PARAMETRIC STUDY OF MACHINE FOUNDATION SUPPORTING RECIPROCATING MACHINE USING ELASTIC HALF SPACE MODEL BY FEM AND CLASSICAL METHOD

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Abstract

Machine foundation is a requisite part of any industry; costs less as compared to the cost of machine and losses caused due to its failure can cause a big loss to any industry. A machine foundation needs to be designed carefully as static as well as dynamic loads are acting on it due to working of machine. The machine weighs several tons and is required to design the foundations having dimensions of several meters but amplitudes restricted to only a few microns. In addition, natural frequency of the machine foundation is depends on the soil lying below the foundation. This necessitated a deeper scientific investigation of dynamic loading and analysis. Elastic Half Space Method (Recommended by ACI 351.3R-04 - "Foundation for Dynamic Equipment") proposed by Whitman and Richart gives thus necessary importance to damping and embedment depth effect. Finite Element (FE) is the most commonly accepted analysis tool for solution of engineering problems. Effective Pre & Post-processing capabilities make modeling and interpretation of results simple. It is relatively easy to incorporate changes if any and re-do the analysis without much loss of time. STAAD Pro V8i is chosen for this Literature for analysis of Machine Foundation by Finite Element Method. In this literature three different machines of 150 rpm, 250 rpm, and 450 rpm are taken into account and six different soil types: Medium Clay, Stiff Clay, Hard Clay, Loose Sand, Medium Sand and Dense Sand are considered. Foundation sizes are optimized according to soil cases and each case is analyzed using classical method and FEM for 0.8, 1 and 1.2 times the soil parameters to cover the confidence range. Codal Criteria are taken as per IS:2974-1982.

Keywords: Machine Foundation, Elastic Half Space Model, Structural Dynamics

I. Introduction

Machine foundation require the special attention of a structural engineer. In addition to static loads due to weight, loads acting on foundation are dynamic in nature. In a machine foundation, a dynamic force is applied repetitively over a large period of time but its magnitude is small, and it is therefore necessary that the soil behavior be elastic, or else deformation will increase with each cycle of loading until soil becomes practically unacceptable. The amplitude of motion of a machine at its operating frequency is the most important parameter to be determined in designing a machine foundation, in addition to determining the natural frequency of a machine foundation soil system. Choice of type of machine foundation basically depends upon machine and its characteristics. Functional characteristics of the machine play a significant role while selecting the type of foundation.

There are three most important categories of machines that generate different periodic forces.

I. Reciprocating machines: Machines that produce periodic unbalanced force (such as

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compressor) belong in this category. The operating speed of such machines is usually less than 600 rpm. For analysis of their foundation, the unbalanced forces can be considered to vary sinusoidally. For such type of machines Block Type Foundation having relatively low Natural frequency is to be provided.

II. Impact machines: Machines that produce impact loads (such as forging hammers) are included in this category. Their speeds of operation are usually 60 to 150 blows per minute. Their dynamic loads attain a peak in a very short interval and then practically die out. Block foundation may also be provided for impact type machine foundation but their detail would be different from reciprocating machines.

III. Rotary machines: High speed machines like turbo generators or rotary compressors may have speed of more than 3000 rpm and up to 10,000 rpm. For such type of machine Frame type foundation is preferred.

Dynamic analysis of Machine Foundation is a trial and error method until it gives acceptable response hence it's a very time consuming and tedious task. Finite Element (FE) is the most commonly accepted analysis tool for dynamic analysis. It is relatively easy to incorporate changes if any and re-do the analysis without much loss of time, but validation of results is the main issue. This gave motivation to make a comparison of results by Excel worksheet with FEM by STAAD ProV8i.

In this paper a reciprocating machine mounted on block type foundation is discussed. Typical diagram of block-type machine foundation is shown in Figure 1.

