# Impact of Construction-Induced Vibration on Vibration-Sensitive Medical Equipment: A Case Study

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**Abstract:** Many metropolitan cities suffer from a shortage of land supply, which results in new development in areas with high building density. Construction activities, particularly piling processes, may generate excessive ground-borne vibrations. The nearby sensitive people, facilities and buildings (e.g. hospitals and healthcare institutions) are often vulnerable to such excessive vibrations. However, the impact of construction-induced vibrations on sensitive medical equipment is rarely discussed. The vibration limits commonly adopted by the construction industry are mainly with regard to structural safety, which are considerably greater than the tolerable limits for sensitive medical equipment. This case study evaluates the potential effect of ground vibrations induced by piling activities on sensitive medical equipment. The ground-borne vibrations induced by two piling methods are quantified by field measurements. The indoor floor vibrations are simulated using building models. The vibration limits for a large number of sensitive items of medical equipment are established through questionnaires to the manufacturers. The potential risk to the functionality of the concerned equipment is illustrated by comparing the tolerable vibration limits with the predicted vibration levels.

**Key words:** construction-induced vibration, mini-piling, safe separation distance, sheet piling, vibration criteria, vibration-sensitive medical equipment.

## 1. INTRODUCTION

To mitigate the land supply shortage in densely urbanized metropolises, new development or redevelopment in high-density areas is becoming a common solution. However, construction projects in close vicinity of existing structures cause various problems. Construction activities such as pile driving and heavy equipment operation induce ground-borne vibrations, which can influence the surrounding sensitive buildings, facilities, and people. For example, in hospitals and healthcare institutions, high-fidelity medical equipment and patients are vulnerable to the vibrations induced by nearby construction activities. In the past two decades, the effect of construction-induced or other man-made vibrations on structures has received substantial research attention (Wiss 1982; Selby 1991; Dowding 1996; Skipp 1997). The California Department of Transportation (2010) summarized typical vibration-exciting construction activities, including vibratory pile drivers, pile excavation, vibration compaction, impact pile drivers, blasting, drop balls, and so on. Among them, pile drivers are one of the major continuous vibration sources. Selby (1991) reported residence annoyance caused by nearby piling activities. Hope and Hiller (2000) studied the propagation prediction model of ground-borne vibrations from percussive piling. Hwang and Tu (2002) measured the ground vibtations induced by vibratory

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gravel pile construction, and characterized them in time and frequency domains. Athanasopoulos and Pelekis (2000) evaluated the effect of vibratory sheet piling on surrounding buildings and occupants. BS 7385-2 (1993) provided a good collection of historical measurement data of construction-induced vibrations. In particular, extensive studies were published on vibrations induced by impact pile drivers (Martin 1980; Wiss 1982; Dowding 1996; Schexnayder and Ernzen 1999; Masoumi *et al.* 2007) and vibratory pile drivers (Wood and Theissen 1982; Wiss 1974; Morris 1991; Masoumi *et al.* 2007). The ground-borne vibration propagates to a distant receiver as an elastic wave. Wave propagation is a rather complex process affected by soil, wave and structural mechanics (Xu *et al.* 2003). Construction-induced ground waves travel predominantly by Rayleigh waves and secondarily by body waves (Amick 1999). The vibration amplitudes attenuate with the distance travelled due to geometric and material damping (Woods and Jedele 1985). Kim and Lee (2000) studied the propagation and attenuation of various ground vibrations induced by blasting, friction pile driving, and hydraulic hammer compaction. Other relevant studies include ground-borne vibrations induced by road and railway traffic (Watts and Krylov 2000; Hao *et al.* 2001; Mhanna *et al.* 2012; Sheng *et al.* 2006; Fiala *et al.* 2006; Yang and Hsu 2006 and ground shocks induced by blasting (Wu *et al.* 1998). Additionally, Xu (2011) and Behnia *et al.* (2013) studied the walking induced vibrations of cold-formed steel floors and composite floors, respectively.

Meanwhile, vibration criteria have been proposed or defined in various specifications and codes in consideration of structural safety, human comfort and equipment functionality (e.g., ASHRAE 2011; BS5228 2009; BS7385 1993; California Department of Transportation 2010; ENV1993-5 1993; HKSARG 2004, 2006). Although construction-induced vibrations have drawn particular attention in the past, their impact on sensitive medical equipment located inside a building is rarely discussed. The vibration limits commonly adopted by the construction industry are mainly based on structural damage, which are not only considerably greater than the tolerable limits for sensitive equipment, but also expressed using a different index. Given that sensitive high-tech equipment requires immense investment and plays an important role in the daily operation of hospitals and healthcare institutions, protecting the sensitive equipment against excessive construction-induced vibrations is essential.

Thus, a systematic assessment of the impact of vibrations induced by construction activities on sensitive medical equipment is conducted in this study based on a real extension project of a healthcare institution located in Hong Kong. The existing vibration criteria in various codes and empirical quantification of construction-induced vibration strength are first introduced in this paper. Field measurements were conducted to quantify the ground-borne vibrations induced by two common piling methods, namely, vibratory sheet piling and mini-piling. The dynamic response of indoor building vibrations is subsequently simulated. The simulation results indicate the potential risk to the functionality of the concerned sensitive medical equipment due to nearby piling activities. Safe separation distances are numerically determined for different limit states. Although this paper evaluates the vibration impact of two piling methods in the case study of a real healthcare institution, the methodology and conclusions of this study will shed light on the vibration study on other sensitive high-tech devices or facilities in terms of construction, traffic, or human activities.

## 2. VIBRATION CRITERIA FOR MEDICAL EQUIPMENT

A variety of vibration criteria have been proposed with regard to structural safety, human comfort, and normal production order. Two vibration indices are commonly adopted, namely, peak particle velocity (PPV) and root mean square (RMS) velocity in 1/3 octave band spectrum. The former is widely used by the construction industry in the vibration criteria to prevent structural damages. For example, Figure 1 shows the acceptable vibration limits defined in Eurocode 3 (ENV 1993-5 1993), Hong Kong's Foundation Design and Construction code by Civil Engineering and Development Department (2006), and British Standard (BS7358 1993) in consideration of potential structural damage. All of them include the vibration criteria for different types of buildings, but only British Standard adopts the frequency-dependent vibration limits. Among them, the Hong Kong code is the most conservative, in which the vibration limits (in terms of PPV), are dependent on building functions and range from 3 mm/s to 15 mm/s.

The vibration criteria suggested by ASHRAE (2011) are widely adopted for human comfort and various sensitive equipment (e.g., in BS5228 2009). The vibration criteria are defined with regard to RMS velocity in the 1/3 octave band spectrum, in which each band covers a specific range of frequencies whose upper band frequency is $\sqrt[3]{2}$ times the lower band frequency. Figure 2 shows the velocity curves corresponding to different vibration criteria. For example, the vibration limits considering building functionality are 800, 400 and 200 μm/s for workshop, office and residential areas,

