

EVALUATION OF GROUND BORNE VIBRATION WITH RESPECT TO PILE DRIVING

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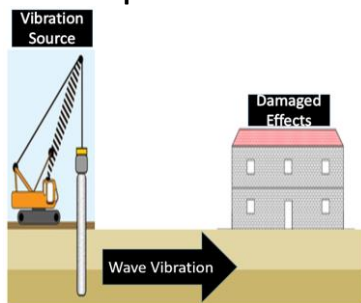
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Graphical abstract



Abstract

Construction activities contribute to ground-borne vibrations, leading to structural damage and adverse environmental effects like noise pollution and human discomfort. Piling, particularly dynamic piling using a hammer drop, is a common construction practice in Malaysia for erecting high-rise buildings. However, this activity, if conducted near urban or residential areas, can result in various issues such as soil settlement and structural damage. Pile-induced vibrations result from the energy transfer initiated by the hammer drop, transmitting through the pile and subsequently propagating into the surrounding soil. The damping effects of these waves decrease with increasing distance from the pile, while the energy transferred to the ground rises with the depth of pile penetration. The relationship between the distance of the pile from the vibration source and Peak Particle Velocity (PPV) is inversely proportional, indicating that as the distance increases, the PPV decreases. Conversely, the relationship between pile depth and PPV is directly proportional, implying that as the pile depth increases, the PPV also increases. The analysis reveals that Peak Particle Velocity (PPV), distance, and pile depth exhibit similar positively skewed distributions with negative kurtosis. Negative linear correlation exists between PPV and distance, while a positive correlation is observed with pile depth. The multiple linear regression equation, $PPV = 1.803 - 0.0810 \text{ Distance} + 0.1176 \text{ Pile Depth}$, highlights PPV's dependence on both variables, with significant P-values. The model's explanatory power, indicated by an 82.80% R-squared value, is notable. Validation shows minor discrepancies within 0.3 mm/s between on-site PPV measurements and regression predictions. Although the highest recorded PPV suggests potential damage, most data remain below 3 mm/s, emphasizing the importance of considering distance and pile depth in managing ground vibrations. The regression model proves reliable. The primary objectives of this study are to establish and analyze the relationships between PPV, pile depth, and distance from the vibration source. Additionally, the study aims to develop a ground-borne vibration model using multiple linear regression.

Keywords: Ground Borne Vibration, Pile Driving, Peak Particle Velocity, prediction model

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1.0 INTRODUCTION

Ground-borne vibration encompasses vibrations in the ground arising from natural sources like earthquakes or human-induced activities such as piling installations (Nabilah et al., 2017). Pile driving is employed in construction when sufficient ground support is lacking, but it introduces negative environmental impacts like noise and air pollution. Predicting vibrations resulting from pile driving is challenging, and its repercussions include significant adverse effects on nearby structures, the environment, and human well-being (Mohamad & Dobry, 1990). Pile-induced ground vibration poses various issues for the surrounding areas, including the potential for structural cracking (White et al., 2002). Rendering piling unsuitable for urban areas due to the risk of structural damage and human disturbance.

Pile dynamics and stress waves aid in determining pile bearing capacity and resistance, providing crucial information about ground vibration resulting from pile driving (Abdel-Rahman, 2011). Three types of ground waves are generated during pile driving: spherical waves from the pile toe, cylindrical waves emitted from the pile shaft and propagating through its length, and surface waves formed by wave refraction on the ground (Musir et al., 2013).

Increasing number of researchers have realized the important influence of soil mass on the dynamic characteristics of piles. Study from (Liu et al., 2017) found that the apparent wave velocity of piles decreases significantly due to the existence of soil plug and this phenomenon can be attributed to the combination effect of soil mass and viscous damping at the pile-soil plug interface.

According to Massarsch et al., the dynamic properties of the soil determine the maximum value of dynamic soil resistance (K. Rainer Massarsch, 2008). The ratio between pile impact and dynamic soil resistance is a key parameter governing ground vibration, helping estimate and understand wave propagation from the pile to the surrounding soil.

