



Vibration Characteristics of Impact Piling of Precast Concrete Piles

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ABSTRACT

The vibration effects of impact piling in Australian conditions are not widely documented in existing literature. Vibration measurements were conducted in an eastern suburb of Sydney where precast concrete piles were driven into the ground using a hydraulic impact piling method. This paper extracts useful vibration characteristics, such as crest factor, peak particle velocity, number of impacts and dominant frequencies which may be used in analytical piling models. An empirical piling vibration versus distance model is presented as well as minimum working distances useful for a building cosmetic damage screening assessment. It was found that a minimum distance of 36 m and 14 m are required for residential and industrial type buildings, respectively. An additional prediction model for determining required drop heights, distances and ram weight required for compliance with selected vibration velocity thresholds, such as those in British Standard 7385 Part 2 and German Standard DIN 4150 Part 3 is presented also.

1 INTRODUCTION

Impact piling generates ground vibration via the transfer of kinetic energy of repeated hammer impacts into the top of a pile via the drive cap and cushion. The energy travels through the pile shaft and to the pile toe as vibrational energy which is transferred into the ground via the pile/soil interface. This vibrational energy then typically propagates through the ground as body and surface waves towards sensitive receiver buildings and buried assets. The magnitude of vibration levels at a measurement location is a function of several factors, such as distance of the pile toe to the measurement location, impact energy, rate of impact, coupling losses, and soil properties and dynamics. Ultimately, significant impact energy and small pile-to-receiver distances can result in vibration of magnitudes with the potential to cause structural damage to nearby buildings or discomfort for building occupants.

Whyley and Sarsby (1992) present peak particle velocity (PPV) versus scaled distance based on vibration measurements and soil stiffness (stiff or dense, stiff or medium dense, or soft or loose soils) for sheet piling. The authors suggest that their data can be used for other types of piling, e.g., impact piling. Massarch and Fellenius (2015) discuss that the site-specific empirical factor k seen in impact piling vibration models is inversely related to pile impedance and support their findings with case studies.

Transport for NSW's (TfNSW) document Construction Noise and Vibration Guideline (Public Transport Infrastructure) (2023) (CNVG-PTI) was recently updated to list 15 m as the cosmetic damage minimum working distance for "piling rig-hammer" with a "12t down force". The authors could not determine what impact energy this corresponds to as a downforce cannot be converted to an energy. Without knowing the impact energy, it is the author's opinion that the minimum working distances for "piling rig-hammer" cannot be readily applied without further clarification from TfNSW, nor can the results presented in this study be compared to the CNVG-PTI.

2 SETTING

In-situ vibration measurements of impact piling were conducted by SLR in an eastern suburb of Sydney to determine the effects of piling vibration on buildings and occupants nearby the construction site. The piles being driven were precast concrete piles of lengths greater than 12 metres, with a square cross-section of 400 mm sides. The piling rig used was Junttan PMx25 with SHK 110-7 hydraulic impact hammer. The hammer ram weight was 7,000 kg and hammer drop heights were between 200-600 mm, corresponding to an estimated impact energy between 14 kJ and 42 kJ. In this paper, 'energy' is expressed in terms of kilogram-meters, i.e., the energy ranged from 1,400 kg·m to 4,200 kg·m. A photo of the piling rig and one of the piles is seen in Figure 1(a).

The ground lithology typically consisted of a top layer of loose, surficial material, followed by layers of dense to very dense sand and silty sand, with some scattered thin layers of stiff to very stiff clay, a layer of clay/silty clay/sandy silt, and bedrock. The piles were driven to depths so the toes were embedded into the dense sand layer which varies from approximately 3 to 6 m from the ground surface.

A PCB Piezotronics 393A03 accelerometer was hot glued to a stake driven in the ground and an Instanetl Mini-mate triaxial geophone was coupled to the ground using soil spikes. The accelerometer was paired with a Rion DA-21 for data logging and data was recorded at a rate of 1,280 samples per second. The triaxial geophone was paired to a Instanetl Series III Minimate Plus and data was recorded at the minimum sampling rate of 1,024 Hz and peak values were reported over two second intervals. A photo of the sensor installation is seen in Figure 1(b).

