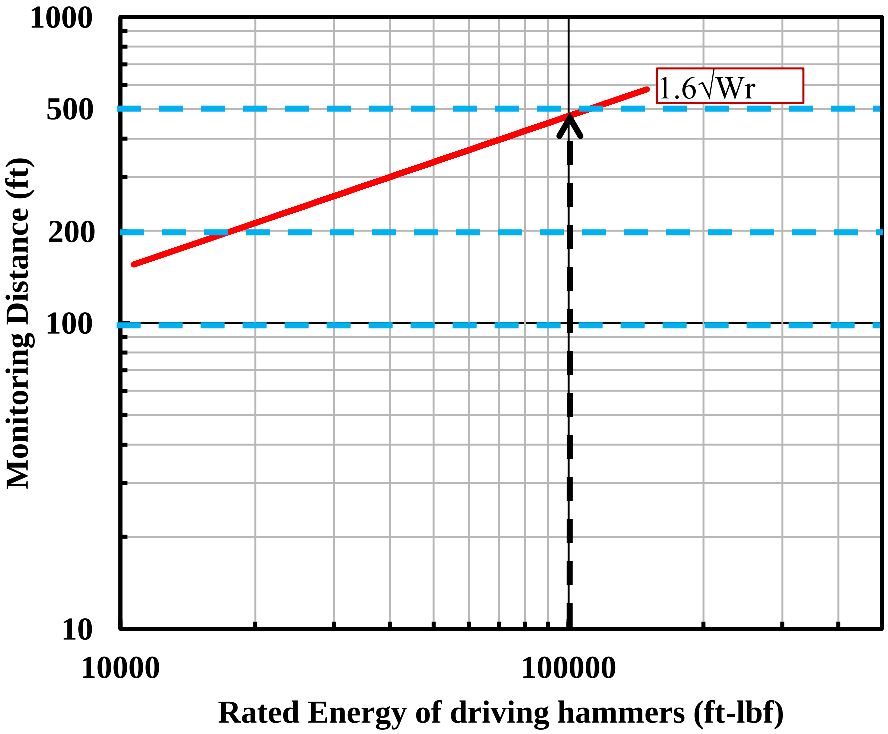


Figure 23
Vibration monitoring distance vs. the rated hammer energy for the special scenario (the threshold PPV = 0.1 in/s)

Figure 23 indicates that for the special scenario (e.g., the potential of dynamic settlement susceptible soils and sensitive or historic buildings at pile driving sites) the vibration monitoring distance should be 500 ft. if the hammer rated energy is less than 100,000 ft-lbf; otherwise, the VMD should be calculated using equation (13) for a larger size hammer (i.e., with larger rated energy). For the special scenario, a pre-construction survey distance of 500 ft. is recommended.

Validation of the Scaled-Distance Based Vibration Monitoring Distance with the FEM Simulations

Basic Information of FEM Models

The FEM model used for verifying the findings from the scaled-distance concept is shown in Figure 24. Since clay is the dominant soil type encountered in the projects used in this study, it was chosen to model a single soil layer with a thickness of 100 ft. The main soil parameters used in the FEM models are listed in Table 8 that were chosen based on: (1) the available soil boring logs of the investigated projects; and (2) the principle that conservative values were used if more accurate information was not available. Table 9 lists the physical and geometry properties of the concrete pile used for the FEM simulations. Two verification cases were considered during the FEM simulations: (1) in the first case, the building is located at a distance equal to the recommended VMD from the driven pile (i.e., 200 ft.) to check whether the structural response is tolerable; and (2) in the second case, the building is located around 150 ft. away from a driven pile so that the magnitude of its nearby ground vibration velocity is close to the recommended threshold PPV value (i.e., 0.5 in/sec) and the structural response was examined.

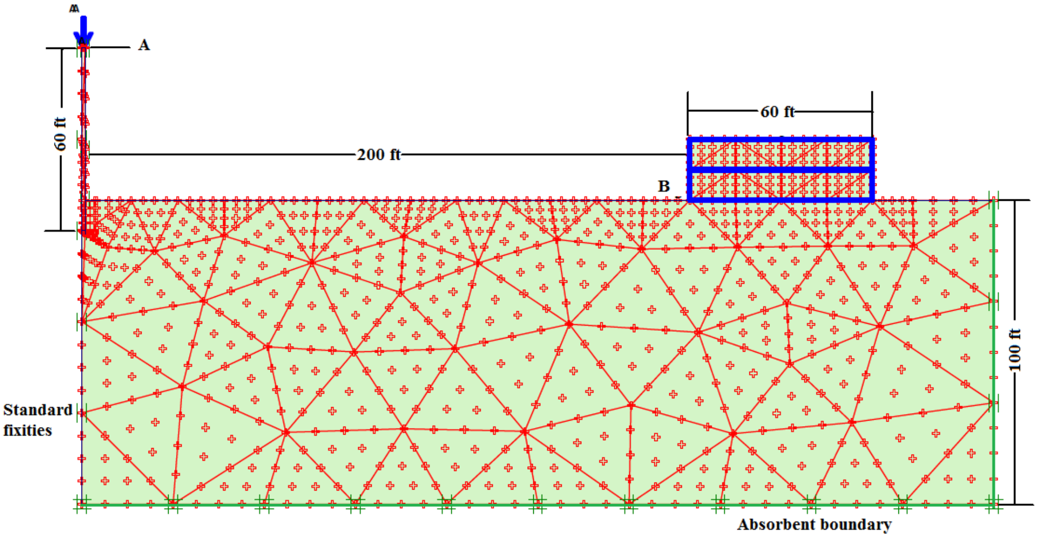


Figure 24

Meshed model of the FEM simulations with the structure at 200 ft. from the driven pile

Table 8

Main parameters of the soil used in the FEM simulations

Soil	Unit Weight	Young's Modulus	Poisson's Ratio	C_{ref}	φ	Damping Ratio	Model Type
	[lb/ft^3]	[lb/ft^2]		[lb/ft^2]	[°]	%	
Clay	114.6	2.00E+05	0.2	20.89	24	3	Linear Elastic

Note: the C_{ref} is the cohesion and φ is the friction angle.

Table 9

Geometric parameters and physical properties of the concrete pile

Pile Material	Length	Diameter	Penetration Depth	Unit Weight	Young's Modulus	Poisson's Ratio
	[ft]	[in]	[ft]	[lb/ft^3]	[lb/ft^2]	
Concrete	60	24	10	152.8	6.27E+08	0.1

Three models were set up for each case to represent different material properties (concrete, steel and wood) of the structures, as reported in Table 10. The modeled structure is 60 ft. wide and has two stories, with each story 10 ft. high.

Table 10

Material parameters of the structure used in the FEM simulations

Material	Flexural Rigidity	Normal Stiffness	Plate Weight	Poisson's Ratio	Damping α	Damping β	Model Type
	[lb-ft^2/ft]	[lb/ft^2]	[lb/ft]				
Concrete	1.35E+09	2.62E+07	3.29E+02	0.1	0.01	0.01	Elastic
Wood	4.50E+08	8.72E+06	1.08E+02	0.1	0.01	0.01	Elastic
Steel	5.08E+08	2.15E+08	6.03E+01	0.1	0.01	0.01	Elastic

One harmonic load pulse was applied to the top of the pile as distributed loading to simulate the hammer impact, which is defined in equation (10) with an amplitude of 280,000 lb/ft^2, a frequency of 20 Hz, and a phase angle of 0°. This distributed loading resulted in 71,600 ft-lbf transferred energy that is equivalent to a hammer with a rated energy of 143,000 ft-lbf and an energy efficiency ratio of 50 percent. The same amount of transferred energy was used in the FEM models for the structures with different materials.

The Results of the FEM Simulations

Since the structure is located at a distance equal to the VMD determined from the scaled-distance approach described early (i.e., 200 ft.), the ground PPV at the VMD is not available. Instead, the ground (Point B) closest to the structure, which is at 196.2 ft. from the pile, was selected to evaluate the ground PPV values from the FEM simulations. The ground PPV values at Point B from the three models are summarized in Table 11, which suggests that all the ground PPV values at 196.2 ft. are much smaller than 0.5 in/s.

Table 11

Ground PPV values at 196.2 ft. predicted from the FEM simulations

Structure Material	Ground PPV at 187.4 ft (in/s)
Concrete	0.243
Steel	0.253
Wood	0.244

Table 12 summarizes the structural responses to the simulated pile driving and indicates that all the structure responses in terms of resulting stresses are far smaller than the corresponding strengths. The results from the first FEM verification case indicate that the VMD of 200 ft. is very conservative for the general scenario.

Table 12
Structural responses from the FEM simulations for the models with structure at 200 ft. from driven piles and typical strength values of different structure materials

Structure Material	Tensile stress	Compression stress	Shear stress	Compression Strength	Shear Strength
	psi	psi	psi	psi	psi
Concrete	1686.4	-1688.7	92.1	2,500	2,500
Steel	524.6	-556.5	282.8	28,300	28,300
Wood	557.7	-556.3	29.7	300~3960	790

To further study the responses of the structure closer to the driven piles where the ground vibration is around 0.5 in/s, another FEM verification model was set up with the structures located at 150 ft. from the driven pile, as shown in Figure 25.

The PPV values of ground vibrations at 146.3 ft. and the structural responses to the simulated pile driving are summarized in Table 13 and Table 14, respectively. The results in Table 13 and Table 14 indicate that although the PPV values of ground vibrations are around the threshold value (i.e., 0.5 in/s), the stresses experienced by different structural materials are generally lower than their respective strengths. These FEM simulation results indicate that the chosen threshold PPV (i.e., 0.5 in/s) should be conservative enough to prevent adjacent buildings from being damaged during pile driving. By comparing the FEM simulation results from two FEM verification cases that are summarized in Table 11 to Table 14, one can notice that only slightly larger stresses are induced in the second FEM verification case, while the PPV values of ground vibrations increase from 0.25 to 0.50 in/s.

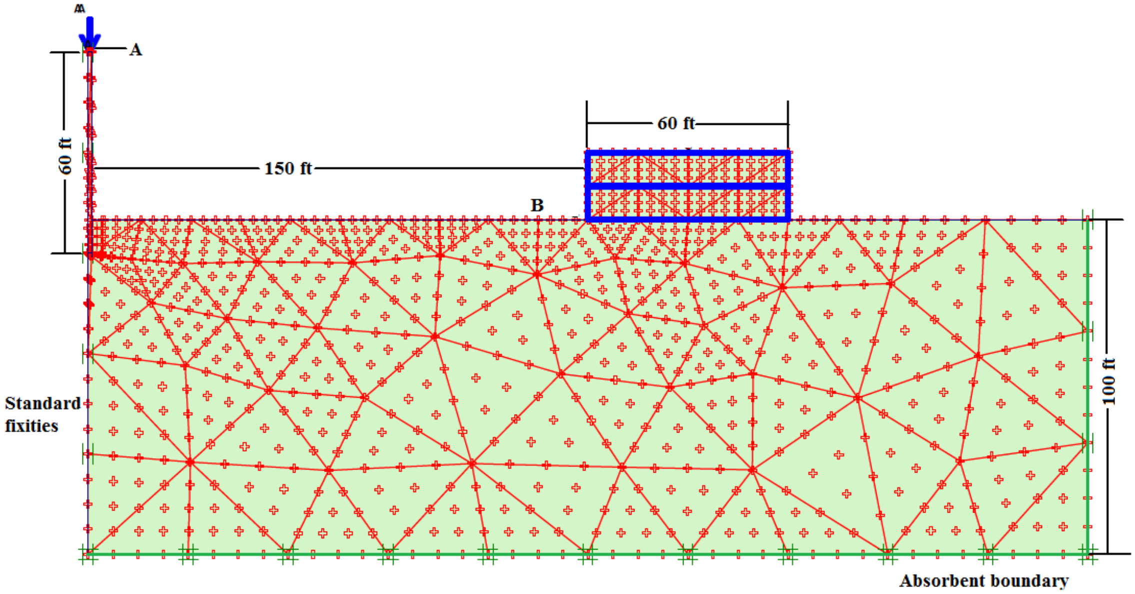


Figure 25

Meshed model of the FEM simulations with the structure at 150 ft. from the driven pile

Table 13

Ground PPV values at 146.3 ft. predicted from the FEM simulations

Structure Material	Ground PPV at 146.3 ft (in./s)
Concrete	0.525
Steel	0.504
Wood	0.474

Table 14

Structural responses from the FEM simulations for the models with structure at 150 ft. from driven piles and typical strength values of different structure materials

Structure Material	Tensile stress	Compression stress	Shear stress	Compression Strength	Shear Strength
	psi	psi	psi	psi	psi
Concrete	1719.2	-1714.3	95.5	2,500	2,500
Steel	534.9	-568.1	321	28,300	28,300
Wood	570.4	-565.3	31	300~3960	790

Mitigation Measures for Addressing the Risk of Pile Driving

Special engineering measures are often recommended by the state DOTs to mitigate pile driving induced vibration problems.

Reducing the Ground and Structure Vibrations

Some well-known mitigation measures include, but are not limited to: (1) using supplementary pile installation techniques, such as predrilling to bypass some shallow stiff soil layers that may result in large ground vibrations; (2) properly choosing the pile types: non-displacement pile, cast-in-place pile, or auger cast pile; (3) using a light hammer, provided that drivability allows, to decrease the ground vibration level; and (4) using fresh and absorbing cushions in the pile driving system to reduce ground vibrations *[1],[24]*.

CONCLUSIONS AND RECOMMENDATIONS

The results from this research study indicate that the current Louisiana special provision for addressing the risk of pile driving is generally too conservative (e.g., the threshold PPV limit of 0.2 in/s and the pre-construction survey distance of 500 ft.) and should be updated according to the major findings from this study as summarized below.

Threshold Peak Particle Velocity Limits

As the essential parameter of any vibration risk management plan, the threshold PPV limits were determined by critically reviewing the current available criteria and specifications suggested by federal agencies and state DOTs. Two frequency-independent threshold PPV limits were chosen for the following scenarios: (1) the general scenario where no historic/sensitive buildings are nearby or no loose sandy soil layers are present at pile driving sites; and (2) the special scenario with nearby historic/sensitive buildings or settlement sensitive (i.e., loose sand) soil layers existing near pile driving sites. For the general scenario, 0.5 in/s is suggested, while 0.1 in/s is recommended for the special scenario.

