Invited paper

International Journal of Mechanical Engineering (IJME)
Volume 4 Issue 3 (March 2014) ISSN : 2277-7059
http://www.ijmejournal.com/

Optimal Design of Machinery Shallow Foundations with Silt Soils

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Abstract

Optimal design of shallow foundations used in supporting various machinery is of vital importance. Badly designed foundations result in serious problems such as soil failure, large soil settlement, low vibration efficiency and resonance of structures near by the foundation.

An optimal design approach based on using MATLAB optimization tool box is used to provide the optimal design of a machinery foundation on a silty soil. To minimize the foundation cost the foundation mass is used as an objective function. To control the high technical quality of the foundation from soil mechanics and vibrations point of view, 10 functional constraints are used.

The soil isolation efficiency of the soil is responsible about the vibration transmitted to the surrounding. Therefore, the effect of the minimum isolation efficiency in the range of 71 – 81 % on the foundation optimal design is investigated in details. The performance of the foundation against the minimum isolation efficiency is outlined so that the civil and mechanical engineers can compromise between cost and performance.

Keywords : Shallow foundations , Optimal design , Foundation _ soil interaction , Silt soils.

1 Introduction

Design techniques of machinery foundations range from following local national codes to optimal approaches. There is a little work done in behalf of optimal design of machinery foundations and this research work comes to fill this gap and introduces an approach for the optimal design of machinery foundations taking into consideration the cost (minimum mass objective function) and performance during operation (through using nine functional constraints). Most of research activities are focused on soil properties required for the foundation design and the foundation-soil interface models.

Gazetas (1983) reviewed the state of art of analyzing the dynamic response of foundations subjected to machine-type loading. He presented his results in the form of formulae and dimensionless graphs [1]. Pecker (1996) reviewed the evaluation of seismic bearing capacity of shallow foundations resting on cohesive and dry cohesionless soils [2]. Adel et al. (2000) applied the expert system approach to foundation design providing the user with means to assess the effect of various foundation alternatives and ground conditions [3]. Pender (2000) explained a model for the cyclic stress-strain behavior of cohesive soil and the application of the model in estimating the dynamic compliance of footing under vertical cyclic loading [4]. Tripathy et al. (2002) studied the void ratio and water content of specimens at several intermediate stages during swelling. They studied the void ratio and water content characteristics of the soil during swelling and shrinkage [5]. Anteneh (2003) presented the foundation performance requirements and the basic steps employed in the design of a machine foundation. He reviewed all the soil parameters required for the foundation design and the basic concepts in foundation vibrations [6]. Ostadan et al (2004) discussed a series of parametric studies for structure-soil interaction damping and presented an effective approach to estimate the system damping for such systems [7]. Park and Hashash (2004) proposed formulations used in nonlinear site response analysis which showed that the equivalent linear frequency domain solution used to approximate nonlinear site response underestimated the surface ground motion within a period range relevant to engineering applications [8].

Dewookar and Huzjak (2005) studied the effect of the effective normal stress , liquid limit and plasticity index on the soil friction angle. They viewed the available models relating soil friction angle and plasticity index [9]. Prakash and Puri (2006) discussed the analysis methods used in determining the foundation response when subjected to vibrating loads. They considered the machine foundation as a mass-spring-damper model with one or two degree of freedom [10]. Chandrakaran, Vijayan and Ganesan (2007) presented a simplified approach for the design of machinery foundations against vertical vibrations [11]. Chakravarti (2008) studied the design of rectangular block foundation for vibrating machines considering both the effect of damping and coupled modes using time-history analysis [12].

Jain et. al. (2010) used an artificial neural network technique to predict the shear strength parameters of medium compressibility soil. They studied the variation of soil cohesion and internal friction angle with soil dry density and degree of saturation [13]. Aziz and Ma (2011) focused on the design and analysis of bridge foundation using four codes. They found which code is better for design and control of the high settlement problem due to loading [14]. Kaptan (2012) proposed an empirical formulation for the rapid determination of the allowable bearing pressure of shallow foundations in soils and rocks. The proposed expression was consistent with the results of the classical theory and proved to be rapid and reliable [15]. Hassaan, Lashin and Al-Gamil (2012) collected some important soil data and casted them in mathematical model suitable for the optimal design of foundations and buildings [16]. Pan, Tsai and Lin (2013) presented the ultimate bearing capacity of shallow foundations. They utilized the weighted genetic programming and soft computing polynomials for the accurate prediction and visible formulas for the ultimate bearing capacity [17]. Shahnazari, Shahin and Tutunchran (2014) utilized the evolutionary polynomial regression, classical genetic programming and gene expression programming for the accurate prediction of shallow foundation settlements on cohesionless soils [18]. Hassaan (2014) studied the optimal design of shallow machinery foundations for clayey soils. He put quite large number of constraints to control the engineering performance of the designed foundation [19].

