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Analysis of Centrifugal Machine Load on Block Foundation

Darlina Tanjung[1], Ahmad Bima Nusa[2], Annisa Muharamah[3], Jupriah Sarifah[4]

[1,2,4]Civil Engineering Study Program, Faculty of Engineering, Universitas Islam Sumatra Utara, Medan, Indonesia
[3]Undergraduate Student, Civil Engineering Study Program, Faculty of Engineering, Universitas Islam Sumatra Utara, Medan, Indonesia

Corresponding Author: Annisa Muharamah (annisa.muharamah64@gmail.com)

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ABSTRACT

In addition to having static load machine foundations receive dynamic load from engine vibrations. Their structure must be able to withstand both loads without failures. This study aims to discuss loads on the machine foundation of a block type machine having a high frequency. The analysis method used lumped parameter system and the foundation dimensions were 6 x 4 x 1 m with a depth of 1 m, with engine frequencies of 1800 and 3000 rpm. The results of this analysis show that the higher the machine foundation was, the smaller the vertical and horizontal amplitude, and rocking amplitude amplitude would be. The value of the natural frequencies of the machine foundation of vertical and horizontal amplitudes got smaller, while the rocking amplitude became bigger. So, the amplitude clearance value of the frequency of 1800 rpm and 3000 rpm met the safety requirements of the machine foundation, namely the maximum vertical amplitude requirement is troublesome to persons, with high frequency machines vertical vibration is 0.002-0.003 and horizontal vibration was 0.004-0.005.

Keywords: Machine foundations, amplitude, damping, static load, dynamic load

INTRODUCTION

Soil supports the building foundation, or the construction material, of the building itself. Foundation is one of the building constructions located at the bottom of a construction.[1] Foundation, as a lower structure, can be divided into deep and shallow foundation. The choice of foundation type depends on the structure, or the load, above it like light or heavy loads, and on the surrounding soil conditions. Machine foundation is used to support dynamic load from all forms of vibrations from the machine placed above the foundation. The foundation that supports dynamic load uses different calculations from the one that supports static load; attention should be directed to dynamic load due to machine work as well as to static load. Generally, dynamic load is smaller than the static one. Machine foundation is greatly affected by the dimensions of the foundation and the weight of the foundation itself.

Machine foundation is different from foundation in general; this foundation is quite complicated because it includes geotechnical, structural, and dynamic analysis. Geotechnical analysis is needed for machine foundation, because the load that the soil receives is relatively up and down.

LITERATURE REVIEW

Machine Foundation

Foundation refers to construction at the base of a structure or building (sub-structure) that functions to forward the load from the upper structure to the soil layer below without causing the soil shear collapse and excessive settlement of the soil or foundation.[2] In the machine foundation analysis, the commonly used method assumes that soil is elastic. This assumption is reasonable to consider the level of vibration in the small strain range. Vibration response of the foundation system is represented by the parameter system, like natural frequency, and vibration amplitude. These two quantities become the most important parameters in the machine foundation planning.

Machine foundation planning has more complex problems than foundations that must withstand static loads (which come from the weight of the engine and the weight of the foundation). The design of machine foundation must consider dynamic load (derived from engine vibration) in addition to static load. Load is transmitted from the engine; what must be understood is related the problem that arises due to the dynamic behavior of the foundation and under the foundation. Wave energy due to dynamic load propagating through the ground must also be limited so as not to cause adverse effects on the surrounding environment. Ideally, the smaller the vibration amplitude is, the better the machine foundation design would be.

There is a requirement that the foundation load itself should be 2-3 times heavier than the weight of the machine, and the foundation weight should also be 3-5 times the weight of the machine when it is active.[3]

Machine Foundation Type

To design the machine foundation two types of machines, namely centrifugal machines and reciprocating machines should be considered. Centrifugal or rotating machines occur in all rotating equipment or equipment such as pumps, motors, electric generators, all types of turbines both steam turbines and gas turbines. Reciprocating means precisely moves back and forth on a straight line, and this working principle occurs in both diesel and auto or gas engines.