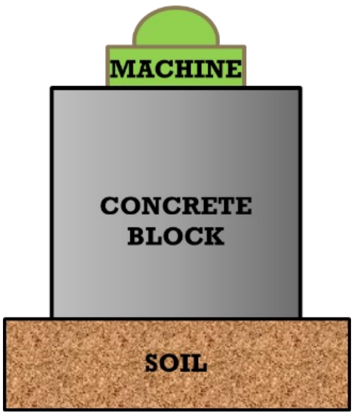


Figure 1: *Block Type Machine Foundation*

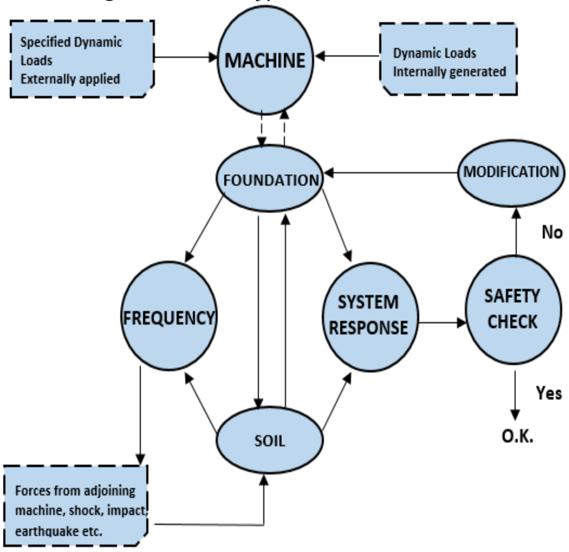


Figure 2: *Schematic Flow of Machine Foundation System*

Machine foundation system broadly comprises of machine, supported by foundation and foundation resting over soil as shown in schematic shown in Figure 2.

Dynamic Analysis of Block-Type Machine Foundation

A foundation concrete block is much rigid as compared to the soil on which it is resting. Hence, it can be assumed that when unbalanced forces acts, the foundation block undergoes translations and rotations with six degrees of freedom as shown in Figure 3.

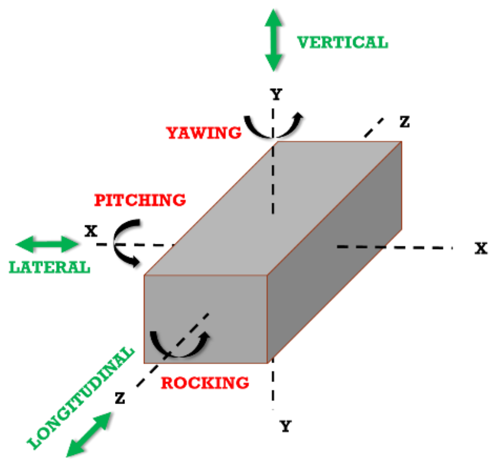


Figure 3: *Degrees of freedom of Machine Foundation*

II. Parameters used in this study

The details of parameters used in this study are listed below:

Modes of Computations for Dynamic Analysis

Machine foundations are analysed by elastic half space method using Classical solution and Finite Element Method. Classical solution of each case was carried by preparing excel worksheets and Finite Element Solution was done by modelling machine foundation in STAAD Pro. Software.

Machine Parameters

Machine parameters used in this study is table below.

Table 1: *Machine Parameters*

Parameters	Unit	Machine 1	Machine 2	Machine 3
Operating Speed	rpm	150	250	450
Weight	kN	36	10	25
Vertical Dynamic Force	kN	-	2.5	-
Horizontal Dynamic Force	kN	12	2	-
Horizontal Dynamic Moment	kN.m	-	4	4.9
Height of Machine C.G. above base of foundation	m	0.6	0.2	0.15

Soil Parameters

Soil properties of all the six soils used in this study are shown in summarized form in the table.