During pile driving, S-wave, P-wave, and R-wave are generated. Shear waves (S-wave) form during impact in the pile shaft and propagate through it, while compressional waves (P-wave) are produced at the pile toe, propagating as spherical waves in all directions (Rockhill et al., 2003). As these waves reach the ground surface, some convert into Rayleigh waves (R-wave) (Marr, 2001)

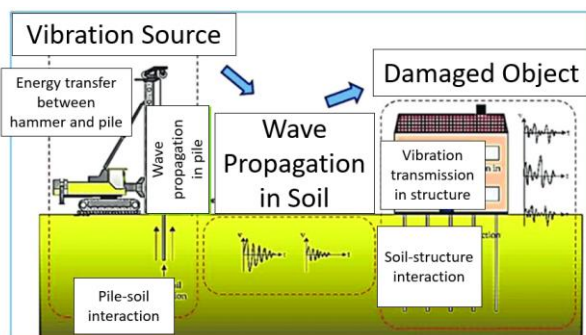


Figure 1 Pile-Soil and Soil-Structure Interaction (Halling et al., 2000)

Upon striking the pile head with the pile driving hammer, energy is transferred from the pile head to the pile itself, and a

wave is initiated at a specific frequency. This wave travels downward through the pile, eventually transferring into the soil (Yeung et al., 2005). As the wave propagates into the soil, it extends to certain distances with diminishing damping effects. Structures within the range of this wave damping experience vibrations. Figure 1 illustrates the energy transfer between the hammer and the pile. The process of the wave propagating through the piles into the soil is termed pile-soil interaction (Halling, Womack, Muhammad, & Rollins, 2000). Subsequently, as the wave continues through the soil, affecting structures and causing vibrations, this phenomenon is referred to as soil-structure interaction.

While previous research has addressed certain limitations, such as data limitations, environmental factors and vibration distance and this study shows that simple mathematical modelling and analysis can be used to forecast performance of ground borne vibration for pile driving in overhead energy transfer. The results also provide insights into environmental factors influencing the vibration towards the pile driving hammer enabling to predict energy transfer initiated by the drop of the hammer onto the pile head for better mitigation of the commencement of construction works.

2.0 METHODOLOGY

2.1 Data Collection

The study was conducted at Setia Alam and Banting, both located in Selangor, as illustrated in Figure 2 and Figure 3. Ground-borne vibration originated from piling activities, and two specific driving piles were selected for vibration monitoring tests. The utilized drop hammer had a weight of 7.5 tons and a drop height of 700mm, paired with spun piles measuring 300mm in size.



Figure 2 Site location at Setia Alam, Selangor



Figure 3 Site location at Banting, Selangor

The seismograph sensor was positioned at various distances

from the pile (sources), specifically at distances of 5m, 7m, 8m, 9m, 11m, 12m, and 16m, measured using a roller measuring wheel. To secure the seismograph sensor in place and prevent movement, a spike was inserted into the ground at the base of the sensor. Figure 4 illustrates the configuration of the seismograph setup.



Figure 4 Instrument setup for vibration monitoring test

At the commencement of the pile driving process, the seismograph time was synchronized with a mobile phone timer to guarantee the accuracy of the experiment's duration. Initially, for the first 9m of the starting pile, the seismograph was positioned at a distance of 5m from the pile. The time required for driving the pile over this 9m stretch was recorded. During the interval when workers were welding the extension of a 12m pile, the sensor location was shifted to 7m from the pile. This sequence was iterated for various sensor distances and pile depths until the entire pile had been securely set.

2.2 Data Analysis

The gathered on-site data comprised Peak Particle Velocity (PPV), the distance between the pile and the sources, and the depth of pile penetration. All collected data underwent meticulous sorting to eliminate any potential errors. Subsequent to the sorting process, a scatter plot was employed to visualize the consistency of the data.