The type of machine foundation can be distinguished by several classifications, where each classification has its own types and the fourth classifications are:

1. Foundation classification is based on design criteria.
   a. producing impact forces such as impact force and compression force.
   b. producing periodic forces such as reciprocating engines (compressors).
   c. high-speed machines such as turbines, rotary compressors.
   d. other auxiliary machines.

2. Foundation classification is based on the shape of the structure.
   a. the block-type foundation consists of a concrete stand, on which the machine is placed.
   b. box or caisson type foundations consist of a concrete block with a hole in the center that holds the machine above it.
   c. a wall-type foundation consists of a wall that holds the machine above it.
   d. frame type foundations consist of vertical columns holding the horizontal frame construction above, on which the machine will be placed.
   e. nonrigid/flexible type.

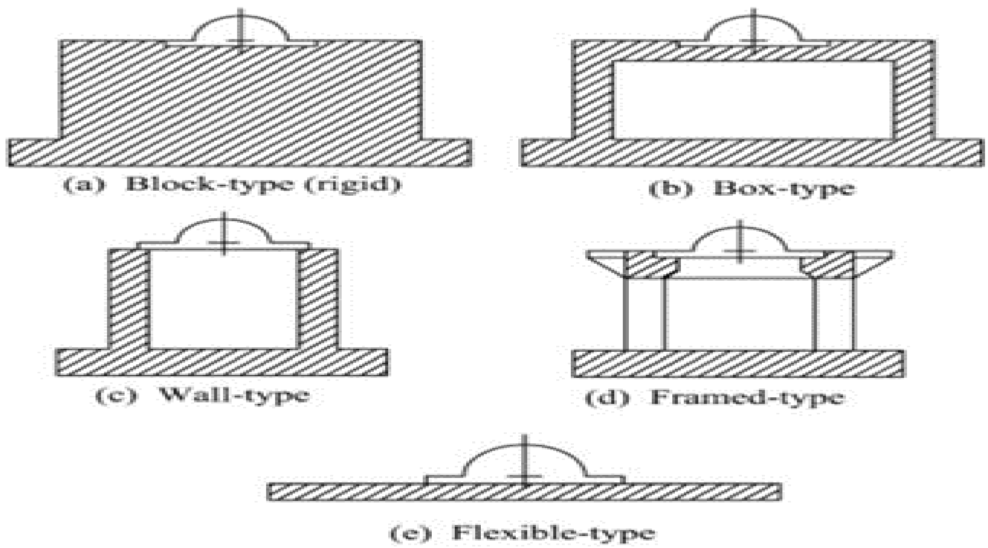

Figure 1. Machine Foundation Type
(Source: Kameswara, 1998: 394)

Most block-type foundations are often used for machines that generate periodic and impulsive forces. The rotating machines are calculated by Revolutions Per Minute (RPM) or speed.[4]

3. Degrees of freedom in machine foundations

Due to the forces and moments by dynamic loads, the block type foundation has 6 vibration directions, namely, translational z-axis direction (vertical), translational x-axis direction (lateral), y-axis direction translation (longitudinal), rotation about the x-axis (pitching), rotation about the y-axis (rocking), and rotation in the z-axis (yawing/torque).[5] Each vibration direction in the block foundation can be divided into six displacement forms separately and has six forms of degrees of freedom with six forms of natural frequencies.

4. Based on the operating frequency, the machines can be divided into three categories, namely, low to medium frequency 0-500 rpm, medium to high frequency 300-1000 rpm, very high frequency > 1000 rpm. Machine foundations must meet design criteria for both static and dynamic loads. In terms of design, twelve conditions should be available (Srinivasulu and Vaidyanathan, 1977 found in writing.[2]