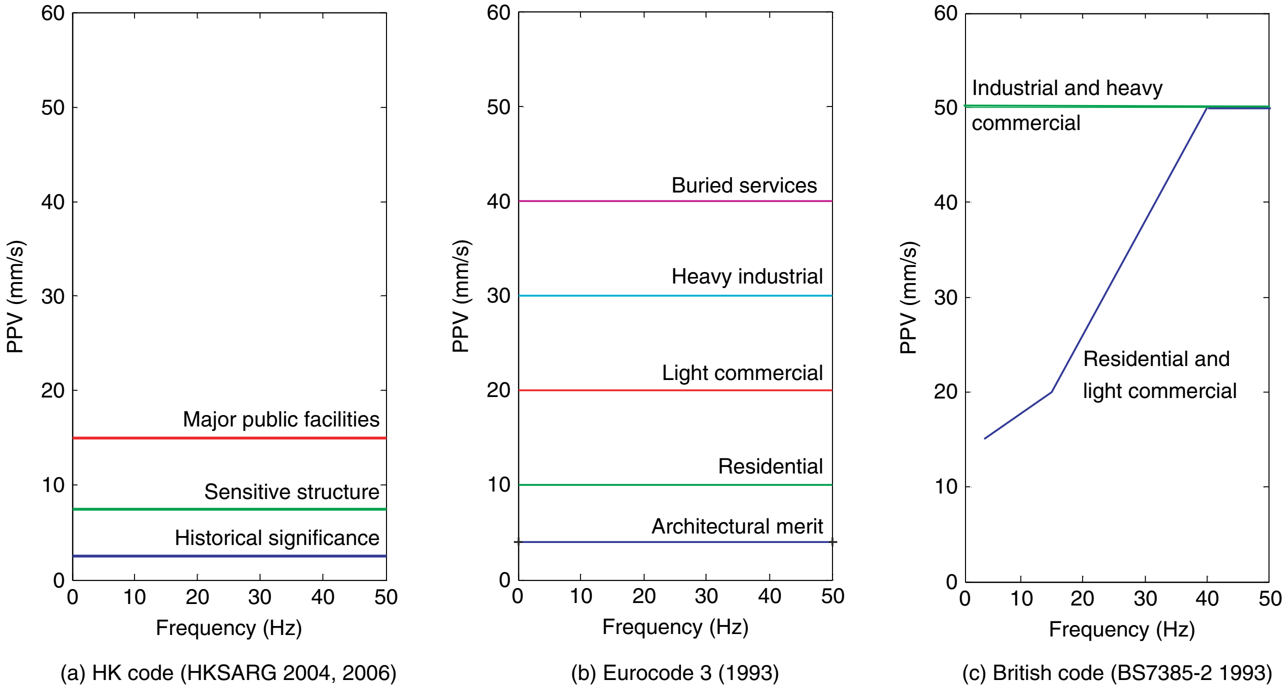


**Figure 1.** Maximum acceptable vibrations to prevent structure damage

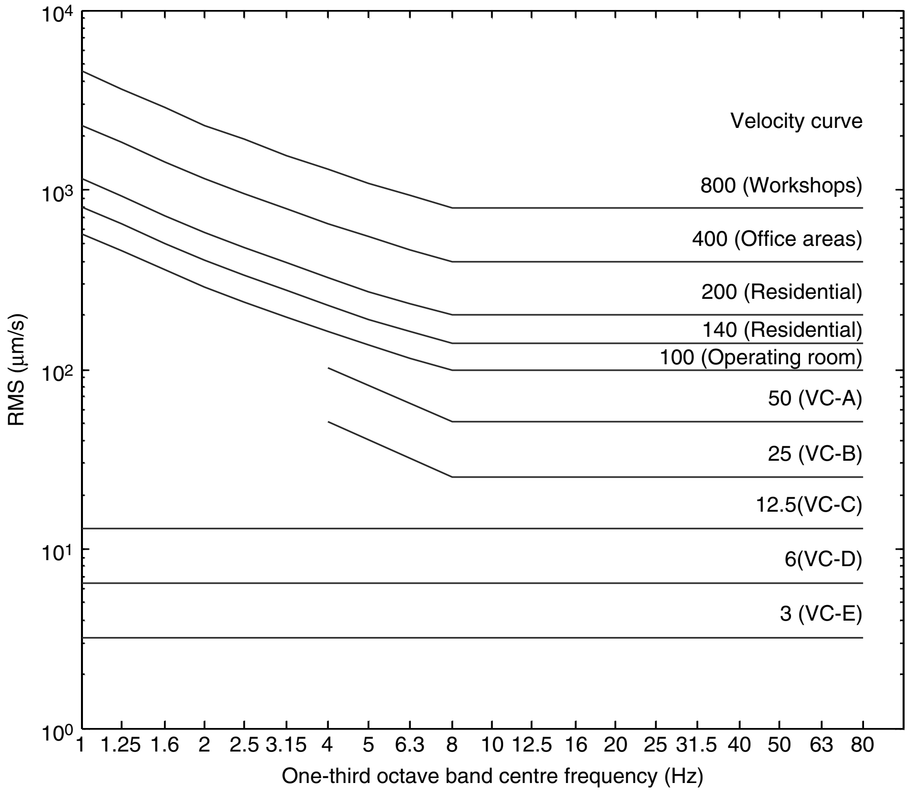


**Figure 2.** Vibration criteria for vibration measured in building structures (ASHRAE 2011)

respectively. The vibration limits for sensitive equipment are much more stringent, ranging from 50 to 3 μm/s. Compared with the aforementioned the vibration limits adopted by construction industry, the stringent vibration limits for sensitive medical equipment are smaller by more than one order of magnitude. They bring new challenges to the construction industry when new development projects are in close vicinity of existing hospital and healthcare institutions. The impact of various construction activities on vibration-sensitive medical equipment should be carefully assessed and minimized.

However, no specific vibration criteria are available in the literature for common medical equipment. In light of this, questionnaires regarding the allowable vibration limits were sent to the manufacturers of 33 types of medical equipment in the concerned healthcare institution in this study. By soliciting professional opinions from the healthcare institution, these 33 types of medical equipment were identified to be vibration-sensitive and critical to the normal operation of the concerned healthcare institution. The results of the questionnaire survey are summarized in Table 1, in which the velocity limits refer to the vibration curves in Figure 2. Although most of the medical equipment can operate safely in office areas (VC-400), some items of equipment require significantly lower vibration levels for normal operation, especially optical equipment. The vibration-sensitive equipment should be well protected if a construction project is ongoing at a nearby location.

## 3. CONSTRUCTION-INDUCED GROUND VIBRATION

The characteristics of ground-borne vibrations generated by construction activities (such as amplitude, frequency and duration) depend on the construction method, soil medium, distance from the source, wave propagation means, and so on. Construction-induced wave propagation from the source through the ground to a receiver is dominated mainly by Rayleigh waves and secondarily by body waves (Amick 1999). The vibration amplitudes attenuate with increasing distance from the source due to the effect of geometric and material damping (Woods and Jedele 1985).

Over the last 30 years, ground-borne vibrations created by traditional dynamic piling techniques have drawn considerable attention. An extensive database of vibrations measured at different construction sites has been compiled, which was used to develop predictive methods (e.g., Head and Jardine 1992). Most of the proposed empirical formulae, although different, take a form of power-law attenuation. A representative example is as follows (Head and Jardine 1992):

$$PPV = C\left(\frac{\sqrt{W}}{D}\right)^n \tag{1}$$

where $C$ is a parameter to be determined according to the measurement, and typically ranges from 0.5 to 1.5; $n$ describes the effect of geometric and material damping.; $D$ is the distance from the vibration source to the location of interest; and $W$ denotes the energy per cycle. The California Department of Transportation (2010) published a guideline that summarizes various transportation- and construction-induced vibrations, in which a highly similar formula is suggested. As the energy per cycle is often unknown for some construction activities, Eqn 1 can be rewritten as follows

$$PPV = \overline{C}\left(\frac{1}{D}\right)^n \tag{2}$$

where the two parameters $\overline{C}$ and $n$ can be determined according to field measurement for different construction activities. Different parameter values are suggested in the standards or literature. The parameter $n$ depends on soil conditions and wave types. For example, Head and Jardine (1992) and Hillier and Crabb (2000) proposed a range from 0.5 to 1, whereas Eurocode 3 (ENV 1993-5 1993) suggests $n$ = 1. California Department of Transportation (2010) defines $n$ based on different soil types that ranges from 1 to 1.4. These parameters can be calibrated according to the extensive database of ground vibration measurement or some site-specific measurements.