Table 2: *Soil Parameters*

SOIL TYPE		Unconfined Compressive Strength (qu)	N - Value
		kN/m2	
1	Medium Clay	75	-
2	Stiff Clay	200	-
3	Hard Clay	450	-
4	Loose Sand	-	8
5	Medium Sand	-	25
6	Dense Sand	-	40

III. Design Criteria as per IS: 2974 (Part I) – 1982

- Mass of Foundation >> Mass of Machine. (General rule of thumb to keep this ratio greater than 3 for Reciprocating Machines)
- The eccentricity <5% of the base dimension of block.
- 1.5 < Frequency Ratio < 0.4
- Limiting Amplitude of foundation is 200 Micron

IV. Finite Element Method for Machine-Foundation-Soil System

Finite element method enables the modeling of machine, foundation and soil in one go, which brings behavior of the machine foundation system closer to that of the prototype, resulting in improved reliability.

Rigid beam elements are used for modeling the machine whereas solid elements are used for modeling the foundation.

Soil is represented by a set of equivalent springs. A set of three translational springs and three rotational springs are either attached at the CG of the base or attached at each node at the base of the foundation in contact with the soil.

Modeling the foundation block with 8-noded brick elements or 10-noded tetrahedral elements works reasonably well and is considered good enough. A higher order solid element would increase the size of the model, requiring more computational time and power.

V. Formulations for Classical Solution

Correlations of dynamic properties of soil:

Correlation of N-value with Modulus of Rigidity (G):

$$G = 35 \times 161.5 \times N^{0.34} \times \sigma_0^{0.4} \quad (1)$$

Where, N = Uncorrected SPT Value
σ_0 = Effective Confining Pressure

Correlation of Unconfined Compressive Strength (qu) with Undrained Shear Strength (Su)

$$S_u = q_u / 2 \quad (2)$$

Correlation of Undrained Shear Strength (Su) with Modulus of Rigidity (G)

$$G = 487 \times S_u^{0.928} \quad (3)$$

Formulations for dynamic analysis of machine foundation by classical model:

Table 3: *Mass Moment of Inertia*

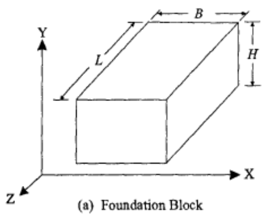
Rectangular Prism	 (a) Foundation Block	$I_x = \frac{1}{12} m (L^2 + H^2)$ $I_z = \frac{1}{12} m (H^2 + B^2)$ $I_y = \frac{1}{12} m (B^2 + L^2)$ $I_y = I_y + \frac{mL^2}{4}$

Table 4: *Equivalent Radius*

Sr No	Mode	Equivalent Radius
1	Vertical	$r_y = \sqrt{\frac{LB}{\pi}}$
2	Horizontal	$r_x = \sqrt{\frac{LB}{\pi}}$
3	Rocking	$r_{\Phi x} = \sqrt[4]{\frac{LB^3}{3\pi}}$
4	Rocking	$r_{\Phi z} = \sqrt[4]{\frac{BL^3}{3\pi}}$

Table 5: *Embedment coefficients for equivalent radius*

Sr No	Mode	Coefficient
1	Vertical	$n_y = 1 + 0.6\,(1 - \nu)\frac{h}{r_z}$
2	Horizontal	$n_x = 1 + 0.55\,(2 - \nu)\frac{h}{r_x}$
3	Rocking	$n_{\Phi x} = 1 + 1.2 * (1 - \nu) * (h/r_{\Phi x}) + 0.2*(2-\nu) * (h/r_{\Phi x})^3$
4	Rocking	$n_{\Phi z} = 1 + 1.2 * (1 - \nu) * (h/r_{\Phi z}) + 0.2*(2-\nu) * (h/r_{\Phi z})^3$

Table 6: *Equivalent spring coefficients*

Sl No	Mode	Spring Stiffness
1	Vertical	$k_y = [G/((1-\nu))] * \beta_y * \sqrt{(B*L)} * \eta_z$
2	Horizontal	$k_x = 2*(1+\nu) * G * \beta_x * \sqrt{(B*L)} * \eta_x$
3	Rocking	$k_{\Phi x} = [G/((1-\nu))] * \beta_\Phi * B * L^2 * \eta_{\Phi x}$
4	Rocking	$k_{\Phi z} = [G/((1-\nu))] * \beta_\theta * B * L^2 * \eta_{\Phi z}$
5	Twisting	$k_\Psi = [G/((1-\nu))] * \beta_\Psi * B * L^2 * 8$

