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ABSTRACT

Vibrations generated during construction often affect adjacent and surrounding buildings and disturb neighboring residents in tightly spaced urban environments. These vibrations can lead to structural damage, especially to older structures. In Charleston, South Carolina, construction vibrations are of special concern due to the tight spacing, age, construction, and historic significance of many of the city's buildings. Of particular interest are the vibrations generated from pile driving activities. Due to the nature of the lower coastal plain soils in the Charleston, SC area, the majority of new commercial structures are being founded on driven pile foundations bearing within the underlying Cooper Marl Formation.

This paper presents the development of vibration threshold levels for both historic and modern structures in Charleston, SC and the case histories of five construction projects in which the developed criteria was used. Vibration data, pre and post-construction surveys, and crack monitoring device data collected during these construction projects were then analyzed to evaluate the vibration criteria.

INTRODUCTION

Vibrations are a cause for concern on most construction projects due to the potential for affecting nearby structures and disturbing neighboring residents. For many construction projects adjacent to or near existing developments, demolition and pile driving activities induce vibrations that can significantly affect neighboring structures. In Charleston, South Carolina, construction vibrations are of special concern due to the tight spacing and the age and historic significance of many of the city's buildings. Due to the presence of soft clays and loose sands in the local soil stratigraphy, many of the buildings and structures under construction are placed on driven pile foundations.

To the authors' knowledge, no standard vibration criteria have been established within the Charleston area that specifically deals with pile driving and other construction vibrations. Therefore, the authors developed a set of vibration threshold levels for the greater Charleston area. These proposed criteria were developed based on knowledge of the local soils and construction practices, previous vibration research, and past construction vibration experience in the Charleston area. This experience consisted primarily of pre-condition surveys of construction areas and measuring vibrations during projects involving driven pile foundations. Construction vibration data, pre/post-construction surveys, and crack monitoring device data were then analyzed from 5 local construction projects to evaluate the proposed vibration criteria.

ESTABLISHMENT OF CHARLESTON AREA VIBRATION CRITERIA

In order to develop vibration criteria for the Charleston area, a general understanding of the soil conditions, local construction practices, and nature of the structures within downtown Charleston and the surrounding area was required. The following paragraphs present a general summary of the general Charleston area soil conditions and construction practices.

Charleston, South Carolina lies within the Lower Coastal Plain geological province of the Atlantic Ocean coast. The near surface "overburden" soils consist primarily of Pleistocene deposits of the Quaternary Period. Pleistocene formations generally consist of sand and clay deposits with varying amounts of shells and occasional organics. The Charleston area has numerous deposits of loose to medium dense poorly graded fine sands that are susceptible to liquefaction, as shown by the Charleston Earthquake of 1886. Stover and Coffman (1993) provide additional details regarding the Charleston Earthquake of 1886.

Beneath the "overburden" soils lies a highly calcareous soil stratum called the Cooper Group, known locally as the Cooper Marl Formation. The Cooper Marl Formation is a marine deposit of late Eocene to Oligocene Periods that underlies a significant portion of the Charleston Area. The Cooper Marl is typically classified according to the Unified Soil Classification System as a low plasticity sandy silt (ML) or sandy clay (CL). Refer to Klecan et al. (2001) for additional details of the Cooper Marl Formation. Depth to the Cooper Marl Formation varies from approximately 12 to 30 meters (~40 to 100 feet) within the downtown Charleston area. Due to the soft clays and/or loose sands that overlay the Cooper Marl formation, most deep foundations within the Charleston area are founded within the Cooper Marl. Groundwater in the Charleston area is typically encountered between 3 to 8 feet below the existing ground surface.

As stated previously, most modern structures within the Charleston area are founded on deep foundation systems. Due to cost considerations and the abilities of local pile driving contractors, driven Pre-Stressed Concrete (PSC) piles are the most common type of deep foundation system, although steel H piles and timber piles are also commonly used. In addition, the limited space within the downtown Charleston area often requires demolition of existing structures prior to the start of new construction.

Older and historic structures in the Charleston area are primarily founded on shallow foundations atop loose to medium dense sand deposits. These shallow foundations are mainly comprised of brick or other masonry for historic structures and concrete for foundations placed in the 18th to 20th century. Typically, these older and historic structures have masonry veneers.

Existing Vibration Criteria

An understanding of past vibration research was required in order to develop vibration criteria for the Charleston area. Typically, the vibration criteria for blasting developed for the United States Bureau of Mines by Siskind et al. (1980), hereafter referred to as USBM in this paper, have been applied to other construction activities, such as demolition and pile driving. The USBM criteria used peak particle velocity (PPV) as the parameter for defining vibration levels. The USBM criteria also acknowledged that vibration frequency was an important component of any vibration criteria. Additional vibration criteria have been proposed by Konon and Schuring (1983) dealing specifically with historic structures. The German Standards Institute (DIN 4150, 1999) also provides vibration criteria for both residential and office buildings.

