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Dynamic Analysis of Block-Type Machine Foundation Using Barkan's Model for Various Soil Parameters

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Abstract

Machine foundation involves both the static loads and the dynamic loads caused by working of the machine. The machine weighs several tons and is required to restrict amplitudes to only a few microns. Inadequately constructed foundations may result in failures exceeding many times the cost of the capital investment required for properly designed foundations. This necessitated a deeper scientific investigation of dynamic loading and analysis. Method proposed by Barkan (recommended by IS: 2974-1982) for design of machine foundations under harmonic load, still remains the most popular method for vibration analysis of block foundations in Indian industry. Finite Element (FE) is very commonly accepted analysis tool for solution of engineering problems. Effective Pre & Post-processing capabilities make modeling and result interpretation simple. The current paper aims to do the parametric study of dynamic analysis of block foundation using Barkan's method. For the same, three different machines of 150 rpm, 250 rpm and 450 rpm are taken into account and six different soil types: (a) Medium, Stiff and Hard Clay and (b) Loose, Medium and Dense Sand are considered. Foundation sizes are optimized according to soil cases and each case is analysed using conventional method and FEM model using STAAD Pro. for 0.8, 1 and 1.2 times the soil parameters to cover the confidence range. This study is further extended for the comparison of concrete quantity consumed. The results grossly show that as the clay varies from medium to hard, and sand from loose to dense, the foundation size required, decreases. It was seen that, with the increase in stiffness of soil, natural frequency of machine foundation soil system increases and amplitude of foundation reduces. Also, FEM method of analysis indicates safer amplitude of foundation compared to classical method of analysis, inferring to conventional method being conservative.

Keywords: Block-Type Machine Foundation, Reciprocating Machines, Barkan's Method, Finite Element Method, IS 2974, Dynamic Analysis

1. Introduction

The initial and installation cost of the machine foundation might be less, but a disruption in working of machine due to failure of improperly designed foundation can block the production chain and cause a heavy loss to the industry. Hence, design of machine foundation and soil investigation should be done carefully. Design and analysis of machine foundation is complex than ordinary foundation, as dynamic forces and moments generated due to operation of the machine acts on it along with the static loads. Therefore, a special design procedure is necessary for a machine foundation to remain stable under the combined effects of static loads and dynamic loads. Weight of the foundation is very high as compared to weight of machine and the dynamic forces produced by the moving parts of the machines are comparatively very low. As, these forces are unceasingly acting for a long time, effect of these forces cannot be neglected. Two most important parameters that are to be determined in design of machine foundation are natural frequency of machine foundation system and amplitude of the foundation. Dynamic forces produced by the machines are transmitted to foundation and then after dissipated into the soil. Hence, type of soil lying under the foundation plays a vital role in the analysis and design of the machine foundation system. Generally, various types of machines are classified into three categories [3], [4]:

Reciprocating machines: This category includes IC engines, piston pumps, compressors, etc. A reciprocating machine consists of a piston rod moving inside a cylinder, a connecting rod, and a crank. The crank rotates around the cross-head pin. This mechanism converts the translation motion into rotary motion and vice versa. Dynamic forces produced at piston rod are translational forces in the direction of movement of piston. At the junction of crank and connecting rod dynamic force and moment are produced which acts in radially outward direction. The operating speeds of these machines are generally less than 1200 rpm. Generally, a block type foundation is provided for reciprocating machines.

Impact machines: This category includes forging hammers, which produce impact loads. Impact machines includes falling ram, anvil, and frame. The operating speed of these machines are generally very low and ranges from 60 - 150 blows per minute.