a. the foundation must be able to accept static and dynamic loads without collapsing.
b. the settlement must be within the permissible limits.
c. resonance of the machine foundation must be avoided; therefore, the system in the natural frequency of the ground machine foundation should be higher or lower than the operating frequency of the machine should be. For low-frequency machines, the natural frequency of the ground-machine-foundation system should be high enough and vice versa.
d. to avoid harmonic resonance at higher frequencies, the natural frequency of the ground machine foundation system should not be an integer for multiple of the operating frequency of the machine.
e. the amplitude that occurs when the machine is running must be within the range of permissible values. The limitation value is generally specified by the machine manufacturer.
f. every part of the machine producing rotational or reciprocating motion must be balanced as well as possible to minimize the unbalanced force and moment. This is the obligation of the machine manufacturer.
g. the amplitude of vibration produced by the machine must not give disturbance to humans, other industrial equipment, or surrounding building structures.
h. the location of the center of gravity (COG) of the combined machine and foundation is as symmetrical as possible to the plane of contact of the foundation with the ground to avoid the generation of moments.
i. for pile foundations, the protrusion of the pile above the ground is avoided as much as possible to prevent large horizontal displacement and rotation.
j. pipes embedded in the foundation should be insulated as best as possible.
k. the groundwater level should be at least a quarter of the foundation width below the base of the foundation. This is to prevent wave propagation, especially compressive waves, where groundwater is a good medium for compressive wave propagation.
l. the foundation should be protected from engine oil by using acid resistance coating or other suitable chemical protection.

Prakash states that machine foundations must meet design criteria based on static and dynamic loads.[6] The design criteria for machine foundations for static and dynamic loads have different criteria. Prakash also argued for static loads, the foundation shall be safe against shear collapse and the foundation should not experience excessive ground settlement.[6] For dynamic loads, the foundation must not be resonant, i.e. the natural frequency of the soil system of the machine foundation must not be the same as the operating frequency of the machine, the amplitude of vibration that occurs must not exceed the permissible value. The permit value is generally required by the machine manufacturer, the natural frequency of the machine foundation soil system shall not be an integer multiple of the operating frequency of the machine. This is to avoid higher harmonic resonance, and vibrations caused by the machine must not disturb or adversely affect people and equipment in the vicinity. Machine foundation failure occurs, if the vibration has exceeded a predetermined limit. The limitations of the machine foundation can be found in the amplitude and speed of the vibrations that occur in machine work operations.

Machine Vibration Theory

Machine foundations, which are part of dynamic free foundations, cannot be separated from the theory of harmonic vibrations. Harmonic vibration is defined as the alternating displacement of a point in a line in such a way that the acceleration of the point is proportional to the distance from an equilibrium position and always leads to the equilibrium position. This is illustrated in Fig. 2.

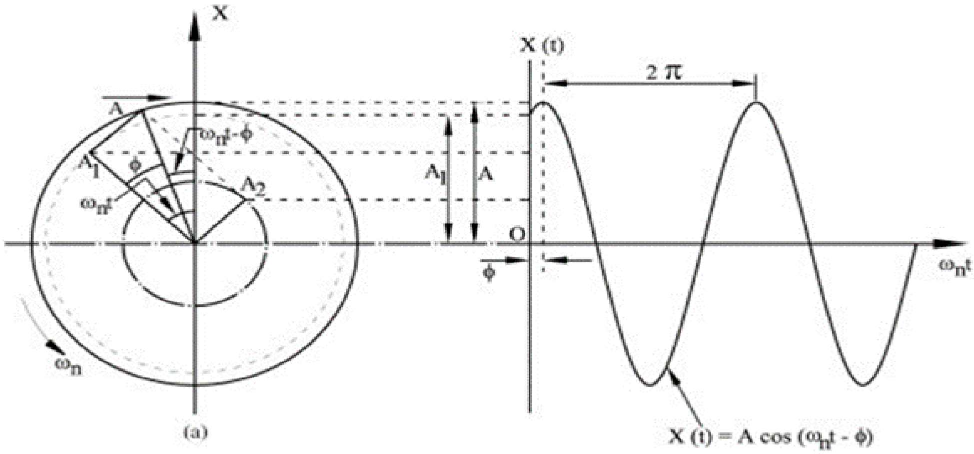

Figure 2. Harmonic Vibration Curve
(Source: Rao 1998[4])

If a mass-spring system is vibrated by an external force so that it experiences harmonic vibrations, then the external force is removed, and the system will vibrate harmonically and continuously with the same amplitude and frequency of vibration. The vibration will decrease little by little which in the end, will stop if the system has a damper that functions as a vibration reducer.