Upon completion of the sorting phase, MINITAB was utilized for data analysis. According to Torres et al., the use of statistical software like MINITAB is essential for acquiring the most representative values of particle velocity in vibrations (Félix et al., n.d.) A multiple linear regression model and equation were generated to predict ground vibration's peak particle velocity, aligning with the approach outlined by (Sulaiman, 2016). The resulting graph depicting PPV, distance, and penetration depth facilitated the derivation of a multiple linear regression equation

3.0 RESULT AND DISCUSSION

3.1 Descriptive Statistics of Data

Descriptive statistics involves the interpretation and assessment of data, providing a summary and analysis through analytical and statistical methods that facilitate model development and variation prediction (Massarsch et al., 2014). Employing graphical methods, it presents trends in the data and includes measurements of central tendency, such as mean, median, and mode. Additionally, descriptive statistics assess

variability, encompassing metrics like standard deviation, variance, minimum and maximum variable values, kurtosis, and skewness.

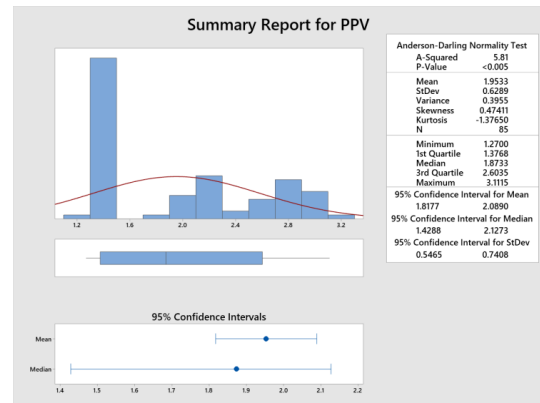


Figure 5 Summary of descriptive data for PPV.

In Figure 5 Peak Particle Velocity (PPV) distribution reveals key characteristics. The mean PPV stands at 1.9533 mm/s, indicating the average velocity of particle movement. The median, at 1.8733 mm/s, signifies the middle value, suggesting a central tendency in the dataset. A standard deviation of 0.6289 and a variance of 0.3955 highlight the dispersion of PPV values around the mean, with a relatively moderate spread. The positively skewed distribution, denoted by a skewness value of 0.47411, implies a longer right tail. However, the negative kurtosis of -1.37650 suggests lighter tails than a normal distribution, indicating fewer extreme values. The PPV range spans from 1.2700 mm/s to 3.1115 mm/s, revealing a relatively narrow spread of values. The PPV distribution exhibits a central location, moderate dispersion, a right-skewed shape, and lighter tails

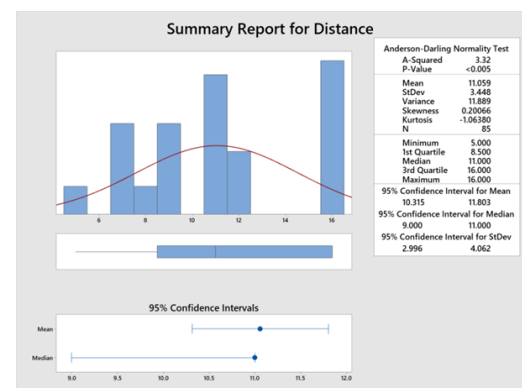


Figure 6 Summary of descriptive data for distance

In Figure 6, the mean value of the distance is depicted as 11.059 meters, with a median value of 11.000 meters, a standard deviation of 3.448, and a variance of 11.889. The distribution of distance is positively or right-skewed, as evidenced by a skewness value of 0.20066. Nevertheless, the kurtosis of distance is negative, specifically -1.06380, indicating lighter tails compared to a normal distribution. The distance

ranges from a minimum value of 5 meters to a maximum value of 16 meters.

