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# Ellis Island: Vibration Effects on Historic Buildings Caused by Pile Driving

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# ELLIS ISLAND: VIBRATION EFFECTS ON HISTORIC BUILDINGS CAUSED BY PILE DRIVING

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## ABSTRACT

The seawalls that surround Ellis Island were constructed in the early 1900s and now show varying degrees of deterioration. The approach to the structural repair of the seawalls consisted of installing H-piles and ground anchors for stabilization of vertical and horizontal seawall movements. The H-piles were driven through the retained soils along the seawalls to top of rock. This paper presents ground vibration data collected simultaneously by four seismographs during driving of 40 piles (up to 100 ft depth) at various distances from the historical buildings. A correlation between the recorded PPV values and the distance to pile driving is presented. Also, a specific comparison between the measured attenuations from an instrumented pile with documented driving energy records and those recommended in published literature is presented. It was found that the vibrations induced by pile driving well exceeded the Peak Particle Velocity limits established in the project specifications and those commonly established in the literature. However, damage to the historical buildings was not significant.

## INTRODUCTION

At the junction of the Hudson River, the East River, and the Upper New York Harbor, Ellis Island (Figure 1) was the gateway for approximately 12 million immigrants as they entered the United States between 1892 and 1954. This Island is currently overseen by the National Park Service, and attracts over 3 million visitors each year.

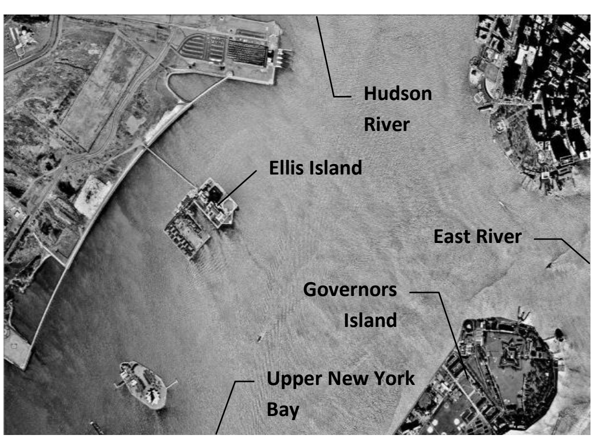


*Fig 1. Ellis Island Location.*

The seawalls, which served to protect and support the artificial fill placed at the island, were deteriorated and presented stability issues. A remedial stabilization plan which consisted of driving piles and installing ground anchors was carried out. One concern with this stabilization plan was that the piles were going to be driven at the retained side of the seawall. This resulted in distances from the piles to the existing historic buildings as short as 20 ft in some areas.

It is known that vibrations induced by pile driving can cause structural damage to existing structures. The damages vary depending on the type of structure and the magnitude of energy transmitted to the surrounding ground.

A vibration and crack monitoring plan was conducted to quantify the amount of vibration transmitted to the ground adjacent to the buildings and to monitor the buildings' response to such vibrations.

This paper presents vibration records in terms of peak particle velocity from 40 driven piles, measured at the Ellis Island site. It also presents the response of the historic buildings to vibrations that well exceeded the limits established on the project specifications, and those commonly found in relevant literature.

BACKGROUND

Ellis Island, originally only 3.5 acres in size, was named for New York merchant Samuel Ellis who owned it until 1794. In the early 1800s, Fort Gibson was erected on the Island, and a wood crib seawall was built to protect the buildings and land from tidal and wave erosion. Between the years 1890 and 1934 and after being selected to house the new U.S. immigration depot, Ellis Island expanded from 3.5 acres to its present size of 28 acres (Robinson, et al 2007). The fill material used was obtained from the ballast of War Department ships and possibly excess earth from the construction of the New York City subway system. The buildings existing present day on the island include a powerhouse, administrative buildings, dormitories, recreation halls, kitchen and laundry buildings, and hospital buildings with contagious disease and psych wards. Some of these buildings are more than 100-years old.

Ellis Island is divided by a ferry slip. The north portion of the island has the current administrative buildings, a police station and a museum/visitors center. In general, the seawall and the buildings on this portion of the island are in good condition. On the other hand, the south portion of the Island presented issues with the seawall integrity and the proximity of existing buildings.