Richart, et al. describes the dynamic loads that occur in machines with harmonic motion as in the following formula: $Q = Q_o \sin \omega t$ in which the $Q_o$is a constant or function of the rotary frequency on the force which is given by below formula: $Q_o = m_e\, e\, \omega^2 = m_e\, e\, 4\,\pi^2 f^2$ where: m_e is the eccentricity of mass.[7] The e is the eccentricity of the radius from the center of rotation to the center of gravity of the mass rotation and the ω angular frequency (rad/sec) and the f^ operating frequency (cycles/sec). For rotation machines on parts moving, theoretically does not produce unbalanced forces during its rotation. However, in practice unbalanced forces are always present and their magnitude is influenced by design, manufacturing, installation, and maintenance procedures. Excessive vibration of the rotary machine and its foundation occurs, helping to reduce the unbalanced forces.

Ground Damping

In general, the available damping is categorized into two types of damping, namely material or internal damping (material damping) and geometric damping or dispersion (geometrical damping). Material damping in the soil can also be defined as the specific damping capacity which is the ratio of the energy absorbed in one vibration cycle to the potential energy at maximum amplitude. Material damping is related to the absorption of energy by the soil mass and the energy density of each wave decreases when the distance from the vibration source increases; the energy density loss can be categorized as geometric damping.

1. Material or Internal Damping

Three methods can be used to obtain the damping value of soil materials, such as, a) decay curve (resonant column test) method is performed by removing the cyclical load in the resonant column test after the steady-state resonance condition is reached, b) response curve for a single degree of freedom system with constant excitation, and c) stress-shear strain hysteretic curve (cyclic triaxial compression test) is basically the measurement of material damping with a hysteretic curve of shear stress-shear strain is done by measuring the energy input at resonance.

2. Geometric Damping or Dispersion

The energy generated by a vibration is propagated in the ground through P, S, and R waves. These three waves will spread into the ground radially from the vibration source. Thus, the spreading medium of each wave will be enlarged so that the energy density of each wave will decrease with increasing distance from the vibration source. As a result, the displacement amplitude also decreases with increasing distance to the vibration source. Some waves on the ground are body waves consisting of compressive (P) and shear (S) waves and surface waves in the form of Reyleigh waves. In addition to these three waves, there are love waves (see Fig. 3) that are categorized as surface waves.

This case of geometric damping causes the amplitude to have a limited value at the time of resonance. In general, geometric damping is about three times the material damping. The geometric damping value in the machine foundation analysis can be obtained through the solution of the lumped parameter model.[8] The lumped parameter system method is the result of research and development of the Elastic Half-Space method to get the price of a parameter by using the method or formula from the Elastic Half-Space theory. The lump parameter system theory is a system used to stiffen foundation blocks using masses, springs, and dashpots. This system applies all components of mass, spring, and damping. This method was developed by.[2]

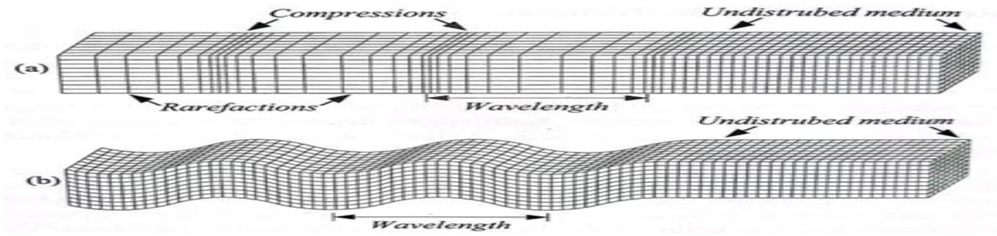

Figure 3. Characteristics of body wave propagation in soil (a) P-wave and (b) S-wave.

