Proceeding *20th SEAGC - 3rd AGSSEA Conference in conjunction with 22nd Annual Indonesian National Conference on Geotechnical Engineering.* Jakarta - INDONESIA, 6 -7 November 2018. ISBN No. 978-602-17221-6-9

Study on The Effects of Vibration due to Pile Driving by Empirical Formulas and Continuous Monitoring

Stefanus Diaz Alvi[1], Ricky Setiawan[2], Andy Sugianto[3], Paulus P. Rahardjo[4]
[1]*Engineer, PT Geotechnical Engineering Consultant, Bandung, Indonesia*
[23]*Engineer, PT Geotechnical Engineering Consultant, Bandung, Indonesia*
[3]*Engineer, PT Geotechnical Engineering Consultant, Bandung, Indonesia*
[4]*Professor of Geotechnical Engineering, Universitas Katolik Parahyangan, Bandung, Indonesia*
E-mail: diaz.stefanus@gmail.com, rickysetiawan.geo@gmail.com, andysugianto.sorong@gmail.com, rahardjo.paulus@gmail.com

ABSTRACT: Pile driving using hydraulic hammer will induce large vibration so that the effects of pile driving needs to be analyzed to avoid building damage and malfunction of the sensitive device. This paper discusses a case study in South Sumatera, Indonesia regarding the effect of pile driving on a sensitive gas plant instrument and building surrounding the project area. The effect of vibration due to pile driving is calculated using empirical formulas (Attewel & Farmer, 1973 and J.M. Ko et al, 1990). However, there is correction factor of the empirical formulas that are dependent to soil types. Continuous monitoring has been carried out in the project area by using geophone sensors to measure vibrations and PDA (Pile Driving Analyzer) to measure actual energy of driving. Peak particle velocity (PPV) from empirical formulas are approaching PPV value from monitoring test at the same energy of pile driving. The results will be used to back analyse to modify the correction factor of the empirical formulas.
Keywords: Peak Particle Velocity (PPV), Pile Driving, Vibration Monitoring.

1. INTRODUCTION

When pile driving operations are carried out near other structures, several technical investigations must be carried out to evaluate the vibration impact of the pile driving. This investigation must take into account the ground vibration due to pile driving, the transmission through the soil media to the nearest structure and how the vibration will affect the structure or sensitive devices.

In general, the type of vibration propagation through the soil is more predictable than its effect on the structure. This is because it depends on the quality of the structure, foundation system and configuration. Ground vibrations that can affect the structure include:

- Soil settlement and foundation due to compaction.
- Vibration in the structure due to impact vibration.
- Vibration in sensitive devices.

Determination of whether the structure will experience a decrease or horizontal vibration due to pile driving can be estimated. Identification of local soil conditions can provide an indication of the potential decline of buildings. The movement of buildings or sensitive devices near pile driving location is a function of soil type, vibration frequency, and amplitude.

Therefore, when the pile is placed near the existing structure or sensitive devices, it is the responsibility of the engineer to evaluate its potential for damage to the structure and the devices. For this reason the engineer must understand how ground vibrations are caused by the pile-up process and how soil parameters such as damping can give effect.

On this paper, case study is taken from a project located in South Sumatera, Indonesia. This project uses a type of pile foundation with a 400 mm diameter spun pile. The hydraulic hammer for driving that will be carried out has vibration issues that have the potential to interfere with the performance of a sensitive instrument that is near that location and existing structure. The closest distance between the pile and the instrument is about 186 m. Vibration monitoring is carried out to estimate the amount of vibration arising from the pile driving of a 400 mm spun pile using the hydraulic hammer. Besides that, PDA monitoring was conducted to determine the actual energy of the hammer that entered the pile foundation during pile driving.

2. PROJECT DATA

2.1 Soil Condition

Before analyze the vibration effect due to pile driving, it is important to understand the soil conditions at the project site. Geotechnical investigation is consists of drill testing and SPT (Standard Penetration Test). The location of the test is shown on Figure 1.