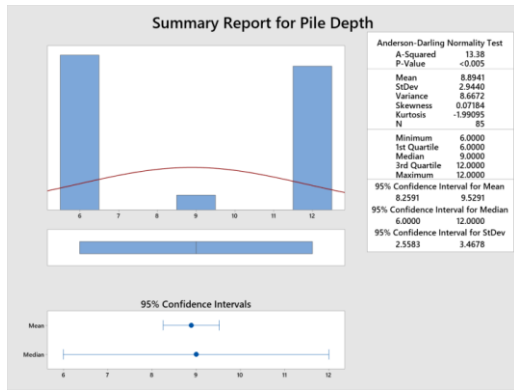


Figure 7 Summary of descriptive data for pile depth

In Figure 7, the mean value for pile depth is presented as 8.8941 meters, with a median value of 9 meters, a standard deviation of 2.9440, and a variance of 8.6672. The distribution of pile depth is positively or right-skewed, evident from a skewness value of 0.07184. However, the kurtosis of pile depth is negative, specifically -1.99095, indicating a tail that is lighter than that of a normal distribution. Pile depth ranges from a minimum value of 6 meters to a maximum value of 12 meters.

3.2 Relationship between PPV and Distance

The relationship between the PPV and the distance was to show the trend of the PPV values when the distance of the pile from the vibration sources was increased.

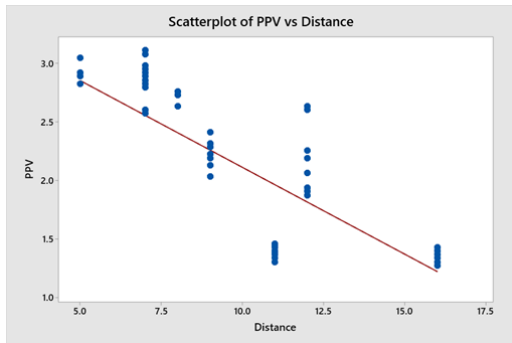


Figure 8 Scatterplot of PPV versus distance.

Figure 8 illustrates a negative linear correlation between the PPV and the distance. Various distances were considered in this study, including 5m, 7m, 8m, 9m, 11m, 12m, and 16m serve as the independent variable influencing PPV, the dependent variable. This equation represent a linear relationship between Peak Particle Velocity (PPV) and distance. The derived equation from this correlation is

$$PPV = 3.594 - 0.1484 \text{ Distance} \quad (1)$$

PPV is Peak Particle Velocity
Distance is distance from the pile

This implies that with an increase in distance, the PPV decreases. The inverse proportionality of the PPV and the distance is evident, signifying that as the distance increases, the PPV decreases, resulting in lower ground vibrations. This linear equation offers a quantitative understanding of the relationship, enabling predictions of PPV at different distances. The negative correlation suggests that as moves farther away from the source will increase the distance, the intensity of the Peak Particle Velocity diminishes and a crucial insight for understanding the dynamics and effects

3.3 Relationship between PPV and Pile Depth

The relationship between the PPV and the pile depth was to show the trend of the PPV values when the pile penetrated deeper into the soil.

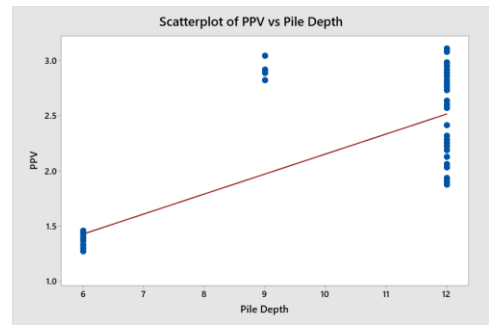


Figure 9 Scatterplot of PPV versus pile depth.

