DYNAMIC RESPONSE ANALYSIS BASED ON FOUNDATION DIMENSIONS AND MACHINE CAPACITY ON BLOCK-TYPE MACHINE FOUNDATION

S N Fitri[1,2*], N S Surjandari[1], Y M Purwana[1], B Setiawan[1], G Chrismaningwang[1], and H Dananjaya[1]

[1]UNS Geoscience Research Group, Civil Engineering Department, Universitas Sebelas Maret, Jebres, Surakarta 57126, Indonesia.
[2]Disaster Research centre, Universitas Sebelas Maret, Jebres, Surakarta 57126, Indonesia.

ABSTRACT

The development of Indonesia's economic sectors and populations leads to huge regional problems, which provide the large community's electricity needs in several areas. The common solution to this issue is to offer the potential natural resources that are safe for the environment and can be used as a source of electricity, such as a small-scale hydroelectric power plant or a Micro-Hydro Power Plant. This structure requires the dynamic foundations to accept dynamic loads caused by machine movements such as rotation, vertical movement, horizontal movement, and torque. The main objective of this work is to analyse the effect dimension of machine foundation and machine capacity in several conditions. This research was conducted on numerous machine capacity, namely machine 1, 2, and 3, which offers different frequency and weight. The foundation length was designed to range between 4 and 6m, which design a similar embedded foundation at 1m and width of 0.5m. The soil properties were conducted in secondary data with CPT results. The outcome provides that the addition of foundation area reduces the amplitude. The results show a similar trend in three categories; vertical, horizontal, and rocking aspects which generate values of approximately 57%, around 40%, and about 50%, respectively, in all machine types. The higher area and length of the foundation, the smaller amplitude will be.

Keywords: Machine; Block-type; Dynamic; Amplitude; Foundation

1. INTRODUCTION

The population growth and the national economy in Indonesia increase yearly, affecting the national community's electricity needs. The State Electricity Company (PLN) estimates that electricity consumption will increase by 4.9% until 2030. Meanwhile, Indonesia has several potential natural resources that are safe for the environment and can be used as a source of electricity, such as water. One of the concepts to generate energy from water is to design a small-scale hydroelectric power plant or a Micro-Hydro Power Plant (Tobi, 2017).

The substructure stage of the building, namely the foundation, is a part of the structure that functions as a load transfer supported by the strength of the foundation materials and loads itself into the subgrade. Generally, structural buildings supported by a foundation

---

[1,2*] Corresponding author: sitinurlitafitri@staff.uns.ac.id

DOI: https://doi.org/10.20885/icsbe.vol4.art8

are dead (static) loads. However, if the building is affected by the machine which keeps moving, it will consider the dynamic load as a dominant variable to calculate the safety factors (Hertiani, 2019). Moreover, the dynamic loads are divided to horizontal, vertical, torsional, and rotational vibrations (Syahidi, 2017). According to (Hill, 2019), foundation rocking for a given rocking amplitude, results in bigger dynamic differential settlements than structural rocking which motion of the buildings is also noticeable in the soil response beneath the structures. At the same time, Failure to use a suitable foundation to support both static and dynamic loads will result in improper machine operation [5], while dynamic impacts can cause noticeable structural damage to some sensitive equipment or devices as well as serious problems with their ability to function (Ali, 2018). In terms of micro hydropower plant buildings, a dynamic foundation design is entailed to withstand dynamic loads for the micro hydro power plant's engine and generate the safety condition in the surrounding environment.

This research generates a design of the micro-hydro power plant foundation, which requires some technical data such as subgrade parameters and dynamic and static properties of the subgrade. This study carries bearing capacity static and dynamic analysis using the Meyerhoff and Lumped Parameter System methods, respectively. One type of machine foundation commonly used is the block type, which has a natural frequency and relatively small deformation (Hassan, 2013). Thus, this research aims to determine the influence of machine capacity and foundation dimensions on the dynamic response of the machine foundation.

2. MATERIALS AND METHOD

2.1. Machines Data

This study carried out the bearing capacity calculation based on a water turbine machine consisting of various parts, such as a rotating part or a rotor. It consists of a shaft with blades mounted around it, which rotates by a collision from the fluid flow to the rotor [8]. Furthermore, three capacity turbine engines were used, namely, 1000 rpm, 1500 rpm, and 1200 rpm. The data have shown in Table 1.

