

THE PROPAGATION BEHAVIOR OF PILE-DRIVING-INDUCED VIBRATION DONE ON SOIL AT VARYING DISTANCES AND ITS EFFECTS ON EXISTING STRUCTURES

Dungca J.R., Acosta D.Y., Juego M.B., Sanchez H.M. and Sanchez I.S.

Gokongwei College of Engineering, De La Salle University Manila, Manila; Philippines

ABSTRACT: Pile driving operations are becoming a prevalent practice in Metro Manila due to the presence of soft soil conditions. However, ground vibrations are induced in the process, which could cause possible structural damages to the nearby existing structures. Ground vibration measurements were recorded at three designated sites at 3, 15, and 30 meters away from the pile-driving source through the use of three of Guralp's accelerometers. A defined attenuation behavior of the emitted vibrations was observed when the pile was in contact with the predominantly sand and silt layers, vibration prediction models for sand and silt layers were formulated and then validated with the measurements obtained at the other two sites, predicted results were correlated to existing vibration limits, a zone of influence was then generated and is capable of identifying the types of structures that are susceptible to structural damage within a radius of the source of pile driving.

Keywords: Attenuation Behavior, Zone Of Influence, Vibration Prediction Model, Vibration Limits, Structural Damage

INTRODUCTION

Pile driving operations are becoming a prevalent practice in Metro Manila due to the presence of soft soil conditions. However, ground vibrations are induced in the process which can lead to cause several negative impacts on the surrounding environment, such as human discomfort, damaging of vibration-sensitive facilities, and ultimately, it could lead to foundation settlements and structural damage.

The case of pile driving is being given more of a concern as many of these operations are being done in highly urban areas, where many structures, such as residential, commercial, old and even heritage buildings are near the project site.

Several vibration limits were established by international agencies to minimize the negative impact these ground vibrations may impart on the environment and vibration prediction models are being constantly formulated and used to predict ground vibration magnitudes, but these models are either too simple or too complicated to be used effectively on site [4], [15].

Since modern construction work is usually done in urban areas, it is essential to determine the different levels of risks that neighboring structures may have when exposed to ground vibrations at different distances away from the vibration source.

BACKGROUND

The transmission of energy from the hammer down to the pile and then to the surrounding soil governs the entire vibration transmission process and forms a crucial part in analyzing the behavior of

ground vibrations. A simple concept of the energy transmission is then presented.

When the hammer hits the pile head, energy is being transferred down to the body of the pile in the form of a compressional body wave [1]. S-waves are generated in the pile shaft and propagate conically from the pile. Compressional (P) – waves and Shear (S) - waves are also generated in the pile toe and they propagate in spherical waveforms in all directions. As these S and P – waves reach the ground surface, a part of the waves are being converted into Rayleigh (R) – waves, as seen in Fig. 1, which attenuate in amplitude in proportion to the square root of distance [2],[3].

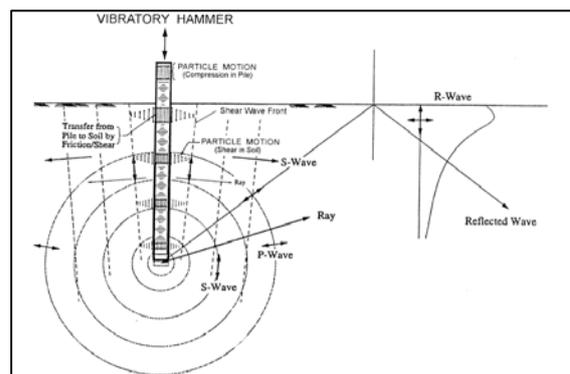


Fig. 1 Waves generated from pile driving operations [5]

Vibration Attenuation and Frequency

Ground vibrations, depending on its type and source of emission, attenuate due to geometric damping. Its attenuation is also influenced by

material damping, due to the presence of different ground properties [5], [18].