Figure 9 depicts a positive linear correlation between the PPV and the pile depth. Various pile depths were considered, specifically 6m, 9m, and 12m. This equation shows linear relationship between Peak Particle Velocity (PPV) and the depth of the pile. The derived equation from this correlation is

$$PPV = 0.3414 + 0.1812 \text{ Pile Depth} \quad (2)$$

PPV is Peak Particle Velocity
Pile depth is depth of the pile

This suggests that with an increase in pile depth, the PPV appears to increase. PPV represents the maximum velocity experienced by particles during a vibration event, often induced by construction activities. As pile depth increases, the influence of vibrations on the ground and nearby structures may undergo changes. The relationship between the PPV and the pile depth is directly proportional, indicating that as the pile depth increases, the PPV also increases, resulting in higher ground vibrations.

3.4 Multiple Linear Regression

A regression model was employed to derive the multiple linear regression equation, with PPV designated as the response variable and both distance and pile depth designated as continuous predictors.

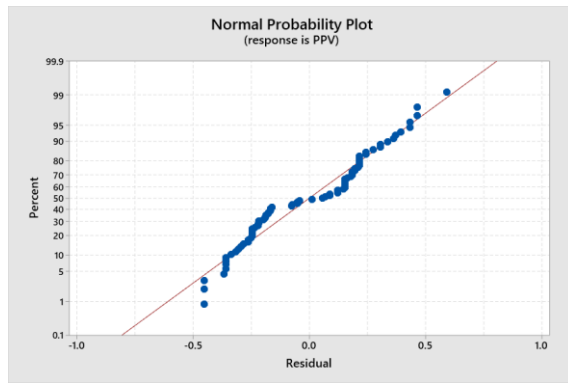


Figure 10 Normal probability plot from fit linear regression.

Figure 10 displays the normal probability plot generated through MINITAB for obtaining the multiple linear regression. This exhibit relationship the Peak Particle Velocity (PPV), distance from the source, and the depth of the pile. The equation indicate the strength and direction of the influence of each parameter on the PPV. The derived equation from the plot is

$$PPV = 1.803 - 0.0810 \text{ Distance} + 0.1176 \text{ Pile Depth} \quad (3)$$

PPV is Peak Particle Velocity
Distance is distance from the pile
Pile depth is depth of the pile

Peak Particle Velocity (PPV) representing the maximum particle velocity during vibration events, is influenced by both pile depth and distance from the source. Pile depth is a critical factor, as deeper foundations can attenuate or amplify vibrations differently. Simultaneously, the distance from the vibration source plays a crucial role in determining the intensity of PPV experienced at a given location. This indicate that PPV is influenced by both the distance of the pile from the vibration sources and the depth of pile penetration into the soil. To assess the significance of these variables, P-values were utilized, specifically for the distance and pile depth in relation to the response variable, PPV.

Table 1 Coefficient, T-value and P-value of the multiple linear regression.

Term	Coef.	SE Coef.	T-Value	P-Value	VIF
Constant	1.8030	0.2230	8.08	0.000	
Distance	-0.0810	0.0113	-7.18	0.000	1.82
Pile Depth	0.1176	0.0132	8.91	0.000	1.82

Table 2 Coefficient, T-value and P-value of the multiple linear regression.

S	R-sq
0.263973	82.80%

Table 1 indicates that the P-values for both the distance and pile length are 0, which is less than 0.05. Consequently, these two variables were deemed significant in determining the PPV values. Table 2 displays the R-squared value of the multiple linear regression, which is 82.80%.

3.5 Data Validation

The derivation of the following multiple linear regression equation to predict the PPV based on the distance and pile depth variables, the equation's validity was assessed using the collected data to ensure its reliability (Ghalib, 2014). During the data validation process, the distance and pile depth were inserted into the equation $PPV = 1.803 - 0.0810 \text{ Distance} + 0.1176 \text{ Pile Depth}$. Table 3 presents the PPV values from the raw on-site data, the PPV values obtained after substituting the distance and pile depth into the multiple linear regression equation, and the differences in PPV values between the two datasets.

Table 3 Comparison and the differences between PPV value from raw data and PPV value from equation.