The south island seawalls of Ellis Island show varying degrees of deterioration. The distressed conditions range from aesthetic concerns to wall stability issues (Figure 2). Wall instability was evident in portions of the seawall that are on timber-relieving platforms and those sitting directly on timber cribbing. The wood was decaying and being attacked by marine borers (Robinson and Gomez, 2008).

The historic buildings on the south portion of the Island were deteriorated. The signs of deterioration range from plaster loss and hair line cracks to cracks of about 1 inch wide and step cracks that goes from foundations through the 4th floor of some buildings. Figure 3 (a) shows a step crack of about ½ inch at one of the exterior walls of one of the buildings. Figure 3 (b) presents the deteriorated condition of the inside of one of the buildings. It shows the exposed reinforcement of one of the main beams, as well as plaster loss at the ceiling. Many of the buildings at the south island present a similar degree of deterioration and structural damage.

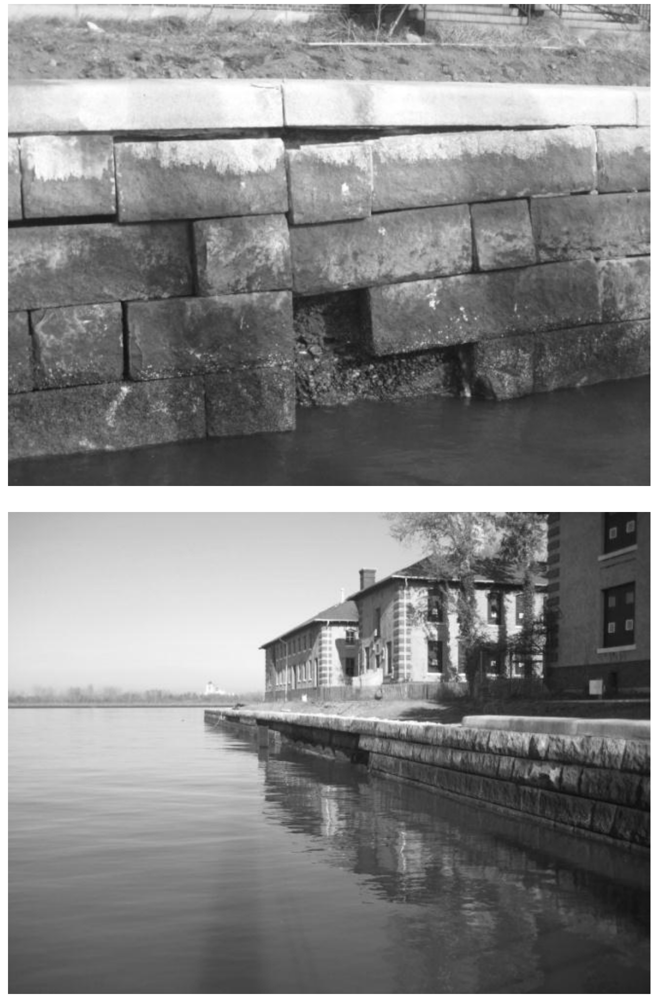

*Fig 2. Ellis Island seawalls condition before remedial stabilization.*

The buildings at Ellis Island are founded on piles. The depth, shape and type of piles are unknown. Most of the buildings are located relatively close to the seawall. The levels of deterioration as well as the proximity of the buildings to the sewall, and therefore, to the pile driving, makes this project unique in its class and a challenge to the contractor and the engineers.

a)

b)

*Fig 3. Deteriorated conditions of buildings at the South Island.*

<u>Subsurface conditions</u>

A total of six borings, located on the perimeters of the south island were available to characterize the subsurface conditions.

The general subsurface soil stratigraphy at the south Island has 3 different soil strata. Fill material (sand, silt, clay and gravel) was encountered from ground surface to a depth of about 15 to 30 ft, with SPT ranging from 10 to 32. Underlain the fill, there is a loose to very loose silty sand and soft clayey silt to a depth of about 30 to 50 ft with SPT ranging from WOH to 13. Glacial till underlie the soft strata extending to top of bedrock located 50 to 100 ft from the ground surface, and consisting of reddish-brown poorly graded sands and gravels with varying amounts of clay and gravel. SPT values range from medium to very dense N = 18 to 100/4". The bedrock is of the Pelham Bay-Type from the Hartland Formation, and consists of strong, slightly weathered, moderately fracture gray Gneiss.