The Bornitz Equation considers the combined effect of both material and geometric damping, allowing the propagation of ground vibrations to be extensively characterized as it moves away from the vibration source, it is then expressed in Eq. (1):

$$A_2 = A_1 \left(\frac{r_1}{r_2}\right)^n e^{-\alpha(r_2-r_1)} \quad (1)$$

A_1 and A_2 are vibration amplitudes at distances r_1 and r_2 , n is the geometric damping coefficient = 1 (surface waves), and α is the material damping coefficient. According to [1] and [2], the material damping coefficient (α) can be estimated as a function of vibration frequency (f), and is expressed in Eq. (2):

$$\alpha = \frac{2\pi Df}{c} \quad (2)$$

Where, c is the propagation velocity of R-waves and D is the damping ratio.

The dominant frequency of vibration can then be approximated by knowing the pile and hammer properties and specifications utilized in the pile driving operation, as suggested by [11], and is given in Eq. (3):

$$f_w = k \left(\frac{c}{2\pi L}\right)^\varepsilon \quad (3)$$

Where, ε is the adjustment factor which is dependent on the pile to ram weight ratio denoted by η , L is the pile length in meters, and $k = 0.5$ (Concrete Piles at restrike).

Table I Adjustment factors (ε) [11]

η	0.01	0.10	0.30	0.50	0.70	0.90	1.00	1.50
ξ	0.10	0.32	0.52	0.65	0.75	0.85	0.86	0.98
η	2.00	3.00	4.00	5.00	10.0	20.0	100	∞
ξ	1.08	1.20	1.27	1.32	1.42	1.52	1.57	π

Empirical Prediction Models

Two empirical vibration prediction models were utilized in the study as a basis for validation against the actual vibration measurements obtained on site. These were the empirical models presented by [6] and [7] respectively.

The model suggested by [6] only takes into account the hammer energy (W_0) and the distance away from the vibration source (r), where no consideration is made on the geological conditions of the site; it is then presented in Eq. (4):

$$v = k \left(\frac{W_0}{r}\right)^x \quad (4)$$

Values of $k = 1.5$ and $x = 1$ were adopted for conservative measurements of vibrations [4].

The said model was then utilized in contrast to a more sophisticated vibration prediction model presented by [7], wherein imperative aspects of energy transfer at the hammer-pile and pile-soil interface, and the influence of the soil properties on the vibration magnitude are considered. The model is then expressed in Eq. (5):

$$v_{sv} = k_s F_v E_T \frac{(F^H W_0)^{0.5}}{r_r} \cos\theta \quad (5)$$

Where, v_{sv} is the vertical PPV measurement in mm/s, and k_s , F_v and F^H are the vibration amplification and efficiency factors associated with the model. E_T is the toe vibration efficacy, θ is the angle of incidence of P-waves and r_r is the radial distance from the pile toe to a certain point away from the pile on the ground surface.

Vibration Limits

Several vibration limits were established by various international agencies that can be used as references alongside the empirical vibration prediction models [16]. This is mainly to aid in mitigating the negative effects of vibrations, specifically by providing threshold values for vibration magnitudes in relation to structural damage.

There are 4 frequently used standards on vibration limits [17], and they were incorporated into a single graph, refer to Fig. 2, as presented by [5]. The graph served as the basis for vibration assessment in the study. The graph can be utilized in identifying structures that are vulnerable to structural damage given a certain magnitude of vibration, in terms of the peak particle velocity, and as well as the frequency of vibration.