Woods (1997) provided a synopsis of the various vibration research as it applies to pile driving activities and a summary of various construction vibration criteria to date. In addition, Bay (2003) also provided a summary of vibration criteria as they relate to pile driving and a summary of human perceptions to vibrations. Selected existing vibration criteria based on PPV and vibration frequency are presented in graphical form in Fig. 1.

In addition to using the data provided by Woods (1997) and others, the authors conducted an independent search of the city, county, and state building codes and regulations to determine if vibration criteria existed for the Charleston, SC region. This search did not yield any existing regulations or criteria for construction vibrations.

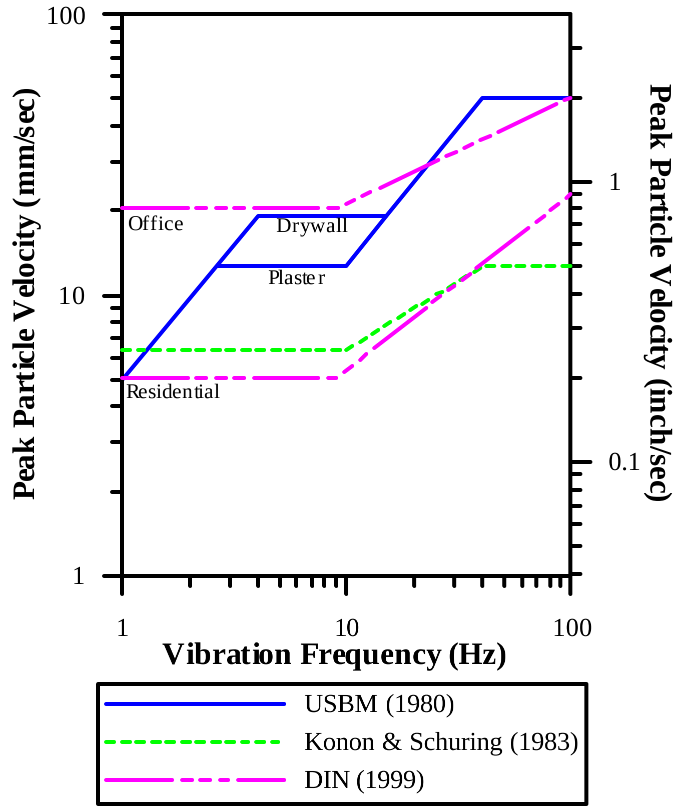


Fig. 1. Summary of selected vibration criteria currently in use (after Woods, 1997).

Proposed Charleston Area Vibration Criteria

A review of the existing vibration criteria showed that while a wide range of criteria existed, it was the authors' opinion that none of these criteria dealt specifically with the local soil conditions (i.e. large deposits of saturated loose to medium dense sands) and types of existing structures (i.e. tightly spaced, 2-3 story buildings that are often historic in nature) common to the Charleston area. Given the lack of existing criteria that could be adapted to the Charleston area and no established legal criteria, the authors developed new vibration thresholds specifically for the Charleston area.

The proposed vibration criteria for the Charleston area were developed by incorporating previous pile driving experience in the Charleston area with various elements of the vibration research previously mentioned. Similar to the existing criteria previously discussed, the proposed criteria are based on peak particle velocity (PPV) and vibration frequency. Figure 2 presents the proposed vibration criteria relative to the USBM (1980) and Konon and Schuring (1983) thresholds.

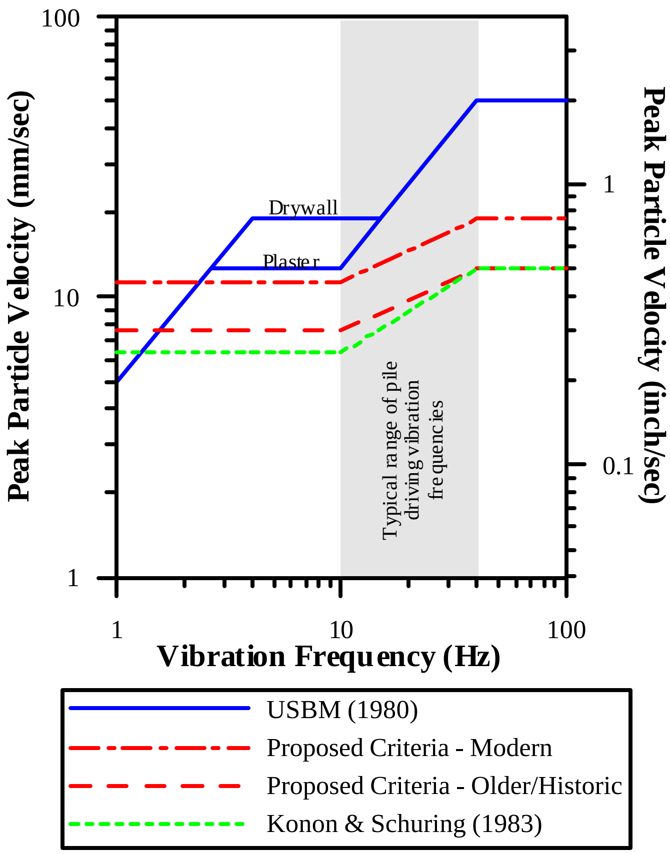


Fig. 2. Proposed Charleston Area vibration criteria.