Table 1. Machine Data

	Frequency (rpm)	Weight (kg)	Rotor Weight (kg)
Machine 1	1000	780	234
Machine 2	1500	1500	450
Machine 3	1200	1000	300

2.2. Soil Data

This paper used the soil properties based on the Cone Penetration Test (CPT) to determine the soil type that existed before. In addition, the results of this test were carried out by the Sebelas Maret University soil mechanics laboratory. Next, this soil parameter was used to calculate the soil spring constant and several parameters in dynamic load analysis ((Syahidi, 2019), (Arya, 1979), (Gunawan, 2017)) . The soil layers have shown in Table 2.

Table 2. Soil Parameters

	Depth (m)	N-SPT	Φ (°)	γ (ton/m^3)	μ	Es (Mpa)	G (Mpa)
Layer 1	0-2,4	4	28	1,5	0,3	19,5	78,306
Layer 2	2,4-3	13	30	1,75	0,2	17	599,1415
Layer 3	3-3,2	50	41	2,25	0,35	74	1364,522

2.3. Machine Fpundation

Foundation is a part of the building elements located near the subgrade, which functions to distribute the load into the soil or rock under the structure. Meanwhile, the dynamic foundation is a foundation that distributes dynamic loads such as horizontal, vertical, torsional and rotational vibrations (Syahidi, 2019). The machine foundation is one type of dynamic foundation because the machine foundation serves to distribute the dynamic load generated by the machine, which is a structure above the foundation and supports the weight of the engine and generator (Hertiany, 2019). This research used a block-type machine foundation which offers the foundation length designed to range between 4 and 6m, and this study design a similar embedded foundation at 1m and width in 0.5m. According to Surapreddi (2019), at larger loads, the square and circular foundations outperform the rectangular foundation. Contrarily, block foundations' qualities for transmitting vibration are unaffected by their shape.

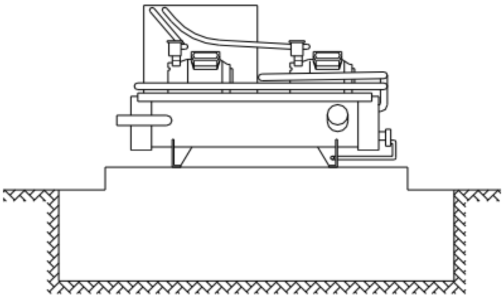

Figure 1. Block Type Machine Foundation [8].

2.4. Lumped Parameter System

This theory was developed in 1996 by Lysmer and Richart, which is used by the system to stiffen a foundation block using springs, dashpots, and masses, where the system itself applies all existing components such as mass, springs, and damping. This model generates the dynamic response of the soil to the foundation and dynamic engine loads, such as the provision of spring with a stiffness coefficient of "k" and damping with a damping coefficient of "c", which both models can be used to model the vertical, horizontal, rocking and torsional responses ((Syahidi, 2019), (Gunawan, 2017)). These dynamic outputs could include coupled modes, rocking oscillation, torsional oscillation, horizontal translation, vertical oscillation, and horizontal translation (Arya, 1975). This method was designed to calculate dynamic vibration analysis by changing the shape to a circular foundation with a radius (ro) whose magnitude depends on the type of vibration. (Das, 1993).

The foundation's shape affects the foundation's vibration analysis to calculate the dynamic vibration analysis. In addition, it is necessary to have an equivalent radius of horizontal, vertical, and rocking vibrations. Which is where the three vibrations require the width and length of the foundation. The equivalent radius equation for rocking vibrations can be calculated using equation (1) below;

$$r_o = \left(\frac{B^3 \times L}{3\pi} \right)^{0,25} \tag{1}$$

The equivalent radius equation for horizontal and vertical vibrations can be calculated using equation (2) below;

$$r_o = \left(\frac{B \times L}{3\pi} \right)^{0,5} \tag{2}$$

With L is the length of the foundation, B is the width of the foundation, and ro is the radius equivalent.