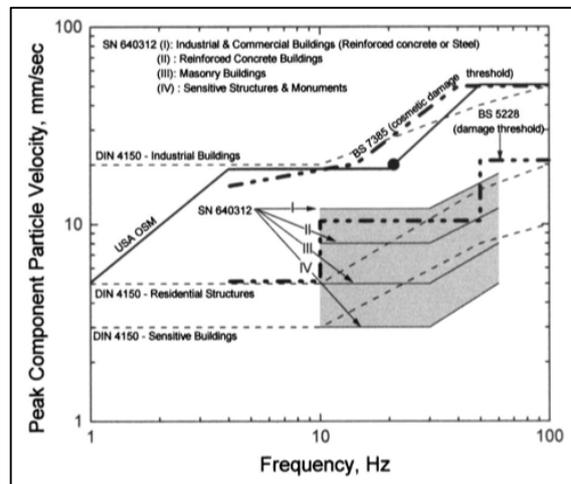


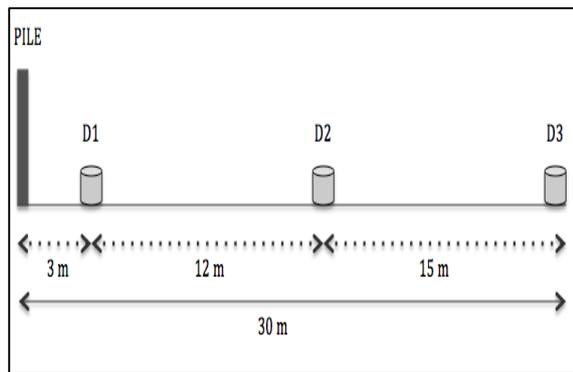
Fig. 2 Vibration Limits suggested by [1]

METHODOLOGY

Data Acquisition

Vibration measurements in terms of the vertical peak particle velocity were taken in AMAIA Steps Pasig condominium in Eusebio, Pasig City (Site A); Three E-com Center in Bayshore Avenue, Pasay City (Site B); and Meridian Park along Diosdado Macapagal Avenue, Pasay City (Site C) through the use of three of Guralp’s Digital Tri-axial Accelerometers positioned at distances 3, 15 and 30 meters away from the vibration source, as seen in Fig 3.

Fig. 3 Placement of accelerometers



Vibration measurements were then recorded throughout the entire duration of the pile-driving operation, they were digitally logged in a computer and were extracted through the use of the SCREAM Software, as provided by Guralp Systems.

The raw data obtained on the three sites were then exported through a strong motion analysis tool, named ART, in which the vibration measurements were analyzed and documented in corresponding measurements of peak particle acceleration, velocity and displacement taken in the North, East and Vertical directions.

Site Information

Geotechnical conditions, determined through the acquisition of the borehole data, revealed that Site A was underlain with predominantly sand and silt deposits having varying soil densities across several layers. Site B was underlain with a top sand layer followed by multiple predominantly silt layers and a sandstone layer at the bottom most soil profile. While, Site C was underlain with a combination of sand, clay and silt layers, with weathered rock layers located at the bottom most layer of the soil profile.

The number of hits needed to drive the piles down to a certain depth below the ground surface were also properly documented together with the corresponding hammer and pile specifications utilized on the three sites, refer to Table II.

Table II Hammer and Pile Specifications

Site	Hammer		Pile	
	Type	Weight	Square	Length
A	Bruce	7100	450	23
B, C	NH70	7000	450	21

ANALYSIS AND RESULTS

Ground Vibrations Measurements

Ground vibration measurements were only taken on the ground surface at the three sites. Upon referring to the times histories, the peak particle velocities (PPV) at each soil type transition were obtained and plotted at three distances away from the vibration source, against the pile penetration depth as shown in Fig. 4.

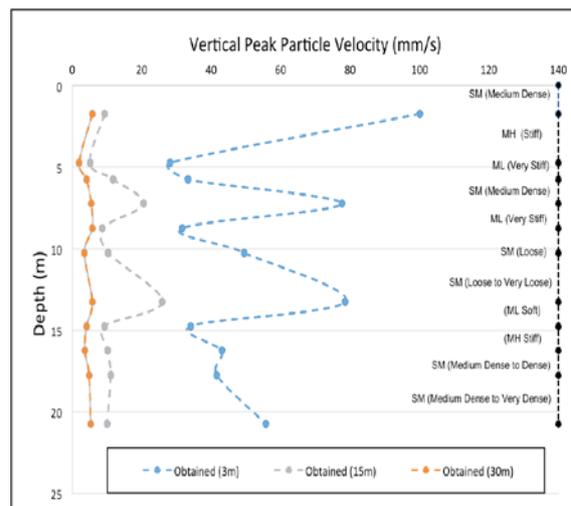


Fig. 4 Vertical PPV readings of the 3rd pile in Site A

During the entire driving process, the highest vertical PPV measurement was obtained when the pile was being driven into the medium dense silty sand layer, situated at 0 - 1.75 m below the ground surface.