Vibration Monitoring Distance

A rational approach to determine a VMD was proposed in this study, which was based on the scaled-distance concept and 99 percent upper prediction level regression equation. This approach was applied to analyze the ground vibration data collected from 10 previous pile driving projects in Louisiana, which leads to the recommended VMD for both the general and special scenarios as follows:

- For the general scenario, a VMD of 200 ft. is recommended.
- For the special scenario, a VMD of 500 ft. is recommended for a pile driving hammer with a rated energy equal to or less than 100,000 ft-lbf; otherwise, the VMD shall be calculated as $\mathrm{VMD} = 1.6 \times \sqrt{\mathrm{W_r}}$, with *Wr* being the rate energy of a pile driving hammer.

The threshold PPV limits and the ensuing VMD obtained from the scaled distance concept were further verified with the FEM simulations, which considered ground-structure interactions during pile driving and compared the predicted stresses in the structures with their corresponding strength values. The FEM simulation results indicate that the scaled-distance based findings are quite conservative and simple to be implemented to manage the risk of pile driving.

Pre-Driving Survey Distance

The pre-construction survey distance is recommended to be the same as the vibration monitoring distance as summarized in the preceding section, and a pre-construction survey should be carried out prior to any pile driving activities.

Recommendations

Based on the findings from this study, a specification draft is recommended for effectively managing risks associated with pile driving, which is ready for immediate implementation by LADOTD in future pile driving projects and included in Appendix E. Such a risk management plan for addressing pile driving induced vibrations should be executed not only prior to any pile driving activities, but be taken into consideration during the planning and design stages as well.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

C.I.	Confidence Interval
CPT	Cone Penetration Test
DOT	Department of Transportation
FEM	Finite Element Method
ft.	foot (feet)
ft-lbf	foot pounds
in.	inch(es)
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
m	meter(s)
MATLAB	MATLAB® is a high-level language and interactive environment that enables you to perform computationally intensive tasks faster than with traditional programming languages such as C, C++, and Fortran.
OSM	Office of Surface Mining
P.I.	Prediction Interval
PCC	Portland Cement Concrete
PPV	Peak Particle Velocity
PPV_s	the threshold PPV for preventing dynamic settlements in loose sand caused by pile driving
PSD	Preconstruction Survey Distance
s	second(s)
SD	Scaled Distance
SPT	Standard Penetration Test
USBM	United States Bureau of Mines
VMD	Vibration Monitoring Distance

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APPENDIX A

Questionnaire Survey Forms

Questionnaire for State DOTs

Name of respondent:_____________ State DOT or Other affiliation:__________________
Title:___________________ Contact information:___________________________

Check Y (Yes) or N (No) or write a short response on the spaces provided.

1. Has your DOT had experience with vibration damage caused by pile driving operations?
Y N
1a. Has your DOT had experience with dynamic settlement caused by pile driving operations?
Y N
1b. Have you used preventive measures to decrease vibration effects of pile installation on structures?
Y N If yes, please specify:
1c. Do you have experience how soil conditions affect pile installation and vibrations of structures?
Y N If yes, please specify
1d. Do you have experience how distances from driven piles affect ground vibrations?
Y N If yes, please specify:

2. Have any of incidents resulted in claims against the:
State DOT Y N
Contractor Y N
Consultant Y N
Other agency Y N If yes, please specify:_____________________

3. Does your state have a standard specification dealing with vibration due to pile driving operations?
Y N
If yes, does your specification limit:
peak particle displacement Y N If yes, please specify the value__________
peak particle velocity Y N If yes, please specify the value__________
peak particle acceleration Y N If yes, please specify the value__________
If yes, please supply a copy of your "standard" specification if possible.

4. Does your specification require a minimum monitoring coverage area?
Y N If yes, how is this minimum monitoring range determined?
5. Does your specification have any frequency reporting requirements?
Y N
6. Does your specification cover?
loading carrying piles Y N
sheet piles Y N
other piles Y N If yes, please specify__________

7. Does your specification require continuous monitoring of ground motion while pile driving is on-going? Y N

or intermittent monitoring? Y N

8. Does your specification specify location(s) where ground measurements are to be made? Y N

If yes, how is the monitoring location(s) prescribed?

____

____

9. Does your state require a pre-driving survey of nearby structures? Y N

If yes, does this survey include:

videotaping Y N

installation of crack gages Y N

photographing existing defects Y N

inspection notes Y N

other? Y N If yes, please specify:

____

What is pre-driving survey coverage range and how is this range determined?

____

10. May contractor do monitoring with their own personnel? Y N

or must an independent third party be employed to do monitoring? Y N

11. Must a state DOT inspector be present to observe all monitoring? Y N

12. Must a record of vibration monitoring and/or predriving survey be submitted to the state? Y N

If no, who else will keep the record(s)?______________________________

13. Are there specific geological profiles or other site conditions which prevail in your state that exacerbate pile driving problems? Y N

If yes, please describe these conditions:

____

____

14. Has experience or certain local conditions led to development of any unique criteria or procedures to address pile driving vibration problems? Y N If yes, please describe:

____

____

15. Are your vibration monitoring database available to the public? Y N

And how these data can be obtained?

Questionnaire for Pile Driving Contractors

Name of respondent:____________________

Title:____________________________

Contact information:___________________________________

Please circle **Y (Yes)** or **N (No)** or write a short response on the space provided for each question.

1. Has your firm been involved in cases where pile driving-induced vibrations have been an issue either due to structural damage to surrounding buildings or perceived damage?
   Y N
   If yes, could you provide more detail or monitored vibration data from these cases?

2. Has your firm experienced any problem associated with ground/structural vibrations or noise during pile driving (e.g., project delays, expenses, law suits, etc.)?
   Y N

3. Does your firm have a standard operating procedure to predict vibrations generated during pile driving?
   Y N
   If yes, could you please provide more detail on the procedure?
   ____
   What vibration limits do you use in your practice?

4. If you are required to monitor vibrations, do you
   Rent equipment and do it yourself Y N
   Hire a vibration monitoring consultant firm Y N
   Hire a vibration consultant Y N

5. Does your firm routinely conduct pre-driving survey of surrounding structures prior to pile driving?
   Y N
   If yes, how is the pre-driving survey area determined?
   ____
   And please briefly describe the type of survey performed.
   ____

6. What types of engineering measures to mitigating vibrations during pile driving have been adopted by your firm?
   ____

7. Does your firm keep records of vibration measurements?
   Always Y N

Only when required by specifications Y N

Leave in possession of vibration firm or consultant Y N

8. Are the records of vibration measurements kept in your firm available for the public?
   Y N
9. For pile driving projects conducted by your firm, is a pre-driving condition survey generally performed?
   Y N
   If yes, what is pre-driving survey coverage range and how is the survey coverage range determined?
   ____
   And does this survey include:
   Videotaping Y N
   Installation of crack gages Y N
   Photographing existing defects Y N
   Inspection notes Y N
   Others Y N
   If yes, please specify__________
10. Do you have experience how soil conditions affect pile installation and vibrations of structures? Y N
    If yes, please specify:
11. Do you have experience how distances from driven pile affect ground vibrations?
    Y N
    If yes, please specify:

Questionnaire for Vibration Monitoring Firm or Vibration Monitoring Consultant

Name of respondent:____________________Title:______________________________
Contact information:______________________________________

Please circle **Y (Yes) or N (No)** or write a short response on the space provided for each question.

1. In cases where you have measured vibrations during pile driving, what is the procedure used to determine monitoring coverage area?
   ____
2. What kind of information is generally collected during pile driving monitoring?
   Peak particle velocity or other vibration parameters Y N
   Driving hammer information (hammer weight, drop height, rated energy) Y N
   Soil information (soil profile, in-situ testing results) Y N
   Information of surrounding structures or buildings Y N

3. Do you obtain vibrations from which frequency data can also be extracted:

Always	Y	N
Only when specified	Y	N
Never	Y	N

What vibration limits do you use in your practice? ________________________

4. Have you ever used any of the following engineering measures to mitigate pile-driving induced vibrations?

Use non-displacement pile	Y	N
Use Jetting or predrilling	Y	N
Change pile spacing	Y	N
Use appropriate sequence of driving	Y	N
Other	Y	N

If yes, please describe

____

5. For pile driving projects conducted by your firm, is a pre-driving condition survey generally performed?

Y N

If yes, what is pre-driving survey coverage range and how is the survey coverage range determined?____

And does this survey include:

Videotaping	Y	N
Installation of crack gages	Y	N
Photographing existing defects	Y	N
Inspection notes	Y	N
Others	Y	N

If yes, please specify_________

6. Do you have experience how soil conditions affect pile installation and vibrations of structures? Y N

If yes, please specify:

7. Do you have experience how distances from driven pile affect ground vibrations.

Y N

If yes, please specify:

APPENDIX B

Summary of Pile Driving Questionnaire Survey Response

State DOT Response

Questions	Response: Yes	No
1. Has your DOT had experience with vibration damage caused by pile driving operations?	28	16
1a. Has your DOT had experience with dynamic settlement caused by pile driving operations?	11	33
1b. Have you used preventive measures to decrease vibration effects of pile installation on structures?(specify if yes)	23	21
	1. Set limits on peak particle velocity (PPV), especially in sensitive areas. (Alaska DOT) 2. Set max Vibration limit, vibration monitoring specification and reduce pile capacity and type. (IDOT) 3. Issue vibration limits for structures on projects where we believe dynamic settlement to be a potential problem. (MNDOT) 4. Pre-boring prior to pile installation, set vibration limits through an independent vibration specialist and monitor adjacent structures. (NHDOT) 5. Specify low resonance pile drivers, set limits on peak particle velocity, pre-augered to a specified depth and in extremely sensitive areas, have auger cast piles or drill shafts installed in lieu of driven piles. (NJDOT) 6. Pre-drill the piles with and without casing or use drilled foundations such as micro-piles or drilled shafts. (NYSDOT) 7. Consider pre-drilling and possibly using sleeves. Reduce allowable hammer size. (PADOT) 8. Limit use of vibratory hammers, direct sequence of pile driving. (CTDOT) 9. Use drilled shaft foundation instead of driven piles. (Iowa DOT)	

	10. Drilled shaft foundations will be used rather than driven piles. Because of the possibility that the contractor will use a vibratory hammer to install and extract temporary casing for the drilled shafts, we will be performing a pre-construction survey and will be conducting a vibration monitoring program during construction of the drilled shaft foundations. (KY DOT) 11. More along the lines of monitoring versus preventive measures. (Kansas DOT) 12. When complaints arise we monitor with vibration monitors and we then make recommendations to agencies. (MSDOT) 13. Monitoring, Surveys, Drilled-in Foundations. (NCDOT) 14. Hire engineering firm to formulate guidelines and monitor program to prevent damage to lighthouse we were repairing-details. (NDDOT) 15. If structures are close to driving operations we monitor vibrations and decrease the delivered hammer energy if necessary to decrease vibrations. (UTAH) 16. Determine ground response spectrum, compute pile impedance. (Alabama DOT) 17. Small tests are done before formal installation. (MDOT) 18. Use non-displacement piles (i.e. H-piles) and/or preformed holes.(FDOT) 19. Some settlement during retrofit driving on a larger structure for seismic concerns. (TDOT) 20. Pile driving, altering design. (WISDOT)
1c. Do you have experience how soil conditions affect pile installation and vibrations of structures?(specify if yes)	14 30
	1. There are certain areas/deposits in the state that have experienced problems, generally loose sands and/or silty sands. (CTDOT) 2. During the design stage, we would recognize the potential for settlement of adjacent structures founded on loose to medium dense sands, and also the vibration effects on sensitive structures (e.g., masonry structures), if piles are used. Would either avoid pile foundations in these cases (i.e., use a drilled foundation), or would implement measures to mitigate the vibration effects (e.g., pre-boring, monitoring of the structure for vibrations, with vibration limits determined by an independent vibration specialist). (NHDOT) 3. Shallow hard layers make the vibration of the structures worse. (FDOT)

	4. Although weak soils may lead to more damage than hard soils, this conclusion must be tested under other parameters. (Michigan DOT) 5. In general, harder driving conditions are caused by harder/stiffer soils or bedrock tends to induce higher vibration levels. (UTAH DOT) 6. We review suspected sites and usually set up a monitoring program during the driving of the piling. (Kansas DOT) 7. We take samples of different site and match with pile driving vibration data.(Arkansas DOT) 8. We have vibrated and driven with impact hammers in all types of soils including cemented sands and limestone. (NDDOT) 9. Dense gravely soils and hard clayey soils tend to create more vibrations. (NJDOT) 10. Different soil types or conditions can or damping vibrations. (WISDOT) 11. Generally greater than 300 feet required to avoid damage. (NMDOT)	
1d. Do you have experience how distances from driven piles affect ground vibrations? (specify if yes)	16	26
	1. No complaints more than about **300 feet** away. No structural damage outside FDOT specification limit. Some cosmetic cracks sometimes within a couple hundred feet. (FDOT) 2. Generally greater than **300 feet** required to avoid damage. (NMDOT) 3. We typically haven't experienced damaging vibrations due to pile driving unless we've been really close to a structure (less than approximately **30 feet**). We have, however, had several vibration problems caused by steady state vibrations (vibrating rollers). (UTAH) 4. Based on the technical literature (e.g., NCHRP Synthesis 253), we would have concerns with any structures located within a radius equal to the pile length that is installed. We would also assess any sensitive structures within a larger radius to avoid claims (sensitive structures include archeological site, historical features, utilities, and structures). (NHDOT) 5. Vibrations are monitored at distance less than pile length from the driven pile. (Alabama DOT)	