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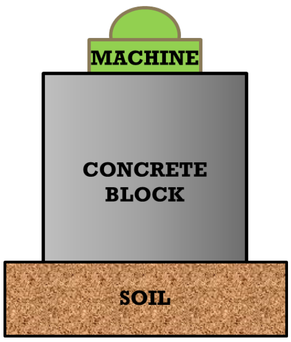


Fig. 1: Block Type Machine Foundation

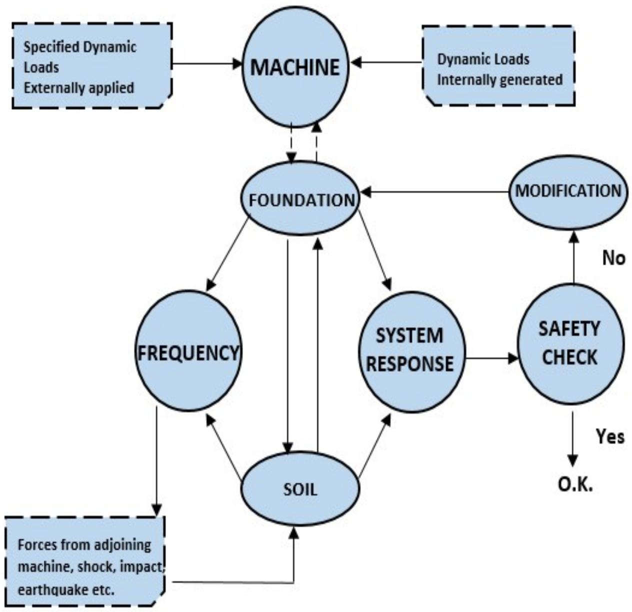


Fig. 2: Schematic Flow of Machine Foundation System

Rotary machines: This category includes high speed machines, like turbo generator, turbine, and rotary compressor, having speed range of 3000 - 10,000 rpm. High speed machines produces less dynamic forces as compared to low speed machines. Frame type foundations consisting are generally used to mount the rotary machines.

The paper discusses about reciprocating machine mounted on block type machine foundation. Typical block-type machine foundation is shown in Fig. 1. It consists of a pedestal of concrete on which the machine rests.

Machine foundation system broadly comprises of machine, supported by foundation and foundation resting over soil as shown in schematic shown in Fig. 2 [3]

2. Dynamic Analysis of Block-Type Machine Foundation

A typical block of concrete is regarded as rigid, in comparison to the soil over which it rests. It is provided for compressors and reciprocating machines. It consists of a pedestal resting on footing [2]. Hence, it may be assumed that it undergoes only rigid-body displacements and rotations. When an unbalanced force acts, the rigid block may therefore undergo displacements and oscillations with six degrees of freedom as shown in Fig. 3.

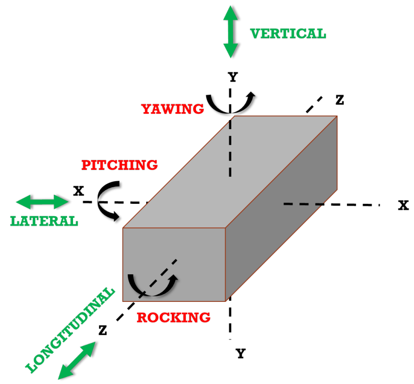


Fig. 3: Degrees of Freedom of Foundation

Table 1: Soil Parameters for Study

	Soil Type	Coefficient of Uniform Compression (Cu) (For Base Area 10m^2) kN/m^3
1	Medium Clay	20000
2	Stiff Clay	50000
3	Hard Clay	90000
4	Loose Sand	15000
5	Medium Sand	40000
6	Dense Sand	70000

Computation for dynamic analysis of machine foundations [10], [9], [8] is using Barkan's method [1] with Classical solution and Finite Element Method. Machine Parameters are as below:

Machine 1:
Operating Speed - 150 RPM.
Weight – 36 kN
Horizontal dynamic force – 12 kN.
Machine center-line hight above foundation – 0.6 m.

Machine 2:
Operating Speed - 250 RPM.
Weight – 10 kN
Vertical dynamic force – 2.5 kN.
Horizontal dynamic force – 2 kN.
Horizontal dynamic moment – 4 kN.
Machine center-line hight above foundation – 0.2 m.

Machine 3:
Operating Speed - 450 RPM.
Weight – 25 kN
Horizontal dynamic moment – 4.9 kN.
Machine center-line hight above foundation – 0.15 m.