The influence of foundation depth is the second variable that affects the dynamic vibration analysis on the foundation. The effect of the foundation embedded is the embedment coefficient, which will be multiplied by the spring coefficient by assuming the shape of the foundation is square or circular. Moreover, the shape of the foundation is assumed to be square to calculate the effect of the embedded foundation. It is necessary to find the coefficient of the square foundation, which is used to calculate the dynamic vibration. This method generated by the machine results in three types of vibration, namely rocking, horizontal, and vertical ((Syahidi, 2019), (Gunawan, 2017)). The equation used to find the value of the embedment coefficient can be seen in equations (3) to (5).

$$\eta_z = 1 + 0,60(1 - v)\left(\frac{D}{r_o} \right) \qquad \textit{for vertical vibration} \tag{3}$$

$$\eta_x = 1 + \left(0,55(2 - v)\left(\frac{D}{r_o} \right) \right) \qquad \textit{for horizontal vibration} \tag{4}$$

$$\eta_\varphi = 1 + \left(1,2(1 - v)\left(\frac{D}{r_o} \right) \right) + \left(0,2(2 - v)\left(\frac{D}{r_o} \right) \right) \qquad \textit{for rocking vibration} \tag{5}$$

With $\eta_z, \eta_x, \eta_\varphi$ is the embedment coefficient, v is poison ratio, D is the depth of the foundation [6]. To find the factor of the depth of embedment on damping ratio on vertical, horizontal, and rocking vibrations, it has described in the equation (6) to (8) below:

$$a_z = \frac{1 + \left(1,9(1 - v)\left(\frac{D}{r_o} \right) \right)}{(\eta_z)^{0,5}} \qquad \textit{for vertical vibration} \tag{6}$$

$$a_x = \frac{1+\left(1{,}9\left(2-v\right)\left(\frac{D}{r_o}\right)\right)}{\left(\eta_x\right)^{0{,}5}} \quad \textit{for horizontal vibration} \tag{7}$$

$$a_\varphi = \frac{1+\left(0{,}7\left(1-v\right)\left(\frac{D}{r_o}\right)\right)+\left(0{,}6\left(2-v\right)\left(\frac{D}{r_o}\right)\right)}{\left(\eta_\varphi\right)^{0{,}5}} \quad \textit{for rocking vibration} \tag{8}$$

With a_z, a_x, a_φ is the factor of the depth of embedment on damping ratio. To find the mass ratio on vertical, horizontal, and rocking vibrations, it has shown in the equation (9) to (11) below:

$$B_z = \frac{\left(1-v\right)}{4}\times\frac{W}{y\times ro^3} \quad \textit{for vertical vibration} \tag{9}$$

$$B_x = \frac{7-\left(8v\right)}{32\left(1-v\right)}\times\frac{W}{y\times ro^3} \quad \textit{for horizontal vibration} \tag{10}$$

$$B_\varphi = \frac{3\left(1-v\right))\times Mmo}{g\left(\frac{y}{g}\right)ro^5} \quad \textit{for rocking vibration} \tag{11}$$

With B_z, B_x, B_φ is the mass ratio, γ is the weight of soil, g is gravity, and Mmo is the mass moment of inertia. To find the damping ratio on vertical, horizontal, and rocking vibrations, it has presented in the equation (12) to (14).

$$D_z = \frac{0{,}425}{\left(B_z\right)^{0{,}5}}\times a_z \quad \textit{for vertical vibration} \tag{12}$$

$$D_x = \frac{0{,}425}{\left(B_x\right)^{0{,}5}}\times a_x \quad \textit{for horizontal vibration} \tag{13}$$

$$D_\varphi = \frac{0{,}15}{\left(1+n_\varphi B_\varphi\right)\left(n_\varphi B_\varphi\right)^{0{,}5}}a_\varphi \quad \textit{for rocking vibration} \tag{14}$$

With D_z, D_x, D_φ is the damping ratio. To find the spring coefficient on vertical, horizontal, and rocking vibrations, it has depicted in the equation (15) to (17).

$$K_z = \frac{G}{1-v}\times B_Z\left(BL\right)^{0{,}5}\eta_z \quad \textit{for vertical vibration} \tag{15}$$

$$K_x = 2\left(1+v\right)GB_x\left(BL\right)^{0{,}5}\eta_x \quad \textit{for horizontal vibration} \tag{16}$$

$$K_z = \frac{G}{1-v}\times B_\varphi B^2 L\eta_\varphi \quad \textit{for rocking vibration} \tag{17}$$