	6. Vibration does disperse with distance. We typically monitor all structures within **100** to **200 feet** of the pile driving operation. (NJDOT) 7. We will require pre-drilling if a buried utility is within **25 feet** of the pile toe. (NYSDOT) 8. In general the farther away you are the less vibration. (IDOT) 9. In general, the father away from the source of the vibration, the less the effect of vibration. (WISDOT) 10. Site conditions determine the effects.(Alaska DOT) 11. We typically monitor pile driving vibrations and have data that we can use to predict future vibration events. (MNDOT)
2. Have any of incidents resulted in claims against the: *State DOT* *Contractor* *Consultant* *Other agency (specify if yes)*	14 29 11 29 7 31 1 28
	1. Generally the damage has been to our existing facilities. (CTDOT) 2. Minor cosmetic damage. (FDOT)
3. Does your state have a standard specification dealing with vibration due to pile driving operations?	23 20
	1. We have a project-specific specification for drilled shaft project where vibrations will be caused during installing and extracting temporary casing by a vibratory hammer.(KYDOT) 2. We have limited vibration levels on a site by site basis but follow USBM standard for blasting. (MSDOT) 3. We have a vibration monitoring specification that is used for all construction related vibrations that would be used for a project with potential pile driving vibration issues. This specification requires the contractor to hire an independent vibration specialist that would assess the structure in question and set allowable vibration limits. The contractor would then be required to adjust the pile driving to stay below the limits and would also monitor the vibrations at the structure during driving. For a sensitive

	structure, would set the vibration limit through the vibration specialist. (NHDOT) 4. We have a special provision that we use depending on the job, but typically we don’t include it for pile driving vibrations only. (UTAH)
If yes, does your specification limit: *peak particle displacement(specify value if yes)*	5 16
peak particle velocity(specify value if yes)	20 13
	1. 0.2 inch/second (Idaho DOT) (NYSDOT) 2. 1 inch/second(CADOT) (NJDOT) (RIDOT) 3. 2.0 inch/second, 1.0 inch/second for sensitive structures or facilities 3 inch/second (IDOT) 4. 2 inch/second (1 inch/second for historic structures) (UTAH DOT) 5. Monitor vibration within 0.25 × √(impact hammer energy, in foot-pounds). Stop driving if Peak Particle Velocity ≥ 0.5 inches/second. 6. It varies for different projects and locations. (Columbia DOT) 7. It varies from project to project but is typically 1.0 in./sec or OSM criteria. (MNDOT) 8. We have limited vibration levels on a site by site basis. But really we go by USBM standards for blasting. (MSDOT)
peak particle acceleration(specify value if yes)	4 16
4. Does your specification require a minimum monitoring coverage area?(how is this minimum monitoring range determined if yes)	14 23
	1. Pile length is major consideration. (Alabama DOT) 2. Monitor **settlement** within a distance, in feet, equal to **0.5 × times the square root of impact hammer energy, in foot-pounds.** (FDOT) 3. We always consider structures between **100 to 200 feet** of the pile driving operation to be monitored. (NJDOT) 4. Any structure within **200 feet** of pile driving location.(RIDOT) 5. Typically monitor nearby structures.(MDDOT)

	6. Typically the closest and or most critical receptor. (MNDOT) 7. No. We would assess this through the vibration specialist described above on a project by project basis.(NHDOT) 8. Contractors must perform vibration risk survey to establish limits. (NMDOT) 9. The contractor submits a plan and it is reviewed by NYSDOT it is determined on a case by case basis. (NYSDOT) 10. It would depend on different cases and different purposes of driving piles.(SDDOT)
5. Does your specification have any frequency reporting requirements?	18 25
6. Does your specification cover? *loading carrying piles* *sheet piles* *other piles(specify if yes)*	23 6 18 11 7 14
	1. They are used for either of above. (Columbia DOT) (IDOT) 2. Test piles. (RIDOT) 3. Driven piles covered under impact vibration limits. Sheet piles covered under steady-state vibration limits. (UTAH) 4. It covers blasting, hydraulic hammer, etc. ? (WISDOT)
7. Does your specification require continuous monitoring of ground motion while pile driving is on-going? or intermittent monitoring?	16 18 14 15
	1. No. Monitoring is intermittent. As driving changes representatively, samples are collected from each condition.(MSDOT) 2. Would require monitoring of the initial piles in order to assess the vibration effects. Would discontinue or reduce the amount of monitoring if the vibration is not a problem based on the initial monitoring. (NHDOT) 3. It becomes continuous when adjacent construction activities make monitoring prudent. (NYSDOT)
8. Does your specification specify location(s) where ground measurements are to be made? (If yes, how is the monitoring location(s) prescribed?)	10 27

	1. It is up to the contractor to develop the monitoring plan. (CADOT) (Kansas DOT) 2. Near building of concern. (IDOT) 3. At an exterior adjacent to the structure being monitored. (MNDOT) 4. Would be determined by the independent vibration specialist. (NHDOT) 5. No, the locations must be provided by the contractor in their comprehensive plan for vibration control and monitoring. (NJDOT) 6. Vibration risk survey determines locations for monitoring. (NMDOT) 7. If pile driving is close to buried utilities or structures that are old and have masonry foundations or plaster walls and ceilings. (NYSDOT) 8. Typically we are trying to protect a certain structure, utility, etc. So particular monitoring locations are often specified (UTAH)	
9. Does your state require a pre-driving survey of nearby structures?	30	11
If yes, does this survey include:		
Videotaping	28	6
installation of crack gages	27	8
photographing existing defects	26	4
inspection notes	23	8
other?(specify if yes)	5	14
What is pre-driving survey coverage range and how is this range determined?	1. Typically **200 feet** but is determined by predicted area where vibration levels will exceed 0.1 inch/second. (MNDOT) 2. At any structure within **200 feet** of pile driving location. (RIDOT) 3. We typically use a distance of **200 feet**, but 100 feet has also been specified. (NJDOT) 4. Usually within **100 feet** of pile driving exceptions on cases specified. (WISDOT) 5. Survey within a distance, in feet, equal to **0.25 times the square root of the impact hammer energy, in foot-pounds, before pile driving begins and again after all pile driving is completed.** (FDOT) 6. Any nearby buildings or structures.(MDDOT) 7. Survey targets on existing adjacent structures, which are monitored several days prior to driving to establish ambient baseline data then during pile driving operations. Seismographs are used on existing adjacent bridges and are monitored for 48 hours continuously prior to pile driving to establish ambient baseline data. A distinction	

	must be made in the report between vibrations caused with and without vehicular traffic. (NJDOT) 8. Generally structures that are immediately adjacent to the bridge but on occasion the building may be away from the pile driving. (NYSDOT) 9. Varies and is up to the contractor. (Kansas DOT) 10. Project specifies special provisions to perform a pre-driving survey of structures can be used on a case by case basis if damage due to pile driving operations is anticipated. (Maine DOT) 11. The range is determined on a project by project basis, based on the subsurface conditions, and the sensitivity of the adjacent structures. (NHDOT) 12. Determined on a project-by-project basis. (UTAH) 13. It depends on Vibration Risk Survey. (NMDOT) 14. Survey for historic properties only. The monitoring coverage area is determined by the vibration consultant. (Iowa DOT) 15. Only in rare instances when an existing bridge nearby is in disrepair. (TDOT)
10. May contractor do monitoring with their own personnel?	19 18
or must an independent third party be employed to do monitoring?	15 10
11. Must a state DOT inspector be present to observe all monitoring?	14 23
	1. No. But monitoring reports must be reviewed by state DOT staff. (Alaska DOT) 2. The vibration specialist must provide reports on-site on the same day and immediately if limits are exceeded. The DOT inspector is readily available when needed. (NHDOT)
12. Must a record of vibration monitoring and/or pre-driving survey be submitted to the state?(If no, who else will keep the record)	29 7
	1. No monitoring is performed for vibration or ground settlement (Colorado DOT) 2. Third Party keeps records. MDOT keeps records. (MSDOT) 3. When the contract requires vibration monitoring, the records are submitted to the state.

	(NHDOT)
13. Are there specific geological profiles or other site conditions which prevail in your state that exacerbate pile driving problems? (describe these conditions if yes)	14 30
	1. Areas with loose sand are a concern for settlement. (MNDOT) 2. Would have settlement related problems with loose sands above and below the water table (i.e., liquefaction). (NHDOT) 3. Miscellaneous unknown fills, gravel and boulders, highly congested traffic areas and highly sensitive environmental areas. (NJDOT) 4. Pre-drilling of pile is sometimes needed when large boulders are encountered in alluvial deposits or when very hard bedrock is encountered. (Colorado DOT) 5. Trying to get below liquefiable layers; presence of boulders or cavities. (TDOT) 6. Cemented soil stream deposits that have large particles prevent use of driven piles in many areas. (AZDOT) 7. If alluvial soils are encountered. (MDDOT) 8. Glacial tills, high groundwater table with fine sands and silts, urban fills. (RIDOT) 9. Saturated sand in west Tennessee subject to liquefaction due to the pile driving. A formation in East Tennessee where a sand layer is formed from weathering of sandstone and is subject to liquefaction due to pile driving. (TNDOT) 10. Sensitive environmental areas and traffic areas. (CADOT)
14. Has experience or certain local conditions led to development of any unique criteria or procedures to address pile driving vibration problems? (describe if yes)	4 38
	1. We limit use of vibratory hammers and some additional monitoring. (CTDOT) 2. No. We assess the potential for vibration issues during the design stage based on soil conditions and the proximity of adjacent structures, and the sensitivity of the adjacent structures, then design the project accordingly (i.e., avoid the use of piles, or employ vibration monitoring with limits set by the vibration specialist). (NHDOT)

	3. Widening of major highway bridges in our cities are typically founded on drilled shafts. Auger cast piles have been used in areas adjacent to historical buildings or sensitive environmental areas. Pre-auger to specified depths also has been utilized to limit vibrations. (NJDOT) 4. We have used drilled shaft with casing as an alternate foundation. (TNDOT) 5. WIS DOT will specify pre-boring in certain conditions based on our experience. (WISDOT)
15. Are your vibration monitoring database available to the public? And how these data can be obtained?	2 37
	1. We do not have a vibration monitoring database. (Arkansas DOT)(Colorado DOT) (NYSDOT) 2. I don’t think we have a database. Please see attached example vibration monitoring report and proposed new specification section which has not been implemented. (FDOT) 3. Available upon request (Idaho DOT) 4. Raw data may be included in the individual project files, no database has been created. (Iowa DOT) 5. The department does not maintain such a database. (Maine DOT) 6. The data is typically stored with the project files and would have to be compiled to be made available, which is not possible at the current time. (MNDOT) 7. No state wide database for vibration monitoring is available. Any vibration data is either stored in the project archive files, or not saved after the project is completed. (NHDOT) 8. There have been a few cases where an adjacent owner has claimed damage and worked with the contractor to address. Our specifications contain a general “protect adjacent property” clause that pertains to all construction, with nothing additional that is specific to pile driving. (TXDOT) 9. WISDOT has not centralized database of vibration records. The records for individual projects are kept with the project files. (WISDOT) 10. Our vibration monitoring project is very sketchy and thus not much information can be provided to your survey. (WSDOT)

Pile Driving Contractor Response

Questions	Response: Yes	No
1. Has your DOT had experience with vibration damage caused by pile driving operations?	16	28
1a. Has your DOT had experience with dynamic settlement caused by pile driving operations?	11	33
1b. Have you used preventive measures to decrease vibration effects of pile installation on structures?(specify if yes)	23	21
	1. Set limits on peak particle velocity (PPV), especially in sensitive areas. (Alaska DOT) 2. Set max Vibration limit, vibration monitoring specification and reduce pile capacity and type. (IDOT) 3. Issue vibration limits for structures on projects where we believe dynamic settlement to be a potential problem. (MNDOT) 4. Pre-boring prior to pile installation, set vibration limits through an independent vibration specialist and monitor adjacent structures. (NHDOT) 5. Specify low resonance pile drivers, set limits on peak particle velocity, pre-augered to a specified depth and in extremely sensitive areas, have auger cast piles or drill shafts installed in lieu of driven piles. (NJDOT) 6. Pre-drill the piles with and without casing or use drilled foundations such as micro-piles or drilled shafts. (NYSDOT) 7. Consider pre-drilling and possibly using sleeves. Reduce allowable hammer size. (PADOT) 8. Limit use of vibratory hammers, direct sequence of pile driving. (CTDOT) 9. Use drilled shaft foundation instead of driven piles. (Iowa DOT) 10. Drilled shaft foundations will be used rather than driven piles. Because of the possibility that the contractor will use a vibratory hammer to install and extract temporary casing for the drilled shafts, we will be performing a pre-construction survey and will be conducting a vibration monitoring program during construction of the drilled shaft foundations. (KY DOT)	

	11. More along the lines of monitoring versus preventive measures. (Kansas DOT) 12. When complaints arise we monitor with vibration monitors and we then make recommendations to agencies. (MSDOT) 13. Monitoring, Surveys, Drilled-in Foundations. (NCDOT) 14. Hire engineering firm to formulate guidelines and monitor program to prevent damage to lighthouse we were repairing-details. (NDDOT) 15. If structures are close to driving operations we monitor vibrations and decrease the delivered hammer energy if necessary to decrease vibrations. (UTAH) 16. Determine ground response spectrum, compute pile impedance. (Alabama DOT) 17. Small tests are done before formal installation. (MDOT) 18. Use non-displacement piles (i.e. H-piles) and/or preformed holes.(FDOT) 19. Some settlement during retrofit driving on a larger structure for seismic concerns. (TDOT) 20. Pile driving, altering design. (WISDOT)
1c. Do you have experience how soil conditions affect pile installation and vibrations of structures?(specify if yes)	14 30
	1. There are certain areas/deposits in the state that have experienced problems, generally loose sands and/or silty sands. (CTDOT) 2. During the design stage, we would recognize the potential for settlement of adjacent structures founded on loose to medium dense sands, and also the vibration effects on sensitive structures (e.g., masonry structures), if piles are used. Would either avoid pile foundations in these cases (i.e., use a drilled foundation), or would implement measures to mitigate the vibration effects (e.g., pre-boring, monitoring of the structure for vibrations, with vibration limits determined by an independent vibration specialist). (NHDOT) 3. Shallow hard layers make the vibration of the structures worse. (FDOT) 4. Although weak soils may lead to more damage than hard soils, this conclusion must be tested under other parameters. (Michigan DOT) 5. In general, harder driving conditions are caused by harder/stiffer soils or bedrock tends to induce higher vibration levels. (UTAH DOT) 6. We review suspected sites and usually set up a monitoring program during the driving

	of the piling. (Kansas DOT) 7. We take samples of different site and match with pile driving vibration data.(Arkansas DOT) 8. We have vibrated and driven with impact hammers in all types of soils including cemented sands and limestone. (NDDOT) 9. Dense gravely soils and hard clayey soils tend to create more vibrations. (NJDOT) 10. Different soil types or conditions can or damping vibrations. (WISDOT) 11. Generally greater than 300 feet required to avoid damage. (NMDOT)
1d. Do you have experience how distances from driven piles affect ground vibrations? (specify if yes)	16 26
	1. No complaints more than about **300 feet** away. No structural damage outside FDOT specification limit. Some cosmetic cracks sometimes within a couple hundred feet. (FDOT) 2. Generally greater than **300 feet** required to avoid damage. (NMDOT) 3. We typically haven’t experienced damaging vibrations due to pile driving unless we’ve been really close to a structure (less than approximately **30 feet**). We have, however, had several vibration problems caused by steady state vibrations (vibrating rollers). (UTAH) 4. Based on the technical literature (e.g., NCHRP Synthesis 253), we would have concerns with any structures located within a radius equal to the pile length that is installed. We would also assess any sensitive structures within a larger radius to avoid claims (sensitive structures include archeological site, historical features, utilities, and structures). (NHDOT) 5. Vibrations are monitored at distance less than pile length from the driven pile. (Alabama DOT) 6. Vibration does disperse with distance. We typically monitor all structures within **100** to **200 feet** of the pile driving operation. (NJDOT) 7. We will require pre-drilling if a buried utility is within **25 feet** of the pile toe. (NYSDOT) 8. In general the farther away you are the less vibration. (IDOT)