It is known that in the case of pile driving in sand deposits, the surrounding soil is being compacted through static pressure [8]. The acquisition of the highest vibration magnitude can be attributed to the compaction of the surrounding soil during pile penetration and as well as the increasing shaft-soil contact area, leading to an increase in the shaft friction of the pile [9].

A sharp decline of the vertical PPV measurement followed upon the transition of the driving from the predominantly sand layer to the stiff clayey silt layer

at a depth of 1.75 - 4.75 m below the ground surface. Pile driving in clayey silt soil layers remoulds the surrounding soil and excess pore water pressures are generated, which could have resulted to the decrease in the shear resistance of the surrounding soil [3],[10], thereby leading to the acquisition of a smaller magnitude of vertical PPV measurement.

The influence of the dynamic soil properties on the vibration magnitude can be evidently seen at a distance near the vibration source, but at a farther distance, it becomes more difficult to determine the influence of the soil types as the vibration magnitudes cluster to a closer range and are almost similar in magnitude.

Frequency Content

Another important parameter in the study is the frequency of vibration, as it is found to be directly proportional to the rate of attenuation, as seen in Eq. (1) and (2). The corresponding frequencies of the vibration measurements were then obtained through the Fourier Transform of the time histories and were analyzed in the Fourier Spectra (Frequency Domain).

In Site A, the frequencies of the vertical PPV measurements ranged from 6 to 15Hz, having an average frequency of 9.33Hz, see Table III. The dominant frequency of the propagating waves due to impact sources has a span of values within 3 to 60 Hz [11], the acquired values were found to fall within the specified range.

Table III Vertical Vibration Frequency in Site A

VERTICAL FREQUENCY FOR SITE A (Hz)										
Depth (m)		1st Pile			2nd Pile			3rd Pile		
Starting Point	End Point	3m	15m	30m	3m	15m	30m	3m	15m	30m
0	0.75									
0.75	1.75	11.33	10.94	8.984	10.94	14.06	10.16	9.375	14.06	9.375
1.75	2.75									
2.75	3.75	8.203	11.33	10.84	9.766	7.422	9.766	7.031	5.859	7.422
3.75	4.75									
4.75	5.75	7.813	7.813	7.422	9.766	8.008	9.375	8.594	12.89	8.984
5.75	7.25	10.55	12.89	7.031	9.766	8.203	7.031	7.813	13.48	11.33
7.25	8.75	8.203	10.16	7.031	7.422	7.813	8.984	9.766	7.813	10.94
8.75	10.25	10.16	13.67	7.031	9.766	8.594	8.594	8.984	12.89	8.984
10.25	11.75									
11.75	13.25	7.031	9.766	7.031	8.594	8.594	7.031	7.422	7.813	7.031
13.25	14.75	10.16	9.766	8.984	8.594	8.594	7.031	8.594	7.817	8.984
14.75	16.25	10.16	9.766	8.789	8.984	8.594	7.031	8.594	8.594	8.984
16.25	17.75									
17.75	19.25	10.16	9.961	8.984	7.813	8.594	10.94	8.984	12.89	10.94
19.25	20.75	8.984	10.16	13.26	8.594	8.594	15.23	8.984	8.984	10.94
Average (Hz)		9.53			9.04			9.42		
Frequency using Svinikin's Model (Hz)		9.78			9.78			9.78		
Percentage Error		2.62			8.19			3.82		

Upon using the model suggested by [11], which is specified in Eq. (3), the dominant frequency of vibration in Site A was calculated and yielded a value of 9.778Hz, It was then compared to the average frequency of the vertical PPV measurements obtained on the three driven piles at Site A and percentage errors less than 10% were obtained as a result.