Previous literature reported extensive *in situ* ground vibration data, especially for impact and vibratory pile drivers. However, the measurement data of rotary pile drivers are limited in the literature. Rotary piling methods, particularly small-diameter mini-piling methods, are more suitable to construction projects in

**Table 1. Vibration limits of the concerned medical equipment**

| Velocity curve | Number of types | Number of pieces | Operation category or item information |
|---|---|---|---|
| 400 | 25 | 88 | Optical, Centrifugal, Balance, Separation |
| 300 | 1 | 2 | Cell processing system |
| 200 | 3 | 8 | Optical, Centrifugal, Radioactive Substance Inside |
| 100 | 2 | 2 | Optical, Centrifugal, Microscope |
| 50 | 1 | 1 | DeltaRange Analytical Balance |
| 25 | 1 | 1 | Genetic Analyzer Applied Biosystems |

vibration-sensitive areas because of their relatively low energy and vibration levels than vibratory and impact pile drivers. To understand the impact of various piling methods, this study conducted field measurements on several construction sites with on-going vibratory sheet piling and mini-piling activities—two piling methods commonly used by construction industry. Sheet piles are often used as retaining walls during soil excavation, large-diameter bore piles are mainly used as pile foundation, and mini-piles are used as either retaining walls or pile foundations.

## 4. CASE STUDY

Given the high demand for medical services in Hong Kong, numerous extension projects are being planned near existing hospitals and healthcare institutions with the continuity of their normal operations. Vibrations induced by constructions, particularly piling activities, may affect the functionality or even safety of certain sensitive items of medical equipment that are critical to their services. To assess the potential impact, piling-induced vibrations of a representative healthcare institution were systematically investigated in this study through a series of field measurements and dynamic simulations. Two common piling methods, namely, vibratory sheet piling and mini-piling, were assessed. The former is a typical vibratory piling method that is a convenient and quick option for retaining walls, but often produces excessive ground-borne vibrations. The latter represents a rotary piling method that is more costly and time-consuming, but is associated with significantly less ground-borne vibrations. When used for the construction of retaining walls, their operations are often in close proximity to the existing buildings in Hong Kong. This section presents the major findings of this case study.

The concerned healthcare institution is a 3-storey concrete building with a floor area of around 1,500 m$^2$. The building was built on a shallow raft foundation, and the typical column space is 6.2 m. Over 100 pieces of sensitive medical equipment are placed in several laboratories inside the building, most of which are located at the near side to the construction site of extension project.

### 4.1. Field Measurement

Although the real extension project was still being planned, a trial mini-pile was driven near the existing building (as shown in Figure 3). The trial mini-pile with a diameter of 219 mm was driven 27.5 m deep using the Odex method until the pile toe slightly penetrated the bedrock. Then, the mini-pile was grouted. The mini-pile was located around 2 m away from the border of

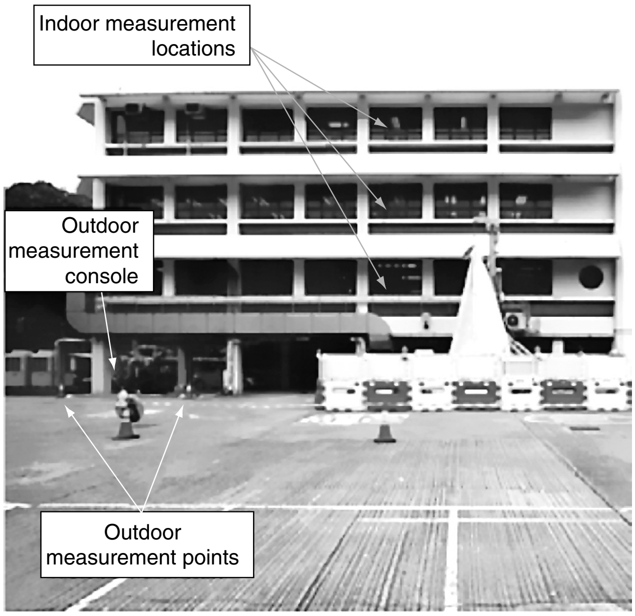


**Figure 3.** Mini-pile test driving location and the nearby hospital building

the existing building, and the distance corresponds to the closest location of the retaining wall in the future extension project. To protect a large amount of sensitive medical equipment in the building, the operation of the healthcare institution was partially stopped during piling. Both the outdoor and indoor vibrations induced by the mini-piling were continuously measured using accelerometers. Figure 3 shows the measurement setup during the trial piling. The ground-borne vibrations were measured at five points with the distances to the vibration source ranging from 4.3 m to 23 m. The acceleration time histories in all three directions were recorded. The accelerometers were mounted on $5 \times 5 \times 5$ cm$^3$ steel blocks, and the steel blocks were tightly attached to the ground. A console for outdoor vibration measurements was set up in the parking area. Four indoor measurement locations were setup in the laboratories with critical equipment (as shown in Figure 4). These locations were distributed from the first floor to the third floor of the building.

Apart from the trial mini-pile test, a series of field measurements were also performed on other construction sites with ongoing vibratory sheet piling, bore piling or mini-piling activities. A similar measurement system was used to measure the corresponding ground-borne vibrations.

### 4.2. Measurement Results

Figure 5 shows the representative time histories of measured ground acceleration in both vertical and radial directions, including baseline, vibratory sheet piling-induced and mini-piling-induced vibration levels. The