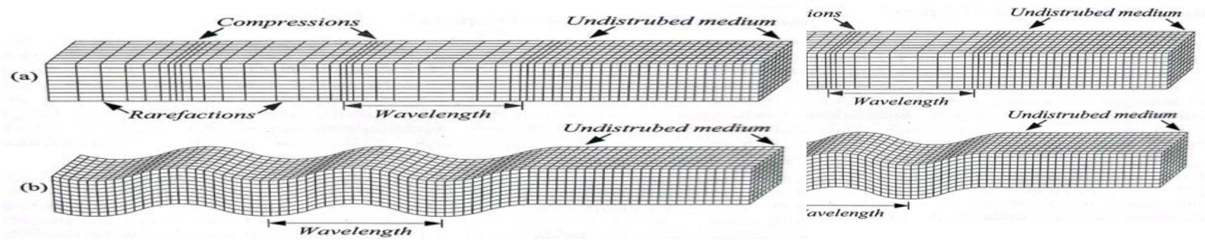

Figure 4. Characteristics of body wave propagation in soil (a) Rayleigh waves and (b) Love waves.
(Source: Bolt, 1976)

Several factors are considered toinfluence the damping value. However, the most important factors in influencing the damping value are strain level, pressure bridle (confining pressure), plasticity index, pore number.[2]

Machine Foundation Analysis

1. Loading

Das argued dead load calculations in the form of machine weight and foundation weight use the Equation (1).[9]

$$Wtot = Wp + Wm \quad (1)$$

in which the $Wtot$ refers to total dead load (kN), the Wp to Foundation weight (kN), and the Wm to Machine weight (kN). The calculation of live load in the form of force due to vibration from the engine involves the Equation (2).

$$Qo = Mr\ e\ \omega 2 \quad (2)$$

in which the Qo means the total live load (kN), the Mr refers to rotor mass (kN sec2/m), the e means Eccentricity (m), and the ω refers to machine frequency (rad/sec).

2. Static analysis

The static analysis calculation of the foundation is idealized as a shallow foundation using the Meyerhof method as in Equation (3).

$$qu = (c\ Nc\ Scdc) + (q\ Nq\ Sqdq) + (0.5\ L\ \gamma\ N\gamma\ S\gamma d\gamma) \quad (3)$$

The qu refers to ultimate bearing capacity (kN/m2), the c points to soil cohesion (kN/m2), the qq designates $Df\gamma$ (kN/m2), the Df indicates the foundation depth (m), the γ refers to weight of soil content (kN/m3), the L points to foundation width (m), the Sc, Sq, $S\gamma$ designates the foundation form factor, the dc, dq, $d\gamma$ means the foundation depth factor, and the Nc, Nq, $N\gamma$ refers to Meyerhoff bearing capacity factor.

3. Dynamic vibration analysis

The calculation of dynamic vibration analysis uses a method developed for circular foundations with a radius (ro) that depends on the type of vibration.[10],[11],[12] Geotechnical considerations that influence the dynamic vibration analysis are foundation shape and embedment.

a. Influence of foundation shape

The foundation shape influences the dynamic vibration analysis on the equivalent radius. Calculation of the equivalent radius of vertical and horizontal vibrations can involve Equation (4) and for rocking vibration to use Equation (5).

$$ro = \sqrt{\frac{BL}{\pi}} \text{ for vertical and horizontal vibrations} \quad (4)$$

$$ro = \sqrt[4]{\frac{BL^3}{3\,\pi}} \text{ for rocking vibration} \quad (5)$$

The ro means equivalent, the L refers to foundation length (m), the P to foundation width (m), and the ro to equivalent radius (m).

b. Effect of foundation embedment ()

The next calculation in the analysis of dynamic vibrations on the machine foundation is embedded. The spring constant in the machine foundation analysis can be calculated using Equations (6) to (8).