With K_z, K_x, K_φ is the damping ratio and G is the soil shear modulus. After calculating the above factors, the next step is to calculate the natural frequency and resonance frequency. Natural frequency is a condition in which a system oscillates when the system is allowed to vibrate without being damped continuously. Meanwhile, resonant frequency is a condition in which an object vibrates due to vibrations that occur in the surrounding objects. The calculation of natural frequency has shown in the equation (18) and (19).

$$\omega_{nz,nx} = \left(\frac{K_{z,x}}{m}\right)^{0,5} \quad \textit{for vertical and horizontal vibration} \qquad (18)$$

$$\omega_{n\varphi} = \left(\frac{K_{\varphi}}{M_m}\right)^{0,5} \quad \textit{for rocking vibration} \qquad (19)$$

With ω_n is the natural frequency and m is the total mass of foundation and machine. The calculation of resonant frequency can be seen in equation (20) below:

$$\omega_{res} = \omega_n \left(1-2D\right)^{0,5} \quad \textit{for all vibrations} \qquad (20)$$

resonance will only occur when the damping ratio is less than 0,7117 [3], [8], [9]. for the calculation of the frequency ratio has presented in the equation (21) below:

$$r = \frac{2\pi \frac{fm}{60}}{\omega_n} \quad \textit{for all vibrations} \qquad (21)$$

With r is the frequency ratio and fm is the machine frequency in rpm. After the natural frequency and resonant frequency have been calculated, the next step is to calculate the amplitude. The amplitude itself can be calculated after the spring constant, damping ratio, and frequency ratio have been calculated. Like vibration, there are also three types of amplitude in the calculation of vibration analysis, namely vertical, horizontal, and rocking amplitudes. The amplitude calculation equation has shown in the equation (22).

$$A_{z,x,\varphi} = \frac{Q_o \times M_{z,x,\varphi}}{K_{z,x,\varphi}} \quad \textit{for all vibrations} \qquad (22)$$

With $A_{z,x,\varphi}$ is the Amplitude, Q_o is the living load from the machine, and $M_{z,x,\varphi}$ is the magnification factor. for the calculation of the magnification factor can be seen in the equation (23) below:

$$M_{z,x,\varphi} = \frac{1}{\left(\left(2D_{z,x,\varphi}r\right)^2 + \left(1-r^2\right)^2\right)^{0,5}} \quad \textit{for all vibrations} \qquad (22)$$

3. RESULTS AND DISCUSSION

In terms of the amplitude calculation, this study had designed several aspects, namely, vertical, horizontal, and rocking amplitude. First, the vertical amplitude was analysed for several variations which are different in the foundation dimensions. The next step was to compare the amplitude of the result on each variation machine against the foundation dimensions. The results have shown in Figure 2 and Figure 3.

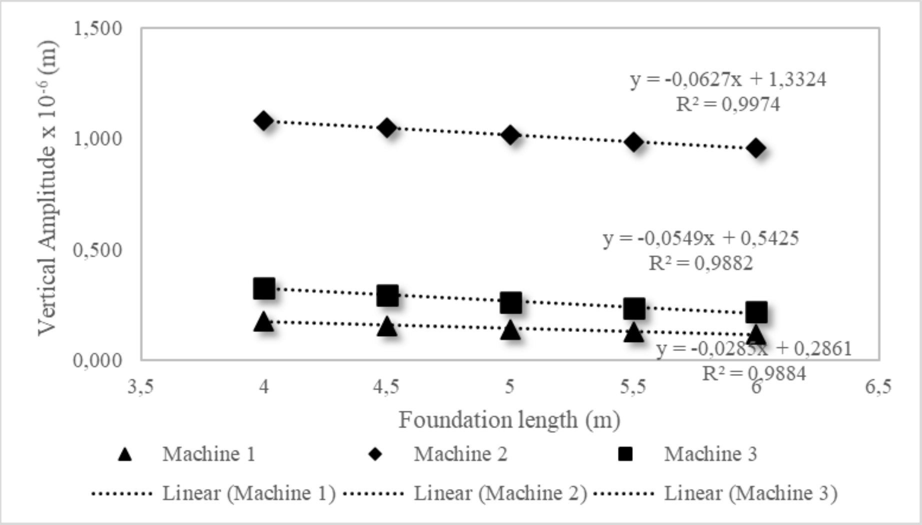

Figure 2 Effect of foundation length and operating machine frequency on vertical amplitude