	9. In general, the father away from the source of the vibration, the less the affect of vibration. (WISDOT) 10. Site conditions determine the effects.(Alaska DOT) 11. We typically monitor pile driving vibrations and have data that we can use to predict future vibration events. (MNDOT)	
2. Have any of incidents resulted in claims against the:		
State DOT	14	29
Contractor	11	29
Consultant	7	31
Other agency (specify if yes)	1	28
	1. Generally the damage has been to our existing facilities. (CTDOT) 2. Minor cosmetic damage. (FDOT)	
3. Does your state have a standard specification dealing with vibration due to pile driving operations?	23	20
	1. We have a project-specific specification for drilled shaft project where vibrations will be caused during installing and extracting temporary casing by a vibratory hammer.(KYDOT) 2. We have limited vibration levels on a site by site basis but follow USBM standard for blasting. (MSDOT) 3. We have a vibration monitoring specification that is used for all construction related vibrations that would be used for a project with potential pile driving vibration issues. This specification requires the contractor to hire an independent vibration specialist that would assess the structure in question and set allowable vibration limits. The contractor would then be required to adjust the pile driving to stay below the limits and would also monitor the vibrations at the structure during driving. For a sensitive structure, would set the vibration limit through the vibration specialist. (NHDOT) 4. We have a special provision that we use depending on the job, but typically we don’t include it for pile driving vibrations only. (UTAH)	
If yes, does your specification limit: *peak particle displacement(specify value if yes)*	5	16

peak particle velocity(specify value if yes)	20 13
	1. 0.2 inch/second (Idaho DOT) (NYSDOT) 2. 1 inch/second (CADOT) (NJDOT) (RIDOT) 3. 2.0 inch/second, 1.0 inch/second for sensitive structures or facilities 3 inch/second (IDOT) 4. 2 inch/second (1 inch/second for historic structures) (UTAH DOT) 5. Monitor vibration within a distance, in feet, equal to 0.25 times the square root of the hammer energy, in foot-pounds. Stop driving if Peak Particle Velocity ≥ 0.5 inches/second. 6. It varies for different projects and locations. (Columbia DOT) 7. It varies from project to project but is typically 1.0 in./sec or OSM criteria. (MNDOT) 8. We have limited vibration levels on a site by site basis. But really we go by USBM standards for blasting. (MSDOT)
peak particle acceleration(specify value if yes)	4 16
4. Does your specification require a minimum monitoring coverage area?(how is this minimum monitoring range determined if yes)	14 23
	1. Pile length is major consideration. (Alabama DOT) 2. Monitor **settlement** within a distance, in feet, equal to **0.5 times the square root of impact hammer energy, in foot-pounds.** (FDOT) 3. We always consider structures between **100 to 200 feet** of the pile driving operation to be monitored. (NJDOT) 4. Any structure within **200 feet** of pile driving location.(RIDOT) 5. Typically monitor nearby structures.(MDDOT) 6. Typically the closest and or most critical receptor. (MNDOT) 7. No. We would assess this through the vibration specialist described above on a project by project basis.(NHDOT) 8. Contractors must perform vibration risk survey to establish limits. (NMDOT) 9. The contractor submits a plan and it is reviewed by NYSDOT it is determined on a

	case by case basis. (NYSDOT) 10. It would depend on different cases and different purposes of driving piles.(SDDOT)
5. Does your specification have any frequency reporting requirements?	18 25
6. Does your specification cover? *loading carrying piles* *sheet piles* *other piles(specify if yes)*	23 6 18 11 7 14
	1. They are used for either of above. (Columbia DOT) (IDOT) 2. Test piles. (RIDOT) 3. Driven piles covered under impact vibration limits. Sheet piles covered under steady-state vibration limits. (UTAH) 4. It covers blasting, hydraulic hammer, etc. ? (WISDOT)
7. Does your specification require continuous monitoring of ground motion while pile driving is on-going? or intermittent monitoring?	16 18 14 15
	1. No. Monitoring is intermittent. As driving changes representatively, samples are collected from each condition.(MSDOT) 2. Would require monitoring of the initial piles in order to assess the vibration effects. Would discontinue or reduce the amount of monitoring if the vibration is not a problem based on the initial monitoring. (NHDOT) 3. It becomes continuous when adjacent construction activities make monitoring prudent. (NYSDOT)
8. Does your specification specify location(s) where ground measurements are to be made? (If yes, how is the monitoring location(s) prescribed?)	10 27
	1. It is up to the contractor to develop the monitoring plan. (CADOT) (Kansas DOT) 2. Near building of concern. (IDOT) 3. At an exterior adjacent to the structure being monitored. (MNDOT) 4. Would be determined by the independent vibration specialist. (NHDOT)

	5. No, the locations must be provided by the contractor in their comprehensive plan for vibration control and monitoring. (NJDOT) 6. Vibration risk survey determines locations for monitoring. (NMDOT) 7. If pile driving is close to buried utilities or structures that are old and have masonry foundations or plaster walls and ceilings. (NYSDOT) 8. Typically we are trying to protect a certain structure, utility, etc. So particular monitoring locations are often specified (UTAH)
9. Does your state require a pre-driving survey of nearby structures?	30 11
If yes, does this survey include: *Videotaping* *installation of crack gages* *photographing existing defects* *inspection notes* *other?(specify if yes)*	 28 6 27 8 26 4 23 8 5 14
What is pre-driving survey coverage range and how is this range determined?	1. Typically **200 feet** but is determined by predicted area where vibration levels will exceed 0.1 inch/second. (MNDOT) 2. At any structure within **200 feet** of pile driving location. (RIDOT) 3. We typically use a distance of **200 feet**, but 100 feet has also been specified. (NJDOT) 4. Usually within **100 feet** of pile driving exceptions on cases specified. (WISDOT) 5. Survey within a distance, in feet, equal to **0.25 times the square root of the impact hammer energy, in foot-pounds, before pile driving begins and again after all pile driving is completed.** (FDOT) 6. Any nearby buildings or structures.(MDDOT) 7. Survey targets on existing adjacent structures, which are monitored several days prior to driving to establish ambient baseline data then during pile driving operations. Seismographs are used on existing adjacent bridges and are monitored for 48 hours continuously prior to pile driving to establish ambient baseline data. A distinction must be made in the report between vibrations caused with and without vehicular traffic. (NJDOT) 8. Generally structures that are immediately adjacent to the bridge but on occasion the building may be away from the pile driving. (NYSDOT)

	9. Varies and is up to the contractor. (Kansas DOT) 10. Project specifies special provisions to perform a pre-driving survey of structures can be used on a case by case basis if damage due to pile driving operations is anticipated. (Maine DOT) 11. The range is determined on a project by project basis, based on the subsurface conditions, and the sensitivity of the adjacent structures. (NHDOT) 12. Determined on a project-by-project basis. (UTAH) 13. It depends on Vibration Risk Survey. (NMDOT) 14. Survey for historic properties only. The monitoring coverage area is determined by the vibration consultant. (Iowa DOT) 15. Only in rare instances when an existing bridge nearby is in disrepair. (TDOT)
10. May contractor do monitoring with their own personnel?	19 18
or must an independent third party be employed to do monitoring?	15 10
11. Must a state DOT inspector be present to observe all monitoring?	14 23
	1. No. But monitoring reports must be reviewed by state DOT staff. (Alaska DOT) 2. The vibration specialist must provide reports on-site on the same day and immediately if limits are exceeded. The DOT inspector is readily available when needed. (NHDOT)
12. Must a record of vibration monitoring and/or pre-driving survey be submitted to the state?(If no, who else will keep the record)	29 7
	1. No monitoring is performed for vibration or ground settlement (Colorado DOT) 2. Third Party keeps records. MDOT keeps records. (MSDOT) 3. When the contract requires vibration monitoring, the records are submitted to the state. (NHDOT)
13. Are there specific geological profiles or other site conditions which prevail in your state that exacerbate pile driving	14 30

problems? (describe these conditions if yes)	
	1. Areas with loose sand are a concern for settlement. (MNDOT) 2. Would have settlement related problems with loose sands above and below the water table (i.e., liquefaction). (NHDOT) 3. Miscellaneous unknown fills, gravel and boulders, highly congested traffic areas and highly sensitive environmental areas. (NJDOT) 4. Pre-drilling of pile is sometimes needed when large boulders are encountered in alluvial deposits or when very hard bedrock is encountered. (Colorado DOT) 5. Trying to get below liquefiable layers; presence of boulders or cavities. (TDOT) 6. Cemented soil stream deposits that have large particles prevent use of driven piles in many areas. (AZDOT) 7. If alluvial soils are encountered. (MDDOT) 8. Glacial tills, high groundwater table with fine sands and silts, urban fills. (RIDOT) 9. Saturated sand in west Tennessee subject to liquefaction due to the pile driving. A formation in East Tennessee where a sand layer is formed from weathering of sandstone and is subject to liquefaction due to pile driving. (TNDOT) 10. Sensitive environmental areas and traffic areas. (CADOT)
14. Has experience or certain local conditions led to development of any unique criteria or procedures to address pile driving vibration problems? (describe if yes)	4 38
	1. We limit use of vibratory hammers and some additional monitoring. (CTDOT) 2. No. We assess the potential for vibration issues during the design stage based on soil conditions and the proximity of adjacent structures, and the sensitivity of the adjacent structures, then design the project accordingly (i.e., avoid the use of piles, or employ vibration monitoring with limits set by the vibration specialist). (NHDOT) 3. Widening of major highway bridges in our cities are typically founded on drilled shafts. Auger cast piles have been used in areas adjacent to historical buildings or sensitive environmental areas. Pre-auger to specified depths also has been utilized to limit vibrations. (NJDOT)

	4. We have used drilled shaft with casing as an alternate foundation. (TNDOT) 5. WIS DOT will specify pre-boring in certain conditions based on our experience. (WISDOT)
15. Are your vibration monitoring database available to the public? And how these data can be obtained?	2 37
	1. We do not have a vibration monitoring database. (Arkansas DOT)(Colorado DOT)(NYSDOT) 2. I don’t think we have a database. Please see attached example vibration monitoring report and proposed new specification section which has not been implemented. (FDOT) 3. Available upon request (Idaho DOT) 4. Raw data may be included in the individual project files, no database has been created. (Iowa DOT) 5. The department does not maintain such a database. (Maine DOT) 6. The data is typically stored with the project files and would have to be compiled to be made available, which is not possible at the current time. (MNDOT) 7. No state wide database for vibration monitoring is available. Any vibration data is either stored in the project archive files, or not saved after the project is completed. (NHDOT) 8. There have been a few cases where an adjacent owner has claimed damage and worked with the contractor to address. Our specifications contain a general “protect adjacent property” clause that pertains to all construction, with nothing additional that is specific to pile driving. (TXDOT) 9. WISDOT has not centralized database of vibration records. The records for individual projects are kept with the project files. (WISDOT) 10. Our vibration monitoring project is very sketchy and thus not much information can be provided to your survey. (WSDOT)

Engineering Consultant Response

Questions	Response: Yes	No
1. In cases where you have measured vibrations during pile driving, what is the procedure used to determine monitoring coverage area?	1. Either by specification or if not specified, 300 feet around the outside of the building footprint or other structure or abutment. (Herbert F. Darling, Inc.)It's either determined by client or by specific cases.(Oklahoma Bridge Company Inc) 2. Vibration specialist would assess the structure in question and set allowable vibration limits, then monitor before and during the pile driving is required to make sure stay below the limits. (Independent Pipe & Steel Inc) 3. Pile load tests, vibration-monitoring using three-component seismographs, monitoring of the existing cracks with crack gages, and field surveys to monitor settlements of the nearby structures were performed during the pile driving operation. Monitoring coverage area is determined based on these information obtained.(Resonance Technology International) 4. Seismographs are placed directly between pile driving and closest structures. (Sauls Seismic) 5. The closest or the most critical receptor is the most concern for the procedure. (TECNAC)	
2. What kind of information is generally collected during pile driving monitoring?		
Peak particle velocity or other vibration parameters	9	
Driving hammer information (hammer weight, drop height, rated energy)	5	4
Soil information (soil profile, in-situ testing results)	6	3
Information of surrounding structures or buildings	5	4

3. Do you obtain vibrations from which frequency data can also be extracted: *Always* *Only when specified* *Never*	5 3 1
What vibration limits do you use in your practice?	1. USBM RI850 7, 1980. (Herbert F. Darling, Inc.) 2. USBN RI 8507 unless otherwise specified. (Sauls Seismic)
4. Have you ever used any of the following engineering measures to mitigate pile-driving induced vibrations? *Use non-displacement pile*	6 1
Use Jetting or predrilling	7 2
Change pile spacing	4 4
Use appropriate sequence of driving	5 3
Other	1. Pre-excavation of sheeting line to final excavation limit and replace excavated materials. (Herbert F. Darling, Inc.) 2. Holes are drilled and piling is set in “lean mix ” concrete. (Sauls Seismic)
5. For pile driving projects conducted by your firm, is a pre-driving condition survey generally performed? If yes, what is pre-driving survey coverage range and how is the survey coverage range determined?	7 2
	1. Not specified, only when it is called for and paid for, or when observation of exist structures make it mandatory. (Herbert F. Darling, Inc.) 2. Different for different projects and specifications (Laquila Group) 3. First row of facing structure by 100 feet.(Oklahoma Bridge Company Inc) 4. Pile load tests, vibration-monitoring using three-component seismographs, monitoring of the existing cracks with crack gages, and field surveys to monitor settlements of the nearby structures were performed during the pile driving operation. Monitoring coverage area is determined based on these information obtained.(Resonance Technology International)

	5. Coverage radius is specified , applicable buildings are determined by GPS, tape , range finder and or Google Earth. (Sauls Seismic) 6. Generally structures that are immediately adjacent to the driving location. (TECNAC)
And does this survey include: *Videotaping*	7 1
Installation of crack gages	5 3
Photographing existing defects	6 2
Inspection notes	5 3
Others	
6. Do you have experience how soil conditions affect pile installation and vibrations of structures? If yes, please specify.	5 4
	1. There are numerous cases on this topic which all follow the general rules.(A Gate Construction Co, Inc) 2. Loose sand is a major problem in most cases.(Oklahoma Bridge Company Inc) 3. A monitoring program is usually set up for this topic.(Resonance Technology International) 4. Usually wet conditions can cause higher readings. (Sauls Seismic)
7. Do you have experience how distances from driven pile affect ground vibrations. If yes, please specify:	4 4
	1. In general the farther away you are the less vibration.(Independent Pipe& Steel Inc) 2. The effect may decrease as the driving site distance increases. (Resonance Technology International) 3. Pile driving vibration dissipate rather quickly relative to distance.(Sauls Seismic)