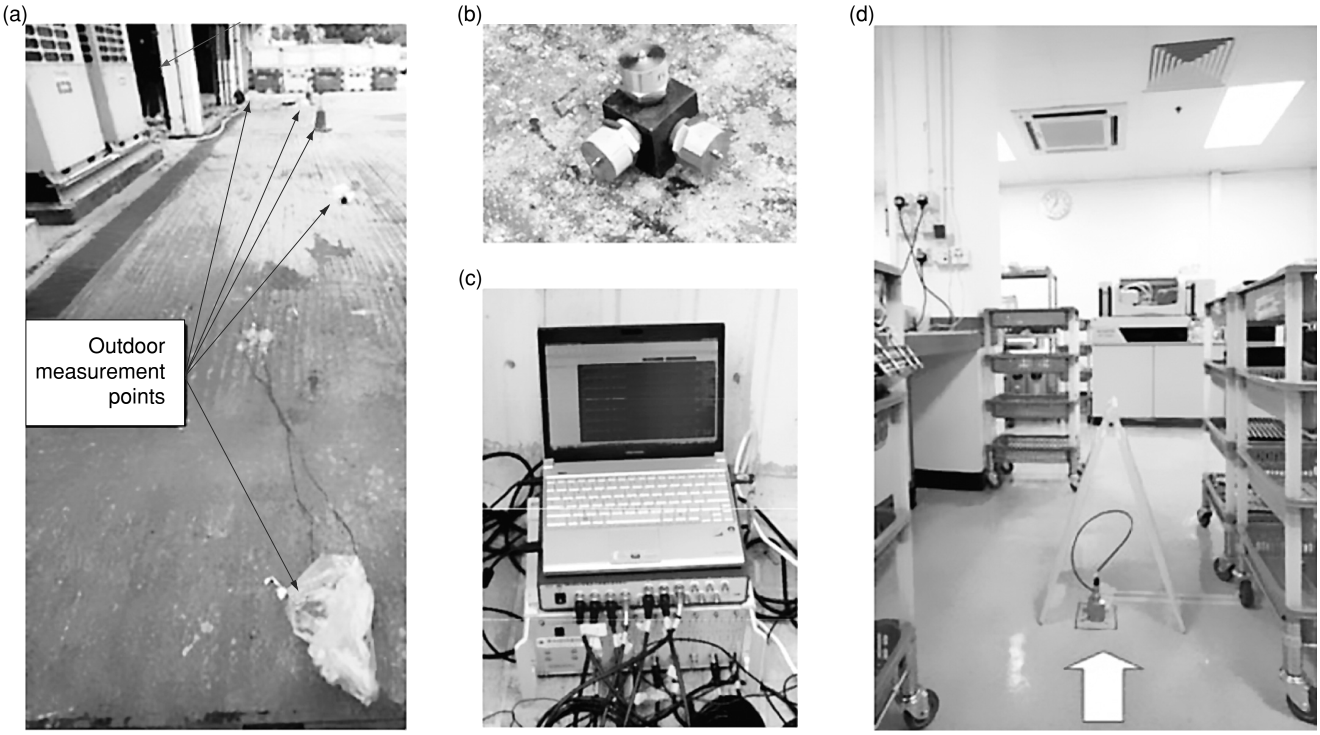


**Figure 4.** Setup of vibration measurement system: (a) outdoor measurement points; (b) accelerometers; (c) data acquisition system and (d) indoor measurement point

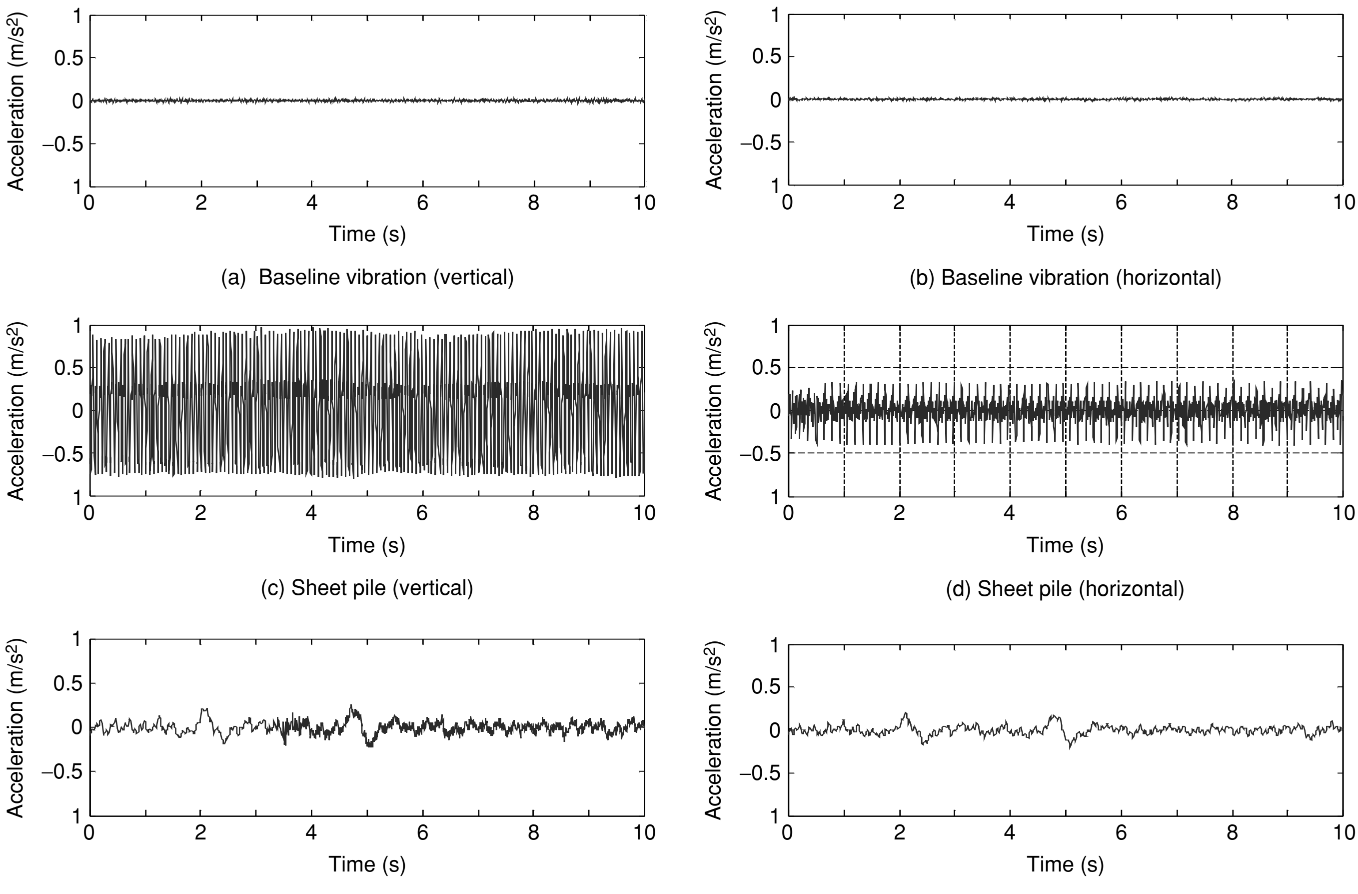


**Figure 5.** Measured ground acceleration time histories

baseline level refers to an ambient vibration level without any construction activities. The comparison indicates that the ground vibration induced by the vibratory sheet piling is over four times greater than that induced by the mini-piling. The ground vibration in the vertical direction is generally larger than that in the horizontal direction for both vibratory sheet piling and mini-piling. The corresponding indoor measurement also reveals that the building floor vibrates predominantly in the vertical direction. Thus, this study mainly focused on the vertical vibrations induced by piling activities.

Since most of the vibration criteria are presented in velocity, the measured acceleration response was integrated to velocity with appropriate signal processing (e.g. filtering). Figure 6 shows the representative time history of the obtained velocity for vibratory sheet piling and mini-piling. The PPV of ground vibrations were identified subsequently. Figure 7 and 8 present the relation between the ground PPV and the plan distance from the vibration source, where the corresponding depth of pile toe is around 2.5 m (the most critical case). Some historical measurement data of vibratory piling in British code BS5228 are also indicated in the Figure 7 by red dots, and they were obtained from the measurements on different sites. The field measurement results obtained in this study were generally consistent with those in the literature. However, no measurement relevant to mini-piling was found in the literature.

It is noteworthy that the PPV value is non-stationary during piling, and is mainly dependent on the measurement duration and calculation method. Considering large scattering in PPV values, the presentation of a single-value PPV may be biased. Thus, the statistical results of PPV are shown in Figures 7 and 8 using a box-and-whisker plot, where the central red mark represents the median, the edges of the box stand for the first quartile Q1 and third quartile Q3, the box height is the interquartile range (IQR), the vertical line represents the normal value range (i.e., from Q1 – 1.5IQR to Q3 + 1.5IQR), and the data out of this range are plotted individually by the dots. For vibratory sheet piling, the normal range of PPV is from 8.3 mm/s to 17.8 mm/s at 2.2 m away from the vibration source; for mini-piling, PPV ranges from 0.76 mm/s to