Depicted in picture 2 is the result of foundation length against vertical amplitude in several conditions. The variations of the machine were calculated in this study, namely, machine 1, machine 2, and machine 3, which provide multiple values with range of differences are 57.01%, 57.0%, and 56.8% respectively. Furthermore, all the results show a similar trend in standard straight-line equations, with R2 always more significant than 0.9. This condition means the behaviour of outcomes offers reliable data in the linear equation, which present the reverse trend of foundation length and vertical amplitude. The greater the length of the foundation, the lower the vertical amplitude will be.
The other results in vertical amplitude have been described in Figure 3. Based on Figure 3, a similar trend has been shown between foundation length and foundation area against vertical amplitude. However, the smaller value of R2 has been presented in this result, which gives the value at 0.67 -0.81. Moreover, significant circumstances have been provided in Machine 2, while the others have no noticeable outcome.

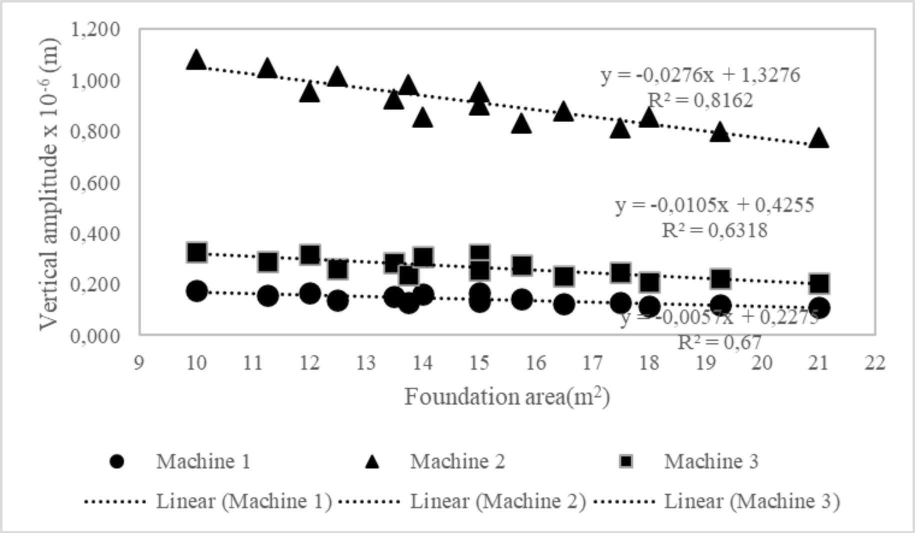

Figure 3 Effect of foundation area and operating machine frequency on vertical amplitude

The results indicate that the addition of dimensions causes the natural frequency, coupling equivalent radius, stiffness ratio, mass moment of inertia, and foundation damping ratio to be larger than before. The large ratio of stiffness and inertia mass moment affects a smaller amplitude. Furthermore, the addition of the engine capacity generates a larger vertical amplitude, and this was due to the increase in the engine frequency, causing the dynamic load to be higher.

The outcome of the horizontal amplitude with the dimensions of the machine foundation can be seen in Figure 4 and Figure 5.