APPENDIX C

Summary of the Pile Driving Projects under Investigation

Measured Ground Vibration Data from the Pile Driving Projects

Table 15
Measured ground vibration data from the pile driving projects

Project	Scaled Distance $(\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}})$	Peak Particle Velocity (in/s)
Millerville Road over Honey Cut Bayou Project (State Project #: 742-06-0043)	0.34	0.19
	0.75	0.07
	0.69	0.13
	1.24	0.03
	1.37	0.02
	1.03	0.05
	0.41	0.13
	0.34	0.14
	0.96	0.06
	0.93	0.07
	0.72	0.12
	0.79	0.14
	0.79	0.11
	0.72	0.16
Bayou Plaquemine Bridge Replacement Project (State Project #: 057-03-0039)	1.70	0.06
	1.16	0.10
	1.14	0.10
The Rigolets Pass Bridge Project (State Project #: 006-05-0076)	1.28	0.07
	0.73	0.13
Bayou Degleises Channel Bridge Project (State Project #: 052-05-0048)	0.66	0.36
	0.66	0.37
	0.51	0.22
	0.51	0.31
Causeway Boulevard Interchange Project	0.18	0.34

Project	Scaled Distance $(\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}})$	Peak Particle Velocity (in/s)
(State Project #:450-15-0103)	0.36	0.26
	0.16	0.44
	0.31	1.06
Causeway Boulevard Interchange Project (State Project #:450-15-0103)	0.16	0.24
	0.31	0.42
	0.16	0.04
	0.33	0.05
Tickfaw River Bridge Near Starns Project (State Project #: 270-02-0018 & 269-02-0010)	0.16	0.99
	0.32	0.64
Amite River Relief Bridge Project (State Project #:260-01-0020)	0.42	0.34
	0.21	0.52
I49 North (U.S. 71 (South) to LA2) Project (State Project #: 455-09-0007)	0.26	0.59
	0.13	0.73
	0.26	0.48
	0.13	0.84
Milly Canal Bridge Replacement Project (State Project #: 824-02-0014)	0.31	0.53
	0.15	1.65
Huey P. Long Bridge Widening Project (State Project # 006-01-0022)	2.67	0.12
	2.20	0.05
	0.71	0.18
	1.96	0.09
	1.45	0.19
	1.49	0.12
	2.67	0.04
	3.45	0.22
	3.14	0.03
	2.35	0.04
	2.35	0.04
	3.14	0.18
	0.75	0.04
	2.24	0.04
	2.24	0.10
	0.75	0.02
	2.24	0.05
	2.24	0.18
	0.75	0.03
	2.24	0.04
	2.24	0.20
	0.71	0.08

Project	Scaled Distance $(\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}})$	Peak Particle Velocity (in/s)
	2.20	0.04
	2.35	0.02
	0.71	0.05
Huey P. Long Bridge Widening Project (State Project # 006-01-0022)	3.14	0.06
	2.27	0.05
	0.71	0.10
	2.35	0.05
	3.14	0.04
	3.14	0.06
	0.71	0.05
	2.31	0.05
	0.67	0.04
	2.35	0.02
	3.14	0.03
	3.14	0.04
	2.35	0.05
	0.71	0.14
	2.20	0.08
	2.20	0.04
	0.71	0.02
	2.35	0.03
	3.14	0.04
	3.14	0.04
	2.35	0.04
	0.71	0.02
	2.20	0.04
	2.35	0.02
	2.35	0.04
	2.20	0.04
	0.71	0.18
	0.71	0.12
	2.20	0.05
	3.14	0.04
	2.35	0.05
	2.35	0.02
	2.2	0.04
	0.71	0.03
	2.20	0.04
	3.14	0.04

Project	Scaled Distance $(\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}})$	Peak Particle Velocity (in/s)
	2.35	0.03
	0.63	0.02
	0.63	0.14
Huey P. Long Bridge Widening Project (State Project # 006-01-0022)	2.27	0.04
	3.14	0.04
	2.35	0.04
	2.35	0.03
	0.63	0.03
	0.63	0.16
	2.35	0.03
	2.35	0.03
	0.63	0.12
	0.63	0.17
	2.35	0.03
	3.14	0.03
	3.14	0.07
	2.27	0.05
	0.63	0.18
	0.63	0.16
	2.27	0.07
	3.14	0.04
	2.35	0.03
	2.35	0.03
	3.14	0.03
	2.27	0.04
	0.63	0.06
	0.63	0.15
	2.27	0.03
	3.14	0.04
	2.35	0.05
	2.35	0.04
	2.27	0.05
	0.63	0.05
	2.27	0.04
	3.14	0.03
	2.35	0.03
	2.35	0.04
	3.14	0.04
	2.27	0.04

Project	Scaled Distance $(\mathrm{ft}/\sqrt{\mathrm{ft-lb}})$	Peak Particle Velocity (in/s)
	0.63	0.03
	0.63	0.3
	2.27	0.04
Huey P. Long Bridge Widening Project (State Project # 006-01-0022)	3.14	0.04
	2.35	0.03
	2.35	0.02
	3.14	0.04
	0.55	0.12
	0.55	0.17
	2.35	0.03
	3.14	0.04
	0.55	0.25
	0.55	0.08
	2.35	0.05
	3.14	0.04
	3.14	0.08
	2.35	0.04
	0.55	0.11
	3.14	0.05
	2.35	0.05
	0.55	0.25
	0.55	0.23
	2.35	0.07
	3.14	0.05
	3.14	0.11
	2.35	0.08
	0.55	0.13
	0.55	0.24
	2.35	0.04
	3.14	0.03
	3.14	0.07
	2.35	0.04
	0.55	0.31
	0.55	0.13
	3.14	0.07
	3.14	0.04
	2.35	0.05
	0.55	0.11
	0.55	0.12

Project	Scaled Distance $(\mathrm{ft}/\sqrt{\mathrm{ft}-\mathrm{lb}})$	Peak Particle Velocity (in/s)
	2.35	0.06
	3.14	0.06
	2.35	0.04
Huey P. Long Bridge Widening Project (State Project # 006-01-0022)	3.14	0.04
	0.55	0.23
	0.86	0.20
	2.35	0.04
	0.86	0.08

Huey P. Long Bridge Widening Project (State Project # 006-01-0022)

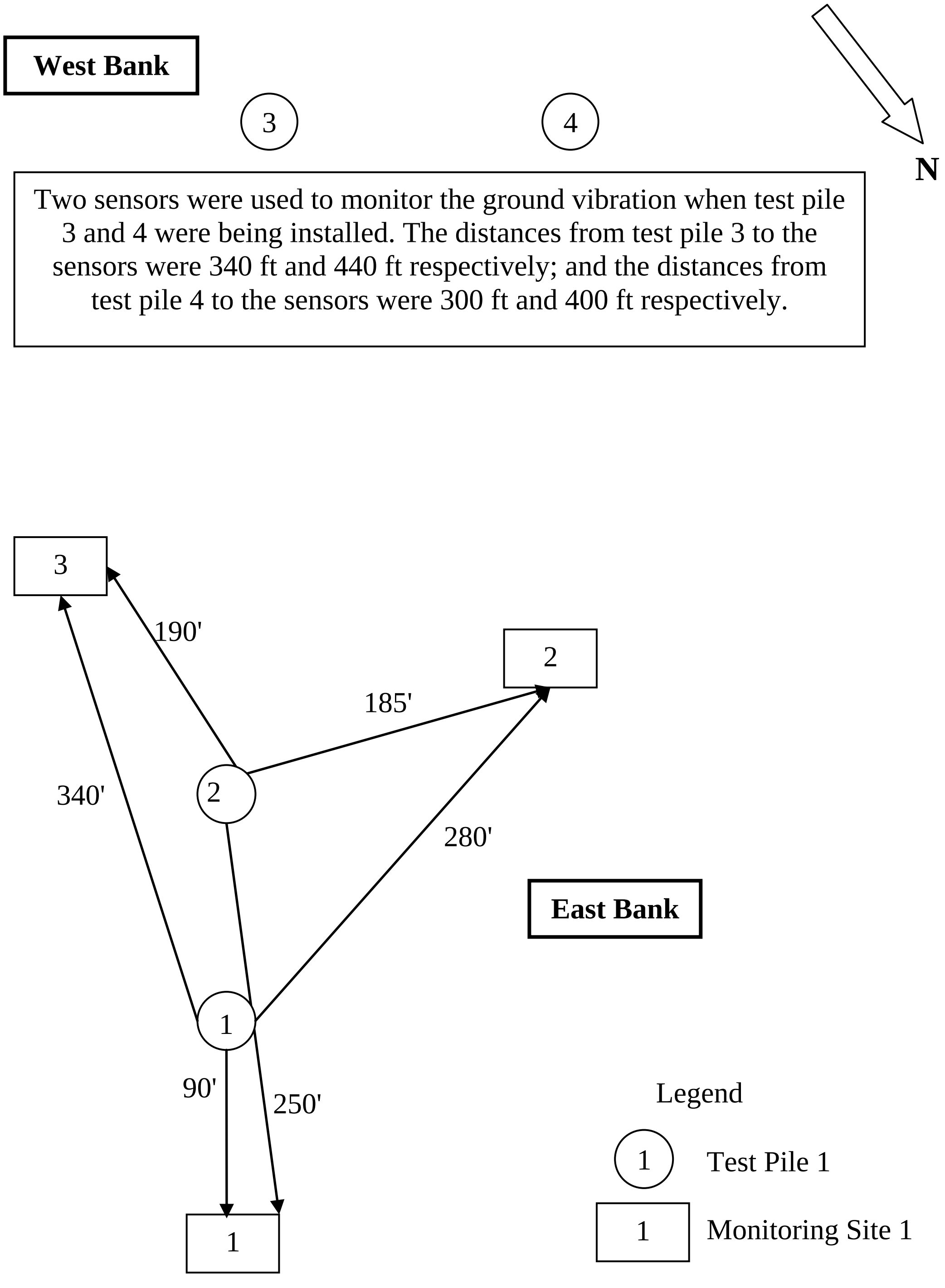
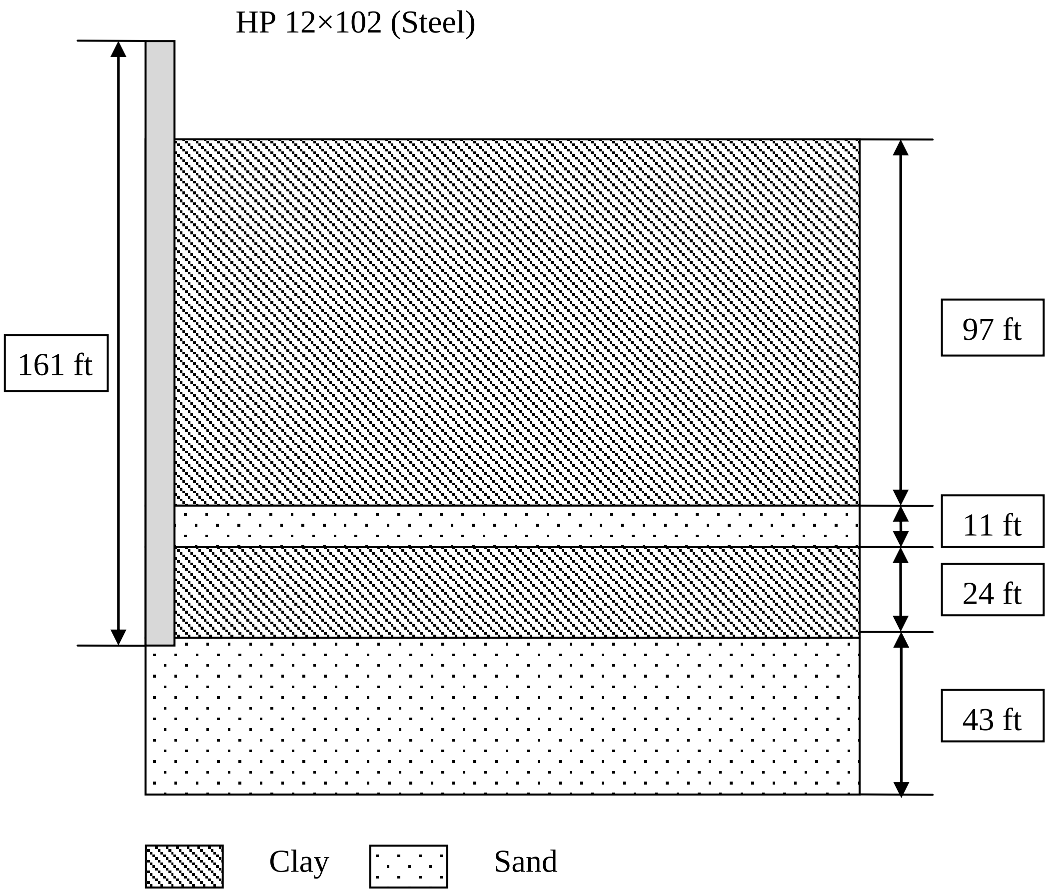
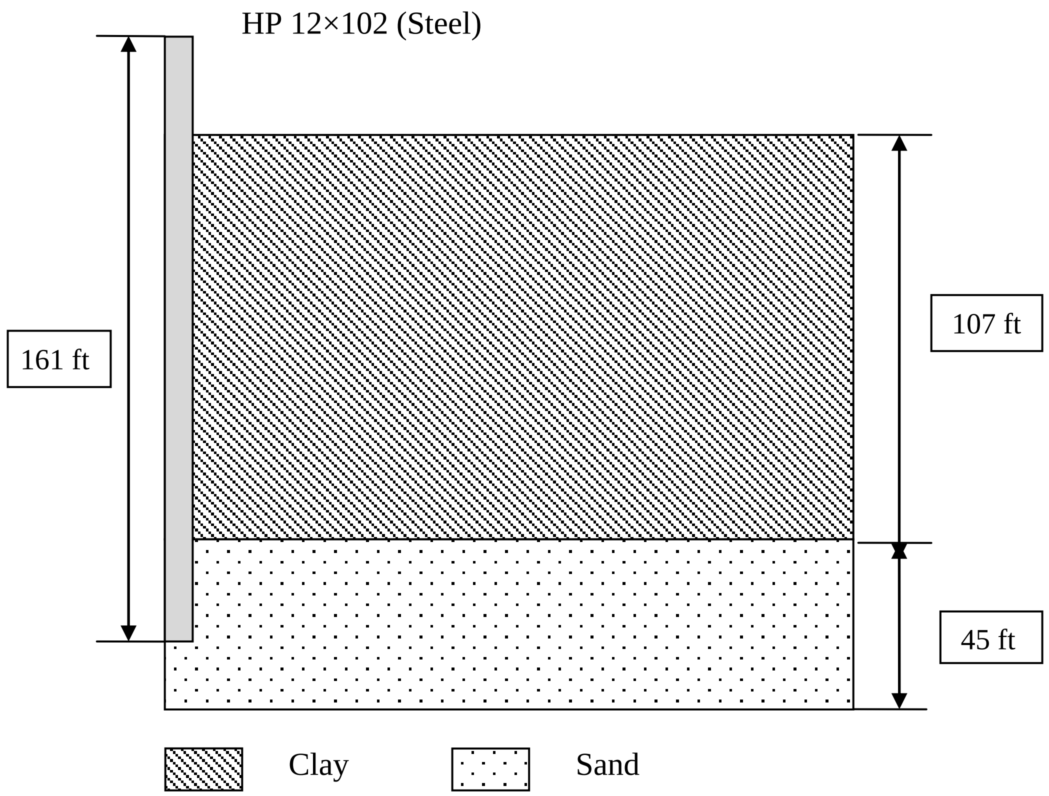

Two sensors were used to monitor the ground vibration when test pile 3 and 4 were being installed. The distances from test pile 3 to the sensors were 340 ft and 440 ft respectively; and the distances from test pile 4 to the sensors were 300 ft and 400 ft respectively.