The soil parameters [6], [7] considered for study are as indicated in Table 1.

2.1 Computation using Barkan's Method

A machine foundation should meet the following requirements in order to be satisfactory (IS: 2974-1982) [5].

For dynamic loads, there should be no resonance. The natural frequency of the machine foundation soil system should not coincide with the operating frequency of the machine to avoid resonance. A zone of resonance is defined in the Indian standard code. The natural frequency of the machine foundation system should not fall in this zone. The foundation may thus be designated as "over tuned" when its natural frequency is greater than the operating speed or as "under tuned" when its natural frequency is lower than the operating speed of machine. As per the code, the permissible range is 1.5 < Frequency Ratio < 0.4.

The amplitudes of the foundation should also not exceed the permissible values. The limiting amplitude specified by code [5] is 0.2 mm for reciprocating machines.

Mass of Foundation >> Mass of Machine. General rule of thumb to keep this ratio greater than 3 for Reciprocating Machines. Also, the eccentricity of machine C.G. should be kept <5% of the base dimension of block because it can cause unequal settlement of foundation due to working of machine. In faulty condition of machine, people may climb on foundation along with equipment to repair the machine. For this purpose, margin of other loads should be kept more than 30 %.

2.2 Formulations

Dynamic analysis of machine foundation by classical method is done by following formulae. [3], [5]

Step 1: Correlation of Coefficient of uniform compression (C_{u1} & C_{u2}) for two foundations of different areas A_1 and A_2

$$C_{u2} = C_{u1} \times \sqrt{\frac{A_1}{A_2}} \tag{1}$$

Step 2: Determination of CG

Determine combined CG for the machine and the foundation in the x, y and z planes and check to see that the eccentricity along x or y direction is not more than 5%. (if eccentricity exceeds 5% the additional rocking occasioned by vertical eccentric loading must be considered in the analysis)

$$X_0 = \frac{\sum mi * Xi}{\sum mi}, \; Y_0 = \frac{\sum mi * Yi}{\sum mi}, \; Z_0 = \frac{\sum mi * Zi}{\sum mi} \tag{2}$$

mi = Mass of element

Xi, Yi and Zi = Coordinates of the CG of the element with reference to the X, Y and Z axis.

Step 3: Determination of Moment of Inertia (I)

Moment of inertia of rectangular base area is given as following equations with reference to diagram shown in Fig. 4.

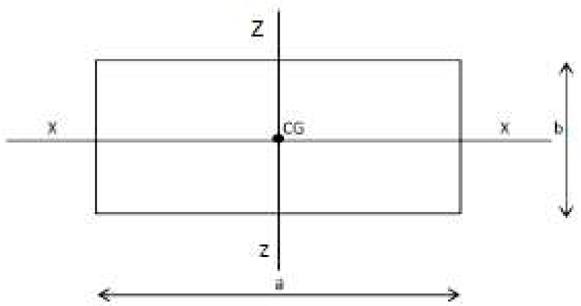


Fig. 4: Determination of Moment of Inertia

$$I_{XX} = \frac{a * b^3}{12} \tag{3}$$

$$I_{ZZ} = \frac{a^3 * b}{12} \text{ and} \tag{4}$$

$$I_{yy} = I_{xx} + I_{zz} \tag{5}$$

Step 4: Determination of Mass Moment of Inertia

The Mass moment of Inertia of the whole system about axis passing through the common Centre of gravity and perpendicular to the plane of vibration

About x-axis

$$\Phi_x = \sum mi/12(lyi^2+lzi^2) + \sum mi(y_oi^2+z_oi^2) \tag{6}$$

About y-axis

$$\Phi_y = \sum mi/12(lxi^2+lzi^2) + \sum mi(x_oi^2+z_oi^2) \tag{7}$$

About z-axis

$$\Phi_z = \sum mi/12(lxi^2+lyi^2) + \sum mi(x_oi^2+y_oi^2) \tag{8}$$

The Mass moment of Inertia about the axis passing through the centroid of the base area and perpendicular to the plane of vibration