CONSTRUCTION

As noted in the previous paragraphs, the seawalls at Ellis Island present various grades of deterioration. To prevent further damage to the historic buildings and address the instability of the seawall, the construction of a system that consisted of soldier piles and anchors was undertaken. Sheet piles were also installed (vibrated) at the areas of the island where the seawall is founded on timber cribbing. The objective of the sheet piles is to protect and enclose the cribbing. This paper only focuses on the vibrations induced by pile driving. However, this paper presents the effects of both pile and sheet pile driving on the historic buildings.

The soldier piles were steel H piles HP 14x89, 300 kip capacity in compression driven to rock. The lateral loads are taken by ground anchors. The piles are located parallel to the seawall as close as 20 ft from the buildings in some areas (Figure 4). The majority of the piles were driven along the South end of the Island. A total of about 120 piles were driven around the South end, East of the South side of the South Island and the ferry slip. Pre-drilling of the first 30 to 35 ft was used to reduce the vibration energy transmitted to the historic buildings.

The piles were driven from a barge with an air hammer. The hammer was a Vulcan-Bull 510 with a theoretical energy of 39,000 lb-ft. Figure 4 illustrates a typical driven piles arrangement and shows a typical location of the seismograph's boxes. These piles were located at the East side of the South Island, where the distances from the piles to the historic buildings are larger than those at the South end.

Fig 4. Typical driven piles and seismograph locations with respect to the buildings.

Monitoring Plan

To prevent damage to the historic buildings, the project engineers established a vibration limit in terms of Peak Particle Velocity (PPV). The threshold value of 0.08 in/s was specified as the limiting vibration of the ground for piles and sheet piles driving. This threshold of PPV is in the lower range of PPV limits suggested in the literature for this type of structures which ranges from 0.08 to 0.5 in/s.

Schnabel Engineering Consultants (Schnabel) was selected to provide vibration and building monitoring of the areas adjacent to the pile driving activities. Schnabel had also previously completed investigation and design efforts on the Island (Robinson, et al 2007). The objective of the vibration monitoring plan was to report to the contractor and the engineers about the vibrations that were transmitted from the pile to the ground in the proximity of the historic buildings.

The vibration monitoring was done with four (4) seismographs, simultaneously recording vibrations and covering a radius of about 200 ft of pile driving activities. The seismographs were enclosed in a metallic box containing a Blastmate seismograph (Figure 5), one battery and one sensor that activated a light on top of the box when the PPV exceeded the threshold. The geophone was located at the same location of the box, buried in the ground at about 1 ft deep from the ground surface.

Fig 5. Vibration monitoring enclosing box with Blastmate seismograph.

The location of the seismographs varied depending on the area that the contactor was driving piles. The concept of moveable stations permitted monitoring of vibrations for a radius of about 200 ft of pile driving at all times. An approximate location of all the used monitoring stations is shown in Figure 6.

In conjunction with the vibration monitoring, Schnabel also monitored the building response to the pile and sheet pile driving activities by means of the use of crack gauges. A total of 72 crack gauges were installed at the South Island and the ferry slip. The crack gauges readings were taken periodically (daily, weekly or bi-weekly), with emphasis on the zones proximal to the buildings that the contractor was driving piles on any particular week. The objective of the crack monitoring program was to, in a proactive matter, monitor the building response to the pile driving activities.