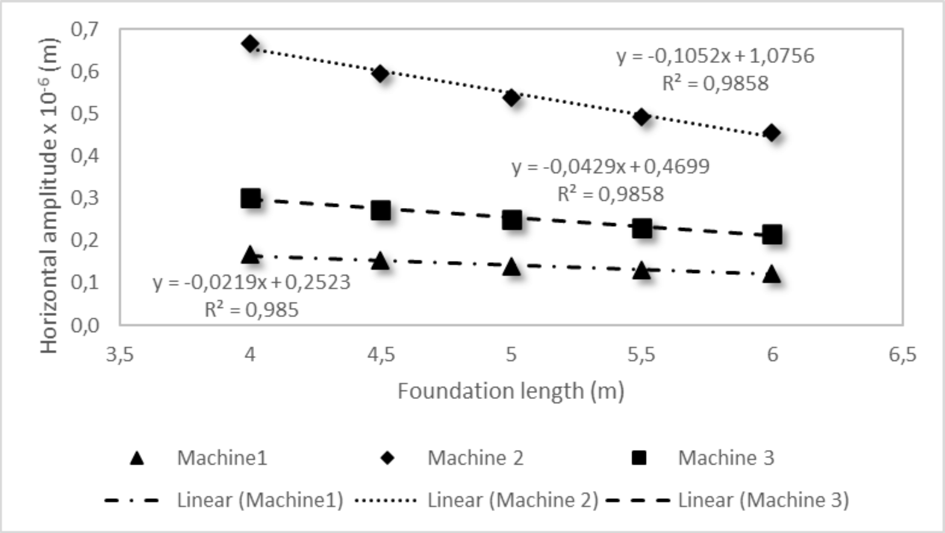

Figure 4 Effect of foundation length and operating machine frequency on horizontal amplitude

According to Figure 4 and Figure 5, it can be concluded that the addition of the dimensions of the machine foundation resulted in a smaller horizontal amplitude. This trend equal to vertical parameters, while machine 1, 2 and 3 depicts the differences value 40.305%, 39.632%, 42.505% respectively. This result can be said to be valid with an R2 value of more than 0.5. These circumstances show a similar trend to vertical amplitude, which presents a large ratio of stiffness and mass moment of inertia resulting in a smaller amplitude. In addition, the addition of engine capacity resulted in a larger horizontal amplitude, and this was due to the increase in the engine frequency, causing the dynamic load to be greater.

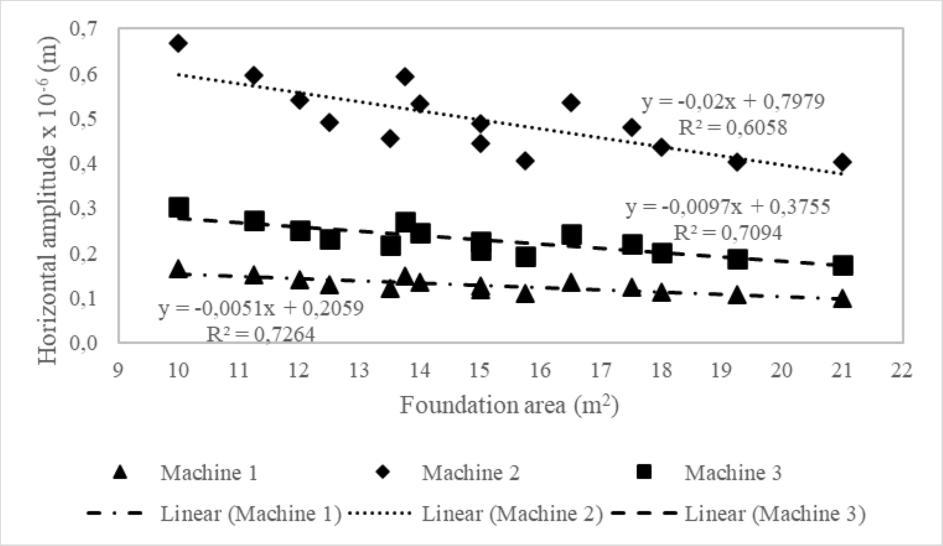

Figure 5 Effect of foundation area and operating machine frequency on horizontal amplitude

In terms of rocking amplitude analysis, the calculation was conducted by similar variations of length and areas of foundation to vertical and horizontal analysis. The results have presented in Figure 6 and Figure 7.