About x-axis

$$\Phi_{ox} = \Phi_x + \Sigma m \, y_o^2 \tag{9}$$

About z-axis

$$\Phi_{oz} = \Phi_y + \Sigma m \, y_o^2 \tag{10}$$

Step 5: Determination of co-relations between the Coefficients of Modulus of subgrade reactions given by Barkan's as follows,

Design Coefficient of Uniform Compression

C_u

Design Coefficient of Uniform Shear

$$C_\tau = 0.5 * C_u \tag{11}$$

Design Coefficient of Non-Uniform Compression

$$C_\theta = C\varphi = 2.0 * C_u \tag{12}$$

Design Coefficient of Non-Uniform Shear

$$C_\Psi = 0.75 * C_u \tag{13}$$

Step 6: The mathematical expressions for computation of equivalent spring constants given by Barkan's are as follows,

Soil spring in Lateral X - directions

$$k_x = C_\tau * A \tag{14}$$

Soil Spring in Lateral Z -Direction

$$K_z = k_x = C_\tau * A \tag{15}$$

Soil Spring in Vertical Y -Direction

$$K_y = C_u * A \tag{16}$$

Soil Spring in rocking θ mode (rocking about X-axis)

$$k_\theta = C_\theta * I_{xx} \tag{17}$$

Soil Spring in Torsional Ψ mode (Rotation about vertical Y-axis)

$$k_\Psi = C_\Psi * I_{yy} \tag{18}$$

Soil Spring in rocking φ mode (rocking about Z-axis)

$$k_\varphi = C_\varphi * I_{zz} \quad (19)$$

Step 7: The mathematical expressions for computation of frequency and amplitudes are as follows:

In case of block foundation there are basically four modes out of which vertical and torsional modes are uncoupled modes and horizontal rocking modes are coupled modes.

Vertical Mode (Translation Along Y-axis): Uncoupled Mode

Natural Frequency

$$w_y = \sqrt{\frac{C_u * A_f}{\sum m}} \quad \text{or} \quad w_y = \sqrt{\frac{k_y}{\sum m}} \quad (20)$$

Amplitude

$$a_y = \frac{F_y}{k_y} * \frac{1}{(1-\beta_y^2)} \quad (21)$$

Sliding and Rocking Mode (Motion in X-Y plane): Coupled Mode

Limiting Frequencies

$$w_x = \sqrt{\frac{C_\tau * A_f}{\sum m}} \quad \text{Or} \quad w_x = \sqrt{\frac{k_x}{\sum m}} \quad (22)$$

$$w_{\theta z} = \sqrt{\frac{C_\theta * A_f}{\sum m}} \quad \text{Or} \quad w_{\theta z} = \sqrt{\frac{k_z}{\sum m}} \quad (23)$$

Coupled Natural Frequencies

The two natural frequencies ω_{n1} and ω_{n2} which represent the coupled (Sliding along X-axis and Rocking about Y-axis) in the X-Z plane are given by the roots of the following quadratic equation,

$$\omega_n^4 - ((\omega_{\theta z}^2 + \omega_x^2)/\alpha_z) * \omega_n^2 + ((\omega_{\theta z}^2 + \omega_x^2)/\alpha_y) = 0 \quad (24)$$

The two roots ωn1 and ωn2 are given by below equations

$$\omega_{n1}^2 = 1/(2*\alpha_z)*[\omega_{\theta z}^2 + \omega_x^2 + \sqrt{(\omega_{\theta z}^2 + \omega_x^2)^2 - 4*\alpha_z*\omega_{\theta z}^2 * \omega_x^2}] \quad (25)$$

$$\omega_{n2}^2 = 1/(2*\alpha_z)*[\omega_{\theta z}^2 + \omega_x^2 - \sqrt{(\omega_{\theta z}^2 + \omega_x^2)^2 - 4*\alpha_z*\omega_{\theta z}^2 * \omega_x^2}] \quad (26)$$