As shown in Fig. 2, the new criteria was divided into two separate vibration thresholds that take into account the age, historic importance, and type of foundation system of adjacent structures. These separate thresholds were designated Modern and Older/Historic and are described as follows:

Modern: Structures that have been built after 1950. Typically, these structures are on deep foundation systems, usually driven piles.

Older/Historic: Structures that have been constructed prior to 1950 and/or are considered to be historic in nature. As a general rule of thumb, the older the structure, the increased likelyhood it is founded on a shallow foundation system.

As with prior vibration criteria, the two proposed vibration thresholds are frequency dependent, especially over the range of 10 to 40 Hertz (Hz), which prior research has shown is the main frequency band for pile driving vibrations (Woods, 1997).

As shown in Fig. 2, the proposed vibration criterion for modern structures is significantly lower than the general criteria developed for the USBM (1980). It was the authors' opinion that lower vibration criteria for modern structures within the Charleston area were warranted for the following two reasons:

1. Lacy and Gould (1985) concluded that settlement from pile driving vibrations can result from vibrations at peak particle velocity levels much lower than those that can cause damage to structures in loose to medium dense uniform sands. As stated previously, sand deposits within the Charleston area are typically poorly graded loose to medium dense sands.

2. Our local experience has shown that small vibrations that are perceptible to humans but are not damaging to structures can generate complaints from adjacent residents. Therefore, by reducing the vibration criteria for structures, the likelihood of generating vibrations perceptible to humans also decreases. A summary of human perception vibration threshold values was prepared by Bay (2003) and is presented in Fig. 3. As shown in Fig. 3, the peak particle velocity ranges of proposed vibration criteria are below the "very disturbing" human perception range. Most of the existing vibration criteria, such as the USBM (1980) and DIN 4150 (1999) have maximum PPV ranges that extend into the "very disturbing" range.

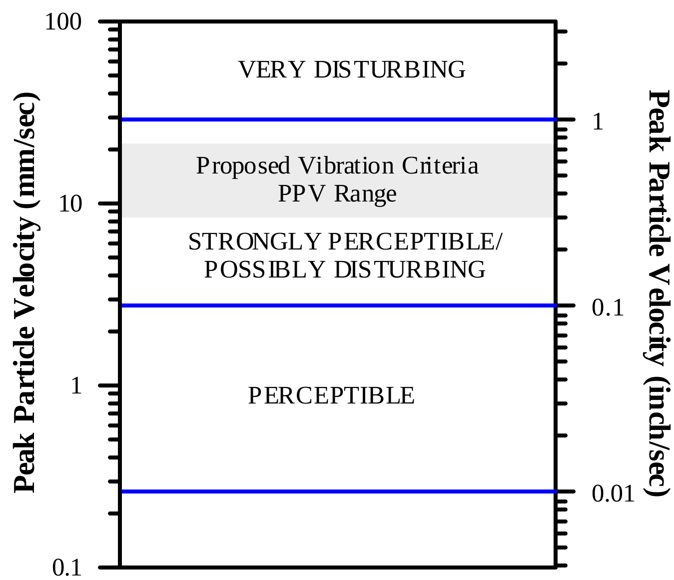


Fig. 3. Summary of Threshold Vibration Levels for Human Perception (after Bay, 2003).

As shown in Fig. 2, the proposed vibration threshold for older/historic structures is slightly higher than that proposed by Konon and Schuring (1983) at the 1 to 10 Hz range. The authors made this change to maintain consistency with the modern structure criteria. However, this slight increase was considered justifiable based on the authors' knowledge and experience with older construction in the Charleston area.

Recently, Bay (2003) suggested that the vibration criteria of 12.7 mm/sec (0.5 in/sec) for residential structures in poor condition proposed by Chae (1978) would be more appropriate for historic buildings. Bay (2003) further suggested that existing European vibration standards for historical structures (e.g. German D4150) are unreasonably low and that buildings that cannot withstand these vibration levels are too fragile to have substantial function. Although the proposed vibration threshold for older/historic structures does not go as high as Bay suggests, it does acknowledge that low vibration standards which are near the levels generated by vehicle and pedestrian traffic or other everyday activities are impractical.