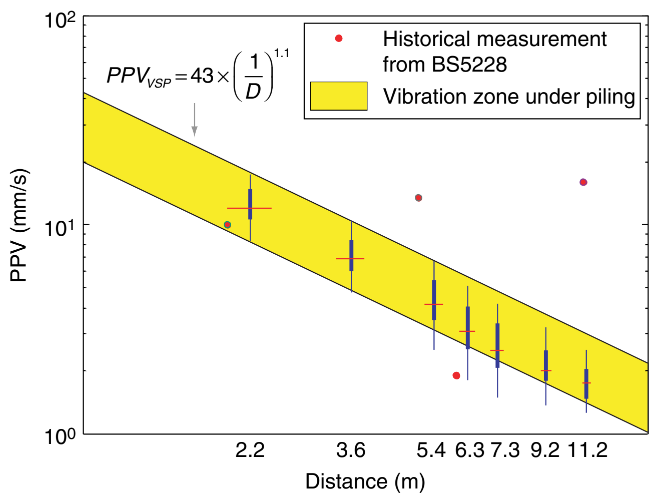


**Figure 7.** Box-and-whisker plot of measured PPV for vibratory sheet piling

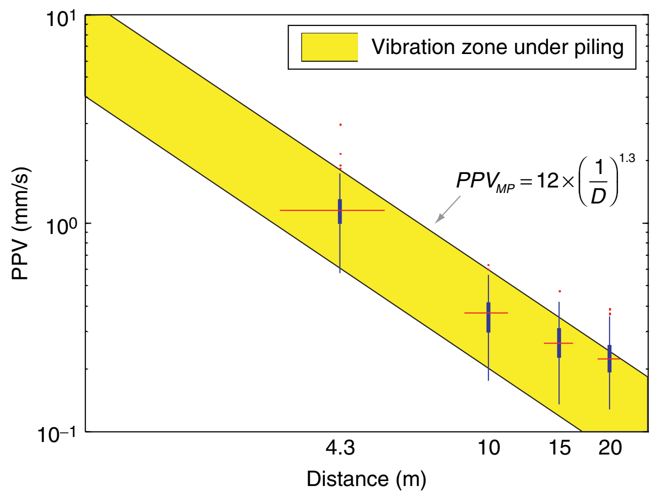


**Figure 8.** Box-and-whisker plot of measured PPV for mini-piling

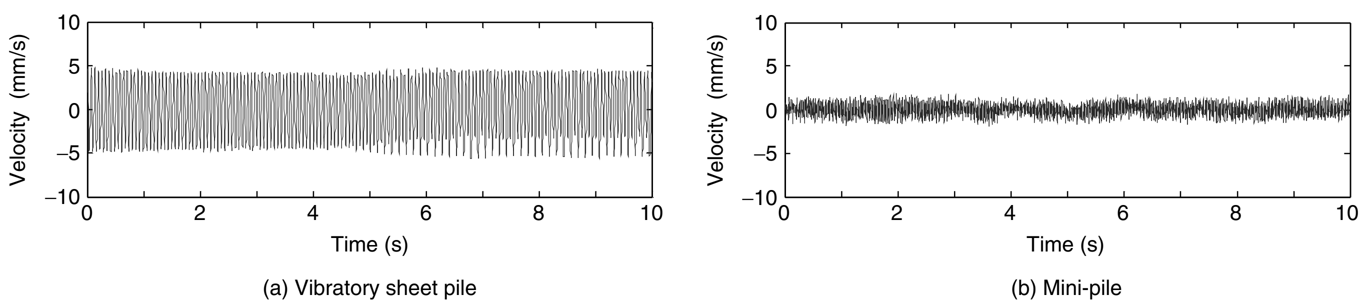


**Figure 6.** Velocity time history (Vertical direction)

1.8 mm/s at 4.3 m away from the source. Figure 8 show that the ground vibrations attenuate rapidly with increasing plan distance. Vibratory sheet piling produces considerably greater vibration levels than rotary mini-piling.

The vibration strength of ground surface also varies considerably with increasing depth during piling. Figure 9 shows the relationship between PPV measured at 4.3 m away from the source and the depth of the test mini-pile toe. The standard penetration test (SPT) was conducted to investigate the soil condition near the piling location, and the corresponding SPT *N* values are shown in Figure 9(c). With increasing pile depth, the soil condition hardened, whereas the maximum PPV in the vertical direction measured on the ground surface decreased. The peak ground vibration occurred when the mini-pile penetrated the top layers of soil. The ground vibration increased slightly at the piling depth of 13 m, when the pile toe encountered a boulder. The frequency analysis of the vibration velocity indicates a dominant frequency of 16 Hz for the ground-borne vibration induced by the mini-piling. The measured sheet piles were only 3 m to 4 m long, and thus no depth effect was clearly observed in the measurement results.

The likely vibration ranges induced by vibratory sheet piling and mini-piling was identified based on the normal value ranges in the box-and-whisker plots and highlighted in yellow color in Figures 7 and 8. The upper and lower bounds were determined through linear regression analysis. The regression functions corresponding to the upper bounds are as follows

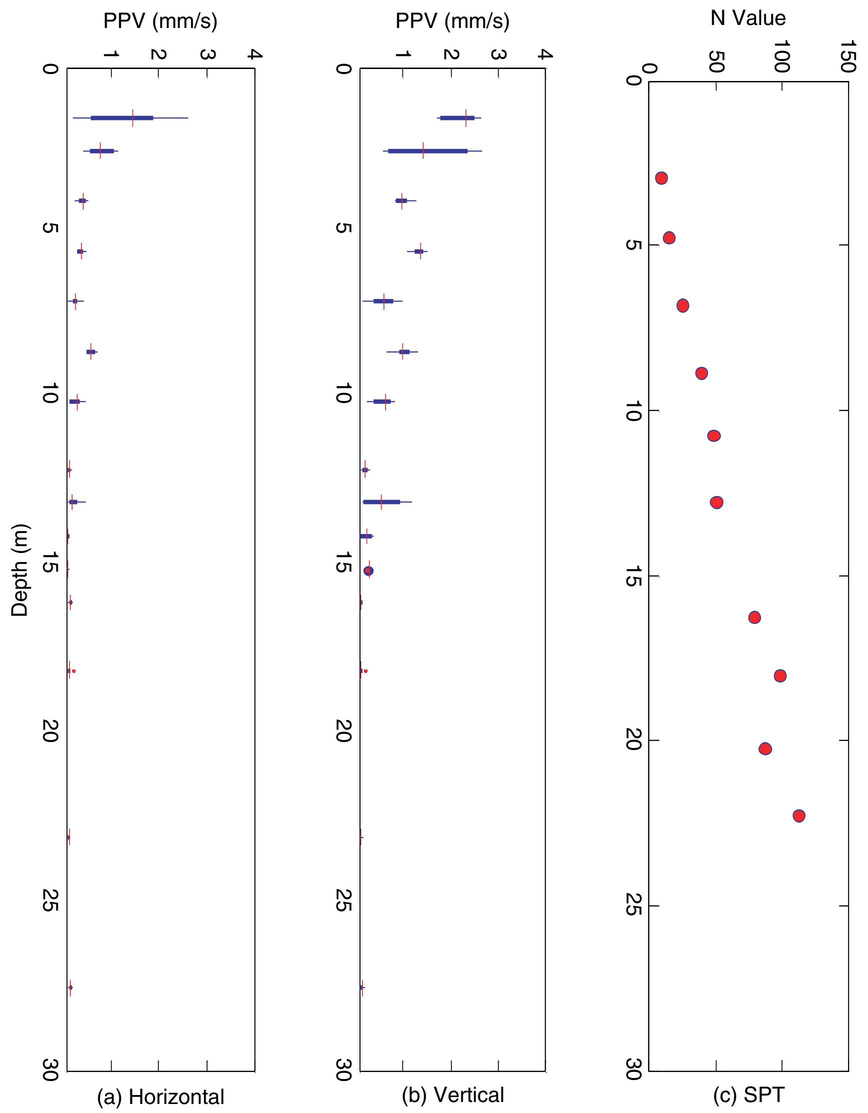


**Figure 9.** Box-and-whisker plot of PPV of mini-pile using Odex method with respect to piling depth

$$PPV_{VSP} = 43 \times (\frac{1}{D})^{1.1}, \text{ (mm/sec)} \quad (3)$$

$$PPV_{MP} = 12 \times \left(\frac{1}{D}\right)^{1.3}, \text{ (mm/sec)} \quad (4)$$

where Eqns 3 and 4 describe the attenuation of ground PPV induced by vibratory sheet piling and mini-piling, respectively. Most of the PPV values in Figures 7 and 8 fall below the two upper bounds. These two empirical formulae were used in the subsequent simulation to predict the spatial attenuation of piling-induced ground-borne vibrations. However, the large dispersion in the observed data and site-specific feature of foundation construction implies that the accuracy of such predictive formulae in real projects may be limited.