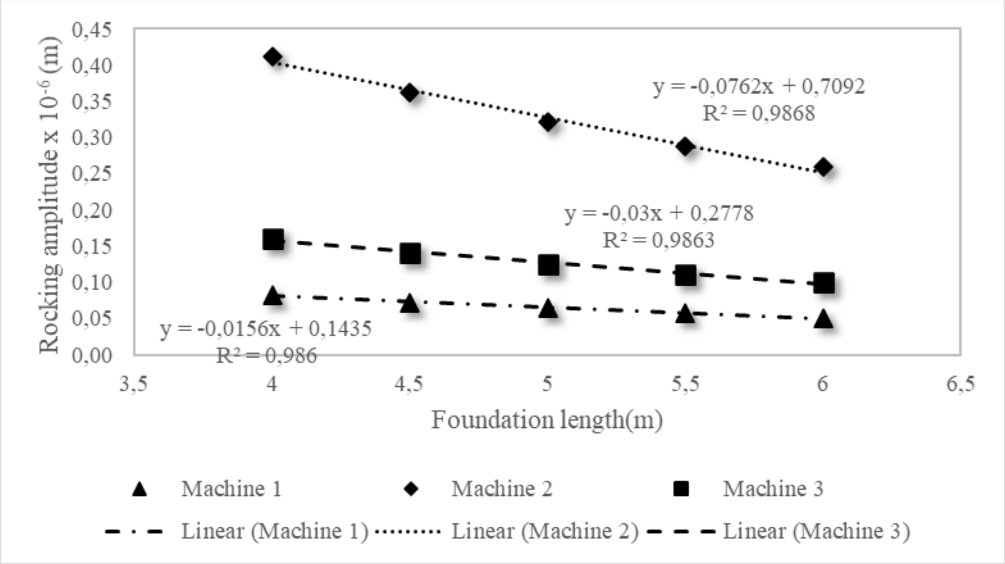

Figure 6 Effect of foundation length and operating machine frequency on rocking amplitude

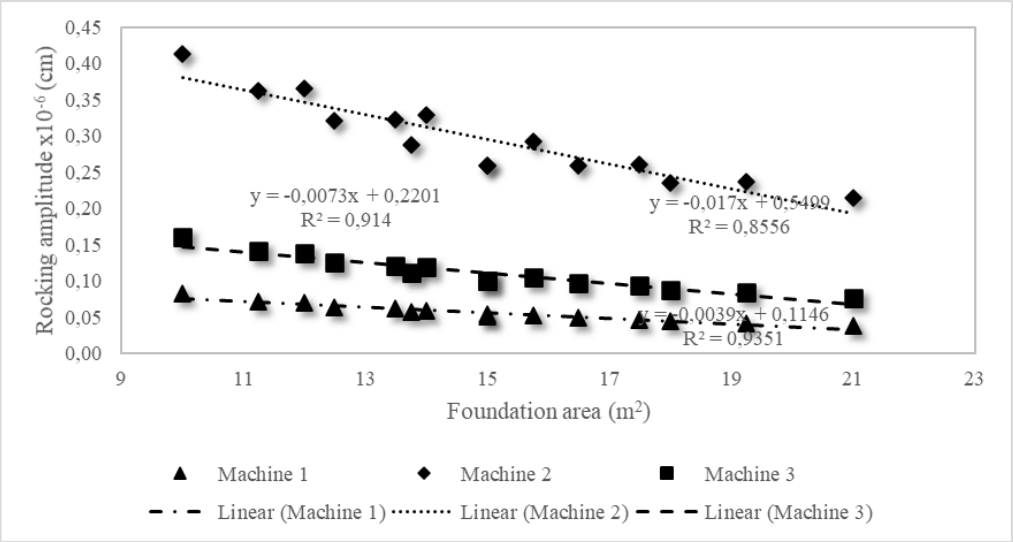

Figure 7 Effect of foundation area and operating machine frequency on rocking amplitude

Based on Figure 6 and Figure 7, the addition of the foundation machine areas gives effect to rocking amplitude. This result shows a valid equation with an R2 value of more than 0.5. This outcome is similar to the other amplitude parameters, vertical and horizontal while the variation value provide diversity with each machine, namely 54.28% for machine 1, 47.98% for machine 2, and 52.28% for machine 3. The notion is that the larger area of foundations provides the dynamic load transfers to subgrade, which affects the amplitude calculations. These circumstances similar to Khaled (2020), when the variation in vibration mode had little impact on the final strain values at the same frequency and the amplitude of displacement in the (Z) direction, whereas the amplitude of displacement in the (Y) direction is higher under rocking vibration and higher value amplitude of displacement in the (X) direction occurs under pitching vibration at the same frequency[15].

4. CONCLUSION

In general, the geometry variations of the foundation affect several dynamic parameters, namely vertical amplitude, horizontal amplitude, and rocking amplitude. All dynamics outcome depicts the lower results due to different foundation dimensions. In summary, the vertical amplitude shows the differences in machine variations, namely machine 1, machine 2, and machine 3, with the gap percentage being 57.01%, 57.0%, and 56.8%, respectively. The horizontal amplitude presents a similar trend with 40.305%, 39.632%, and 42.505%, respectively. Meanwhile, the rocking aspects describe the range of 54.28% for machine 1, 47.98% for machine 2, and 52.28%. The greater length and area of the foundation, the lower the dynamic amplitude will be. The highest diversity percentage shows in vertical aspects, while the lowest has shown in horizontal amplitude.