The proposed vibration criteria for the Charleston area were developed as a general guide for construction vibrations. These vibration criteria can and should be modified based on the conditions of older/historic structures and their proximity to construction operations. In addition, the presence of sensitive equipment near the pile driving operations will require additional modification of these criteria.

EVALUATION OF PROPOSED VIBRATION CRITERIA

In order to evaluate the proposed criteria, data was collected from 5 separate construction projects (i.e. case histories) in the Charleston area. The construction activity that generated vibrations for 4 of the 5 projects was pile driving, while the fifth project involved demolition of an existing structure. A summary of these projects is provided in Table 1. Figure 4 shows the locations of each site relative to the Charleston area.

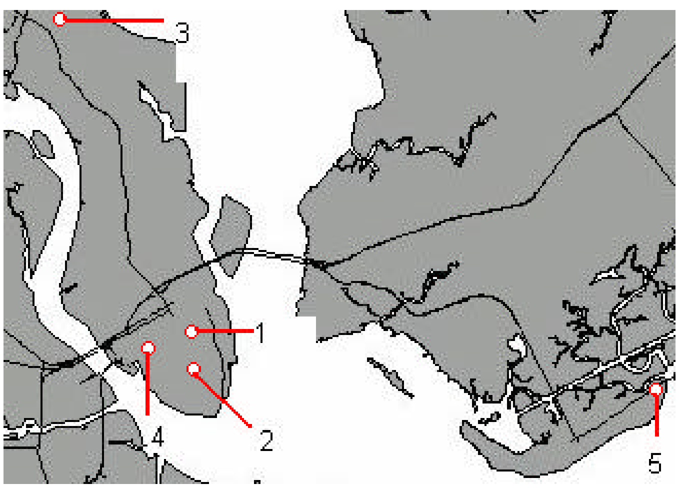


Fig. 4. Location of Evaluation Case History Projects.

The following paragraphs provide a brief description of the 5 case history sites.

SITE 1: A new 3 story library was constructed in downtown Charleston, SC in a neighborhood with many historic buildings. A total of 589 0.3 m (12 inch) square by 29 m (95 feet) Pre-Stressed Concrete (PSC) piles driven into the Cooper Marl formation is the foundation system for the new building. The nearest adjacent structure was 4.6 m (15 ft) feet from a pile location. The piles were pre-augered with a 0.3 m (12 in) diameter auger to a depth of 15.2 m (50 ft).

SITE 2: A new 3 story office building was constructed in downtown Charleston, SC in a neighborhood with several historic buildings. An existing 2 story building and shallow foundations for this building were demolished. The nearest neighboring structure, a 2 story structure with un-reinforced brick masonry that was over 100 years old, was immediately adjacent to the demolition activities.

SITE 3: An addition to an existing single story school and a new stand-alone classroom building in North Charleston, SC were constructed. The existing building addition was founded on 12 HP12x53 piles, while the new classroom building was founded on a total of 94 0.3 m (12 inch) square Pre-Stressed Concrete (PSC) piles. The HP piles were located within 1.8 m (6 ft) of the existing building, while the PSC piles were located 9.1 m (30 ft) from the structure. The HP and PSC piles were driven 15.2 m (50 ft) below the existing ground surface and into the underlying Cooper Marl Formation. The piles were pre-augered with a 0.3 m (12 in) diameter auger to a depth of 10.7 m (35 ft).

SITE 4: A power plant expansion for an existing 5 story medical facility was constructed in downtown Charleston, SC. The foundation consisted of 12 HP12X53 steel piles by 25.9 m (85 ft) long driven into the underlying Cooper Marl Formation. The 5 story modern medical facility and a historic 2 story brick building were located within 1.8 m (6 ft) and 5.6 m (18.5 ft), respectively, from the pile locations. The piles were pre-augered with a 0.2 m (8 in) diameter auger to a depth of 5.2 m (17 ft).

SITE 5: A new residence and below ground pool on Sullivan's Island, SC were constructed and founded on 78 203mm (8 inch) tip diameter timber piles for a new residence. The piles were driven to 13.7 m (45 ft) below the existing ground surface. The piles were pre-augered with a 0.3 m (10 in) diameter auger to a depth of 3.0 m (10 ft). The nearest structure was 8.5 m (28 ft) from the pile locations.

Table 1. Case History Project Summary

Site	Vibration Activity	Location
1	Pile Driving	Downtown Charleston, SC
2	Site Demolition	Downtown Charleston, SC
3	Pile Driving	North Charleston, SC
4	Pile Driving	Downtown Charleston, SC
5	Pile Driving	Sullivan's Island

<u>Case History Evaluation Data</u>

Four types of data were collected from the case history sites to evaluate the proposed criteria: pre-condition surveys, crack monitoring devices, vibration monitoring, and post-condition surveys. A summary of the various data collected for each project to evaluate the proposed vibration criteria is provided in Table 2.