EFFECT OF PILE DRIVING

Seismic waves are generated by pile driving by the same mechanisms piles transfer load to the ground. Shear waves are generated by skin friction. Both P and S waves are generated at the pile tip. The pile driving generates body waves that are then converted to surface waves (Rayleigh) when they get to the ground surface. The surface or Rayleigh wave carries more energy than body waves. This wave transmits up to 2/3 of the total energy applied to the ground and decay much slower than body waves. Thus, Rayleigh wave is the most damaging to nearby structures (Richard 1970). This wave is generated in short distance from the source, even when the energy source is below the surface (as in pile driving) (Dowding 1996). The amplitude of energy of each wave depends on many factors like the hammer energy delivered to the pile, depth of the pile into the ground, hardness and uniformity of the soil. However, the energy transmitted from the pile to the ground depends more on the hammer and the pile properties (dimensions and material), and is less dependent on the soil. This was demonstrated by Heckman and Hagerty 1978 when they presented the significance of the impedance of the pile (pile properties) on the vibration energy transferred to the surrounding soil during pile driving. They developed the following semi-empirical equation to relate pile driving energy to the distance from source to a target structure:

$$z = K\sqrt{\frac{E_n}{D}} \qquad \text{(Eq .1)}$$

a)

b)

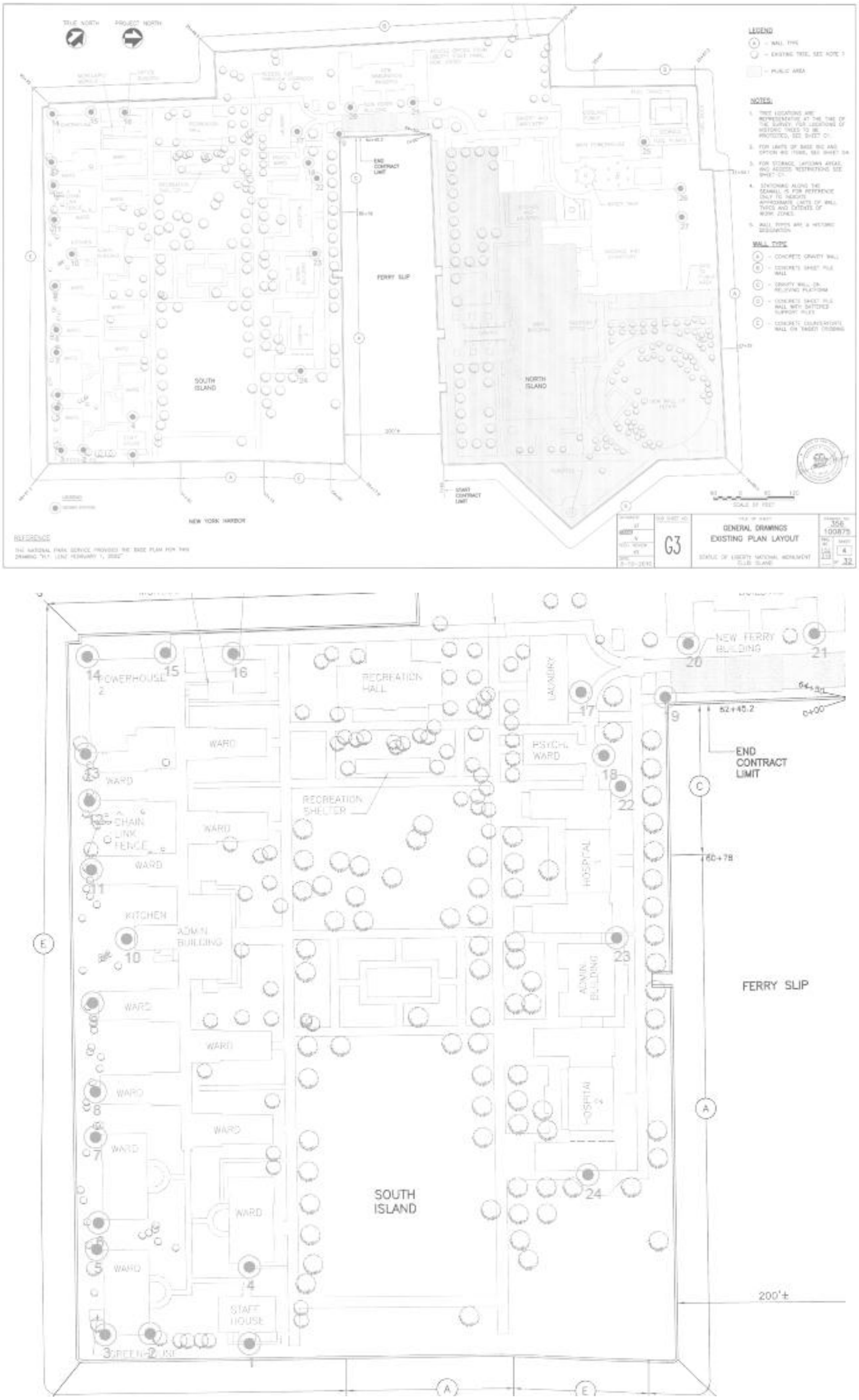


*Fig 6. Vibration monitoring stations; a) General plan; b)South Island*

Where:
z = peak particle velocity in mm/sec;
K = a factor dependant on pile impedance;
$E_n$ = energy of blow;
D = distance from source.

A similar equation that uses a reference peak particle velocity (PPV), distance and energy is better used in practice to estimate the PPV from impact pile drivers and is defined as follows:

$$PPV = PPV_{Ref}(25/D)^n x \left(E_{equip}/E_{Ref}\right)^{0.5} \quad \text{(Eq .2)}$$

Where:
$PPV_{ref}$ = 0.65 in/sec for a reference pile driver at 25 ft;
D = distance from the pile driver to the receiver in ft;
n = value related to the vibration attenuation rate trough ground which range from 1.1 to 1.5;
$E_{ref}$ = 36,000 lb-ft as the rated energy of reference pile driver and Equip is the rated energy of impact pile driver.