$Kz = G$ 1-$v\beta z\sqrt{PL}\ \eta z$ for vertical vibration (6)

$K\ x$ =2(1+v)$G\beta x\sqrt{LP}\eta x$ for horizontal vibration (7)

$K\ \varphi = G$ 1-$v\beta\varphi L2P\eta\varphi$ for rocking vibration (8)

Respectively, the Kz,x,φ, G, v, βz, P, L, ηz, refer to spring constant (kN/m), soil shear modulus (kN/m2), poisson's number, square foundation coefficient, foundation width (m), foundation length (m), and embedding coefficient. Meanwhile, the damping ratio in machine foundation analysis can be calculated using Equations (9) to (11).

Drz =0.425 $\sqrt{Bzaz}$ for vertical vibration (9)

Drx =0.288 $\sqrt{Bxax}$ for horizontal vibration (10)

$Dr\varphi$ = 0.15 (1+$n\varphi B\varphi$)$\sqrt{n\varphi B\varphi a\varphi}$ for rocking vibration (11)

The $D\ rz,x,\varphi$, $B\ z,x,\varphi$ and $a\ z,x,\varphi$ refer to damping ratio, mass ratio, and damping ratio embedding factor respectively. The natural frequencies of vertical, horizontal, and rocking vibrations are calculated using Equation (12).

ωnz=ωnx=$\omega n\varphi$=$\sqrt{Kz,x,\varphi\ Mtot}$ (12)

The ωnz, $\omega\ nx$, $\omega\ n\varphi$, Kz,x,φ, and Mtot designate to vertical natural frequency (rad/sec), horizontal natural frequency (rad/sec), natural rocking frequency (rad/sec), spring constant (kN/m), and total mass (kN sec2/m) respectively. Whether resonance occurs or not can be calculated using Equation (13).

Drz,x,φ> 1 2$\sqrt{2}$ (no resonance occurs) (13)

The Drz,x,φ means the damping ratio. The resonant frequencies in vertical, horizontal, and rocking vibrations are calculated using Equation (14).

$\omega resz$=$\omega resx$=$\omega res\varphi$=$\omega nz,nx,n\varphi$$\sqrt{1\text{-}}$ 2Drz,x,φ2 (14)

The $\omega resz$, $\omega resx$, $\omega res\varphi$, $\omega nz,nx,n$ω, and Drz,x,φ, refer to vertical resonance frequency (rad/sec), horizontal resonant frequency (rad/sec), rocking resonance frequency (rad/sec), natural frequency (rad/sec), and damping ratio respectively. To check whether the condition of the resonant frequency is safe or not, the Equation (15) can be used.

$\omega res\ \omega$>2 or $\omega res\ \omega$<1 2 (safe) (15)

The ωres, and ω refer respectively to resonance frequency (rad/sec) and machine frequency (rad/sec). to analyze the amplitude due to vibration can use Equations (16) to (18).

$Az = Qo\ Kz$ $\sqrt{}$(1-r2)2+(2Dzr)2 (for vertical vibration) (16)

$Ax = Qo\ Kx$ $\sqrt{}$(1-r2)2+(2Dxr)2 (for horizontal vibration) (17)

$A\ \varphi$ =Qo(TBm+ T)$M\ K\varphi$ (for rocking vibration) (18)

Respectively, the $Az\ Ax$, $A\varphi$, Qo, Kz,x,φ, r, Dz, T, and M refer to vertical amplitude (m), horizontal amplitude (m), rocking amplitude (m), live load (kN), spring constant (kN/m), frequency ratio, damping ratio, foundation height (m) and dynamic magnification.

MATERIALS & METHODS

The method used in this research is mixed method. This research approach uses quantitative and qualitative data collection in the same writing. The research model used is a selection model between project primary data, journals and books with a descriptive analysis survey method. The data used includes primary data and secondary data. This stage begins with collecting quantitative data, then the data is analyzed quantitatively to determine the stages in the dynamic analysis of the machine foundation. From these results, a qualitative comparison is made to obtain data through qualitative data collection, then the collected data is analyzed qualitatively so that qualitative results are obtained.