Figure 26
Schematic plan view of pile driving monitoring sites at Huey P. Long Bridge widening project



(a)



(b)

Figure 27

Soil profiles of Huey P. Long Bridge widening project, for (a) test pile 1 & 2; and (b) test pile 3 & 4

Millerville Road over Honey Cut Bayou Project (State Project #: 742-06-0043)

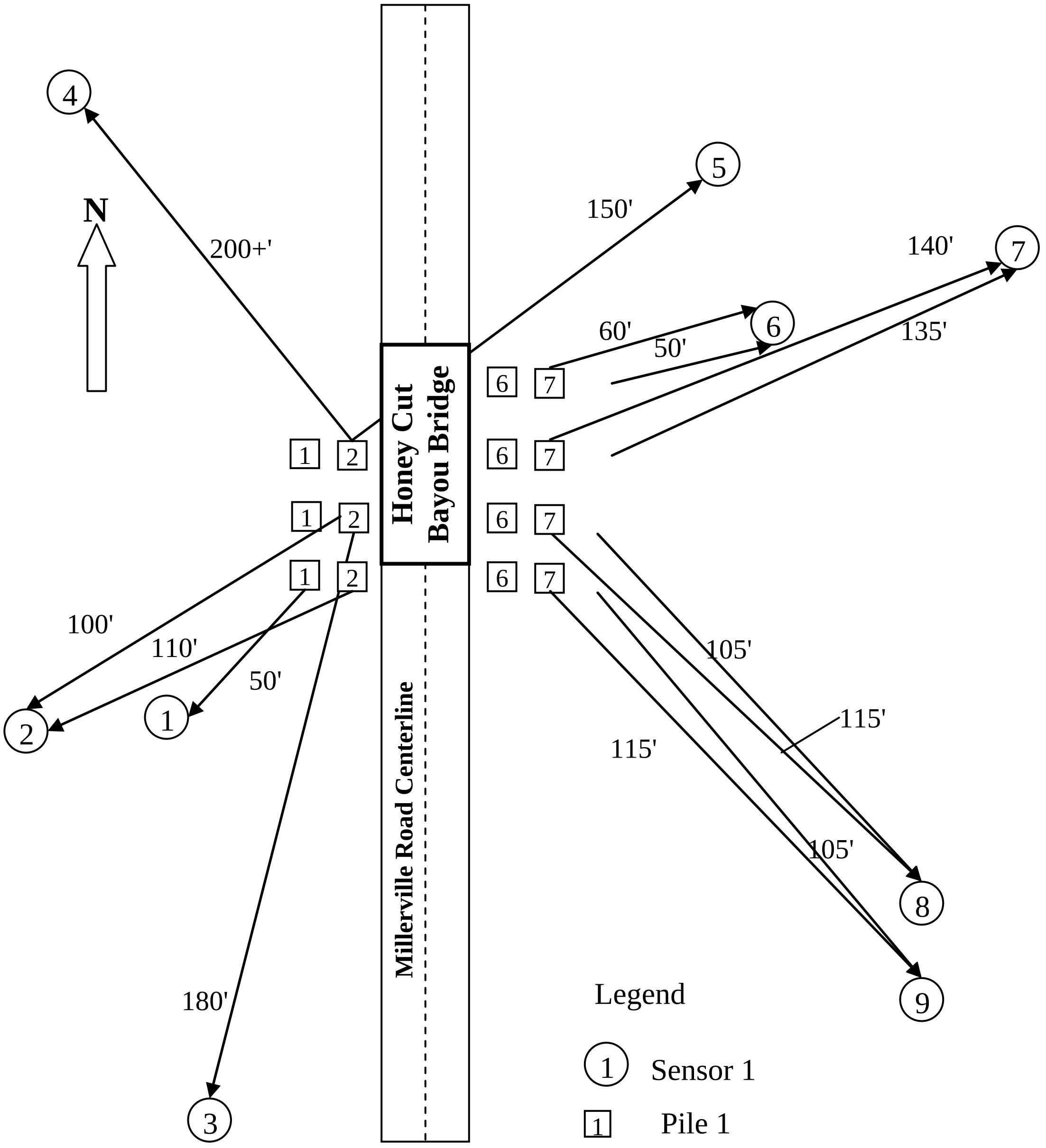
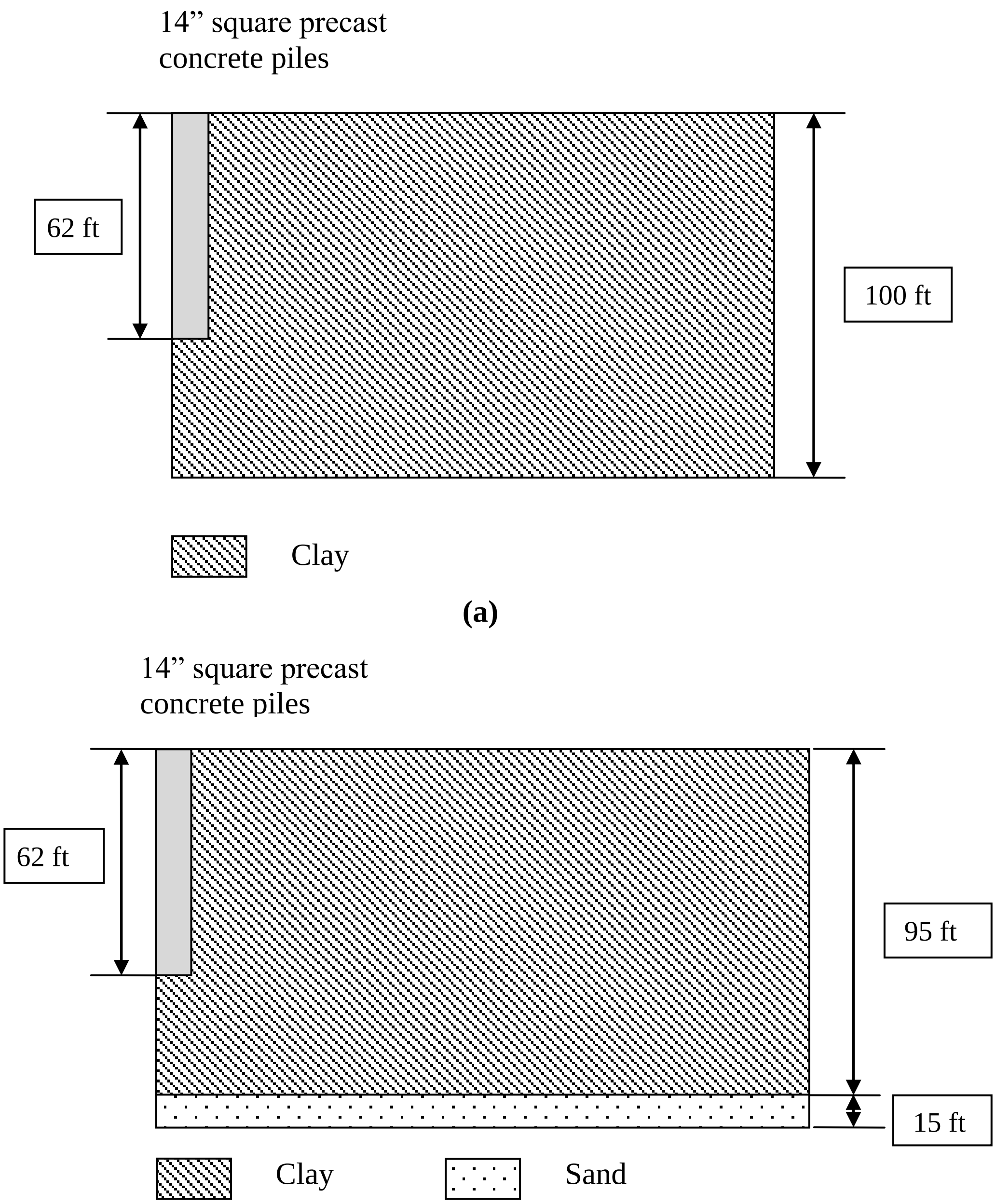


Figure 28

Schematic pile driving plan view of Millerville Road over Honey Cut Bayou project



(a)

(b)

Figure 29

Soil profiles of Millerville Road over Honey Cut Bayou project for (a) test pile 6 & 7; and (b) test pile 1 & 2

Bayou Plaquemine Bridge Replacement Project (State Project #: 057-03-0039)

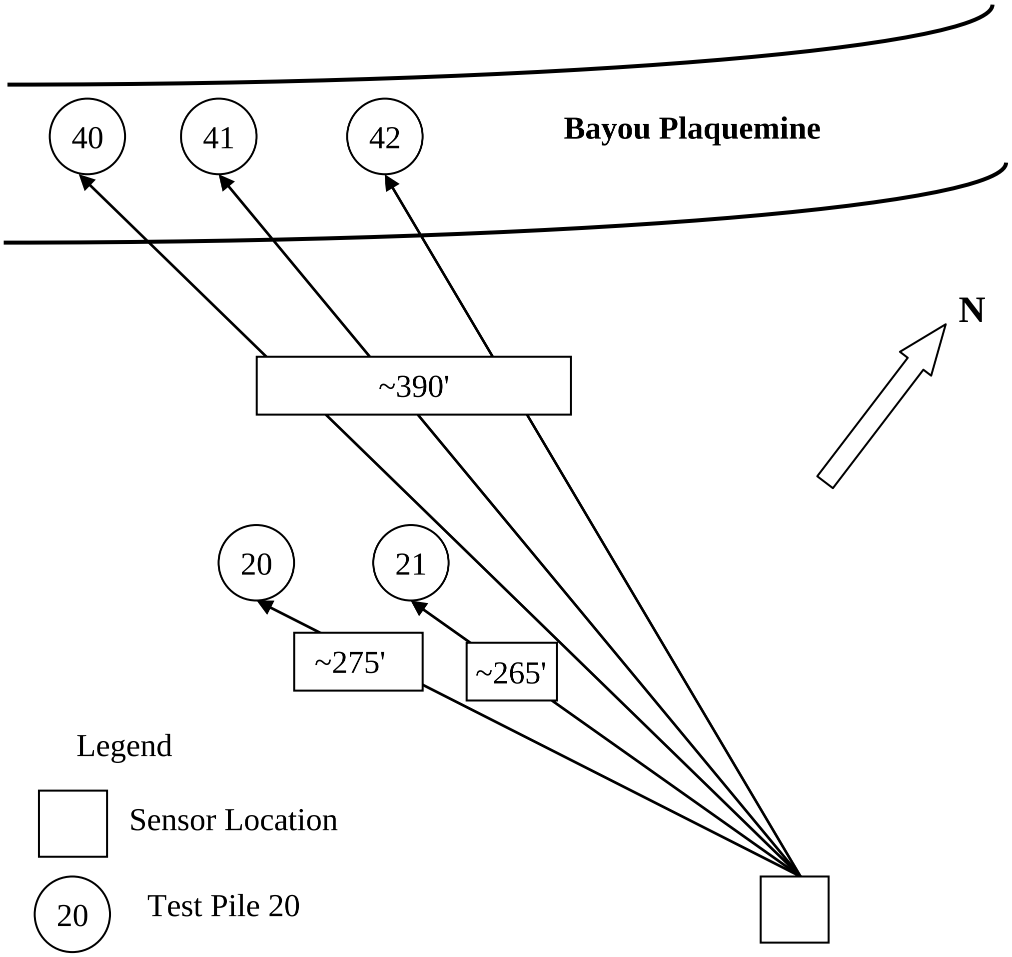
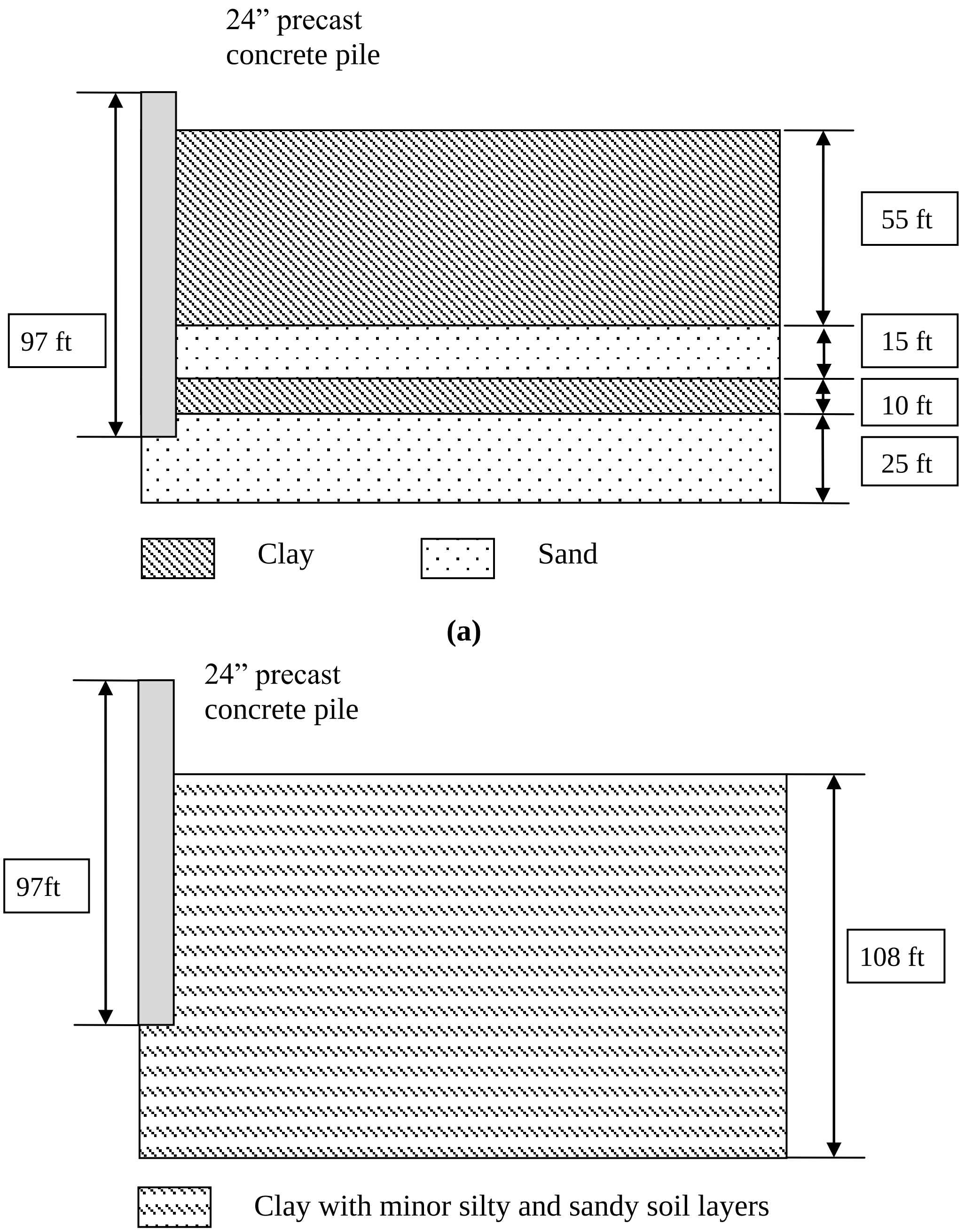