Where, $\alpha_z = \Phi_z/\Phi_{oz}$

Amplitude

$$x_0 = [\delta_x \frac{(1-\beta_\emptyset^2)}{(1-\beta_1^2)(1-\beta_2^2)} - h\delta_\emptyset \frac{\beta_x^2}{(1-\beta_1^2)(1-\beta_2^2)}] \quad (27)$$

$$\emptyset_0 = [\delta_\emptyset \frac{(1-\beta_x^2)}{(1-\beta_1^2)(1-\beta_2^2)} - \delta_x \frac{\beta_\emptyset^2}{(1-\beta_1^2)(1-\beta_2^2)}] \quad (28)$$

$$Here, \delta_x = \frac{F_x}{k_x} \quad \& \quad \delta_\emptyset = \frac{M_\emptyset}{k_\emptyset}$$

Sliding and Rocking Mode (Motion in Y-Z plane): Coupled Mode

The natural frequencies and amplitudes are given by the same equation as mentioned above by interchanging suffixes x and z.

Yawing or Twisting Mode (Motion @ Y-axis): Uncoupled Mode

Natural frequency

$$w_\Psi = \sqrt{\frac{C_\Psi * I_{yy}}{\Phi_y}} \quad \text{Or} \quad w_\Psi = \sqrt{\frac{k_\Psi}{\Phi_y}} \quad (29)$$

Amplitude

$$a_\Psi = \frac{F_\Psi}{k_\Psi} * \frac{1}{(1-\beta_\Psi^2)} \quad (30)$$

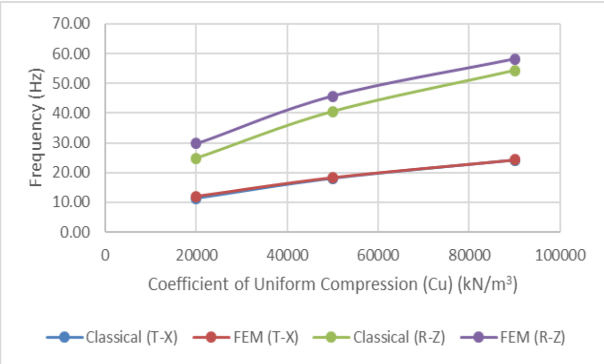
2.3 Computation using Finite Element Method

Finite Element Method (FEM) is vastly use today for the analysis of the various engineering problems. Its results are more precise and the results at different locations can be easily known. In case of machine foundations, analysis of foundations with complex geometries, higher foundation eccentricity and response history can be very tedious task which makes manual calculation difficult. Finite Element Modelling can easily handle all such complexities. As analysis of machine foundation is a trial and error based process, it is easy to make changes in FEM and re-run the analysis. Effective Pre & Post-processing capabilities makes modelling and interpretation of results simple. Also, the dynamic behaviour of machine foundation can be easily understood.

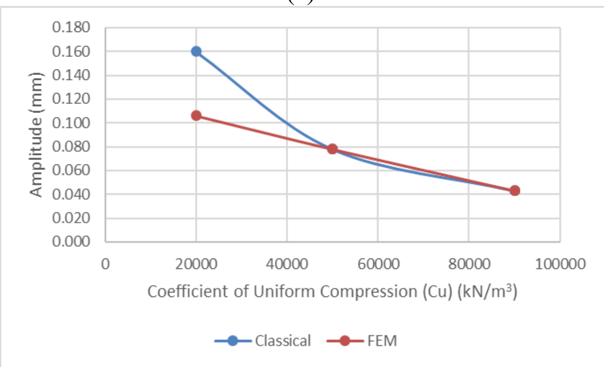
In present study, Finite Element Analysis is done in STAAD.Pro software. Foundation is modelled as 8-Noded Concrete brick element and soil is modelled as springs to which stiffness is assigned. In order to assign dynamic loads at machine C.G. point rigid beams are modelled. Dynamic forces are applied at respective bearing locations. Machine mass is considered lumped at appropriate locations so as to simulate the CG location.