RESULT

The data taken and adjusted to the data requirements refers to the calculation of the centrifugal machine load on the block foundation. Data collection is done through literature studies and journals related to this writing. The method used is the lumped parameter system. This method was developed by.[2] In this method, the dynamic response of the soil to the foundation and dynamic loads are modelled as springs and damping. The spring and damping model can model both vertical, horizontal, and rocking responses. The following is the calculation of the machine foundation with dimensions of 6 x 4 x 1 m and using different engine data including the HLA575C-WJ-62 type turbine engine with a motor speed of 1800 rpm and a centrifugal single stage turbo-compressor type engine with a motor speed of 3000 rpm.

DISCUSSION

The recap calculation results of the data evaluation are as follows:

Table 1. Block-type machine foundation to support the HLA575-WJ-62 type turbine engine with a frequency of 1800 rpm.

No.	Parameters		Vertical Excitation	Horizontal Excitation	Rocking Oscilation
1	Dynamic Force (F)	kN	2,70	2,70	5,40
2	Natural Frequency $(F)_n$	Rpm	1184,121	1149,40	1690,977
3	Frequency Ratio		1,520	1,566	1,102
4	Magnification Factor (M)		0.711	0.685	1,306
5	Transmissibility Factor (T)		2,306	1.952	1,410
6	Vibration Amplitude (A)	In	0.000066	0.000068	0.000047
7	Amplitude Check (Atotal)	In	0.000160	0.000162	
8	Horizontal Peak Velocity	In/sec		0.0305	
9	Force Transmitted (P)	kN	6,238	5,279	7,625

No.	Conditions	Security
1	Amplitude	Barely noticeable to persons < Troublesome to persons
2	Amplitude Velocity	Very good < Good
3	Conclusion	Vibration caused by the engine is almost not disturbing or not felt against the engine. neighborhood.
Source	*r: Evaluation Calculation Result*	*i Data)*

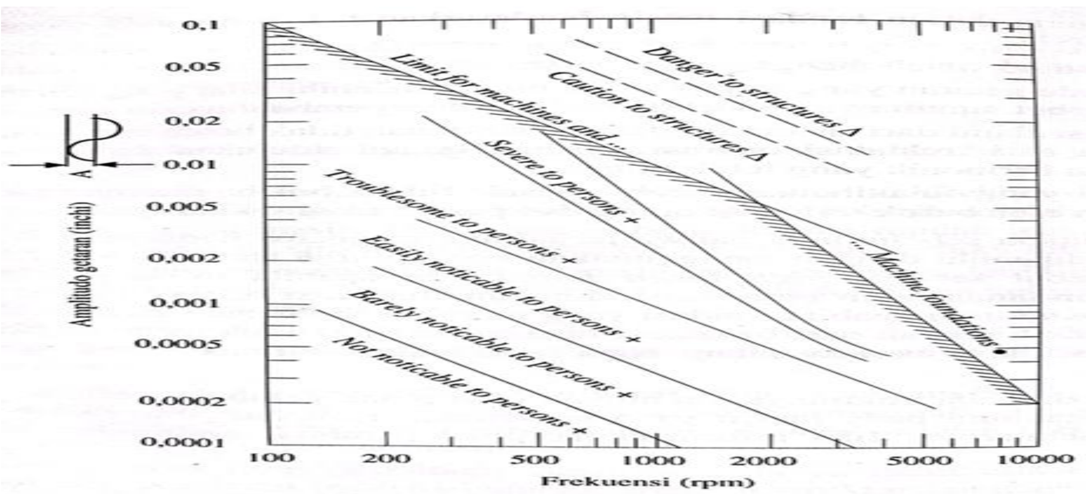

Figure 5. Vertical Amplitude Limitation
(Source: Richart, 1962)

Table 2. Horizontal Amplitude Speed Criteria

Horizontal Peak Velocity (in./sec.)	Machine Operation
< 0.005	Extremly smooth
0.005 – 0.010	Very smooth
0.010 – 0.020	Smooth
0.020 – 0.040	Very good
0.040 – 0.080	Good
0.080 – 0.160	Fair
0.160 – 0.315	Slightly rough
0.315 – 0.630	Rough
0.630	Very Rough

(Sumber : Sidharta, 2016: 19)

Table 2 shows that the horizontal amplitude is within the "very good" limit. The maximum requirement for horizontal amplitude velocity is the "good" limit, so the horizontal amplitude meets the safety requirements. This maximum amplitude velocity requirement states that the machine is in very good condition. The criteria for machine foundations based on static loads is that the foundation should not experience excessive soil settlement. Likewise, the criteria for machine foundations based on dynamic loads are that the foundation must not experience resonance and the vibrations caused by the machine must not disturb or give a bad situation to other people and the surrounding environment.