Table 7: *Mass ratio*

Sl No	Mode	Mass ratio(B)
1	Vertical	$B_y = [\frac{(1-\nu)}{4}] * [\frac{W}{\varrho * r_y{}^3}]$
2	Horizontal	$B_x = [\frac{(7-8*\nu)}{32*(1-\nu)}] * [\frac{W}{\varrho * r_x{}^3}]$
3	Rocking	$B_{\Phi x} = [\frac{3*(1-\nu)}{8}] * [\frac{I_{\Phi x}}{\varrho * r_{\Phi x}{}^5}]$
4	Rocking	$B_{\Phi z} = [\frac{3*(1-\nu)}{8}] * [\frac{I_{\Phi y}}{\varrho * r_{\Phi z}{}^5}]$

Table 8: *Geometrical Damping Ratio*

Sl No	Mode	Geometrical Damping Ratio
1	Vertical	$D_{gy} = [\frac{0.425}{\sqrt{B_y}}] * \alpha_y$
2	Horizontal	$D_{gx} = [\frac{0.288}{\sqrt{B_x}}] * \alpha_x$
3	Rocking	$D_{g\Phi x} = [\frac{0.15 * \alpha_{\Phi x}}{(1+n\varphi * B_{\Phi x}) * \sqrt{n\varphi * B_{\Phi x}}}]$
4	Rocking	$D_{g\Phi z} = [\frac{0.15 * \alpha_{\Phi z}}{(1+n\varphi * B_{\Phi z}) * \sqrt{n\varphi * B_{\Phi z}}}]$

Table 9: *Embedment coefficients for soil damping ratio*

Sl No	Mode	Coefficient
1	Vertical	$\alpha_y = \frac{1+1.9*(1-\nu)*(\frac{h}{r_z y})}{\sqrt{\eta_y}}$
2	Horizontal	$\alpha_x = \frac{1+1.9*(2-\nu)*(\frac{h}{r_x})}{\sqrt{\eta_x}}$
3	Rocking	$\alpha_{\Phi x} = \frac{1+0.7*(1-\nu)*(h/r_{\Phi x})+0.6*(2-\nu)*(h/r_{\Phi x})^3}{\sqrt{\eta_{\Phi x}}}$
4	Rocking	$\alpha_{\Phi z} = \frac{1+0.7*(1-\nu)*(h/r_{\Phi z})+0.6*(2-\nu)*(h/r_{\Phi z})^3}{\sqrt{\eta_{\Phi z}}}$

- **Frequency and Amplitude formulations**

1. Vertical Vibration

$$\omega_{nz} = \sqrt{\frac{K_z}{m}}$$

$$A_z = \frac{F_Z}{K_z\left[\left\{1-\left(\frac{\omega}{\omega_{nz}}\right)^2\right\}^2 + \left(2\xi_z\frac{\omega}{\omega_{nz}}\right)^2\right]^{1/2}}$$

2. Torsion Vibration

$$\omega_{nz} = \sqrt{\frac{K_\psi}{M_{m\psi}}}$$

$$A_z = \frac{F_Z}{K_\psi\left[\left\{1-\left(\frac{\omega}{\omega_{n\psi}}\right)^2\right\}^2 + \left(2\xi_\psi\frac{\omega}{\omega_{n\psi}}\right)^2\right]^{1/2}}$$