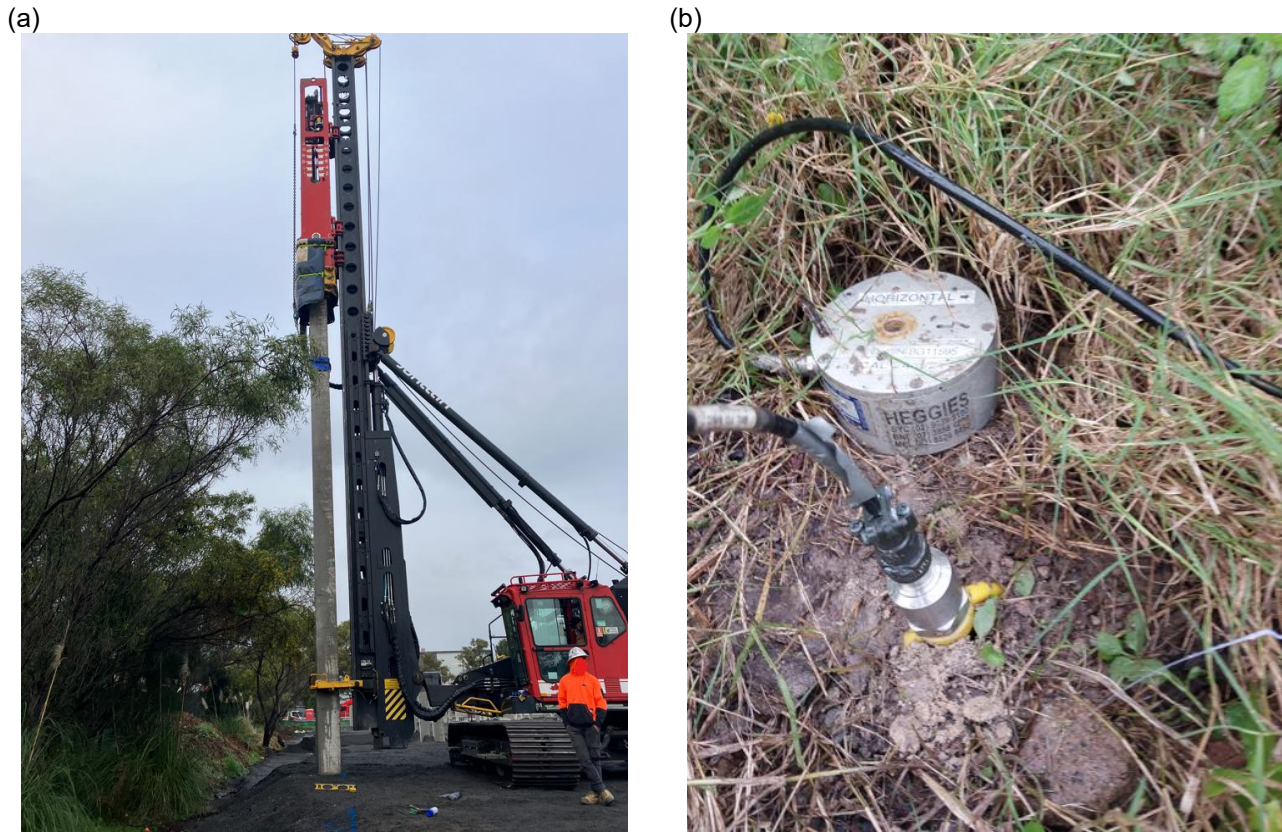


Figure 1: (a) Piling rig and pile (b) accelerometer and geophone installation

The horizontal distance of the vibration sensors to four piles are presented in Table 1. It is more appropriate to use the pile toe to measurement location distance (Massarsch and Fellenius, 2015), however the pile toe depth was not tracked throughout the measurements and the four piles discussed in this paper were driven to approximately the same depth.

Table 1: Horizontal distance from pile to vibration sensors

	Pile 1	Pile 2	Pile 3	Pile 4
Distance (m)	32.1	27.5	10.7	11.8

3 RESULTS

Figure 2 presents vertical acceleration (top sub plot) captured using the PCB 393A03 accelerometer of four pile impacts and the corresponding velocity (middle sub plot) obtained by integrating the acceleration signal and applying a third-order Butterworth high-pass filter with a 1 Hz cutoff. In the velocity time-trace, an individual “impact window” is highlighted, which contains a peak event, i.e., the peak particle velocity corresponding to the impact, and the subsequent decay in vibration preceding the next hammer strike. The bottom subplot is the peak velocity

spectrum of the first impact (1 Hz resolution), showing that the dominant frequency is approximately 25 Hz, with vibrational energy mostly contained between 5 Hz and 35 Hz.