## 5. DYNAMIC SIMULATION

### 5.1. Modeling of Existing Building

A 3D finite element model (FEM) of the concerned building was built using software SAP2000 (Figure 10). All major structural elements, including beams, columns, floor slabs and core walls, were properly modeled according to the design drawings. As micro vibrations were studied and the building was designed to be elastic in normal operating conditions, all the materials were assumed to be linearly elastic. The dead and imposed loads were determined according to the Hong Kong Code of Practice (HKSARG 2011). No load factors were applied for the serviceability limit state. The Winkler model (Gazetas 1991; Lam *et al.* 1991) was used to model the effect of soil-structure interaction

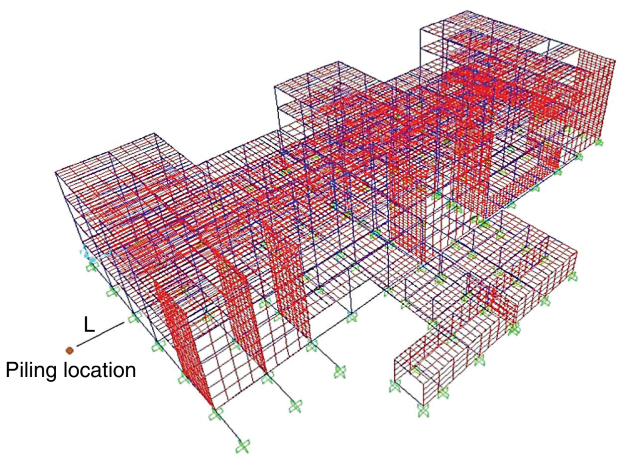


**Figure 10.** Building model of the BTS hospital in SAP2000

at the foundation. In Winkler model, soil-structure interaction is simulated by a soil spring-and-dashpot model. The equivalent stiffness of soil spring can be calculated based on the modulus of elasticity, Poisson's ratio of soil and the dimension of foundation. Comparative simulations were conducted to investigate the effect of soil-structure interaction.

The piling location is on the left of the existing building (as shown in Figure 10). The simulated piling location is consistent with that of the trial mini-pile test in the field measurement. The simulation used the measured ground-borne vibrations induced by mini-piling or sheet piling as the input excitations. According to Eqn 3, the ground motions at the foundations are scaled based on the distance from the vibration source. Thus, non-uniform ground motions were input at the column base. Different cases were simulated to consider the effect of piling depth and the plan distance of piling locations. The FEM model, particularly the property of the soil springs, was updated using the field measurement results of the mini-pile test. The possible vibration levels of the building floors were simulated under the ground motions induced by mini-piling or sheet piling, and then compared with the vibration limits for the concerned medical equipment. Vibration mitigation measures should be taken when the floor vibration is greater than the vibration criteria for medical equipment functionality.

### 5.2. Effect of Piling Depth

Figure 13 shows the effect of penetration depth of the mini-pile on floor vibrations, where the RMS velocity stands for the peak value of one-third octave band spectrum at the dominant frequency. The simulated and measured results, as well as their relative difference, are shown in the figure. The floor vibrations in the figure are the maximum vibration levels within the entire floor plan. The average error was around 10% when the penetration depth was less than 10 m. This value increased with increasing piling depth. The floor vibrations induced by mini-piling decreased with increasing piling depth. Even when the pile toe reached a boulder or rock layer at 11.5 m deep and the piling method was changed to the down-the-hole hammer, the induced floor vibration was significantly smaller than the corresponding penetration of top soil layers using the Odex method.

Thus, the most critical vibration of the building occurs when piling is performed in the top soil layers. Table 2 compares the simulated and measured vibration levels at four indoor measurement points, where the corresponding piling depth is 2.5 m. The average

**Table 2. Comparison of the simulated and measured vibration of building floors induced by mini-piling (piling depth = 2.5 m)**

| | Vibration level: 1/3 octave band spectrum RMS velocity (μm/s) | | | |
|---|---|---|---|---|
| | Point 1 (1/F) | Point 2 (2/F) | Point 3 (3/F) | Point 4 (3/F) |
| Field measurement | 184 | 156 | 173 | 55 |
| Numerical simulation | 178.4 | 188.1 | 193.5 | 62.4 |

difference was around 10%. Based on the significant uncertainties in the modeling of building structures and ground vibration attenuation, the simulation results agree with the measurements reasonably well. Thus, the established FEM model is a satisfactory representation of the concerned building in this case study.

### *5.3. Distribution of Floor Vibrations*

Figures 11 and 12 show the distribution of the floor vibration levels induced by mini-piling and sheet piling, where the vibration levels were evaluated based on the peak value of the one-third octave band spectra. Each room is colored according to the maximum vibration of the floor slab in this room. For example, red means that the maximum floor vibration in the room exceeds the VC-800 curve, but is below the VC-1600 curve. In general, the vibration levels on the three floors have similar magnitudes, but the indoor floor vibration is significantly smaller than the outdoor ground vibration. The dynamic simulations without considering the soil-structure interaction were also performed, although the results are not presented in this paper. The comparison indicates that the consideration of the soil-structure interaction in the building model significantly reduces the floor vibration magnitudes.

The overall floor vibrations induced by mini-piling were small, even if the pile was located 2 m away from the building (as shown in Figure 11). However, the floor vibrations of several rooms exceeded VC-100, which may affect the functionality of eight pieces of medical equipment with very stringent vibration limits (as shown in Table 1). The vibration induced by vibratory sheet piling at the same location was considerably larger (as shown in Figure 12). The maximum RMS velocities of the floor vibration were 1,975, 1,458, and 1,726 μm/s, respectively, for the first, second, and third floors. Thus, the functionality of the majority of sensitive medical equipment would be severely affected. In both cases, the floor vibrations attenuated rapidly with increasing distance to the vibration source. The far end (i.e., the right side) of the