Table 2. Case History Evaluation Data Summary

Site	Pre-Condition Survey	Crack Monitoring Devices	Vibration Monitoring	Post-Condition Survey
1	X[1]	X	X	X
2	X[1]	X	X	X
3	X		X	
4	X		X	X
5	X		X	

NOTES:
1. Includes Interior Survey of selected structures

Pre-Condition Survey: The pre-condition surveys consisted of examining and documenting the exteriors of the structures surrounding the site. Unless otherwise noted, building interiors were not examined. Woods (1997) noted that past experience with pile driving has shown that direct damage to structures is not likely to occur at a distance from the driven pile of (a) more than 15 m (49 feet) for piles 15m (49 feet) long or less, or (b) equal to 1 pile length for piles greater than 15m (49 feet) in length. However, the pre-condition surveys were typically conducted up to distances of 4 piles lengths from the planned driven pile locations.

Crack Monitoring Devices: At locations determined by the pre-condition survey, Crack Monitoring Devices (CMD's) were installed over existing cracks at various structures. The CMD's were recorded on a weekly or bi-weekly basis. Ambient air temperatures were taken at the time of the readings to account for any temperature expansion/contraction affects.

Vibration Monitoring: Vibration monitoring was conducted within and around the project sites by measuring vertical, transverse, and longitudinal ground velocities at selected monitoring points using tri-axial velocity transducers. Monitoring points were located at or near adjacent structures as well as at various intervals from the construction activities to determine attenuation relationships for the different sites. Attenuation relationships of the case histories presented in this paper are discussed by Hajduk et al. (2004).

Post-Condition Survey: The post-condition surveys consisted of examining and documenting the exteriors of the structures surrounding the site. Specific attention was provided to the properties of adjacent neighbors whom registered complaints during construction. The post-condition surveys were typically limited to structures immediately adjacent to the site unless a complaint was registered.

Use of Evaluation Data

The following methodology was used in evaluating the proposed vibration criteria based on the collected data:

Step 1: The measured construction vibration PPV's were plotted with respect to vibration frequency to determine if they exceeded the proposed vibration criteria.

Step 2: The pre and post-condition surveys were compared to determine if structural damage had occurred over the construction activity time period.

Step 3: The CMD measurements were analyzed to determine if movement occurred over the construction activity time period.

Data Results – Measured Vibrations

Figures 5 through 9 present the measured Peak Particle Velocities (PPV) vs. vibration frequency for the five case history projects. The proposed vibration thresholds for modern and older/historic structures are also presented in Figures 5 though 9 as well as the USBM (1980) criteria. These figures present the maximum peak particle velocity for each construction event (i.e. driven pile or demolition activity). No distinction was made between determining the maximum PPV from the vertical, transverse, or longitudinal vibration data. Peak Vector Sums (PVS) of the measured vibrations were not used since vibration frequency could not be determined from these values. However, examination of the maximum PPV and PVS showed only an average difference of around 7%.

As shown in Figures 5 through 9, measured PPV exceeded the proposed vibration criteria for 3 of the 5 projects (i.e. Sites 2, 4, and 5). For the other 2 projects, measured PPV's were close to or at the proposed vibration criteria. In order to determine if the measured PPV's that exceeded or were near the proposed criteria were within the distance of the nearest adjacent structures, the PPV results were analyzed with respect to distance from the vibration event. Figures 10 through 14 show the measured PPV's vs. distance as well as the distance from the vibration activity to the nearest structure(s).

For Site 2, it was observed that five of the measured PPV's that exceeded the proposed criteria were beyond the distance to the nearest structure. For Site 4, one measured event past the distance to the nearest modern building exceeded the proposed criteria, while vibrations measured at the historic 2-story brick building were not exceeded. At Site 5, none of the measured vibrations at a distance beyond the nearest structure had exceeded the proposed vibration thresholds for modern buildings.

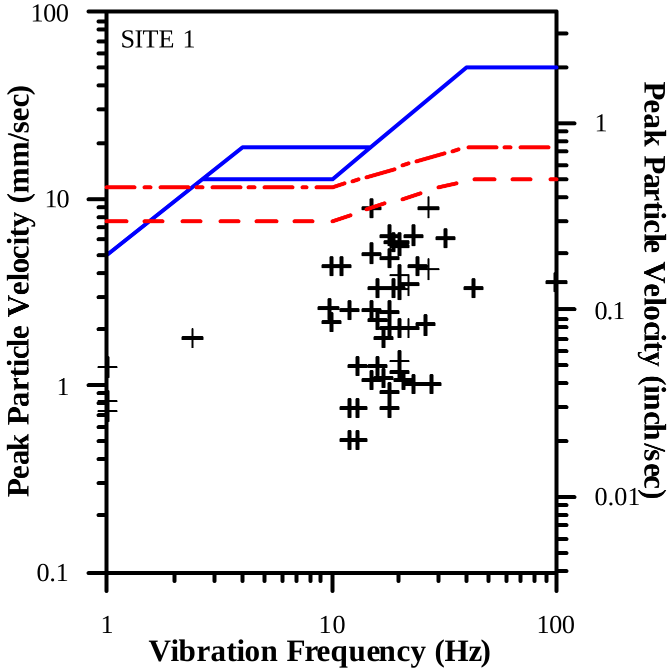


Fig. 5. PPV vs. Vibration Frequency for Site 1.