3. Results

The analysis of each problem is done by classical method (manual computation) and by Finite Element Modelling using STAAD Pro. V8i for Barkan's Model. The results obtained in terms of (a) Frequency and (b) Amplitude are shown in the form of graphs from Fig. 5 to Fig. 10 for w.r.t Coefficient of Uniform Compression (C_u), for foundation with different machine resting on all six types of soil under consideration.

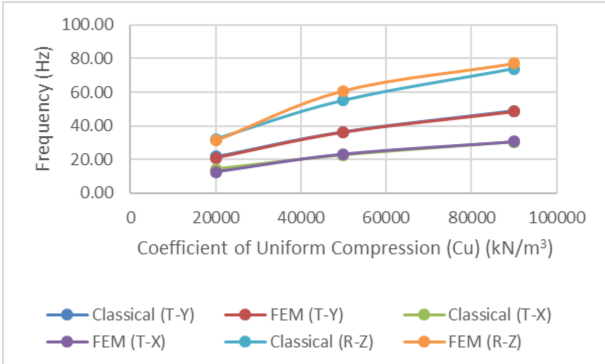


(a)

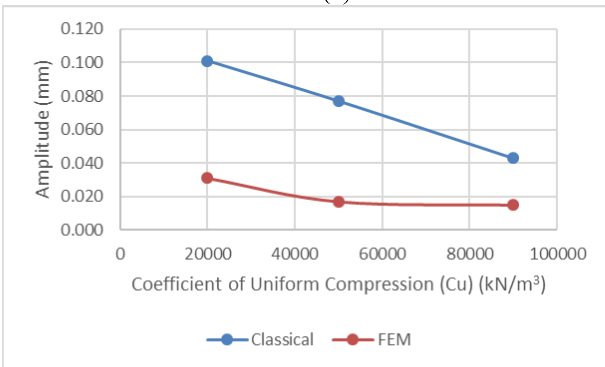


(b)

Fig. 5: (a) Frequency and (b) Amplitude of Machine 1 resting on Clay

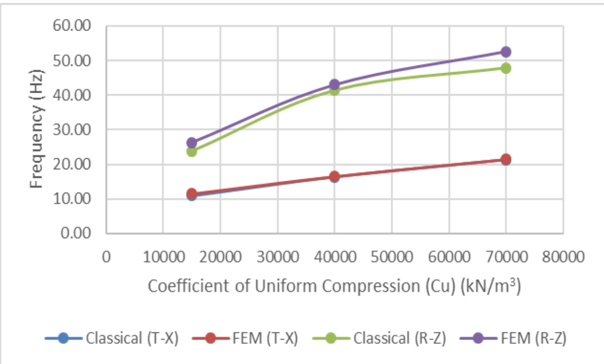


(a)

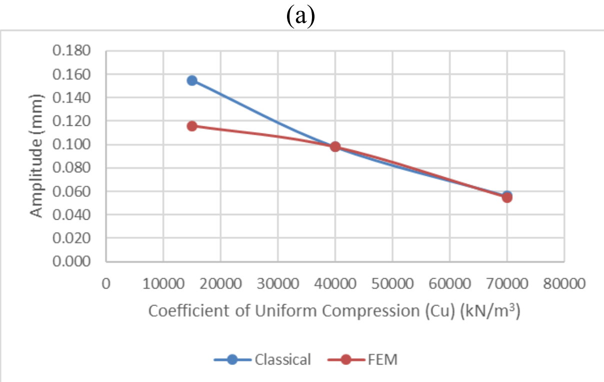


(b)

Fig. 7: (a) Frequency and (b) Amplitude of Machine 2 resting on Clay

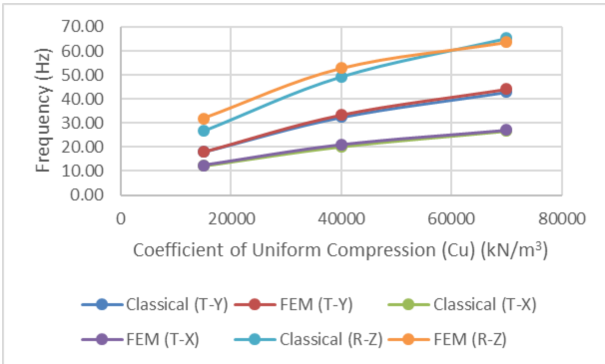


(a)