Damage Threshold

The pile driving using impact hammers can cause structural damage to structures that are too close to the pile driving activities. These damages can range from simple (loosening paint and small plaster cracks) to major (structural weakening, load support ability affected, cracks of several mm in walls). Several authors and agencies have developed vibration criteria or thresholds in terms of PPV, for limiting the amount of vibration amplitudes transmitted to the surrounding ground adjacent to buildings. Table 1 presents a summary of some of the vibration criteria for continuous/frequent intermittent source of maximum PPV to prevent damage in historic buildings.

Table 1. Typical vibration criteria for historical and sensitive buildings.

| Category | Source | PPV (in/s) |
|---|---|---|
| Constructions very sensitive to vibrations; objects of historic interest | Wiss (1981) | 0.12 |
| Ruins and ancient monuments | Whiffen (1971) | 0.08 |
| Historic and some old buildings | Dowding (1996) | 0.5 |
| Historic sites or other critical locations | ASSHTO (1990) | 0.1 |

From Table 1, the vibration limiting criteria based on PPV for historic and ancient buildings range from 0.5 to 0.08 in/s.

RECORDED VIBRATIONS

Schnabel recorded vibrations for more than 120 driven piles at the Island. However, for the sake of this paper, only the vibration records of 40 piles are presented. These piles were selected based on the amount of energy that was transmitted to the surrounding soils. We present the piles that generated greater values of PPV. Figure 7 shows the general attenuation of the pile driving vibrations at the Ellis Island site. The PPV values represent the maximum vector sum of the lateral, longitudinal and vertical directions. The distance represents the measured diagonal (in plane) distance from a specific driven pile to the seismographers. From this Figure it is noted that the maximum recorded PPV due to pile driving was about 0.51 in/sec, for a distance of about 20 ft. However, this value of PPV seems to be isolated, with a more typical maximum PPV of about 0.4 in/sec for the same amount of distance. At this site, the energy transmitted from the pile to the ground attenuates quickly. The recorded PPV diminished from 0.4 in/sec at 20 ft, to 0.015 at 200 ft.