Figure 30
Schematic pile driving plan view of Bayou Plaquemine Bridge Replacement project



(a)

(b)

Figure 31

Soil profiles of Bayou Plaquemine Bridge replacement project for (a) test pile 40, 41 & 42; and (b) test pile 20 & 21

The Rigolets Pass Bridge Project (State Project #: 006-05-0076)

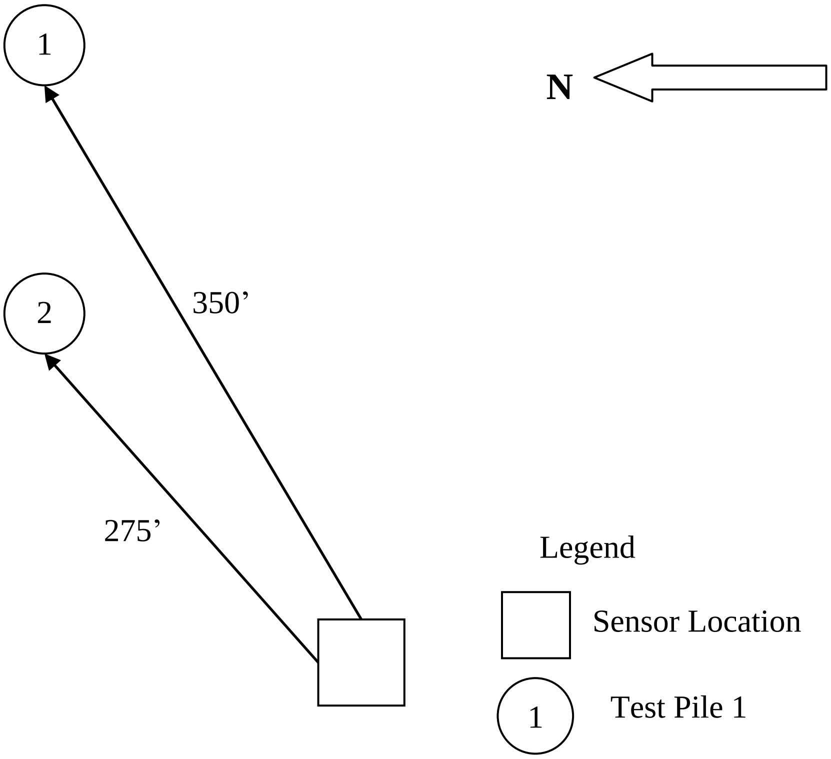
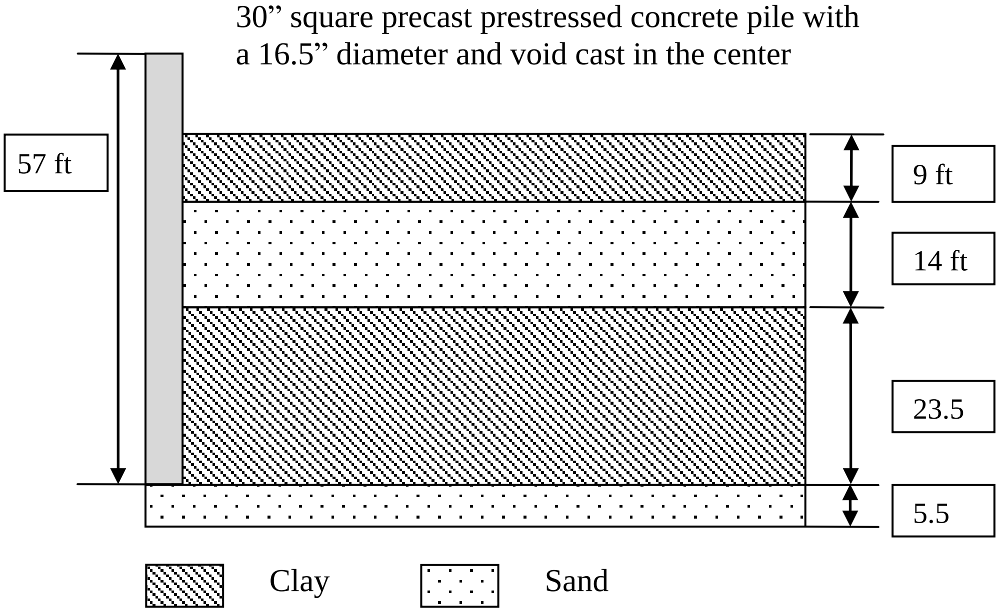
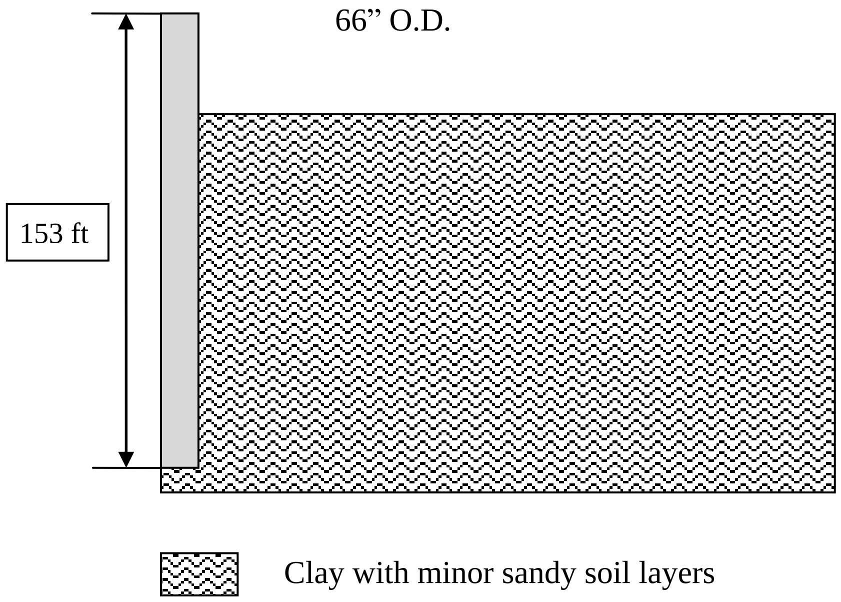


Figure 32
Schematic pile driving plan view of Rigolets Pass Bridge project



(a)



(b)

Figure 33

Soil profiles of Rigolets Pass Bridge project for (a) test pile 1; and (b) test pile 2

Bayou Degleises Channel Bridge Project (State Project #: 052-05-0048)

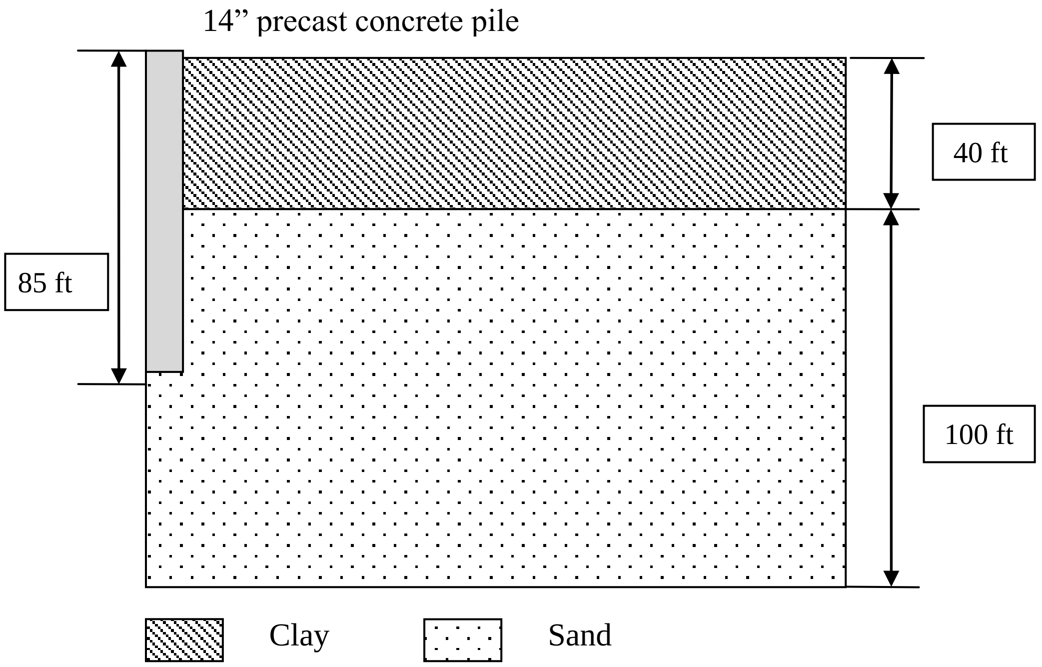


Figure 34

Soil profiles of Bayou Degleises Channel Bridge project

Causeway Boulevard Interchange Project (State Project #:450-15-0103)

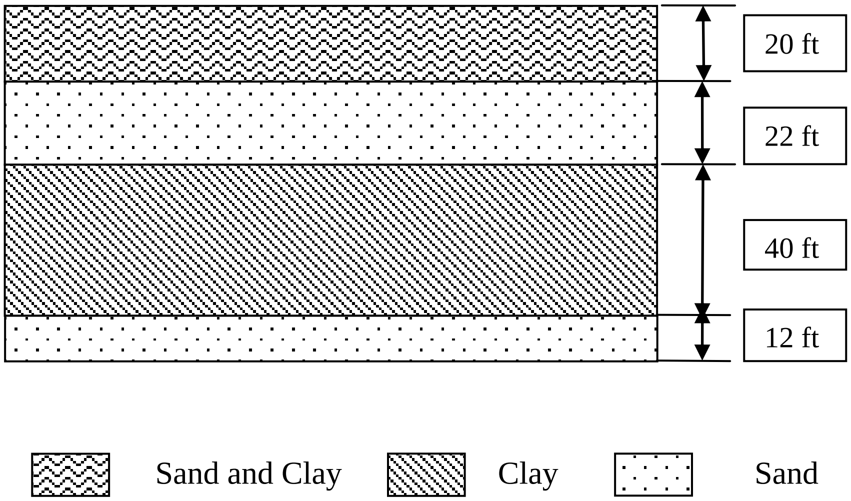


Figure 35
Soil profiles of Causeway Boulevard Interchange project

Tickfaw River Bridge near Starns Project (State Project #: 270-02-0018 & 269-02-0010)

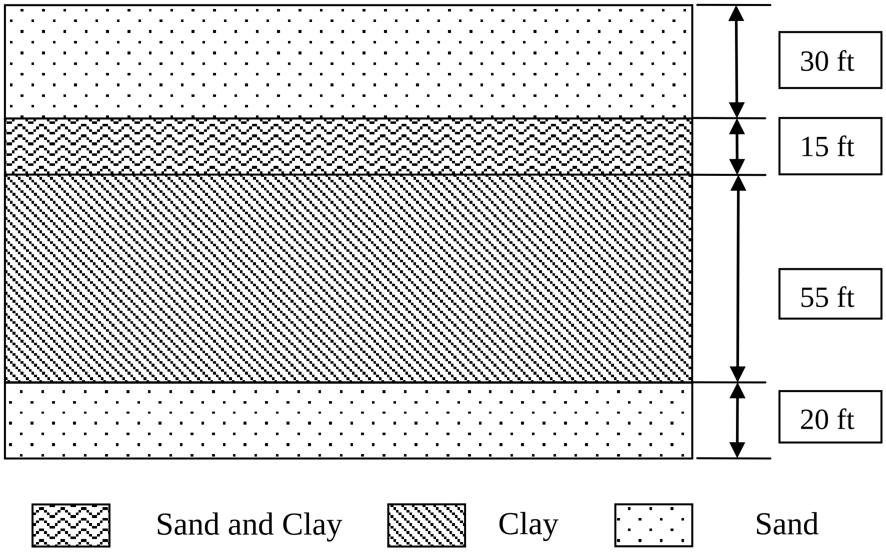


Figure 36
Soil profiles of Tickfaw River Bridge near starns project

Amite River Relief Bridge Project (State Project #:260-01-0020)