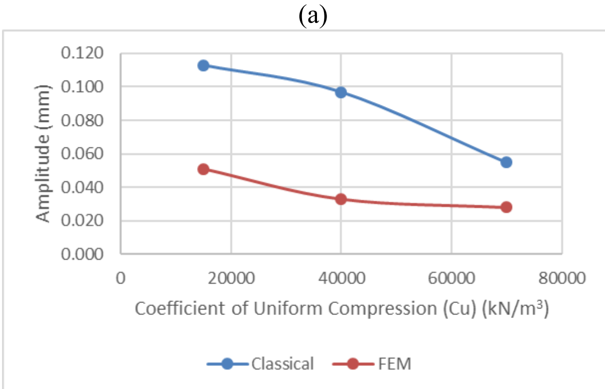


(b)

Fig. 6: (a) Frequency and (b) Amplitude of Machine 1 resting on Sand

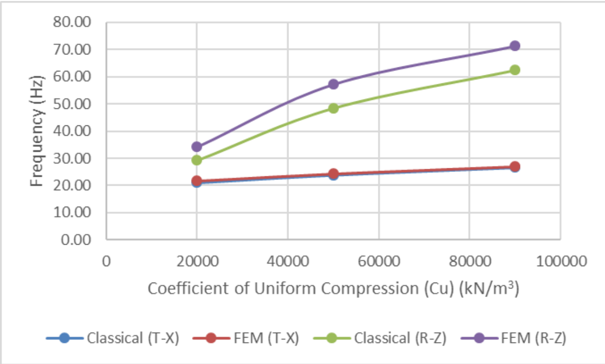


(a)

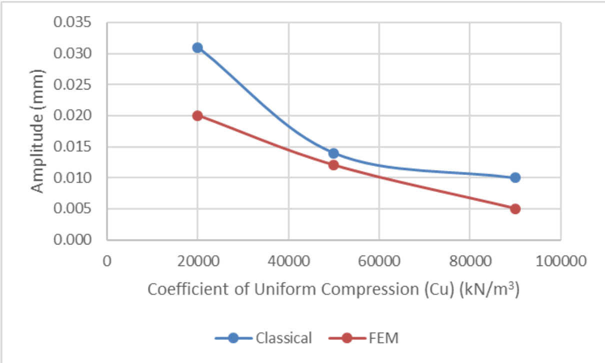


(b)

Fig. 8: (a) Frequency and (b) Amplitude of Machine 2 resting on Sand

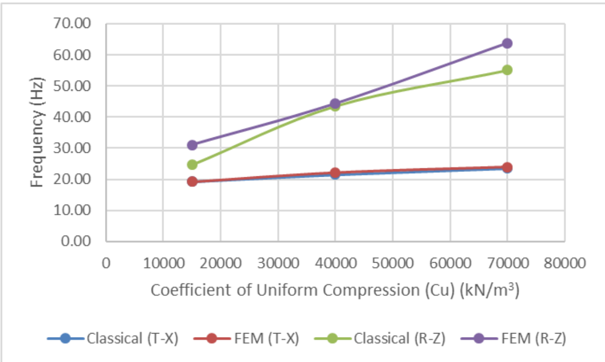


(a)

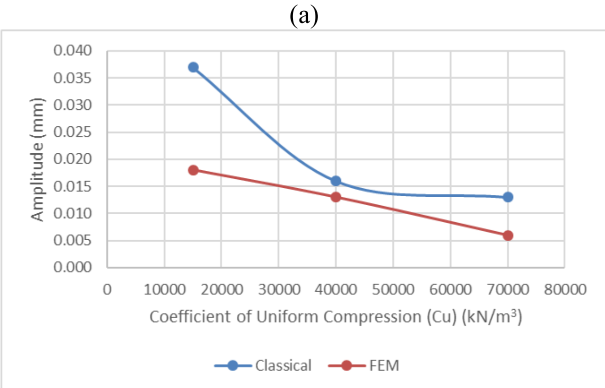


(b)