3. Coupled sliding and rocking Vibration

$$\omega_{nx} = \sqrt{\frac{K_x}{m}}$$

$$\omega_{n\phi} = \sqrt{\frac{K_\phi}{M_{m\phi}}}$$

- Damped natural frequencies obtained as the roots of the following equation:

$$\left[\omega_{nd}^4 - \omega_{nd}^2\left\{\frac{(\omega_{n\phi}^2 + \omega_{nx}^2)}{r} - \frac{4\xi_x\xi_\phi\omega_{nx}\omega_{n\phi}}{r}\right\} + \frac{\omega_{nx}^4\omega_{n\phi}^2}{r}\right]^2 + 4\left[\frac{\xi_x\omega_{nx}\omega_{n\phi}}{r}\left(\omega_{n\phi}^2 - \omega_{nd}^2\right) + \frac{\xi_\phi\omega_{nd}\omega_{n\phi}}{r}\left(\omega_{nx}^2 - \omega_{nd}^2\right)\right]^2 = 0$$

- Undamped natural frequencies can be obtained by the applied moment, can be obtained as below:

$$\omega_{nL\,2}^2 = \frac{1}{2r}\left[\left(\omega_{nx}^2 + \omega_{n\phi}^2\right) \pm \sqrt{\left(\omega_{n\phi}^2 + \omega_{nx}^2\right)^2 - 4r\omega_{nx}^2\omega_{n\phi}^2}\right]$$

- Damped amplitudes for motion occasioned by the applied moment, can be obtained as below:

$$A_X = \frac{M_y}{M_m}\frac{\left[\left(\omega_{n\phi}^2\right)^2 + (2\xi_x\omega_{nx})^2\right]^{\frac{1}{2}}}{\Delta(\omega^2)}$$

$$A_\phi = \frac{M_y}{M_m}\frac{\left[\left(\omega_{n\phi}^2 - \omega^2\right)^2 + (2\xi_x\omega_{nx})^2\right]^{\frac{1}{2}}}{\Delta(\omega^2)}$$

Where $\Delta(\omega^2)$ is given by Eq.

$$\Delta(\omega^2) = \left[\left\{\omega^4 - \omega^2\left\{\frac{(\omega_{x\phi}^2 + \omega_{nx}^2)}{r} - \frac{4\xi_x\xi_\phi\omega_{nx}\omega_{n\phi}}{r}\right\} - \frac{\omega_{nx}^4\omega_{n\phi}^2}{r}\right\}^2 + 4\left\{\frac{\xi_x\omega_{nx}\omega}{r}\left(\omega_{n\phi}^2 - \omega^2\right) + \frac{\xi_\phi\omega_{n\phi}\omega}{r}\left(\omega_{nx}^2 - \omega^2\right)\right\}^2\right]^{\frac{1}{2}}$$

- Damped amplitudes for motion occasioned by an applied force F_X acting at the center of gravity of the foundation may be obtained as below:

$$A_X = \frac{F_x}{m\,M_m}\frac{\left[(-M_m\omega^2 + K_x + L^2K_x)^2 + 4\omega^2\left(\xi_\phi\sqrt{K_\phi M_{mo}} + L^2\xi_x\sqrt{K_x m}\right)^2\right]^{\frac{1}{2}}}{\Delta(\omega^2)}$$

$$A_X = \frac{F_xL}{m\,M_m}\frac{\omega_{nx}(\omega_{nx}^2 + 4\xi_x\omega^2)^{\frac{1}{2}}}{\Delta(\omega^2)}$$

VI. Results

The dynamic analysis of machine foundation is done by classical method as well as Finite Element Method using STAAD Pro. V8i by Elastic half space method. Change in Natural Frequency of machine foundation and amplitude of foundation is shown with respect to unconfined compressive strength (qu) for clay and SPT N-Value for sand.