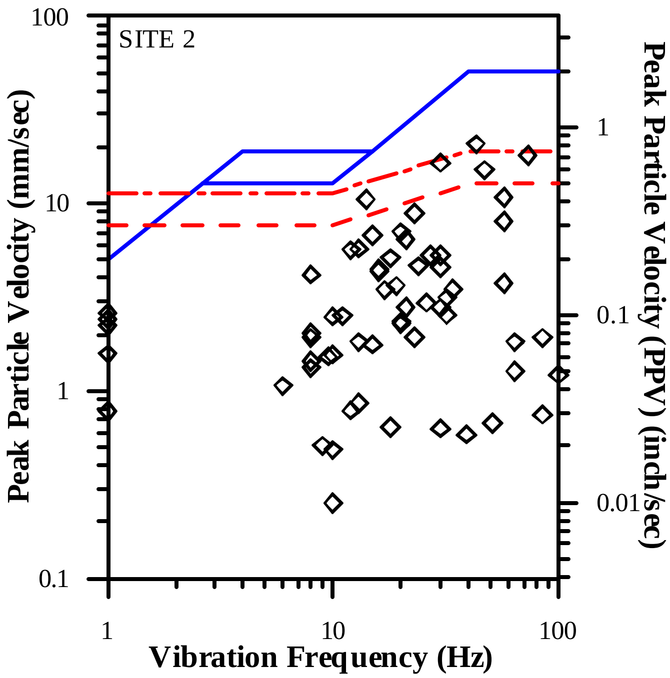


Fig. 6. PPV vs. Vibration Frequency for Site 2.

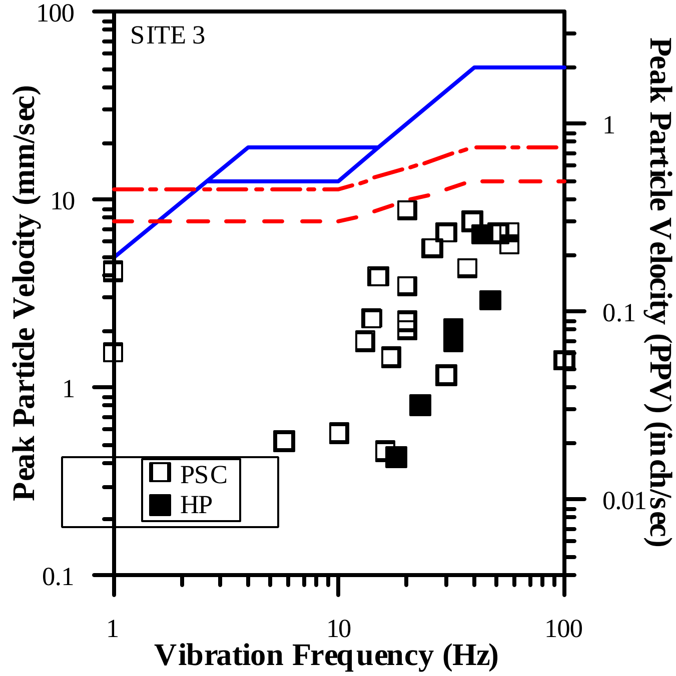


Fig. 7. PPV vs. Vibration Frequency for Site 3.

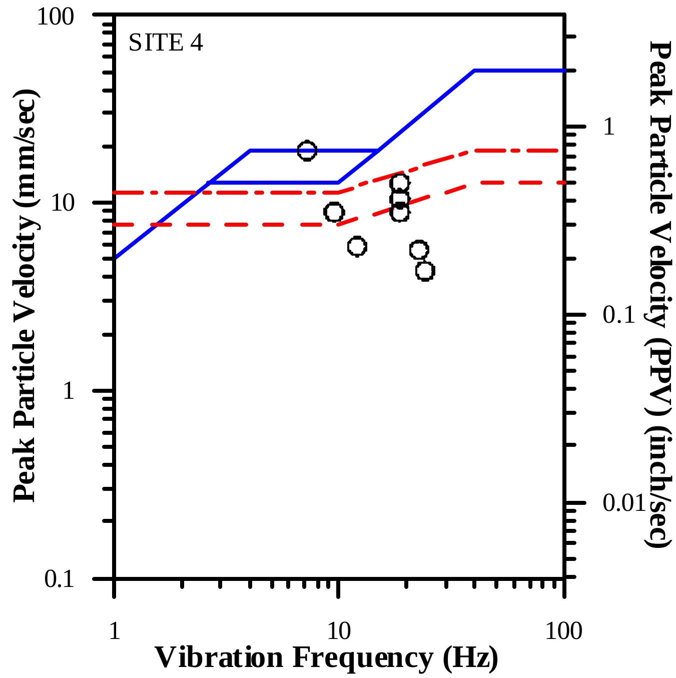
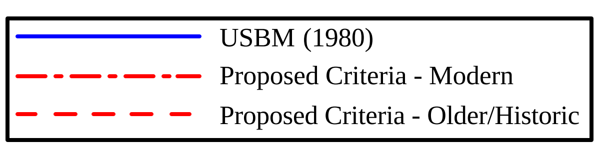