Fig. 9: (a) Frequency and (b) Amplitude of Machine 3 resting on Clay



(a)



(b)

Fig. 10: (a) Frequency and (b) Amplitude of Machine 3 resting on Sand

In figures, nomenclature are as follows:

T-X = Translation in X axis
T-Y = Translation in Y axis
R-Z = Rotation about Z axis

Foundation sizes are optimized according to soil cases and each case is analysed using classical method and FEM model for 0.8, 1 and 1.2 times the soil parameters to cover the confidence range. This is done primarily to check the safety of foundation such that the frequency ratio and amplitude are within permissible limits even in 20% uncertainty variation of soil parameters. This study is further extended for the comparison of concrete quantity consumed. The computed volume is as shown in Table 2 to Table 7.

Table 2: Quantity Comparison for Machine 1 on Clay

Soil Type	**Dimensions (m)**			**Volume**
	Length	**Width**	**Height**	**(m^3)**
Medium Clay	3.2	3.2	0.6	6.14
Stiff Clay	2.8	2.8	0.6	4.70
Hard Clay	2.8	2.8	0.6	4.70

Table 3: Quantity Comparison for Machine 1 on Sand

Soil Type	**Dimensions (m)**			**Volume**
	Length	**Width**	**Height**	**(m^3)**
Loose Sand	3.6	3.6	0.5	6.48
Medium Sand	2.8	2.8	0.6	4.70
Dense Sand	2.8	2.8	0.6	4.70

Table 4: Quantity Comparison for Machine 2 on Clay

Soil Type	**Dimensions (m)**			**Volume**
	Length	**Width**	**Height**	**(m^3)**
Medium Clay	2.0	2.0	0.6	2.40
Stiff Clay	1.5	1.5	0.6	1.35
Hard Clay	1.5	1.5	0.6	1.35

Table 5: Quantity Comparison for Machine 2 on Sand

Soil Type	**Dimensions (m)**			**Volume**
	Length	**Width**	**Height**	**(m^3)**
Loose Sand	2.2	2.2	0.6	2.90
Medium Sand	1.5	1.5	0.6	1.35
Dense Sand	1.5	1.5	0.6	1.35

Table 6: Quantity Comparison for Machine 3 on Clay

Soil Type	Dimensions (m)			Volume
	Length	Width	Height	(m^3)
Medium Clay	3.0	3.0	0.5	4.50
Stiff Clay	2.6	2.6	0.6	4.06
Hard Clay	2.4	2.4	0.6	3.46

Table 7: Quantity Comparison for Machine 3 on Sand

Soil Type	Dimensions (m)			Volume
	Length	Width	Height	(m^3)
Loose Sand	3.2	3.2	0.5	5.12
Medium Sand	3.0	3.0	0.5	4.50
Dense Sand	2.4	2.4	0.6	3.46

4. Conclusions

This study was undertaken to evaluate dynamic response of reciprocating machine mounted on block type foundation by classical method and FEM, as per Barkan's method. 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:

In all machine foundations studied here, natural frequency increases and amplitude decreases with the increase in base contact area of foundations. It was seen that, with the increase in stiffness of soil, natural frequency of machine foundation soil system increases and amplitude of foundation decreases. There is a significant decrease in natural frequency and increase in the amplitude, with the increase in height of the foundation.

With the increase in dynamic forces produced due to operation of machine, amplitude of the foundation increases. Size of machine foundation is governed by mass ratio in the case where soil stiffness is high. It is observed that the difference in translational mode frequency, computed both manually and by FEM is negligible. While frequency variation in rotational mode is around 10% to 30%.

Amplitudes obtained using Classical Methods are higher than those computed using FEM. This infers that modelling machine foundation using FEM is less conservative. The results grossly show that as the clay changes from medium to hard, and sand from loose to dense, the foundation size required, decreases.

Disclosures

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