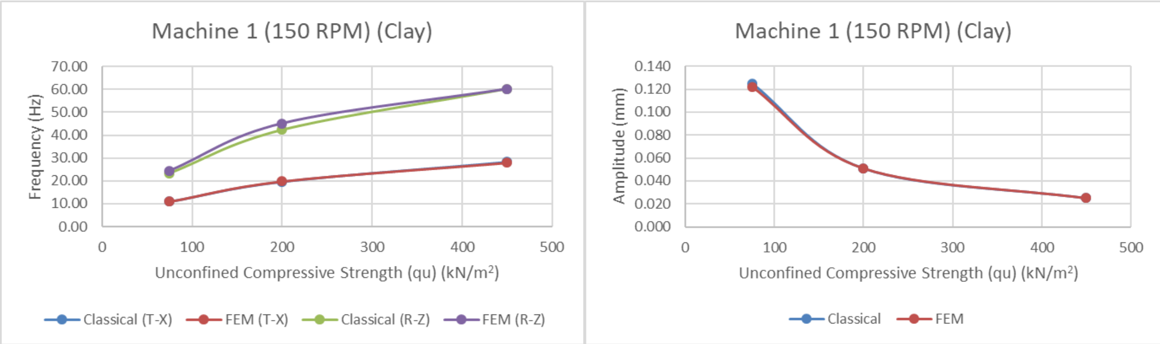


Figure 4: *Frequency and Amplitude of Machine 1 resting on Clay*

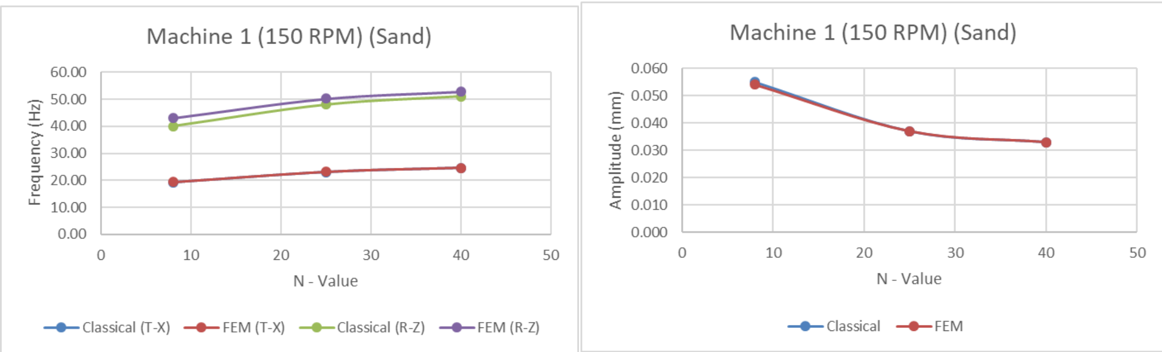


Figure 5: *Frequency and Amplitude of Machine 1 resting on Sand*

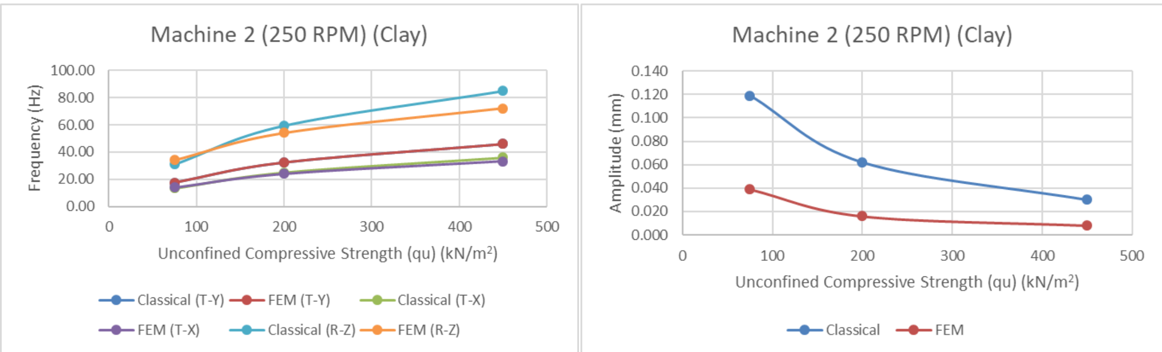


Figure 6: *Frequency and Amplitude of Machine 2 resting on Clay*

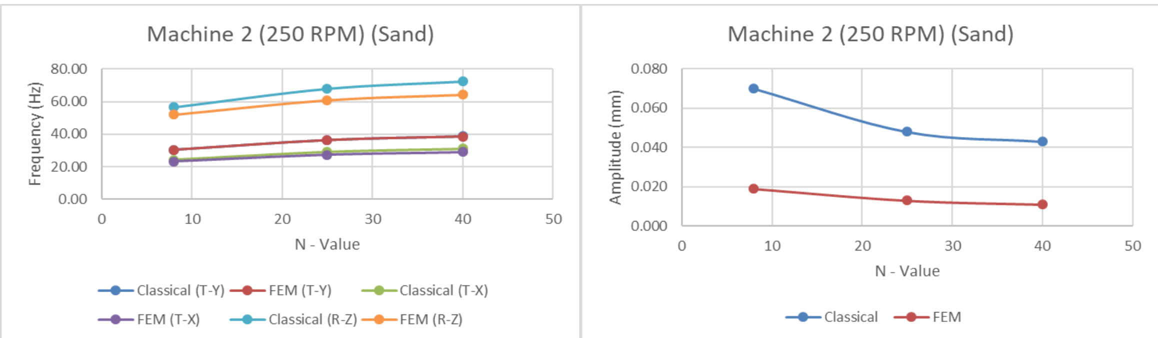


Figure 7: *Frequency and Amplitude of Machine 2 resting on Sand*

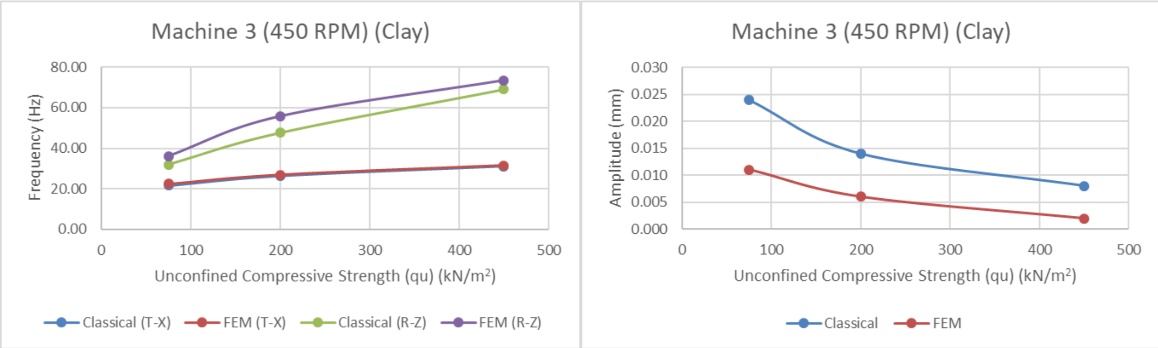


Figure 8: *Frequency and Amplitude of Machine 3 resting on Clay*

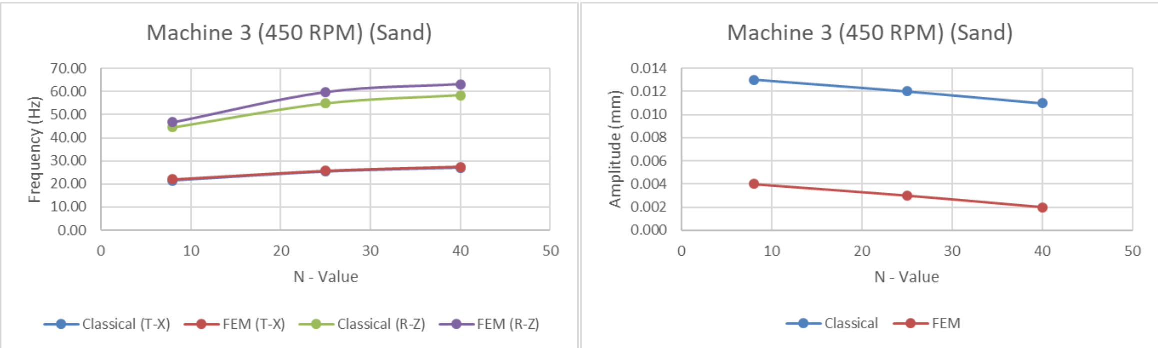


Figure 9: *Frequency and Amplitude of Machine 3 resting on Sand*

Sizes of foundation are optimized for all the cases. Also, each foundations is checked to fulfil all codal criteria even in 20% variation in soil parameters to cover the confidence range. The concrete quantity consumed in each case is also compared. The dimensions of foundation and computed volume is as shown in Table 10 to Table 15.

Table 10: *Volume of foundations for machine-1 resting on clayey soil*

Soil Type	Dimensions (m)			Volume (m3)
	Length	Width	Height	
Medium Clay	3	3	0.6	5.40
Stiff Clay	2.8	2.8	0.6	4.70
Hard Clay	2.8	2.8	0.6	4.70

Table 11: *Volume of foundations for machine-1 resting on sandy soil*

Soil Type	Dimensions (m)			Volume (m3)