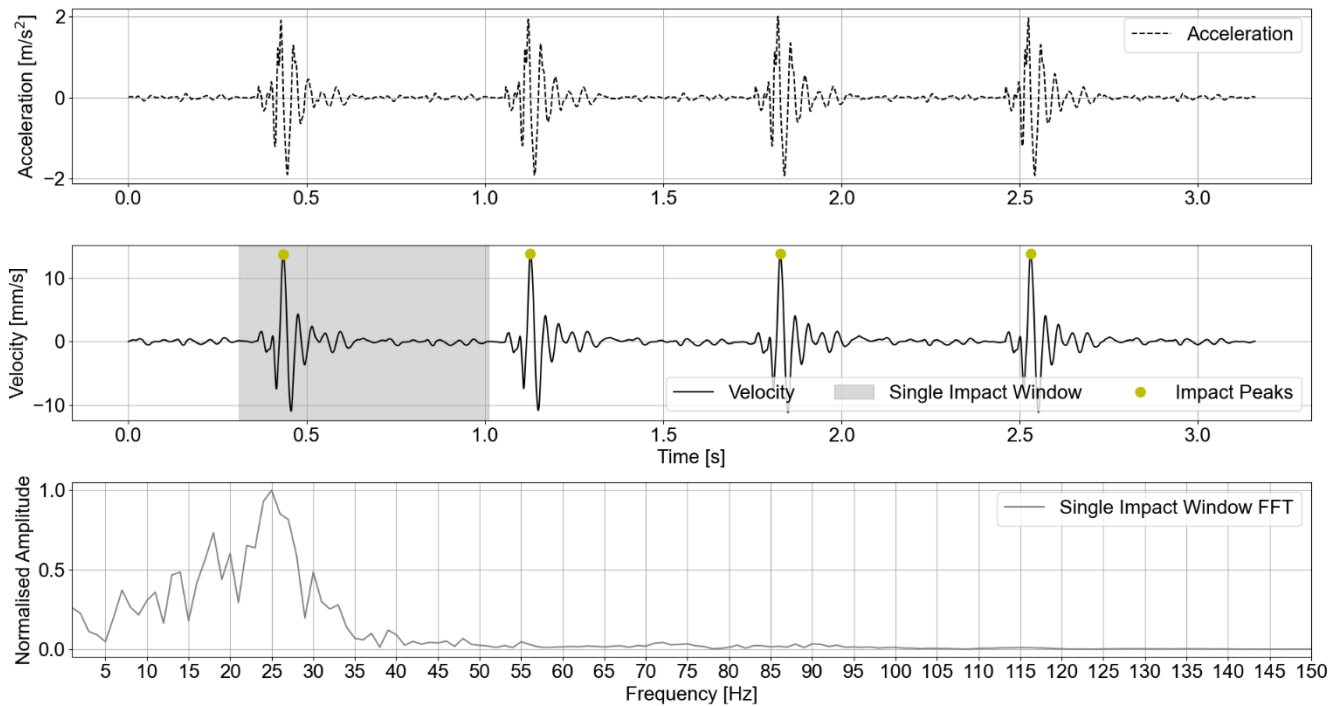


Figure 2: Vibration acceleration (top) and velocity (middle) of four pile impacts and normalized velocity spectrum (bottom) of a single impact.

Figure 3 shows the change in PPV and dominant frequency over the measurement program for three orthogonal directions and the resultant (peak vector sum, PVS) as measured by the triaxial geophone. Pile 3 and Pile 4 had the smallest offsets to the monitor and correspondingly had the highest PPV. On average, the maximum PPV was highest in the vertical direction for all piles except Pile 3 and occurred in the latter half of the pile segment. For Pile 3, the longitudinal direction recorded the highest PPV and occurred in the first half of the pile segment. For all four piles, there is also significant variability in vibration levels for the same direction. Notwithstanding, assessment of vibration in the vertical direction is important as vertical vibration is “most damaging to structures”, “humans are more sensitive to vertical vibration” (Whyley and Sarsby, 1992) and vertical vibration is more prone to amplification than vibration in horizontal directions on suspended floor slabs.

The dominant frequencies displayed in Figure 3 are those that correspond to a PPV greater than 1 mm/s. The range in dominant frequencies recorded across any direction is 10 Hz or greater. The highest PPVs across all four piles correspond to a narrower frequency range of 20-30 Hz.

Figure 4 and Figure 5 present the change in absolute velocity over time for Piles 1 and 4, respectively, based on the accelerometer measurements. A 5 Hz high-pass filter was applied before integration of the acceleration data and any extraneous measurements (such as from footfall) were removed from the analysed dataset. The crest factor (CF) for each pile impact is also presented, where the crest factor is the ratio of PPV to root-mean square (RMS) for each impact window. The figures also show the spectrogram (0.5 Hz resolution and spectra calculated every one second, i.e., 50% overlap) for Piles 1 and 4; the dominant frequency is highlighted using grey circles and is seen to be constant for segments of the piling duration.