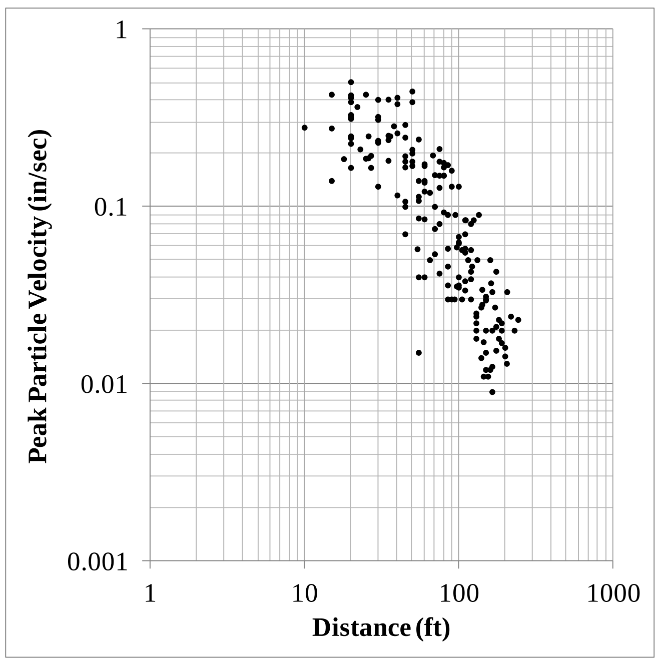


Fig 7. Attenuation of PPV with distance.

To better understand how the energy attenuates with distance from source (considering pile embedment) at the site, we selected a pile where the energy transmitted from the hammer to the pile as well as accurate readings of PPV with depth were known. We measured vibrations with four seismographs stations located at 27, 70, 94 and 146 feet from the pile. The pile was driven from a depth of 36 ft until refusal at a depth of about 57 ft from the ground surface. Figure 8 presents the energy attenuation of the selected pile in terms of the scaled distance. The scaled distance is defined as the distance from source divided by the square root of the transmitted energy. The distance from source was taken as the diagonal distance from the tip of the driven pile to the seismographs. The PPV is presented in terms of the peak vector sum. Also, a comparison of predicted PPV attenuation using Equation 2 is presented. The maximum recorded PPV for this pile is about 0.2 in/sec at the station located closest to the pile, and about 0.01 in/sec at the farthest station.

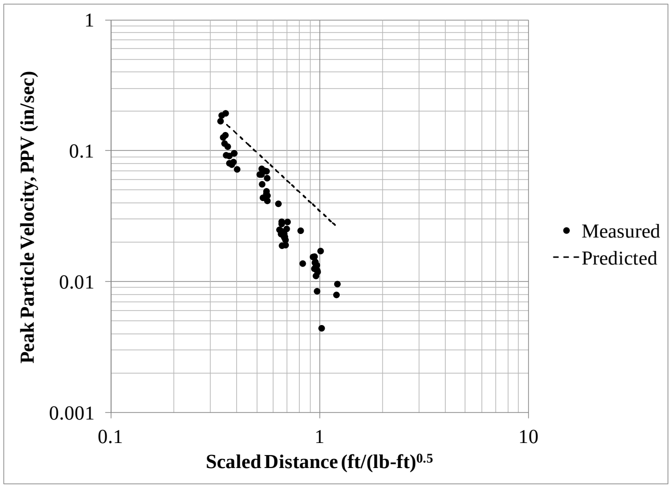


Fig 8. Relationship of PPV versus scaled distance.

The parameters used for predicting the PPV using Equations 2 were, the recorded energy transmitted to the pile, the diagonal distance from the tip of the pile to the seismographs and a value of n = 1.5.

The calculated PPV with scaled distance using Equation 2 suits well the recorded PPV for scaled distance of less than 0.6 ft/(lb-ft)$^{0.5}$. It over predicts the PPV for scaled distance greater than 0.6 ft/(lb-ft)$^{0.5}$.

## VIBRATION EFFECTS

Damage to structures induced by pile driving range from plaster loss and hair line cracks to differential settlement and irreversible structural damage. The firs indication of structural damage is often evidence by the generation of cracks. Other evidence of damage may be water leaks, distortion in buildings and gap openings.

The deteriorated conditions of the historic buildings, as well as the proximity to the pile driving activities were the major concerns for this project. Preventive measurements (pre-drilling) intended to reduce the amount of vibrations transmitted to the surrounding structures were taken. However, as shown in Figure 7, the recorded PPV well exceeded the limits established for the project.

To ensure that structural instability of the historic buildings was limited during pile driving activities, Schnabel monitored some of the existing cracks in a proactive matter. At the time of this paper, the crack gauges had been read for about 2 years. Schedule of readings solely depended on the amount of pile or sheet pile driving activity at a certain area. Also, the crack gauges located at a radius of about 50 ft from the pile driving activities were checked right after each pile was driven that exceeded the established vibration limit.