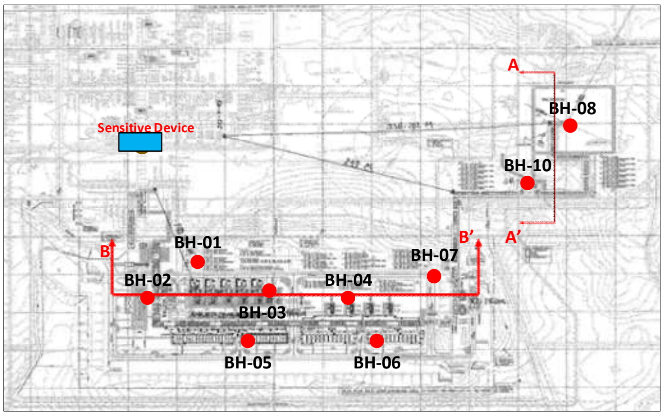

Figure 1. Geotechnical Investigation Location

Soil stratification on this project is represented by Section A-A' and Section B-B' as follows.

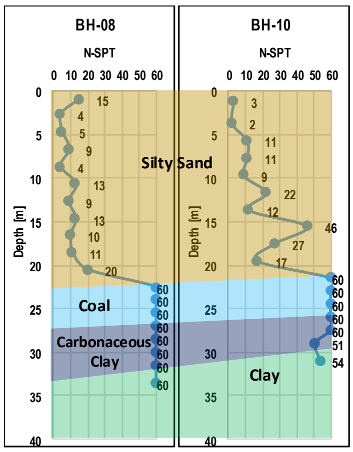

Figure 2. Section A-A'

Soil stratification on section A-A', which are represented by BH-08 and BH-10, shows that around 22 m of the top layer is loose to medium silty sand. Layer 2 is coal with 6 m thickness. Layer 3 is a dark brown brittle carbonaceous clay. Layer 4 is a layer of clay with very hard consistency. In this section, it is shown that coal layer tends to be uniform even though there are different elevation.

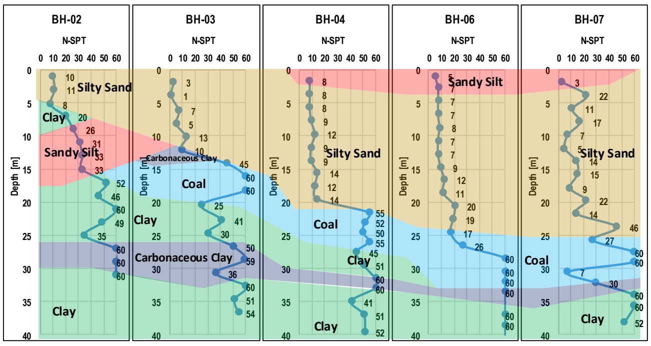

Figure 3. Section B-B’

Section B-B’ shows different soil stratification from Section A-A’ where the coal depth is vary. In the upper layer there is sandy silt and silty sand. The layer below is a coal layer that is brittle with thicknesses ranging from 6-10 m at various depths. The layer below is carbonaceous clay. The layer is found between the layers of hard clay. Hard soil layers are found at different depths in each area.

2.2 Piling Method

The foundation system on this project is 400 mm diameter spun pile. The pile driving will be done with a hydraulic hammer with hammer specifications as follows.

- Hammer type : NH-70
- Hammer weight : 7 tons
- Energy efficiency : 60-70%
- Blow speed : 25 blows / minute
- Hydraulic pressure : 210 kg/cm^3

Piling with a hydraulic hammer will induce great vibration so that the vibration impact of the piling done needs to be analyzed so that the pile driving does not cause damage to the building, malfunctioning of the existing gas plant instrument, and failure of concrete settings after pouring concrete on the need for casting the shallow foundation in the surrounding area.

3. STUDY ON THE EFFECTS OF VIBRATION BY EMPIRICAL FORMULAS

Peak particle velocity (PPV) values can be calculated by empirical formula from Attewel & Farmer (1973) or J.M Ko (1990). Attewell and Farmer (1973) conducted an analysis of the results of measurements of vibration due to the pile driving on several variations of soil and pile type. They suggested that the peak particle velocity (v) due to pile pile driving could be predicted with the following formula.

$$v = C\,\frac{\sqrt{W_o}}{r} \qquad (1)$$

where :

v = peak particle velocity (mm/s)
C = constant value
Wo = hammer energy (Joule/blow)
r = distance of the point of purging to the location being reviewed (m)

The equation states that the partivle velocity at any point is proportional to the square root of hammer energy and inversely proportional to the distance of a point at the stake location. This vibration reduction has a linear tendency to distance in the logarithmic scale. The proposed equation is then adopted by Eurocode 3. The constant C is used to express the variation in soil conditions and type of pile type. The value of C ranges from 0.25-1.50. Eurocode 3 recommends a value of 0.7 for piling vibratory. At impact piling, the value of C is around 1.0 for solid or firm soil and 0.5 for loose or soft soil. Here is the relationship of the distance of one point from the location of the location of the peak particle velocity according to Eurocode 3.