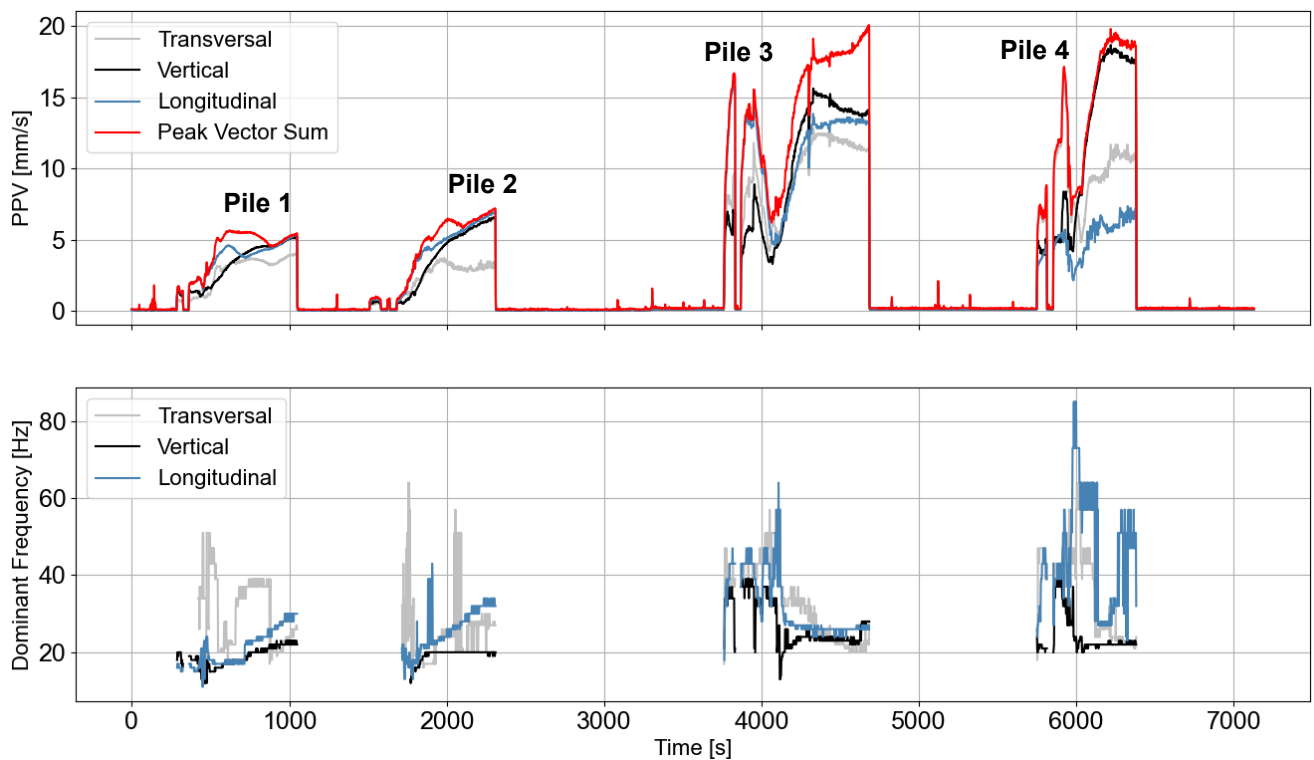


Figure 3: Triaxial PPV (top) and dominant frequency (bottom) measured by geophone. Only dominant frequency of PPV greater than 1 mm/s are shown.

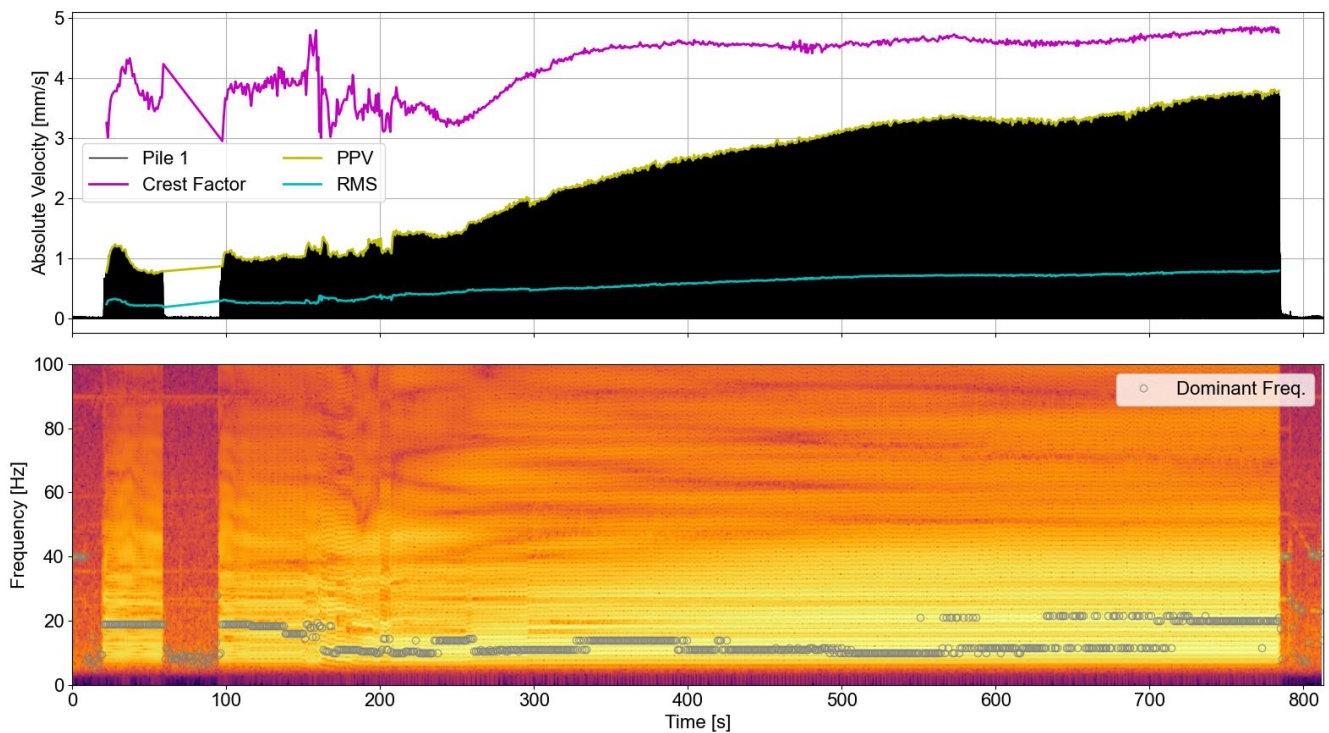


Figure 4: Absolute vertical velocity, crest factor, PPV and RMS time-trace for Pile 1 (top) and spectrogram (bottom). Yellow corresponds to greater energy and purple to lower energy in the spectrogram.