This would entail to the rationale that dominant

frequencies of ground vibrations could be estimated with accuracy prior to pile driving if pile-hammer properties and specifications are known. Leading the frequency parameter to serve as a reliable reference in analyzing the attenuation behavior of vibrations even before the start of any pile driving activity.

Predicted and Actual Vibration Measurements

The actual vertical PPV measurements obtained at the three distances at Site A were plotted against the calculated theoretical values obtained through the empirical models suggested by [6] and [7] as shown in Fig. 5 and 6 respectively.

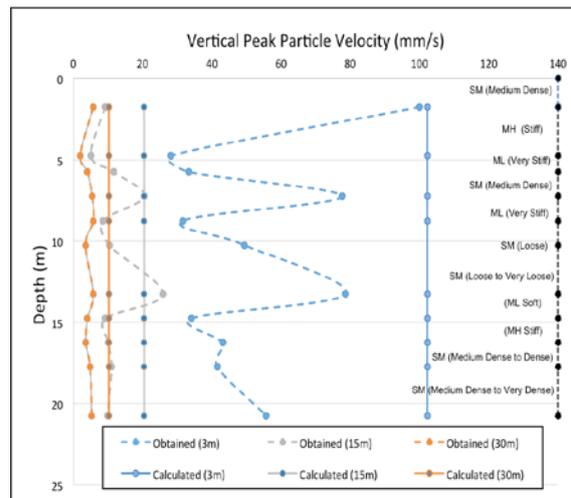


Fig. 5 Actual and Calculated Vertical PPV readings from the model suggested by [6]

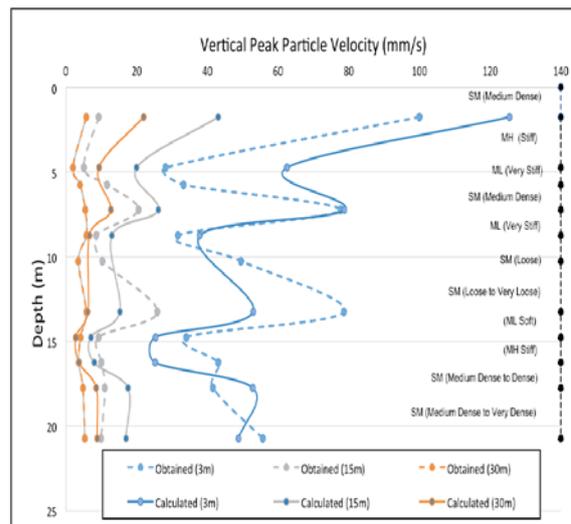


Fig. 6 Actual and Calculated Vertical PPV readings from the model suggested by [7]

Conservative measurements of vibration magnitudes were obtained upon using the model suggested by [6], however no consideration was

made on the possible influence of the different soil properties on the vibration readings, which resulted to the calculation of similar magnitudes even at different depths below the ground surface, as seen in Fig. 5. On the other hand, vibration measurements obtained through the use of the model suggested by [7] have shown to satisfactorily depict the influence of the soil properties on the vibration magnitude, as seen in Fig. 6.

However, it can be seen in Fig. 6, that overestimations of the vertical PPV measurements are made on the upper layers while there is an underestimation on the lower layers correspondingly, the overestimation of the measurements on the upper layers can be attributed to the use of a low associated P-wave velocity in calculating the vibration magnitude, while the underestimation can be attributed to the use of the radial distance, refer to Eq. (5), in determining the vertical PPV measurements at the lower layers.

Upon comparing the predicted and actual values of the vertical PPV readings, it was observed that it is still difficult to predict vibration measurements with high accuracy, as many factors such as the soil, hammer, and pile properties, and possible events of wave interference can greatly contribute to the changes in the vibration magnitude. Despite the complex nature of predicting ground vibrations, the attenuation behavior was found to hold substantial information on the extent to which the ground vibrations would be of significance in the study.