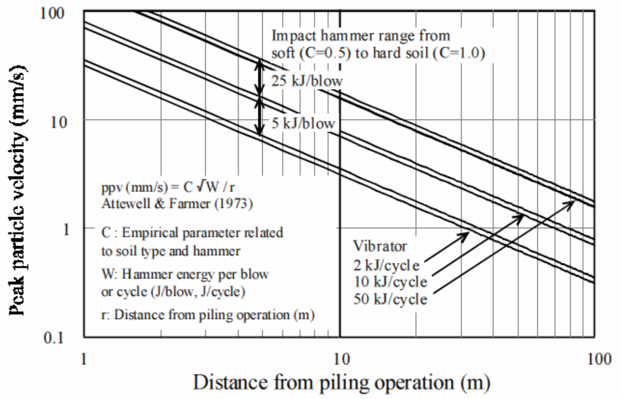

Figure 4. Correlation between Distance from Piling Operation and Peak Particle Velocity (Eurocode 3)

The other empirical formulas derived by J.M. Ko et al. (1990) are as follows:

$$v = 70 \cdot \sqrt{\frac{1}{r}} \cdot \exp\left[-\alpha \cdot (r-1)\right] \qquad (2)$$

where :

v = particle velocity (mm/sec)
r = distance from the vibration source to the location observed (m)
α = damping coefficient (depends on the soil), about 5-20%

4. STUDY ON THE EFFECTS OF VIBRATION BY CONTINUOUS MONITORING

4.1 Vibration Monitoring

Vibration monitoring is carried out by a geophone sensor as an accelerometer. The geophone is used to recording particle velocity (v) and frequency (f). The data is displayed against time so that variations in particle velocity or frequency with time can be obtained along piling. The reading of particle velocity and frequency is done in 3 axis directions (x, y, and z) so that analysis can be carried out on the three directions. From the measurement of the three directions, the resultant magnitude of the three directions will be calculated.

Vibration monitoring is carried out using 2 sensors. The first tool is used to measure vibration in the sensitive device (existing GTC). The second tool measures in 4 different directions with varying distances to obtain a vibration relation to the distance from the point of piling. From the test at each point, the particle displacement, particle velocity, acceleration, and frequency will be obtained. The monitoring results will be concentrated on the final set condition as a critical condition.

Pile driving is carried out in 2 stages. In the first stage the piling is located at 200 m from the existing GTC where the vibration measurements were carried out at distances varying from the point of pile driving (30 m, 40 m, 60 m, 90 m, 115 m, 120 m, and 200 m). The measurements at various distances is used to evaluate safe distance. Pile driving in the second stage was carried out at New GTC Unit 1 which was as far as 186.19 m from the existing GTC. The pile that was placed on the New GTC Unit 1 was the location with the closest distance between the location of the existing GTC. In other words, the measurement of vibration due to pile driving at the New GTC Unit 1 will obtain vibration data in critical conditions. The data to be used in this paper only refers to the data taken in the final set condition.

The location of stage 1 piling point (loc pilling) and stage 2 piling point (New GTC Unit 1) to the existing GTC location can be seen in Figure 5 and Figure 6. The value of peak particle displacement, peak particle velocity, peak particle acceleration, and the maximum frequency measured from monitoring is shown in Table 1 and Table 2.