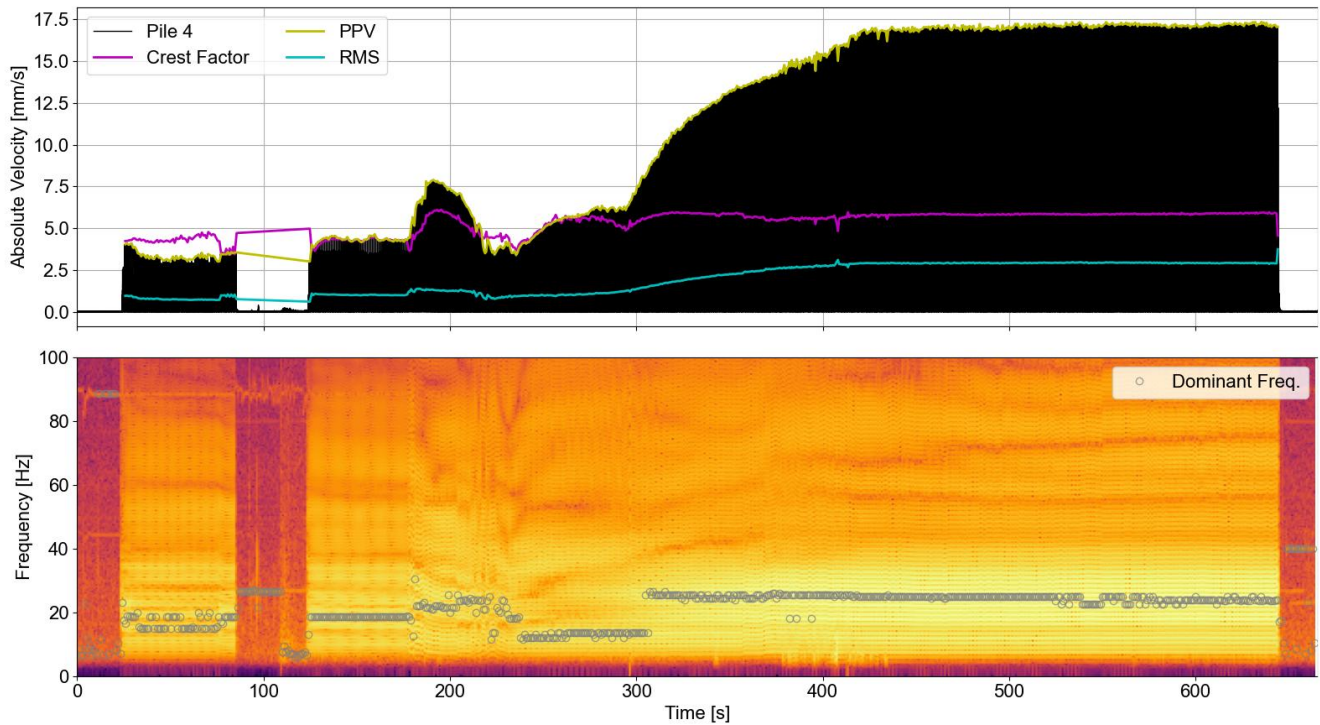


Figure 5: Absolute vertical velocity, crest factor, PPV and RMS time-trace for Pile 4 (top) and spectrogram (bottom). Yellow corresponds to greater energy and purple to lower energy in the spectrogram.

The four pile datasets were further analysed to extract parameters that may be useful for piling vibration models and analysis. Impact window duration, piling time of the analysed dataset, total number of impacts, maximum vertical PPV, crest factor and dominant frequency corresponding to the maximum vertical PPV are summarised in Table 2.

Table 2: Pile summary and vibration characteristics

Pile	Time between Impacts (s)	Piling time examined (s)	Total Impacts	Max. Vert. PPV (mm/s)	CF for Max. Vert. PPV	Dominant Freq. for Max. Vert. PPV (Hz)
Pile 1	0.51 – 1.06	813	990	3.8	4.8	20
Pile 2	0.52 – 1.01	885	1003	5.4	5.1	19
Pile 3	0.47 – 1.11	904	1056	14.2	6.7	25
Pile 4	0.54 – 1.06	793	665	17.4	5.9	25

3.1 Site Law

A large quantity of additional impact piling vibration measurements were conducted across several days for the same construction site. A summary of the maximum PPV levels of each pile versus source-to-monitor distance is provided in Figure 6 (note the log-log scale). In the figure, PVS velocity of each pile is used to develop the plot instead of the peak component particle velocity (PCPV) for conservatism. Because the pile toe depth was not tracked, up to a 6 m depth was used to determine the source-to-monitor slant distance depending on when the maximum PPV value occurred, e.g., if the maximum value occurred at the end of the pile activity then the slant distance is the vector sum of the horizontal distance and 6 m. Data that was measured on soil or on the foundation of a nearby building are distinguished in the figure.

A general ground vibration propagation model from ‘point a’ to ‘point b’ (Amick, 1999) can be described in the following form:

$$v_b = v_a \left(\frac{r_a}{r_b} \right)^\gamma e^{\alpha(r_a - r_b)} \quad (1)$$

where v is the vibration value (e.g., PPV), r is the distance of the point from the source, γ is the exponent associated with attenuation due to geometric spreading and α is the exponent associated with attenuation due to soil damping. This equation can be simplified to a standard power regression curve in the form

$$v = Cr^{-\gamma} \quad (2)$$

when $\alpha = 0$ (no damping is considered), which is a straight line on the log-log plot.