Figure 9 presents a summary of the maximum recorded crack opening for the period of time that the crack gauges were read. The abscissa is the crack gauge number, the ordinate denotes the resultant crack gauge opening from the horizontal and vertical components. The presented maximums include any increase in crack opening caused from pile driving, sheet pile installation, vibrations from equipments and seasonal expansion contraction of the materials were the crack gauges were installed (concrete, brick, etc.).

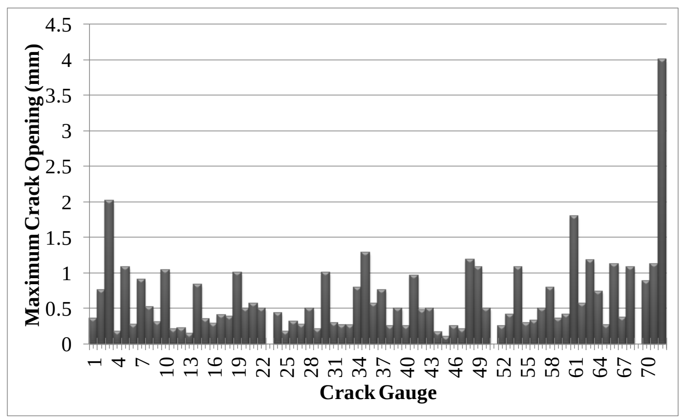


Fig 9. Maximum recorded crack opening during construction.

The maximum recorded increase in crack opening, with the exception of crack gauge # 72, was about 2 mm (7.87 x $10^{-2}$ in). Crack gauge #72 was not installed on a crack, but on a joint between an old and a new construction of a hallway. For this crack gauge, the maximum recorded opening was about 4 mm (0.16 in).

The recorded crack gauges readings indicate that the constructions activities at the Island did little to none effect on the historic buildings.

At the time that this paper was written, the construction of the full system to stabilize the seawall at Ellis Island was not completed. Therefore, the information from the post construction survey was not available. However, the recorded crack gauge data shows that the existing cracks of the historic buildings didn't present any significant movement that leaded to think of any vibration induced structural or aesthetical damage.

## CONCLUSIONS

The seawalls and the historic buildings at Ellis Island are deteriorated. The stabilization plan using driven H-Piles and ground anchors threatened to induce further damages to the historic buildings. The vibration monitoring plan accomplished its objectives, providing the project engineers records of the vibrations transmitted from the driven piles to the surrounding ground close to the historic buildings. Using moveable vibration monitoring stations, Schnabel was able to fulfill the project specifications maintaining a coverage of a radius of 200 ft at all times of pile driving activities with the use of only 4 seismographs.

The recorded PPV induced by the majority of the driven piles at Ellis Island exceeded the limits established on the project specifications. Also, some of the piles exceeded the maximum PPV commonly used in the literature. The common maximum recorded PPV was 0.4 in/sec, which is 5 times higher than the 0.08 in/sec established limit.

Estimated PPV attenuation using Equation 2 well suited the measured. It provided good prediction of PPV with scaled distance for distances to source of up to 100 ft. For distances greater than 100 ft, this equation over estimated the PPV at the Ellis Island site.

The recorded PPV exceeded the threshold established on the project specifications, as well as the limits established by the Swish Standards, Whiffen (1971) and ASSHTO (1990). However, the crack monitoring shows that the existing cracks didn’t open significantly. The maximum recorded increase in opening of a crack was about 2 mm throughout the course of construction. This amount of increase in crack opening is considered nominal and not of a concern for the historic structures.

The historic buildings at Ellis Island were not greatly affected by the vibrations induced by pile and sheet pile driving. For this type of construction, the PPV limiting criteria that best suited was that proposed by Dowding (1996), which is 0.5 in/sec.

The fact that the buildings are founded on piles may be reason of why these buildings withstood the induced vibrations in such manner. It is possible that, if the buildings were founded on shallow foundations, the behavior under induced vibrations of such magnitude would have been more significant.

ACKNOWLEDGMENTS

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