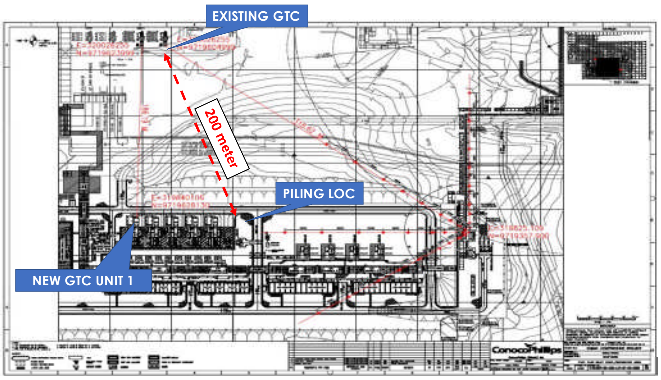

Figure 5. Piling and Existing GTC Location

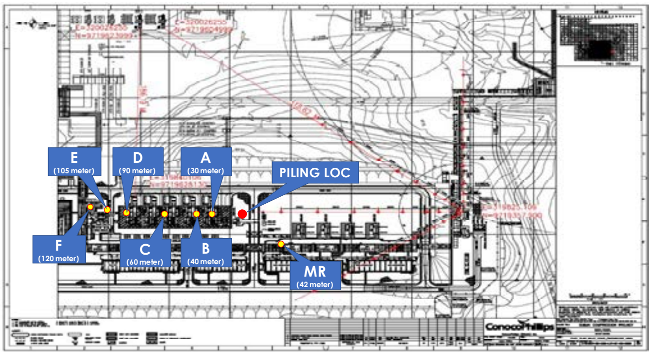

Figure 6. Vibration Monitoring Location

Table 1. Monitoring Data (First Stage)

Distance [m]	Peak Particle Displacement [mils]	Peak Particle Velocity [mm/s]	Peak Particle Acceleration [m/s^2]	Maximum Frequency [Hz]
30	2.37	5.35	0.978	37.5
40	4.41	3.44	0.588	37.5
60	2.64	1.14	0.120	23.5
90	1.26	0.67	0.095	15.5
115	2.91	0.49	0.048	20.5
120	2.24	0.36	0.052	27
200	1.63	0.29	0.104	66

Table 2. Monitoring Data (Second Stage)

Distance [m]	Peak Particle Displacement [mils]	Peak Particle Velocity [mm/s]	Peak Particle Acceleration [m/s^2]	Maximum Frequency [Hz]
186.19	2.11	0.22	0.05	90.5

4.2 Energy Monitoring

Pile Driving Analyzer (PDA) is a useful tool to measure and determine the effect of hammer blows on pile foundations. The hammer blow given to the pile head is intended to penetrate into the ground (pile foundation) or only to test the pile bearing capacity. PDA is consist of the transducer sensor (to measure strain) and accelerometer sensor (to measure acceleration of pile foundation).

There are two or four sides of the pile foundation head consisting of transducer sensor and accelerometer sensor. PDA computers are tools for recording measured data from transducer sensors and accelerometer sensors. Based on these data, the hammer energy transferred to the pile can be interpreted.

The pile hammer used to carry out the spun pile is a hydraulic hammer coded NH-70 where the weight of the hammer is 7 tons with a high gradual fall (multiples of 0.16 m) and a maximum falling height of 1.28 m. The height of the hammer falls when testing is set at 0.32 m.

The energy produced by the hammer blow can be calculated theoretically by multiplying the weight of the hammer by the height of falling hammer. However, the energy received by the pile foundation will be smaller than theoretical energy. The reduction in hammer energy (efficiency) is calculated by dividing the amount of energy measured on the pile foundation divided by the theoretical maximum energy in percent. The PDA can monitor the amount of energy received by the pile foundation by doing integral to the product measuring force (f) multiplied by velocity (v) against the time up to 2L / c which is formulated as follows.

$$E = \int f.v.dt \qquad (3)$$

The pile driving was carried out with a hydraulic hammer where 7 tons ram weight and 0.32 m ram stroke, so that theoretical energy was obtained at 2.24 t.m. PDA test equipment shows that with the same hammer weight and falling height the actual energy is in the range of 1.2 - 2.01 (see Figure 7) and is taken on an average of 1.501. Energy efficiency was taken based on the actual average energy divided by theoretical energy, so that the energy efficiency obtained in the hydraulic hammer was obtained by 67%.

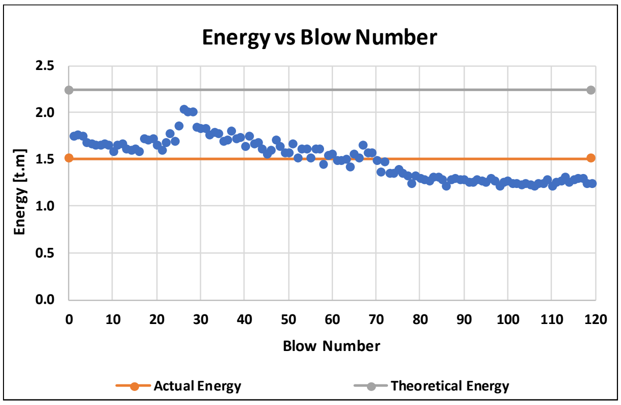

Figure 7. Energy Measured from PDA Test

5. THE EFFECTS OF VIBRATION DUE TO PILE DRIVING ON SENSITIVE DEVICE AND EXISTING BUILDING

5.1 The Effect of Vibration to Sensitive Device on Existing GTC

Around the project site, there is a gas plant that is very sensitive to vibration. If the vibration received by the gas plant exceeds the allowable limit, there will be a shutdown of the gas plant. The closest distance between the pile and the gas plant is 186 m. The maximum vibration acceleration allowed is 0.4 mm/s2 and the maximum allowable frequency is 1.2 Hz. The maximum particle speed is determined by the following equation.

$$v = \int a.dt \qquad (4)$$

$$v = a.\frac{1}{f}$$

$$v = \frac{a}{f}$$

So that the required peak particle speed is 0.33 mm/s.