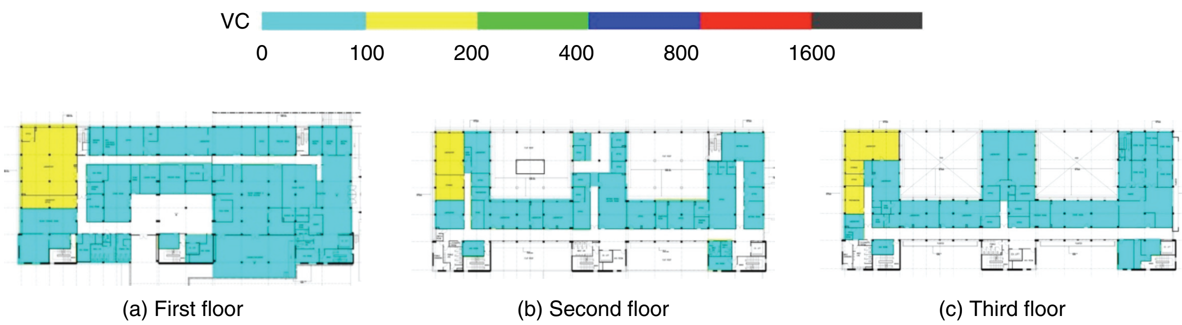


**Figure 11.** Floor vibration level induced by mini-piling (distance = 2 m, depth = 2.5 m)

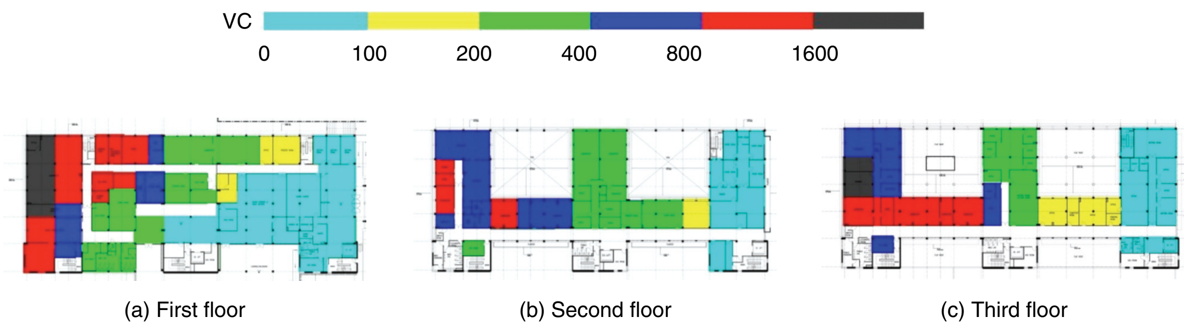


**Figure 12.** Floor vibration level induced by vibratory sheet piling (distance = 2 m)

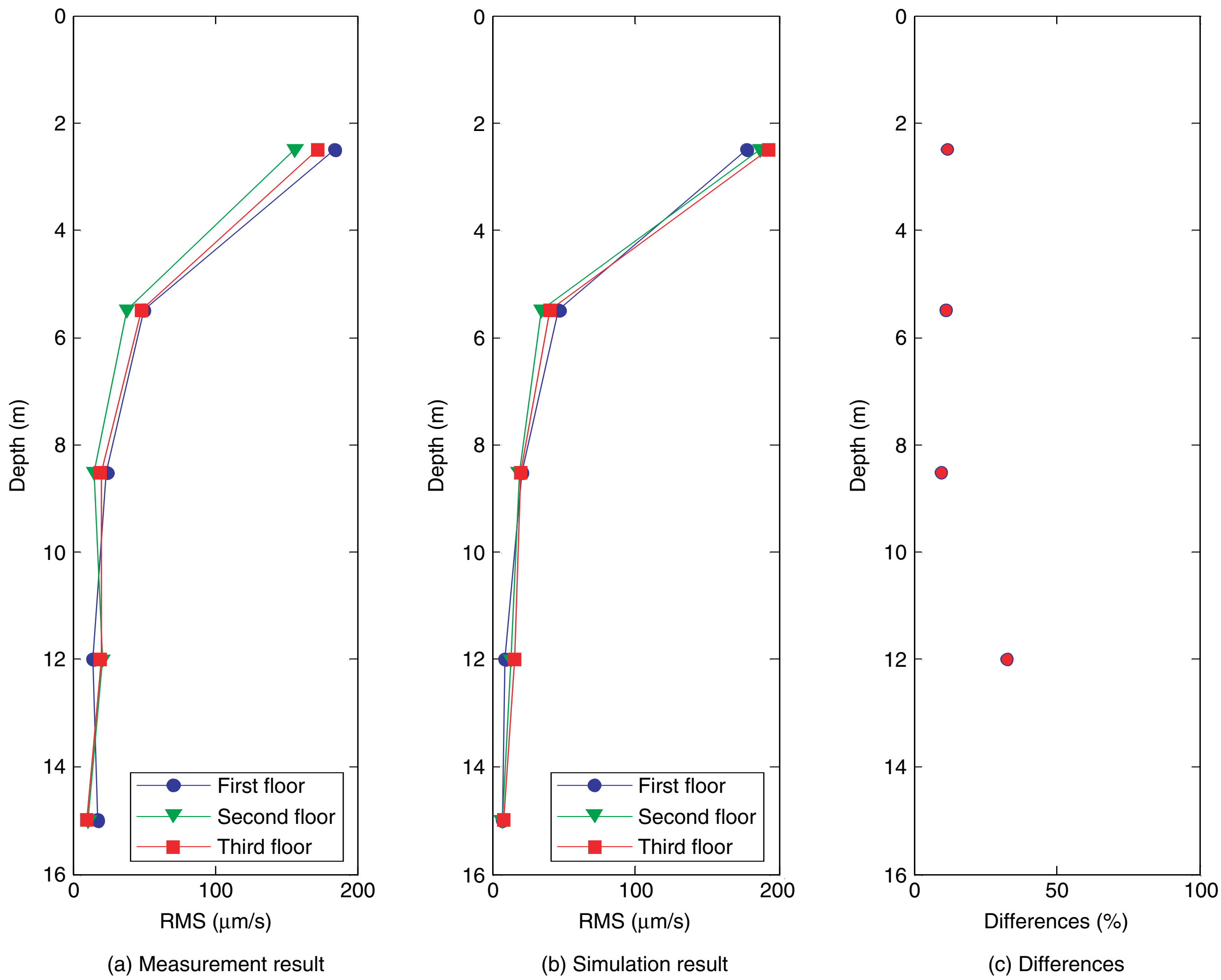


**Figure 13.** Floor vibration vs. piling depth

building floors experienced minimal vibrations, even in sheet piling. Therefore, vibratory sheet piling, as well as other vibratory piling methods, should not be employed if the piling location is very close to a hospital or healthcare institution with sensitive medical equipment, even though this construction method is convenient and quick for retaining walls. The impact piling method also produces a vibration influence similar to the vibratory methods according to the literature and should also be avoided in construction sites that are close to hospitals or healthcare institutions.

For mini-piling, the vibrations of the three floors were highly similar. For vibratory sheet piling, the vibration of the first floor was slightly larger than that of the second and third floors, and the vibration of second floor is the smallest. The results imply that the piling-induced floor vibrations may not attenuate with increasing height in the vertical direction. The vertical distribution of floor vibration levels need to be carefully studied in future research.

### *5.4. Effect of Piling Distance*

Figure 14 shows the comparisons between the ground PPV and the vibration limits considering the structural damage defined in Eurocode 3 (ENV 1993-5 1993), where the PPVs of ground motions induced by mini-piling and sheet piling are described by Eqns 3 and 4. Safe separation distances, defined as the minimal clearance distances between the piling and structural locations to avoid potential functionality or safety problems of structures, were identified from Figure 14 for different types of structures, and are summarized in Table 3. Excessive vibrations produced by vibratory sheet piling may cause severe damage to nearby structures. By contrast, relatively small vibrations associated with mini-piling can ensure structural safety as long as structures are located 2 m away from the piling locations.