Attenuation of Ground Vibrations

The attenuation behavior of the vertical PPV measurements in Site A were generated and analyzed by plotting the vibration readings at three different distances away from the vibration source. They were subdivided into two main groups, vibration readings emitted on the predominantly sand and predominantly silt layers, this was made in order to analyze the difference between the attenuation behavior of the two different types of soils, as seen in Fig. 7 and 8.

The vertical PPV measurements at a distance of three meters away from the vibration source were found to be dispersive and yielded higher magnitudes as it is near the source of vibration; this was seen on both the attenuation graphs of the predominantly sand and silt layers. The said behavior can be attributed to the influence of the dynamic soil properties on the vibration magnitude, thereby explaining the acquisition of a dispersive set of readings.

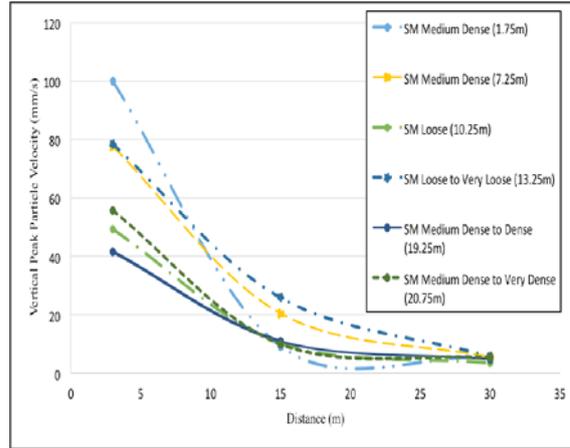


Fig. 7 Attenuation of vertical PPV in Sand Layers at Site A (3rd Pile)

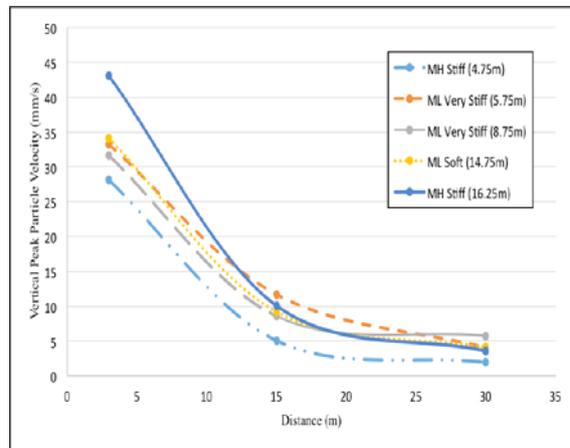


Fig. 8 Attenuation of vertical PPV in Silt Layers at Site A (3rd Pile)

However, the measurements obtained on the predominantly sand layers damped considerably to a narrow range at a distance of 15 and 30 meters away from the vibration source. While measurements obtained on the predominantly silt layers did not come to a closer range until a distance of 30 meters from the vibration source.

Having observed a defined attenuation behavior on both the predominantly sand and silt layers, a best fit line was then developed through the regression analysis of the field data of Site A, involving two main parameters, the dominant frequency of the vibrations and the distance from the vibration source. Vibration prediction models for sand and silt layers were then generated and are being proposed in the study, they are expressed in Eq. (6) and (7):

$$y = e^{0.3649 \ln(x_1) - 1.1780 \ln(x_2) + 4.8072} \tag{6}$$

$$y = e^{-1.144 \ln(x_1) - 0.0902 \ln(x_2) + 5.0949} \tag{7}$$

Where, y is the vertical PPV in mm/s at a distance x_2 from the vibration source having a dominant frequency of x_1 .

The vibration velocities obtained through the use of Eq. (6) and (7) showed to have correlated well with the actual vibration measurements of Site A, yielding an R square value of 0.94 and 0.86. The predicted values were then validated with the measurements of Sites B and C and good agreement was found between the predicted values and the actual vibration measurements obtained in the other two sites. The magnitude of vibration can then be predicted by using the proposed models.