Fig. 8. PPV vs. Vibration Frequency for Site 4.



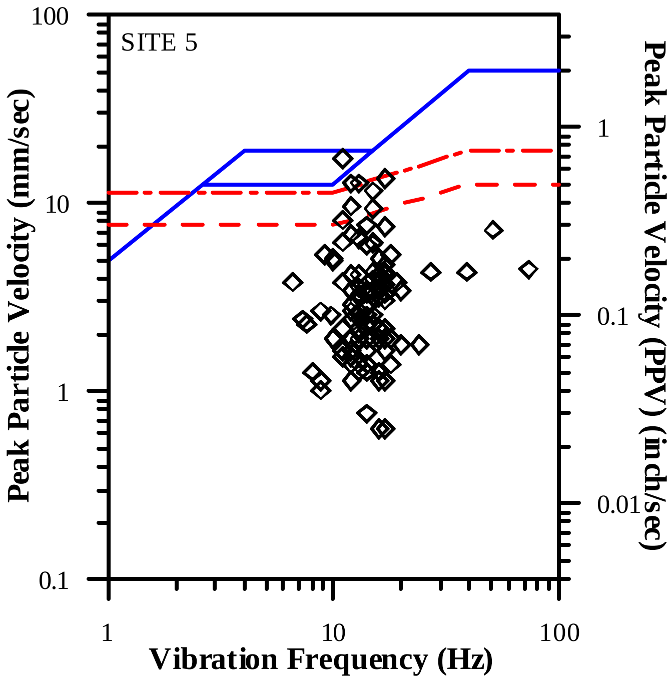


Fig. 9. PPV vs. Vibration Frequency for Site 5.

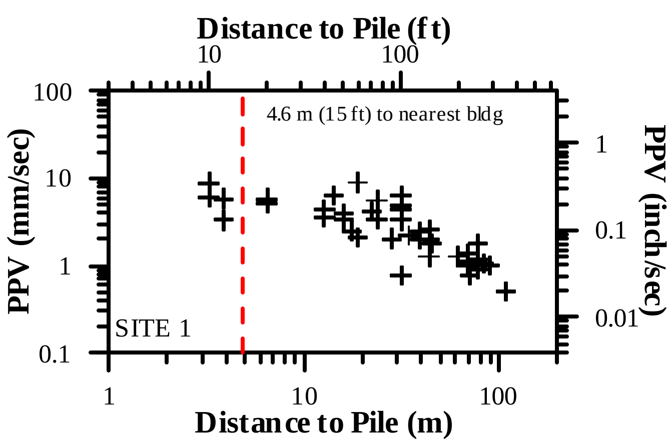


Fig. 10. PPV vs. Distance for Site 1.

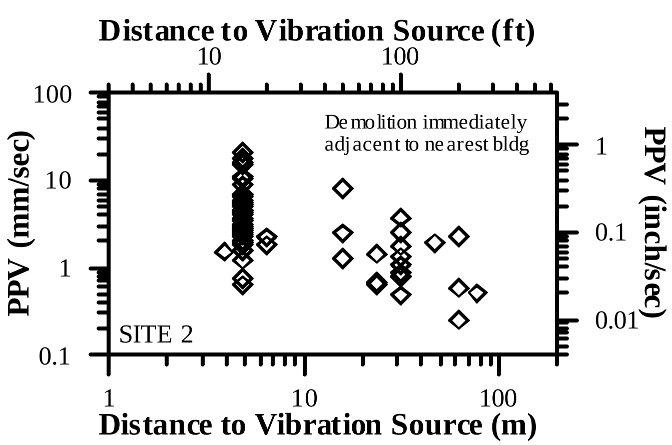


Fig. 11. PPV vs. Distance for Site 2.