Figure 15 shows the relationship between the indoor floor vibration levels and the separation distance from the building to the vibration source, where the vibration levels induced by mini-piling and sheet piling are

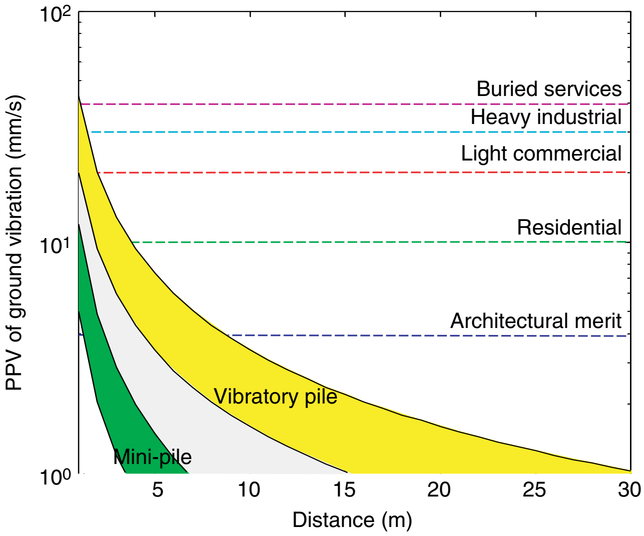


**Figure 14.** The comparison of piling-induced ground PPV with vibration limits

**Table 3. Safe separation distance to satisfy vibration criteria (1)**

| Limit state | Criteria | Safe distance (m)[4] Vibratory sheet pile | Mini-pile |
|---|---|---|---|
| Structural damage[2] | Buried services | 2 | 2 |
| | Heavy industrial | 2 | 2 |
| | Light commercial | 2 | 2 |
| | Residential | 3.8 | 2 |
| Structural functionality[3] | VC400 | 13.5 | 2 |
| | VC200 | 31 | 2 |
| | VC100 | 60 | 6 |
| | VC50 | 100 | 10 |

(1) Assume single piling is conducted at any moment;
(2) Vibration criteria are defined in Eurocode 3 (1993);
(3) Vibration criteria are defined in ASHREA (2011);
(4) The minimum separation distance is set as 2 m, as no vibrations in closer distance were measured in this case study.

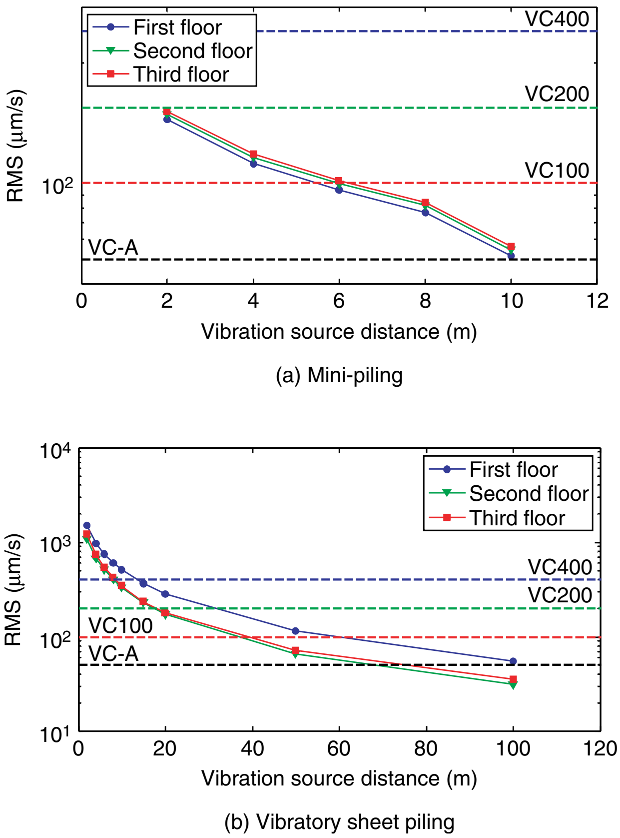


**Figure 15.** Floor vibrations vs. vibration source distance

expressed with regard to the maximum value of the 1/3 octave band spectra within the entire floor area. Typical vibration limits for sensitive equipment are also shown in Figure 15 for comparison. The indoor floor vibrations attenuate with increasing separation distance. Similarly, safe separation distances can be identified from Figure 15 for different vibration limits, and the results are also summarized in Table 3. Compared with structural damage, the functionality of sensitive equipment raises more stringent requirements on the separation distance. Excessive vibrations produced by sheet piling result in a significantly larger separation distance and affected area. This result indicates that vibratory sheet piling (as well as other vibratory piling methods) should be avoided in future extension projects of hospitals and healthcare institutions in Hong Kong because the extension parts are usually very close to the existing buildings. Mini-piling is a preferred alternative because small vibrations are induced. However, mini-piling may still exceed the vibration limits of sensitive medical equipment if minimal separation distance cannot be guaranteed. Other management or mitigation measures should be considered to solve the potential problems, for example, relocating sensitive equipment to farther distances, staggering construction and hospital service schedules, and installing passive or active vibration isolation tables.

## 6. DISCUSSION AND CONCLUSION

In this case study, the impact of construction-induced vibration on sensitive medical equipment in a hospital or healthcare institution was systematically investigated through a questionnaire survey, field measurements, and numerical simulations. The vibration limits of 102 pieces of sensitive and critical medical equipment in a concerned healthcare institution were established by administering 32 questionnaires to the manufacturers or suppliers. The review of different vibration criteria for structural damage, human comfort, and equipment functionality reveals that the vibration criteria for sensitive medical equipment are significantly more stringent than those for structural damage, which are commonly adopted by the construction industry. Two common piling methods, namely, vibratory sheet piling and mini-piling, were evaluated and compared in this study. A trial mini-pile test was conducted near the concerned healthcare institution for the study. Based on the literature review and field measurements, the empirical formulae of spatial attenuation of ground-borne vibrations induced by these two piling methods were developed. Dynamic simulations of indoor floor vibrations were carried out using a 3D FEM model of the healthcare institution building, in which the soil-structural interaction and non-uniform ground motions were properly considered. The impact of vibratory sheet piling and mini-piling was subsequently evaluated by comparing the results with the allowable vibration limits. Both the ground and floor vibrations generally decrease with increasing penetration depth during piling. When located close to the existing building, vibratory sheet piling causes excessive vibrations, which affect the functionality of the majority of sensitive medical equipment and result in some possible damage to the building structure. By contrast, mini-piling induces considerably smaller vibrations of the ground and building floors, and is unlikely to cause any damage to the nearby structures. The safe separation distances corresponding to different levels of vibration limits were identified for vibratory sheet piling and rotary mini-piling through numerical simulations. The substantial separation distance required by vibratory sheet piling may not be realistic in hospital or healthcare institution development projects, in which the extension structures are often adjacent to the existing buildings. Thus, vibratory sheet piling, as well as a wide variety of impact and vibratory pile driving methods, should be avoided in future construction projects with nearby hospitals or sensitive structures. Rotary piling methods (e.g., mini-piling or bore piling) are preferred in these projects to minimize the vibration impact on sensitive medical equipment. However, even mini-piling may exceed the stringent vibration criteria for some extremely sensitive medical equipment when piling is in close proximity to the existing building. Continuous vibration monitoring systems and necessary vibration mitigation measures should be applied to protect vibration-sensitive, critical, and costly medical equipment against excessive construction-induced vibrations. The effectiveness of various mitigation measures, such as trenches, underground barriers, vibration isolation tables, and vibration damping systems, should be carefully evaluated in future research.

Only piling methods are discussed in this paper. The impact of other vibration-prone construction activities needs to be systematically investigated in future. In addition, construction-induced vibrations are highly site-dependent. Factors, such as soil conditions, construction methods, energy levels of construction equipment, and structural properties of nearby buildings, considerably affect the magnitude of construction-induced vibrations. By considering great variability and uncertainty in these site-specific factors, caution should be exercised when using the quantitative results of this study for predictions in any specific projects.

## ACKNOWLEDGEMENTS

The authors are grateful for the financial support from the Hospital Authority of Hong Kong and the Construction Industry Institute Hong Kong (Project No. 5-ZJHG). Findings and opinions expressed here, however, are those of the authors along, not necessarily the view of the sponsor.

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