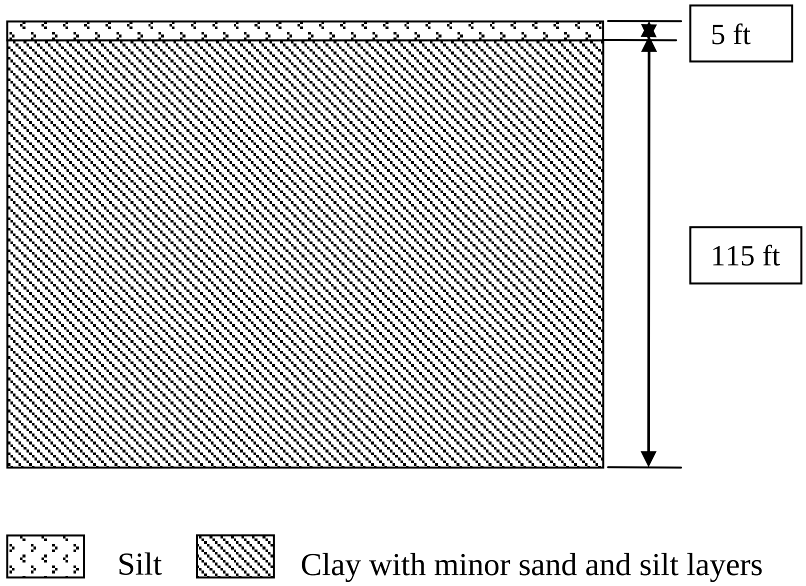


Figure 37

Soil profiles of Amite River Relief Bridge project

I49 North [U.S. 71 (South) to LA2] Project (State Project #: 455-09-0007)

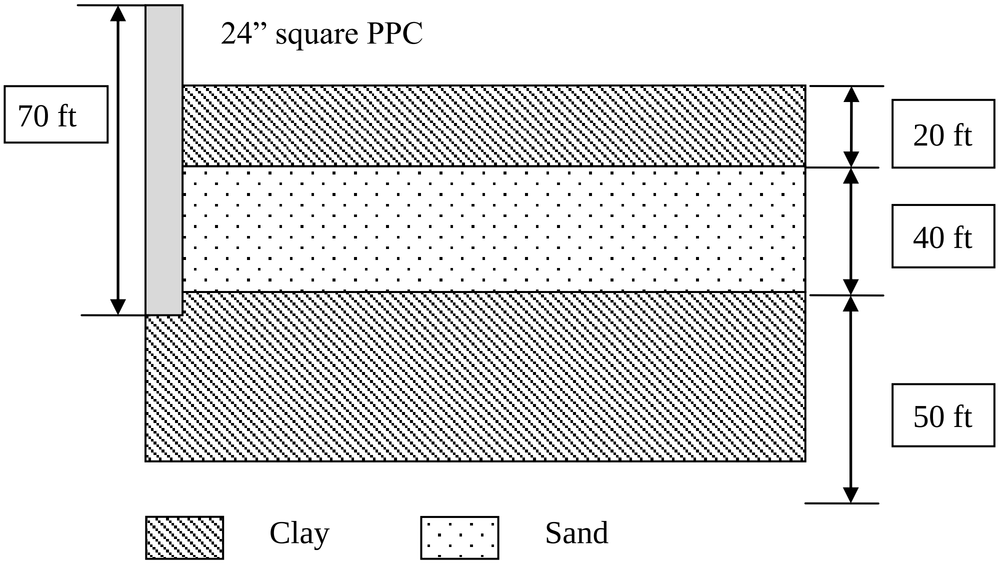


Figure 38
Soil profiles of I49 north [U.S. 71 (south) to LA2] project

Milly Canal Bridge Replacement Project (State Project #: 824-02-0014)

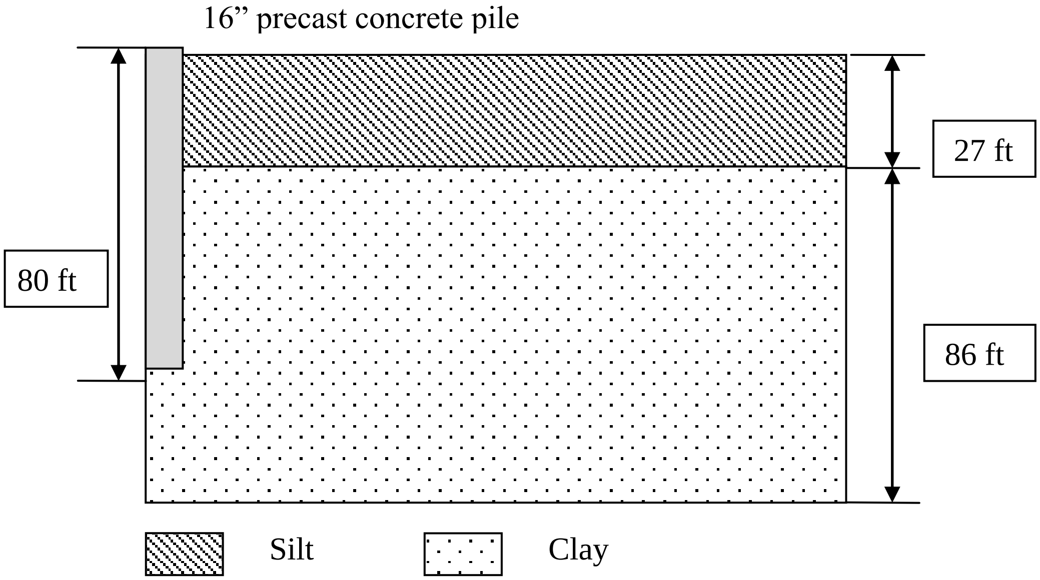


Figure 39
Soil profile of Milly Canal Bridge replacement project

APPENDIX D

MATLAB Code for Performing Nonlinear Regression Analyses

```
function prediction
Raw_Data=xlsread('R:\MATLAB\Database of Regression Analysis.xlsx','Converted');
x=Raw_Data(:,1);
y=Raw_Data(:,2);
beta0=0.0008;
[beta,R,J,COVB,MSE]=nlinfit(x,y,@myfun,beta0);
[y_pre99,deltap99]=nlpredci(@myfun,x,beta,R,'jacobian',J,'predopt','observation','simopt','on'
,'alpha',0.01);
[y_con99,deltac99]=nlpredci(@myfun,x,beta,R,'jacobian',J,'alpha',0.01);

y_cupper99=y_con99+deltac99;
y_clower99=y_con99-deltac99;

y_pupper99=y_pre99+deltap99;
y_plower99=y_pre99-deltap99;
plot(x,y,'o');
hold on;
plot(x,y_cupper99,'r*');
hold on;
plot(x,y_pupper99,'g*')
beta_pu=nlinfit(x,y_pupper99,@myfun,beta)
beta_pl=nlinfit(x,y_plower99,@myfun,beta)
beta_cu=nlinfit(x,y_cupper99,@myfun,beta)
beta_cl=nlinfit(x,y_clower99,@myfun,beta)


function yhat=myfun(beta,x,y)
yhat=beta*x.^(-1);
```

APPENDIX E

A Proposed Specification Framework for Louisiana Department of Transportation and Development Pile Driving Vibration Risk Management

A) General Provisions

This specification is intended to establish controls for pile driving 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.

Public awareness-The contractor shall contact via written communications or personal contact residents, institutional operators, and business establishments that are within the specified area. This contact shall be made prior to the beginning of any pile driving activity. The contractor shall furnish the LADOTD project 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 project engineer.

Permanent displacement-A line (location) and grade (elevation) survey shall be performed by a surveyor licensed by the state in which the construction occurs. It will establish control and guideline to detect movements along the exterior faces of the buildings. This survey shall be done on all buildings within a 200-ft. radius of the construction site. Reports shall be delivered monthly to both engineer and contractor. All control lines and grades shall reference existing benchmarks, which shall be established far enough from the construction site to be preserved for all surveys. Reference points shall be at a distance greater than 750 ft. from the site, so they are well beyond the reach of pile driving operations.

Tilting of the nearest walls of structures will be established by measurement with a portable tilt-meter. 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.

B) Preconstruction Survey

The objective of pre-construction survey is to determine the buildings' susceptibility to disruption from pile driving vibrations. Disruption includes impact on sensitive equipment and operations as well as cosmetic cracking and effects on the surrounding geological and/or geotechnical materials. The results obtained from the preconstruction survey will help the engineer confirm the adequacy of construction survey area and vibration monitoring area, select appropriate ground/structural vibration limits, and choose effective engineering measures to mitigate vibration if unacceptable vibrations are expected. The preconstruction survey shall be conducted by the contractor and the results of the survey shall be made available by the contractor to the DOTD.

Preconstruction Survey Distance. A preconstruction survey shall be undertaken prior to the start of any activity on the site, including the test pile program. The survey will include all buildings within pre-construction survey distances of 200 ft. for the general scenario. For the special scenario, a pre-construction survey distance of 500 ft. is recommended for pile driving hammers with a rated energy less than 100,000 ft-lbf, while it should be calculated from the following equation: $1.6 \times \sqrt{W_r}$, where W_r is the hammer's rate energy, when a hammer's rated energy exceeding 100,000 ft-lbf is planned to be used. These recommendations are based on the threshold PPV value for preconstruction of 0.5 in/s for the general scenario and 0.1 in/s for special conditions, respectively.

Microvibrations and sensitive equipment and/or operations-An important part of the preconstruction survey should deal with the possible nearby presence of sensitive equipment and/or operations, such as hospitals, computerized industries or banks, or industrial machinery. It is necessary to take this information into account for the establishment of the controls.

Pre-construction Condition Survey. A condition survey shall be undertaken by the contractor for all buildings within a pre-construction survey distance as described previously. This survey shall document the existing exterior and interior conditions of these buildings within the recommended distance from the driven pile.

This survey shall include documentation of interior subgrade and above grade accessible walls, ceiling, floors, roof, and visible exterior as viewed from the grade level. It will detail, by videotape and/or photographs, the existing structural, cosmetic, plumbing, and electrical conditions, and shall include all walls, and not be limited to areas of building showing existing damage. Notes and sketches may be made to highlight, supplement, or enhance the photographic documentation.

The condition report shall present engineering notes and photographs or video records. The report shall also summarize the condition of each building and define areas of concern. Reports of the condition surveys shall be made available to the LADOTD for review prior to the start of any pile driving activities.

C) Particle Velocity Controls

Definitions. The *peak particle velocity* is the maximum rate of change of position with respect to time, measured on the ground. The velocity magnitude is given in units of inches per second.

The *frequency* of vibration is the number of oscillations that occur in 1 second. The frequency units given are in hertz (cycles per second).

The *dominant frequency* is usually defined as the frequency at the maximum particle velocity, which will be calculated visually from the seismograph strip chart for the half cycle that has its peak, the maximum velocity.

The *scaled distance* is equal to the distance from the pile driving to a building or other target, measured along the path traveled by the vibrations, divided by the square root of the energy expended in each blow of the pile driving or each cycle of the vibratory pile driving. Common units are foot (ft.) and foot-pounds.

Controls. Pile driving shall be controlled by limiting ground particle velocity so that structural damage due to pile driving can be minimized or avoided. Peak particle velocity shall be measured with the instrumentation and methods described in Section E of this specification. Peak particle velocity shall satisfy one of the following controls:

The peak particle velocity shall be less than a specific control limit at the nearest structure. The type of structure and distance between this structure and the nearest pile will dictate the allowable value as described in Table 16. Particle velocity shall be recorded in three mutually perpendicular axes. The maximum allowable peak particle velocity shall be that of any of the three axes.

Table 16
Limiting particle velocity *[25]*

Structure and Condition	**Limiting Particle Velocity (in./sec)**
Historic and some old structures	0.1
Residential structures	0.5
New residential structures	1.0
Industrial building	2.0
Bridges	2.0

Application of the Particle Velocity Control. If the contractor exceeds 80 percent of the ground vibration control limit for any single axis during a pile driving operation, he/she shall cease all pile driving activities and submit an additional written report to the LADOTD engineer. This report shall give the vibration measurements data and include the corrective action for the next pile to be driven to ensure that the vibration limit will not be exceeded. The next pile shall not be driven until the engineer acknowledges, in writing, that a driving process change has been implemented.

If the contractor exceeds 100 percent of the ground vibration control limit for any single axis during pile driving, he or she shall cease all pile driving related activities and submit a written report to the LADOTD engineer. This report shall give the driving and vibration data and include necessary proposed corrective action for the next pile to be driven to ensure that the specified limit will not be exceeded or an alternative foundation design to driving piles in case corrective/mitigation action is not effective.

D) Monitoring of Ground Vibrations

Recorded Data. *Peak particle velocity*-All three components (longitudinal, transverse, and 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.

1. The vibration monitoring distance (VMD) shall be 200 ft. for residential structures for the general scenario.
2. The VMD shall be 500 ft. for historical /sensitive structures or settlement sensitive ground as shown on the plans.

The contractor shall monitor ground vibrations at appropriate locations (e.g., at a location with a distance equal to the VMD from driven piles and near the building closest driven piles within the VMD range if it is relevant). Background vibrations due to passing traffic or other activities should also be monitored prior to pile driving activities.

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 plan in the pile installation plan to monitor the pile driving vibrations and permanent deformation of the strategic structures. On-site measurements will be made by the contractor and provide a copy of the measurements to the LADOTD engineer.

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. (Type I must be used for Option 2 monitoring.) 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. Both Types I & II can be employed for Option 1.

Transducer Attachment (Coupling). When the measurement surface consists of steel (or other metal), asphalt, or concrete, the transducers shall be bonded to the measurement surface with adhesive. At soil locations burying the transducers or sand bags over the transducers can aid with coupling to soil.

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 LADOTD with all data necessary for record-keeping purposes. These data shall be kept by both parties for at least 3 years, 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 and their locations and orientations.
- All driving records correlated with monitored data.
- All weather conditions occurring during the driving activities.

E) Pile Driving

Driving Plan. No less than three weeks prior to commencing the test pile program, 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 LADOTD engineer for review. The driving plan shall contain: (1) all information required under the general piling specifications and (2) all information relative to ground vibrations and vibration controls, as described in the following sections.

Test Pile Program. The contractor shall monitor vibration at the specified locations as mentioned in Section D. The number, type, and location of the seismographs used to monitor the test pile program shall be approved by the LADOTD engineer.

F) Engineering Measures to Mitigate Vibrations

If special ground site conditions susceptible to vibration damage are identified, such as loose sand, harder/stiffer soil at shallow depths, dense gravely soils, silty sands, hard clay, weak soils, bedrock, sensitive environmental areas, high groundwater and wet condition, and a close distance between the structure and the driven pile, the contractor shall submit a written mitigation measure for LADOTD's approval. No pile shall be installed prior to approval.

G) Basis of Payment

Pay item	Pay unit
Pre-construction condition survey	lump sum
Ground vibration monitoring	per day or event