Acknowledgments

This study was carried out by funding a Research group Grant from LPPM Universitas Sebelas Maret, Surakarta 2022, with contract number: 254/UN27.22/PT.01.03/2022. All the authors express their gratitude for the financial support.

5. REFERENCES

A. F. Ali, M. Y. Fattah, and B. A. Ahmed, “Response of circular footing on dry dense sand to impact load with different embedment depths,” *Earthquake and Structures*, vol. 14, no. 4, 2018, doi: 10.12989/eas.2018.14.4.323.

Braja M Das, *Principles of Soil Dynamic*. Boston - United State Of America.: outhern Illinois University at Curbandale, PWS - Kent Publishing Company, 1993.

H. Gunawan, R. H. Dananjaya, and B. Setiawan, “Pengaruh Tinggi, Kedalaman Pondasi Mesin Jenis Blok dan Parameter Tanah Berbutir Halus Terhadap Amplitudo,” Universitas Sebelas Maret, Surkarta, 2017.

I. R. H. H. C. and F. F. Hertiany, “Analisis Dinamik Fondasi Mesin Generator Sets Pada Power House Building Project Lube Oil Blending Plant,” *Jurnal Tekno Global*, vol. 8, no. 1, 2019.

K. W. A. Al-Kaream, M. Y. Fattah, and Z. S. M. Khaled, “Effect of mode of vibration on the response of machine foundation on sand,” in *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 737, no. 1. doi: 10.1088/1757-899X/737/1/012089.

M. D. Tobi and V. N. van HARLING, “Studi Perencanaan Pembangunan Pltmh Di Kampung Sasnek Distrik Sawiat Kabupaten Sorong Selatan Provinsi Papua Barat,” *Electro Luceat*, vol. 3, no. 1, 2017, doi: 10.32531/v3i1.63.

M. M. Hassan, N. Cheraghi, G. W. Norlander, and J. Bagga, “Dynamic analysis of machine foundation systems,” in *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, 2013, vol. 3, no. January.

M. O. and G. P. Sharda Arya, Design of Structures & Foundations for Vibrating Machines. Houston, London, Paris, Tokyo: Gulf Publishing Company, 1979.

O. S. Ali and M. Mahamid, “Effect of Soil-Foundation Interaction on the Dynamic Response of a Four-Cylinder Compressor Foundation,” *Practice Periodical on Structural Design and Construction*, vol. 23, no. 3, 2018, doi: 10.1061/(asce)sc.1943-5576.0000380.

R. Dewi, Y. Hastuti, and A. Mentari, “Foundation modelling for cooling water pump machine in PT Pupuk Sriwijaya (PURSI) II-B projects,” *Jurnal Teknologi*, vol. 78, no. 8–5, 2016, doi: 10.11113/jt.v78.9605.

S. C. Arya, R. P. Drewyer, and G. Pincus, “Foundation Design For Vibrating Machines.,” *Hydrocarbon Processing*, vol. 54, no. 11, 1975.

S. Prakash and V. K. Puri, “Foundation for Vribatting Machines,” *Journal of Structural Engineering, Madrash*, 2006.

S. Surapreddi and P. Ghosh, “Impact of Footing Shape on Dynamic Properties and Vibration Transmission Characteristics of Machine Foundations,” *International Journal of Geosynthetics and Ground Engineering*, vol. 8, no. 1, 2022, doi: 10.1007/s40891-021-00347-x.

S. Syahidi, R. H. Dananjaya, and B. Setiawan, “Pengaruh Luas Penampang Pondasi Mesin Jenis Blok Dan Parameter Tanah Berbutir Halus Terhadap Amplitudo,” Pengaruh Luas Penampang Pondasi Mesin Jenis Blok Dan Parameter Tanah Berbutir Halus Terhadap Amplitudo, 2017.

T. Hill *et al.*, “The dynamic soil-structure interaction of shallow foundations on dry sand beds,” *PhD Thesis, University of Cambridge*, vol. 48, no. June 2018, 2019.