In Figure 6, a power regression curve is fit through the soil dataset (solid grey line) to obtain the site-specific geometric attenuation value γ of 1.2 and coefficient C of 349.7 (referred to as the “average soil model”, herein). The measurements conducted on the foundation of nearby receivers were not used in the regression analysis as the data is clustered at greater distances where damping losses are expected to be more pronounced and the measurements include the coupling loss between the soil and foundation. Fitting a vibration propagation curve without damping terms is therefore conservative as it does not consider attenuation due to damping and only accounts for geometric attenuation. Amick (1999) states that γ value of 1.2 corresponds to value between sands and clays (1 to 1.5, respectively), which fits well to the description of the construction site’s ground lithology.

The worst-case model is derived using the slope from the average soil model and fitting it to the worst-case data point. The worst-case value can be thought of as the data point for which fitting the average soil model to results in no other data point above the regression curve, which means the worst-case model can be considered an upper-bound. Additionally, a worst-case model which incorporates geometric damping and soil damping is derived ($\alpha = 0.008 \text{ m}^{-1}$) which can be seen to be fit mostly to the data measured on soil. From Amick (1999), a soil coefficient of 0.008 m^{-1} which is within the range of “sand and silts” and “saturated clay with sand and silt” after adjusting from metres to feet, which also fits well to the description of the construction site’s ground lithology.

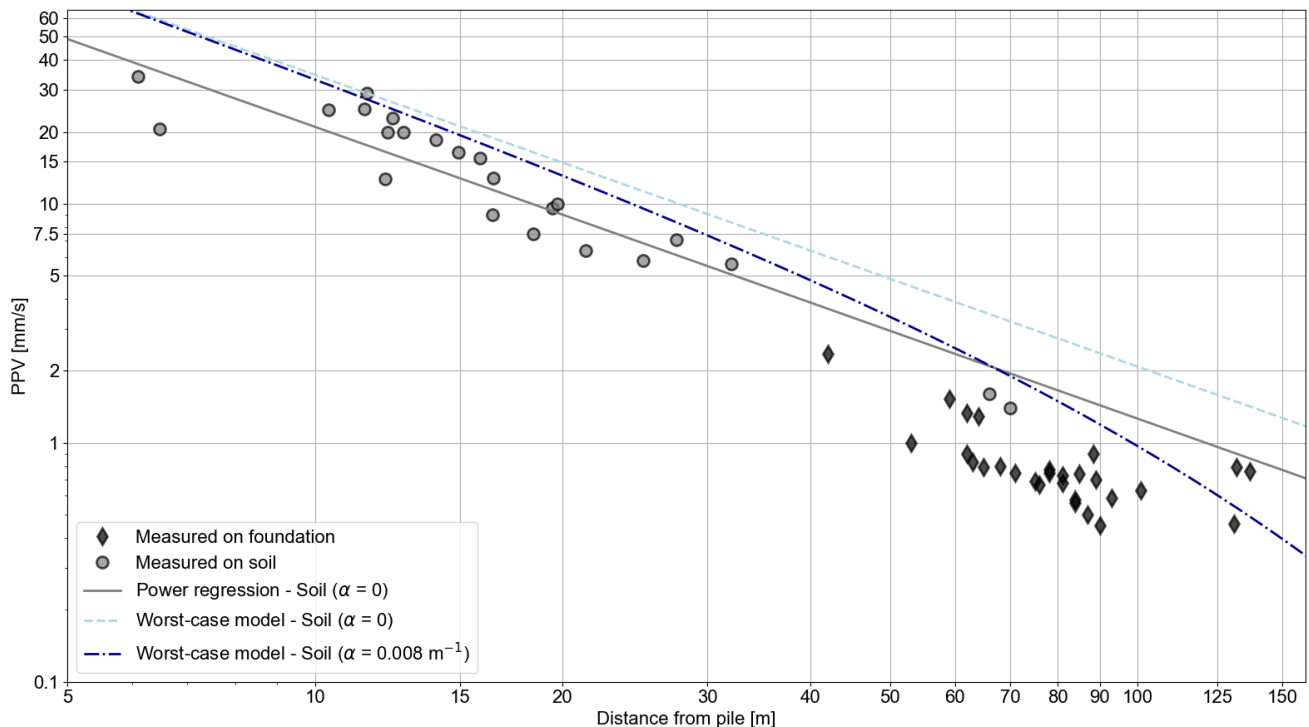


Figure 6: Pseudo-power law for ground vibration peak vector sum versus distance from pile.