Based on the monitoring data, it was found that the pile driving was carried out at the closest distance, the peak particle velocity and acceleration that occurred in the GTC area was smaller than required. The frequency that occurs exceeds the required frequency. However, the particle velocity and particle acceleration occurs small, so that the existing GTC is in a safe condition.

5.2 The Effect of Vibration to Existing Building

Criteria for damage to the building structure as in Figure 8 shows that the peak particle velocity that occurs due to pile driving is included in the safe category. Nevertheless, these criteria are only used to determine the structural conditions of the building so that it cannot be used for evaluation of other needs such as the effect of pile driving on the gas plant instrument.

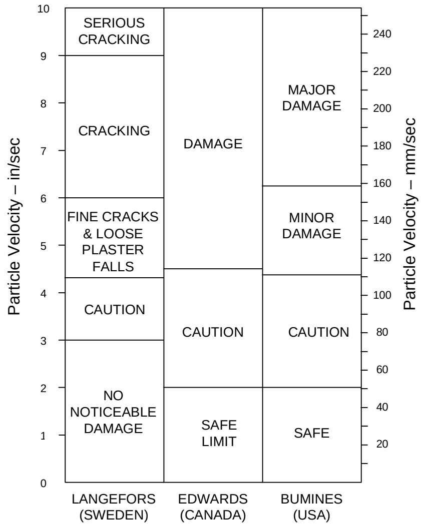

Figure 8. Damage Criteria for Building due to Vibration (J.F.Wiss,1981)

Concrete material has a limit of receiving vibration with the amount of PPV (Peak Particle Velocity) of 50 mm/s. This limit is based on the structural limit of the structure to vibration in Figure 8. The closest distance between piling point and the existing building is 30 m. Based on the monitoring result, the PPV is less than requirement (50 mm/s). Hence, the existing building is safe.

6. BACK ANALYSIS

The following is the peak particle velocity (PPV) obtained from the Attewel and Farmer Method (1973), J.M. Method. Ko (1990), and the results of monitoring in the field.

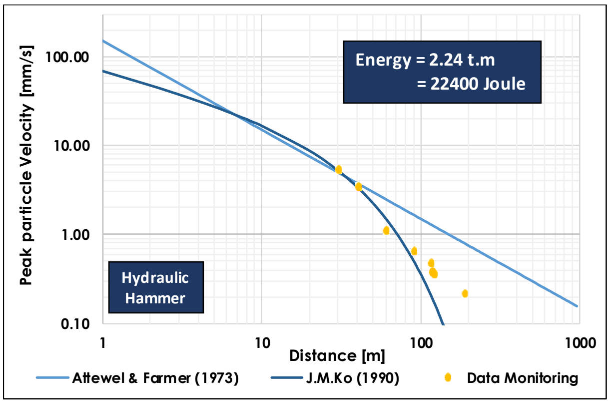

Figure 9. Relationship Between Distance from Piling Operation and Peak Particle Velocity from Empirical Formulas and Continuous Monitoring

Based on Figure 9, it can be seen that the relationship between peak distance and particle velocity (PPV) from the results of monitoring in the field forms a linear line in the logarithmic scale. The relationship of distance and PPV obtained by empirical formulas from the Attewel and Farmer (1973) forms a linear line whereas from the J.M. Ko (1990) does not form a linear line on a logarithmic scale. With the similarity of the linear function form, it is necessary to do a back analyze the empirical formula from Attewel and Farmer (1973) based on the results of monitoring as a reference for determining the PPV value for various distances on certain energy quantities.

The amount of energy is determined based on theoretical energy, which is 2.24 t.m. With a large energy of 2.24 t.m or equal to 22400 Joule, a modification of the Attewel & Farmer equation is obtained for this project which can be seen in the following equation.

$$v = 15\frac{\sqrt{W_o}}{r^{1.75}} \qquad (5)$$

where :

v = peak particle velocity (mm/s)

Wo = hammer energy (Joule/blow)

r = distance of the point of purging to the location being reviewed (m)

The relationship between distance and PPV value from the modified formula forms a linear line in the logarithmic scale as shown in the following figure.