No.	PPV (mm/s) (Raw Data)	PPV (mm/s) (From Equation)	PPV (mm/s) (Diff.)	Distance (m)	Pile Depth (m)
1	2.6035	2.4564	0.1471	5	9
2	2.2543	2.4564	-0.2021	5	9
3	2.7940	2.6472	0.1468	7	12
4	2.2225	2.4852	-0.2627	9	12
5	1.3655	1.6176	-0.2521	11	6
6	1.3990	1.6176	-0.2186	11	6
7	2.6988	2.5662	0.1326	8	12
8	2.2225	2.2422	-0.0197	12	12
9	1.3653	1.2126	0.1527	16	6
10	1.3970	1.2126	0.1844	16	6

Discrepancies were observed when comparing the actual PPV measured on-site with the theoretical PPV calculated from the multiple linear regression equation. The negative sign of the difference is insignificant, merely indicating whether the measured PPV on-site was higher or lower than the theoretical PPV. Notably, the disparities in PPV were less than 0.3 mm/s, rendering them negligible. Even instances where on-site data had identical distances and pile lengths exhibited differences exceeding 0.3 mm/s. For instance, the data measured on-site for data points 1 and 2, both having a distance of 5m and a pile depth of 9m, showed a difference of 0.3492 mm/s.

3.6 Ground Vibration Limit

According to the on-site data, the highest recorded PPV value exhibit in Figure 5 was 3.1115 mm/s, falling within the caution level range (where damage is not necessarily inevitable), as outlined in the DOE guidelines provided in Table 4 (Svinkin, 2008). The majority of the collected data remained below 3 mm/s, indicating a generally safe level.

Table 4 Recommended limits for damage risk in buildings from steady state vibration (Svinkin, 2008)

Damage Description	Vertical Vibration Peak Velocity v_{max} [mm/s] (0 to Peak0 (10-100 Hz)
Safe	Less than 3
Caution Level (Damage Not Necessary Inevitable)	3 to 5
Minor Damage	5 to 30
Major Damage	More than 30

3.7 Application of the Equation/Model

By validating the data for a dependable and accurate PPV prediction, this multiple linear regression model becomes a practical tool for forecasting ground-borne vibrations using two variables: the distance of the pile from the vibration sources and the pile penetration depth into the soil (Dehghani et. al., 2011). Table 4 demonstrates that substituting the distance and pile depth values into the equation yields the PPV values. The PPV values in Table 4 align with theoretical expectations, indicating that an increase in distance leads to a decrease in the PPV value, while an increase in pile depth results in an increased PPV value.

Table 5 PPV value obtained from the substitution of the distance and pile depth into multiple linear regression equation.

Distance (m)	Pile Depth (m)	PPV (mm/s)
10	6	1.6986
10	12	2.4042
10	18	3.1098
20	6	0.8886
20	12	1.5942
20	18	2.2998
30	6	0.0786
30	12	0.7842
30	18	1.4898

4.0 CONCLUSION

The correlation between distance and PPV exhibited an inverse proportionality. As the distance between the pile and the vibration source increased, the PPV value decreased. This phenomenon was attributed to wave propagation in the soil. The damping effects of the wave played a crucial role, causing the vibration to diminish. The longer the distance, the lower the damping effect, leading to a decrease in PPV.

On the other hand, the connection between pile depth and PPV demonstrated a direct proportionality. With deeper penetration of the pile into the soil, the PPV value increased. This outcome was a result of the energy transfer initiated by the drop of the hammer onto the pile head. As the pile delved deeper into the soil, more energy was required by the drop hammer to drive the pile further, attributed to the skin friction between the pile and the soil. Deeper penetration kept the friction, resulting in an elevated PPV value.

To predict ground-borne vibration due to piling, a multi-linear regression equation was employed. This predictive equation aimed to furnish information on PPV values during the preliminary design stage of piling activities. This proactive approach ensures that adequate precautions and mitigation measures are implemented well in advance of the commencement of construction works.

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