3.2 Minimum Working Distances

Minimum working distances (also known as “buffer distances”) for vibration-intensive plant listed in the CNVG can be used as an initial screening tool in the pre-construction phase for highlighting potential vibration impacts to buildings. For the buffer distances derived, conservatism is often favoured to ensure potential risk is captured in the assessments. Based on the site law derived in this study, CNVG-style cosmetic damage buffer distances are

derived using the cosmetic damage thresholds from British Standard 7385-Part 2: 1993 for industrial and heavy commercial structures (Line 1) and residential and light framed structures (Line 2, 4 Hz and 10 Hz) thresholds; a 50% reduction is applied due to the potential for vibration amplification from resonance. The cosmetic damage minimum working distances for the hydraulic hammer piling rig presented in Table 3 are based on the three models seen in Figure 6. The worst-case models correspond to a maximum nominal input energy of 4,200 kg-m (600 mm drop height with 7 tonne ram mass).

Figure 3 to Figure 5 show that the dominant frequency for PPVs greater than 1 mm/s are above 10 Hz, however, it is expected that this dominant frequency range varies depending on factors such as piling technique, site conditions and measurement location. In this study, thresholds for dominant frequencies of 4 Hz and 10 Hz are considered. Potentially higher thresholds can be adopted once in-situ measurements have confirmed the dominant frequencies for a specific site.

Table 3: Minimum working distances of impact piling from sensitive receivers

Equipment	Approx. Size/Weight/Model	Soil damping	Coefficient C	Minimum working distance Cosmetic Damage		
				Residential or light commercial (7.5 mm/s, 4 Hz)	Residential or light commercial (9.1 mm/s, 10 Hz)	Industrial or heavy commercial (25 mm/s)
Hydraulic hammer piling rig	70 t rig with 7 t hammer <600 mm drop height	$\alpha = 0$	C = 349.7 (average)	24 m	20 m	9 m
		$\alpha = 0$	C = 570 (worst-case)	36 m	30 m	14 m
		$\alpha = 0.008$	C = 570 (worst-case)	30 m	26 m	13 m

Figure 7 presents PPV versus scaled distance derived using the worst-case and average soil models (no damping) seen in Table 3 and an impact energy of 4,200 kg-m (approximately equal to 42 kJ). The scaled distance (SD) is defined in Equation (3)

$$SD = \sqrt{J}/r \tag{3}$$

where J is the impact energy in Joules and r is the slant distance from the pile toe to the point of interest in metres. For reference, the worst-case point corresponds to a scaled distance of approximately 17.5.

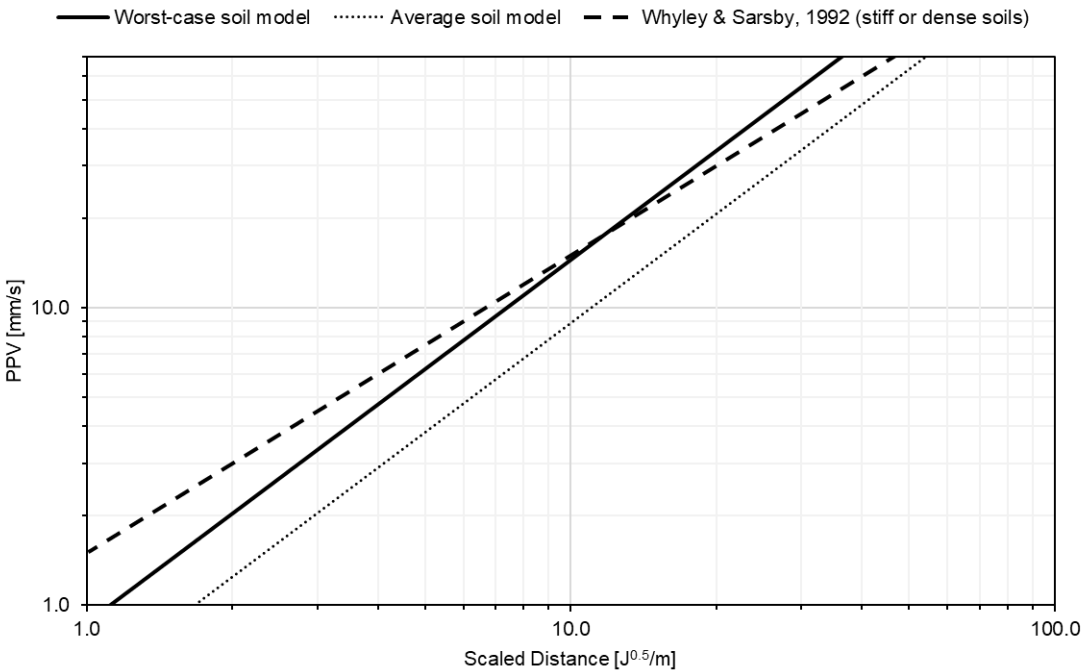


Figure 7: Comparison of peak particle velocity versus scaled distance model between present study and Whyley and Sarsby (1992).

In the figure, it can also be seen that the model derived herein predicts similar PPV values as Whyley and Sarsby (1992)'s model for stiff or dense soils for scaled distances between 1 to 20. It should not be expected for the two models to match due to the different site conditions in which the measurements were undertaken, however similar results are expected as both models are for stiff soils.

Figure 8 uses the worst-case soil model to determine the allowable impact energy required to comply with various PPV thresholds based on the pile-to-receiver offset. For example, for a pile toe-to-receiver distance of 20 m, to comply with a PPV threshold of 7.5 mm/s requires an impact energy of approximately up to 1,000 kg·m; for example, this impact energy could be achieved with a 0.25 m drop height and a ram mass of 4,000 kg.