The predicted vibration measurements obtained through the use of Eq. (6) and (7) can then be correlated with the vibration limits suggested by [5], which can be referred to in Fig. 2 and a zone of influence can then be generated, with the origin on the location of the vibration source, refer to Fig. 10, the zone of influence can be utilized to identify nearby existing structures, located at different distances away from the vibration source, and determine if they are vulnerable to structural damages caused by the ground vibrations induced by pile-driving.

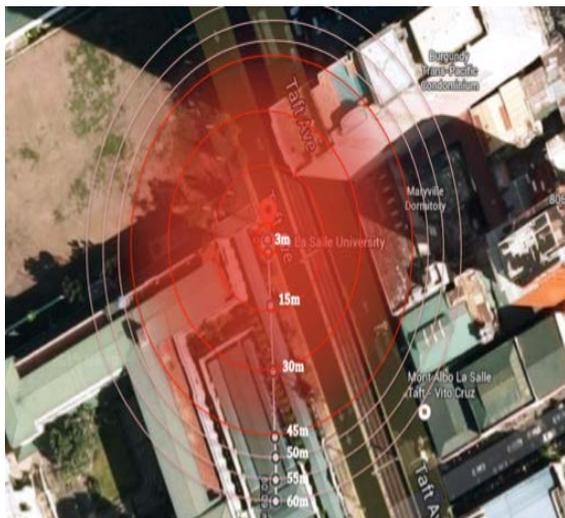


Fig. 10 Zone of Influence

The zone of influence can be used as means for allowing government officials, engineers and even concerned parties to be more aware of the negative effects that pile-driving can bring to the surrounding environment. By having the information provided by the proposed models, vibration limits and the plotted zone of influence, means of minimizing and preventing possible structural damages to existing structures can be sought after, to fully safeguard the lives of the people nearby and as well as the occupants of the buildings from unwanted life hazards.

Several limitations bind the use of the proposed

prediction models and they are stated as follows, only vibration measurements generated through impact pile-driving operations obtained at the ground surface, at a distance of at least 15 meters away from the pile-driving source can be predicted with higher accuracy, as measurements near the vibration source were found to be dispersive. The energy imparted by the hammer unto the pile should be within the range of 41,000 – 41,130 Joules and that there should be a minimum individual layer thickness of 0.75 meters as indicated in the site borehole data for both sand and silt layers.

CONCLUSION

There has long been a concern for the damages that impact pile driving may bring to nearby existing structures. Therefore, it is necessary to establish reliable references to ensure the safety of the structures within a certain radius from the source of pile driving.

Based on the findings in the study, different types of soils, possessing varying dynamic properties, greatly influence the vibration magnitude, which makes the geological conditions of the site a highly important consideration in analyzing ground vibrations, however, the influence of the soil dynamic properties can only be evidently seen at a distance near the vibration source, in this particular case at a distance of three meters where dispersive sets of readings were obtained.

At farther distances, vibration measurements are more suited to be analyzed based on their attenuation behavior. Measurements obtained on the predominantly sand and silt layers on Site A damped considerably and clustered at a closer range at a distance of 15 and 30 meters away from the vibration source, regardless of the type of soil layers the vibrations were emitted from.

Upon having observed a defined attenuation behavior, two vibration prediction models were developed through regression analysis and are capable of predicting vibration magnitudes at a certain distance away from the vibration source just by knowing the dominant frequency of vibration. The prediction models were validated with the data on Sites B and C and good correlation was found to exist between the obtained measurements.

The prediction models can then be correlated with the vibration limits presented in the study to map a zone of influence, where structures that are vulnerable to structural damage within a certain distance or radius of pile driving can be identified.

ACKNOWLEDGEMENTS

The support of GEOMATE is gratefully acknowledged. The authors would also like to express their gratitude to the thesis adviser, Dr. Jonathan Rivera Dungca for his constructive

comments and thorough review on this paper. Much thanks is also given to the pile driving company for granting permission to use the sites, and to Condoza Software Solutions for providing the accelerometers, which made the acquisition of data possible for this research.