Table 3. Block-type machine foundation used to support a centrifugal single stage turbocompressor type turbine engine with a frequency of 3000 rpm.

No.	Parameters		Vertical Excitation	Horizontal Excitation	Rocking Oscilation
1	Dynamic Force (F)	kN	7,51	7,51	15,03
2	Natural Frequency $(F)_n$	Rpm	1286,81	1249,20	1940,469
3	Frequency Ratio		2,331	2,402	1,632
4	Magnification Factor (M)		0.225	0.208	0,491
5	Transmissibility Factor (T)		1,180	0,948	0,618
6	Vibration Amplitude (A)	In	0.000059	0.000057	0.000049
7	Amplitude Check (Atotal)	In	0.000157	0.000155	
8	Horizontal Peak Velocity	In/sec		0.049	
9	Force Transmitted (P)	kN	8,875	7,131	9,164

No	Conditions	Security
1	Amplitude	Easily noticeable to persons < Troublesome to persons
2	Amplitude Velocity	Good
3	Conclusion	Vibration caused by the engine is slight felt towards the surrounding environment.

(Source: Data Evaluation Calculation Results)

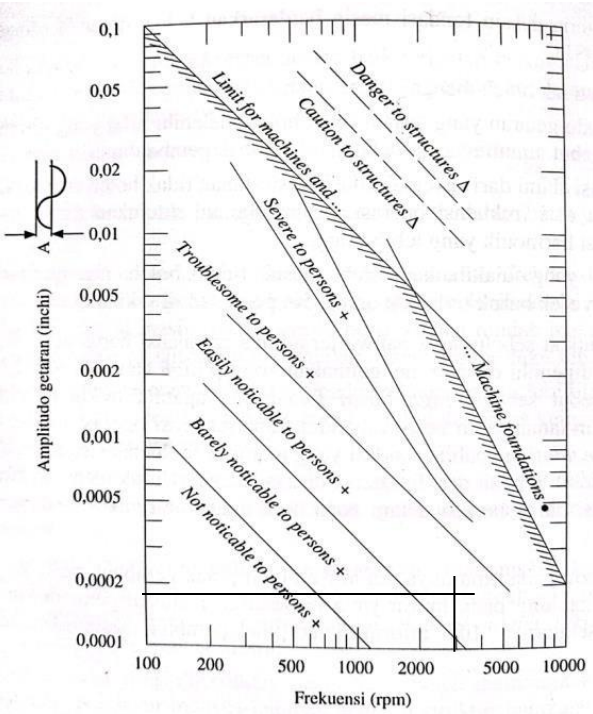

Figure 6. Vertical Amplitude Limitation
(Source: Richart, 1962)

CONCLUSION

The followings are the conclusions taken form the analysis.

1. The criterion in the design of the machine foundation for dynamic loads notes that the foundation must not experience resonance. In the machine foundation safety criteria the engine operating frequency is ± 20% of the resonance frequency.
2. Dynamic analysis of the block machine foundation shows that the machine foundation with dimensions of 6 x 4 x 1 m and with a frequency of 1800 rpm is more stable than the frequency of 3000 rpm. However, both planned machine foundations are able to withstand static and dynamic loads simultaneously.
3. In the amplitude velocity of the engine from the data evaluation, the frequency 1800 rpm with vertical excitation amplitude 0.000160 *in* falls within the amplitude limitation of "barely noticeable to persons" where it is almost not felt by the surrounding environment. While the frequency of 3000 rpm with an amplitude of 0.000157 *in* is included in the amplitude limit of "easily noticeable to persons" where it is slightly felt to the surrounding environment.

Declaration by Authors

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