	Length	Width	Height	
Loose Sand	3	3	0.6	5.40
Medium Sand	2.8	2.8	0.6	4.70
Dense Sand	2.8	2.8	0.6	4.70

Table 12: *Volume of foundations for machine-2 resting on clayey soil*

Soil Type	Dimensions (m)			Volume (m3)
	Length	Width	Height	
Medium Clay	1.8	1.8	0.6	1.94
Stiff Clay	1.5	1.5	0.6	1.35
Hard Clay	1.5	1.5	0.6	1.35

Table 13: *Volume of foundations for machine-2 resting on sandy soil*

Soil Type	Dimensions (m)			Volume (m3)
	Length	Width	Height	
Loose Sand	1.9	1.9	0.6	2.17
Medium Sand	1.5	1.5	0.6	1.35
Dense Sand	1.5	1.5	0.6	1.35

Table 14: *Volume of foundations for machine-3 resting on clayey soil*

Soil Type	Dimensions (m)			Volume (m3)
	Length	Width	Height	
Medium Clay	2.8	2.8	0.5	3.92
Stiff Clay	2.5	2.5	0.6	3.60
Hard Clay	2.4	2.4	0.6	3.46

Table 15: *Volume of foundations for machine-3 resting on sandy soil*

Soil Type	Dimensions (m)			Volume (m3)
	Length	Width	Height	
Loose Sand	2.8	2.8	0.5	3.92
Medium Sand	2.5	2.5	0.6	3.75
Dense Sand	2.4	2.4	0.6	3.46

VII. Discussion

This study was undertaken to evaluate dynamic response of reciprocating machine mounted on block type foundation by classical method and FEM, as per Elastic Half Space Model. Three different type of machines and six different type of soil were considered for the study. Based on the study presented here in, the following conclusions can be drawn:

- Size of machine foundation is governed by mass ratio in the case where soil stiffness is high.
- It is advisable to keep height of the foundation less as compared to its length and width to design over-tuned foundation. As with the increase in height of the Foundation, Natural Frequency decreases significantly and amplitude of the foundation increases.
- From the Elastic Half Space Model, it is observed that the difference in translational mode frequency, computed both manually and by FEM is negligible. Frequency variation in rotational mode is around 10% to 20%.
- It has been observed that, with the increase in base contact area of foundation,

natural frequency of the Machine Foundation soil system increases and amplitude decreases.

- Natural frequency of machine foundation system increases and amplitude of foundation decreases, with the increase in stiffness of soil.
- Classical Method is more conservative as compared to FEM, as the amplitudes obtained using classical method are higher than those computed using FEM.
- The results grossly show that as the clay changes from medium to hard, and sand from loose to dense the volume of the foundation decreases.

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