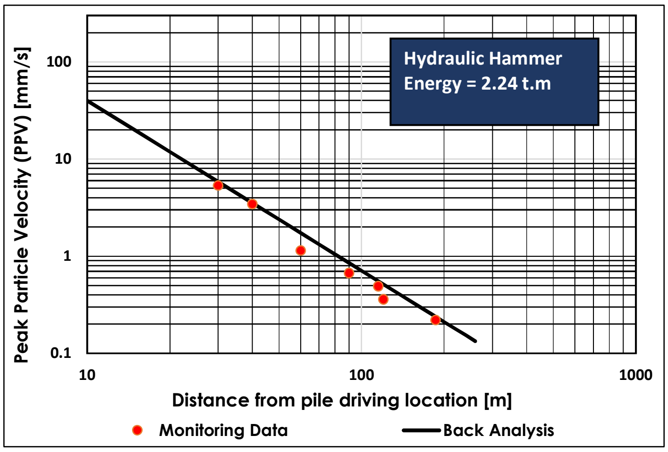

Figure 10. Relationship Between Distance from Piling Operation and Peak Particle Velocity from Back Analysis

Based on Figure 10, it can be obtained that to meet the maximum particle speed requirements of 0.33 mm / s, the required minimum GTC distance from the minimum purging point is 150 m. From these results it can be obtained that the particle velocity at a distance of 186.19 m with hammer energy 2.24 t.m meets the safe criteria. Radius of vibration influence due to pile driving on this case is 300m.

7. CONCLUSION

- The case study is taken from South Sumatera, Indonesia regarding the effect of pile driving on a sensitive gas plant instrument and building surrounding the project area. Soil condition in the project area is consists of silty sands in the upper layer, coal and carbonaceous clay in the middle, and the underlying layer is hard clay.
- The effect of vibration due to pile driving is calculated using empirical formulas (Attewel & Farmer, 1973 and J.M. Ko et al, 1990). However, there is correction factor of the empirical formulas that are dependent to soil types. To overcome the uncertainty of the correction factor, continuous monitoring by geophone sensors to measure vibrations and PDA (Pile Driving Analyzer) to measure actual energy of driving.
- The pile driving is done using a hydraulic hammer which uses NH-70 with 7 tons ram weight and 0.32 m ram stroke. The theoretical energy obtained is 2.24 t.m while the average actual energy from the PDA test is 1,501 t.m, so that the energy efficiency of the hydraulic hammer is 67%.
- In existing GTC, the maximum vibration acceleration allowed is 0.4 mm/s^2 and the maximum allowable frequency is 1.2 Hz. The maximum allowable particle velocity is 0.33 mm/s. Based on the monitoring data, it was found that the pile driving was carried out at the closest distance, peak acceleration, and particle

velocity that occurred in the GTC area was smaller than required. The frequency that occurs exceeds the required frequency. However, due to small particle switching, the existing GTC is in a safe condition.

- Radius of vibration influence due to pile driving on this case is 300m.

8. REFERENCES

Attewell, P. B. & Farmer, I. W., (1973) "Attenuation of Ground Vibrations from Pile Driving", Ground Engineering, vol. 3, No. 7, July.

Deep Foundation Research Institute (DFRI). (2017) "Manual Pondasi Tiang Edisi 5". Universitas Katolik Parahyangan. Centre of Excellence for Geotechnical Engineering (GEOCENTER)

Eurocode 3, (1992). "Design of steel structures, chapter 5, piling." DD ENV 1993-1-1:1992

FHWA, 2016, "Design and Construction of Driven Pile Foundations – Volume I" FHWA-NHI-16-009

Ko, J.M., Luk, S.T., and Cheng, C.Y., (1990), "Vibration and Noise-Measurement Prediction and Control", Proceedings of Australian Vibration and Noise Conference 1990.

PT GEC, 2017, "Analisis Vibrasi Akibat Pemancangan, Sumatera Selatan", Final Report

PT GEC, 2017, "Laporan Hasil Monitoring Vibrasi dan PDA Test", Final Report

Wiss, J.F., 1967."Damage Effects of Pile Driving Vibration", Highway Research Record, Number 155, P.14-20

Wiss, J.F., 1981, "Construction Vibrations: State-of-the-Art", Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, No. 6T2, pp. 167-181, February,.