REFERENCES

- [1] Woods, R.D. (1997). Dynamic Effects of Pile Installations on Adjacent Structures. NCHRP Synthesis 253, National Cooperative Highway Research Program, Transportation Research Board, National Academy Press, Washington D.C., USA.
- [2] Selby, A. (1991). Ground Vibrations Caused by Pile Installation. *Proceedings Of The 4Th International Conference On Piling And Deep Foundations*.
- [3] Deckner, F. (2013). *Ground vibrations due to pile and sheet pile driving - influencing factors, predictions and measurements* (Ph.D). Royal Institute of Technology.
- [4] Deckner, F., Viking, K., & Hintze, S. (2012). Ground vibrations due to pile and sheet pile driving – prediction models of today. *Proceedings Of The 22Nd European Young Geotechnical Engineers Conference. ECGD 4122-Foundation Engineering*. (2008).
- [5] Athanapoulos, G., & Pelekis, P. (2000). Ground vibrations from sheetpile driving in urban environment: measurements, analysis and effects on buildings and occupants. *Soil Dynamics And Earthquake Engineering*, 19(5), 371-387. doi:10.1016/s0267-7261(00)00008-7
- [6] Attewell, P.B. & Farmer, I.W. (1973). Attenuation of ground vibrations from pile driving. *Ground Engineering*, Vol. 3, No. 7, pp. 26-29.
- [7] Massarsch, K.R., Fellenius, B.H. (2008). Ground Vibrations Induced By Impact Pile Driving. The 6th International Conference on Case Histories in Geotechnical Engineering. Arlington, Virginia.
- [8] Terzaghi, K. (1996). Soil Mechanics In Engineering Practice (3rd ed., pp. 322 - 323).
- [9] Hope, V.S. & Hiller, D.M. (2000). The prediction of groundborne vibration from percussive piling. *Canadian Geotechnical Journal*, Vol. 37, No 3, pp. 700-711.
- [10] Rajapakse, R. (2008). Pile design and construction rules of thumb. Burlington, MA: Elsevier/Butterworth-Heinemann.
- [11] Svinkin, M. R. (1992). "Pile driving induced vibrations as a source of industrial seismology." *Proc., 4th Int. Conf. on the Application of Stress-Wave Theory to Piles*, The Hague, the Netherlands, F. B. J.
- [12] Dowding, C.H. (1996). *Construction Vibrations*. Prentice Hall, Upper Saddle River, USA.
- [13] Woods, R.D.(1997).Dynamic Effects of Pile Installations on Adjacent Structures. NCHRP Synthesis 253, National Cooperative Highway Research Program, Transportation Research Board, National Academy Press, Washington D.C., USA.
- [14] Svinkin, M. (2004). Minimizing construction vibration effects. *Practice Periodical On Structural Design And Construction*, 9(2), 108—115.
- [15] Jongmans, D. (1996). Prediction of ground vibrations caused by pile driving: a new methodology. *Engineering Geology*, 42(1), 25--36.
- [16] Ali, H., Castellanos, J., hart, D. Ali, H., Castellanos, J., & Nukunya, B. (2003). Real-time Measurement of the Impact of Pile Driving Vibrations on Adjacent Property During Construction. *TRB 2003 Annual Meeting CD-ROM*.
- [17] Amick, H., & Gendreau, M. (2000). Construction Vibrations and Their Impact on Vibration-Sensitive Facilities. *Construction Congress*, 758-767. doi:10.1061/40475(278)80
- [18] Abdel-Rahman, S., Abdel-Fattah, S., & Helal, M. Vibration Generated Due To Pile Driving In Water And Soil.

International Journal of GEOMATE, May, 2016, Vol. 10, Issue 21, pp. 1877-1883

MS No. 5223 received on June 16, 2015 and reviewed under GEOMATE publication policies.

Copyright © 2015, Int. J. of GEOMATE. All rights reserved, including the making of copies unless permission is obtained from the copyright proprietors. Pertinent discussion including authors' closure, if any, will be published in Jan 2017 if the discussion is received by July 2016.

Corresponding Author: Dungca J.R