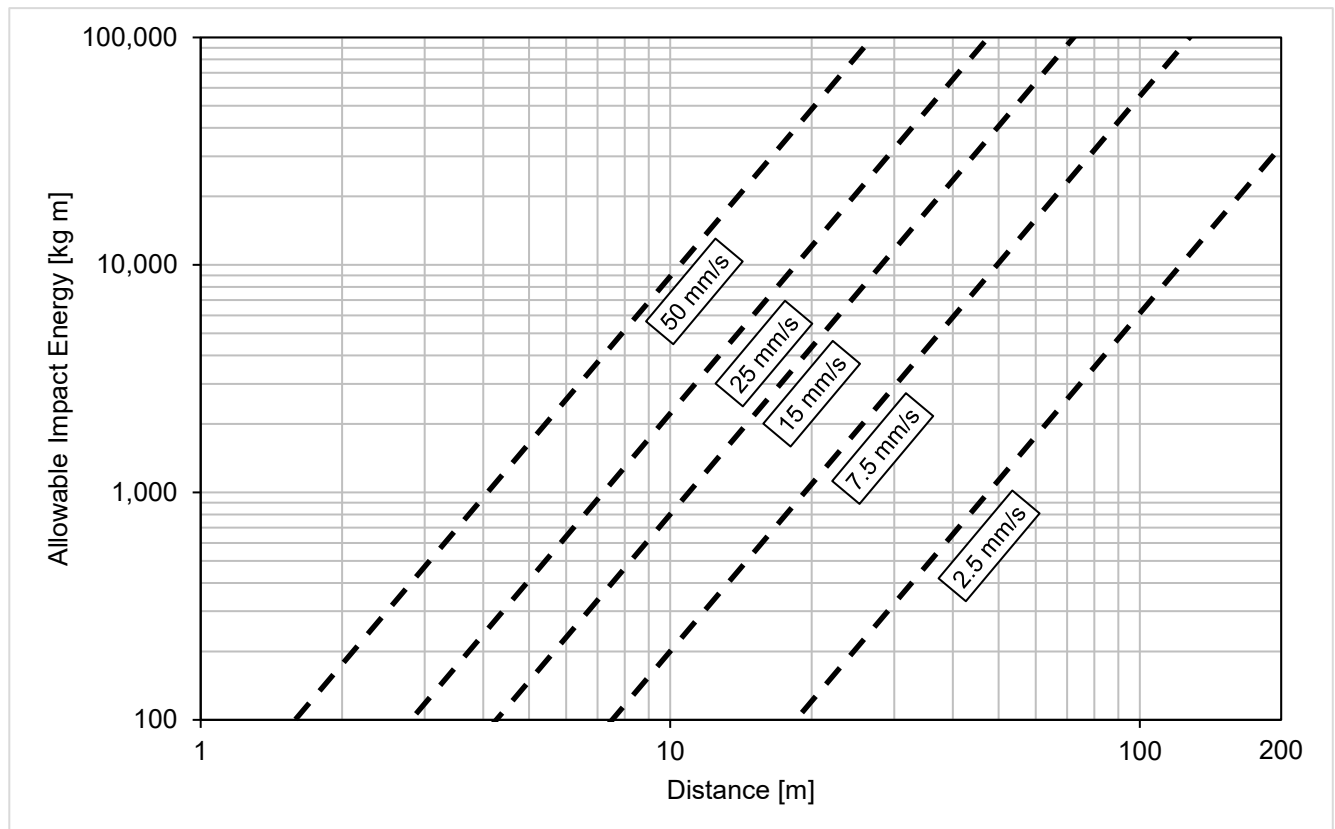


Figure 8: Allowable impact energy versus distance for compliance with PPV thresholds.

4 CONCLUSIONS

Vibration measurements of impact piling of precast concrete piles in an eastern suburb of Sydney are presented in this study. Maximum impact energy considered was 4,200 kg·m, which corresponds to a 7 tonne ram weight falling 600 mm. Parameters such as PPV, piling time, number of impacts, dominant frequency and crest factors which may be useful for impact piling vibration models were extracted from the data. It was seen that vibration is typically highest in the vertical direction, although may be significant in horizontal directions also. The piling vibration energy was mostly contained in the 5-35 Hz range, with dominant frequencies typically around 20-30 Hz, although dominant frequencies as low as 10 Hz were observed.

An empirical model for predicting peak particle velocity of impact piling vibration based on distance was derived based on the average and worst-case measurement data, where no soil damping and site-appropriate soil attenuation ($\alpha = 0.008 \text{ m}^{-1}$) were considered. From this model, minimum working distances for cosmetic damage screening were derived based on thresholds for residential and industrial type buildings as per British Standard 7385-Part 2:1993; the corresponding minimum working distances were 36 m and 14 m, respectively, when soil damping was not considered.

Another variation of the empirical model for determining appropriate piling construction methodology was derived based on the worst-case measured data. The model allows for determining drop heights, ram weight and required

offset from the pile toe to receiver required to comply with chosen PPV thresholds, such as those for buried assets or cosmetic damage for buildings.

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