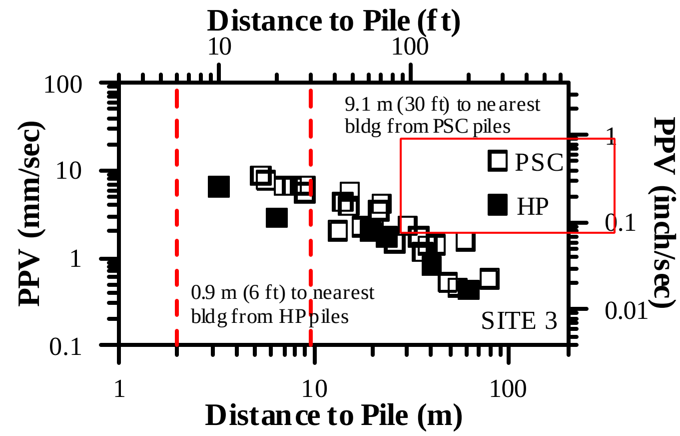


Fig. 12. PPV vs. Distance for Site 3.

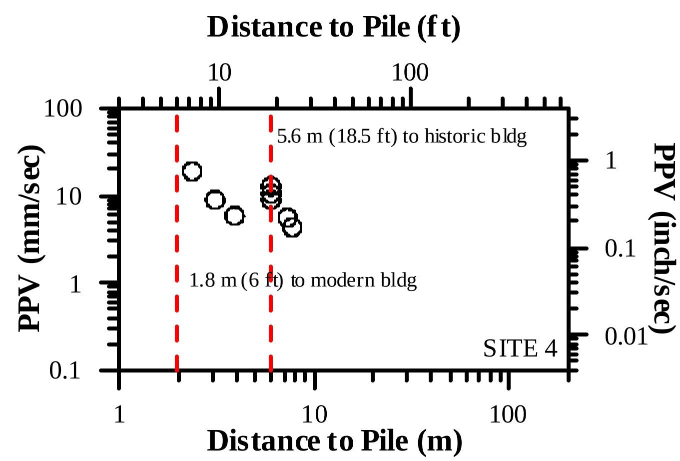


Fig. 13. PPV vs. Distance for Site 4.

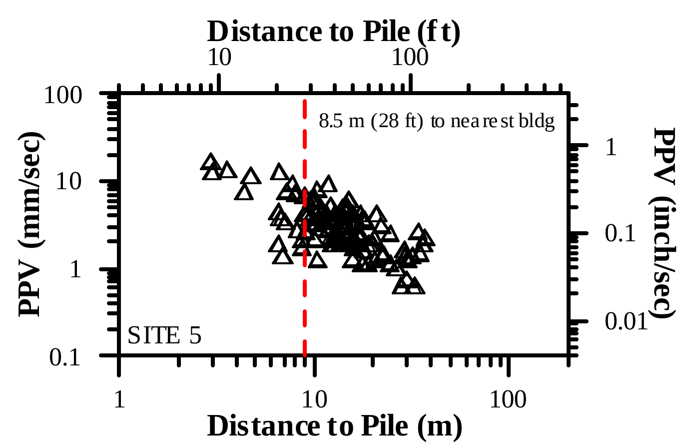


Fig. 14. PPV vs. Distance for Site 5.

Data Results - Pre and Post Condition Survey Comparisons and CMD Monitoring

Comparisons between the pre and post-condition surveys did not detect any significant change in documented cracks on adjacent structures or new cracks on the exterior of these structures. For the sites that did not have post-condition surveys conducted, no complaints were filed with the project general contractors concerning structural damage to property.

CMD monitoring for Sites 1 and 2 did not reveal any significant movement [i.e. movement greater than 1 mm (0.04 in)] of the existing cracks that could not be attributed to temperature effects.

Evaluation Summary

The evaluation data showed that with the several noted exceptions, no vibrations greater than the proposed criteria were monitored. In addition, the other evaluation data showed that no structural damage had been caused to the adjacent and neighboring buildings.

Although not part of our evaluation process, the number of neighboring complaints was used as an informal means of evaluating the proposed vibration criteria. With the exception of Site 1, no complaints stating that structural damage was done to their homes were lodged by residents adjacent to or near the construction sites. Comparison of the pre-condition survey photographs to post-construction conditions for the complaints at Site 1 showed no new or expanded cracks or other evidence of structural damage within the complaint residences. While there is no way of determining if the proposed criteria prevented or reduced neighbor complaints with regards to vibrations, the authors note that only two of the five sites (Sites 1 and 2) had complaints registered with the general contractor regarding discomfort from vibrations and noise.

CONCLUSIONS

Vibration criteria for construction activities were developed for the Charleston, SC area based on past vibration research and local geotechnical and construction experience and knowledge. The proposed criteria accounts for vibration frequency, possibility of settlements within the local loose sands due to vibration densification, and perceptions of neighboring residents to vibrations from construction sites. Evaluation of the proposed criteria using data collected from five separate projects showed that the criteria is effective in preventing structural damage to adjacent structures.

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