2 Analysis

Objective function:

The foundation mass, M_f is used as the objective function of the optimization problem to reduce its cost. It is related to the foundation length L, width B and height H_f through:

$$M_f = \rho LBH_f \tag{1}$$

Where ρ is the foundation density.

Functional constraints:

(i) Length / width ratio constraint, C_1:

$$C_1 = B / L \quad (\leq 1) \tag{2}$$

This constraint means that the foundation has a rectangular or square shape.

(ii) Hight / Width ratio constraint, C_2:

$$C_2 = H_f / B \quad (\leq 2) \tag{3}$$

This constraint may be less than 1 for shallow foundations or the limit may go up to 4 [20].

(iii) Soil working stress constraint, C_3:

$$C_3 = M_t g / (BL) \quad (\leq Q_{all}) \tag{4}$$

where:
M_t = total foundation-machine mass = $M_f + M_m$
M_m = machine mass.
Q_{all} = allowable bearing capacity of the soil = Q_u / FS
Q_u = ultimate bearing capacity of the soil.

FS = design factor of safety

The soil ultimate bearing capacity Q_u is related to the soil properties parameters through [21]:

$$Q_u = [(c/\tan\varphi) + 0.5\gamma B\sqrt{K_p}]\,[K_p\, e^{\pi\tan\varphi} - 1] \quad (5)$$

Where:

c = soil cohesion
φ = soil internal friction angle
K_p = Rankin's coefficient = (1 + sinφ)/(1-sinφ)

(iv) Soil elastic settlement constraint, C_4:

The soil settlement is the resultant of 3 types of settlements: elastic, primary consolidation and secondary consolidation. Here, we are going to consider only the elastic type with setting the upper bound the lowest range of the allowable settlement which is 25 mm [22] .

The elastic settlement as given by Meyerhof depends on the foundation width B as follows [22]:

$$C_4 = 2C_3/N_{60} \text{ for } B \le 1.22 \text{ m} \quad (6)$$

And $$C_4 = (2C_3/N60)[B/(B+0.3)] \text{ for } B > 1.22 \text{ m} \quad (7)$$

Where N_{60} = standard penetration number.

N_{60} is function of the soil internal friction angle φ. Carter and Bentley gave this relation in a graphical form [23]. The following polynomial model if fitted by the authors to the graphical data with 0.9998 correlation coefficient:

$$N_{60} = 42.422122955322 - 4.69926404953\varphi + 0.120638884604\varphi^2$$

Where φ is in degrees.

(v) Maximum vibration amplitude in lateral direction, C_5:

According to the work of Prakash and Puri, the foundation vibration in the horizontal and vertical directions can be considered as uncoupled and defined by a SDOF dynamic model [10]. The maximum vibration amplitude of a SDOF system excited by a rotating unbalance is function of the specific unbalance me/Mt and the system damping ratio. That is:

$$C_5 = (me/M_t) / [2\zeta_x \sqrt{(1-\zeta_x^2)}] \quad (8)$$

Where me is the machine unbalance, ζ_x is the damping ratio of the soil in the lateral direction.

According to Gazetas, the damping ratio in the lateral direction ζ_x is given by [1]:

$$\zeta_x = 0.29/\sqrt{B_x} \quad (9)$$

where B_x is the mass ratio in the lateral direction:

$$B_x = M(2 - \nu)/(8\rho R^3)$$

ν = soil Poisson's ratio
M = foundation mass
R = equivalent radius of the equivalent circular foundation $= \sqrt{(BL/\pi)}$

(vi) Maximum vibration amplitude in vertical direction, C_6:

The maximum vibration amplitude of a SDOF system excited by a rotating unbalance is function of the specific unbalance me/M_t and the system damping ratio in the z-direction ζ_z. That is:

$$C_6 = (me/M_t) / [2\zeta_z \sqrt{(1-\zeta_z^2)}] \quad (10)$$

Where according to Gazetas [1]:

$$\zeta_z = 0.425/\sqrt{B_z} \quad (11)$$

B_z is the mass ratio in the vertical direction:

$$B_z = M(1 - \nu)/(4\rho R^3)$$

(vii) ***Soil isolation efficiency in the lateral direction, C_7:***

The isolation efficiency in the lateral direction is defined as:

$$C_7 = 100(1-TR_x) \quad (12)$$

where TR_x is the vibration transmissibility in the lateral direction given by:

$$TR_x = \left\{ \frac{1 + (2\zeta_x r_x)^2}{(1 - r_x^2)^2 + (2\zeta_x r_x)^2} \right\}^{0.5} \quad (13)$$

r_x is the frequency ratio in the lateral direction:

$$r_x = \omega/\omega_{nx} \quad (14)$$

where ω is the angular exciting frequency of the forced vibrations of the foundation, and ω_{nx} is the lateral natural frequency of the foundation-soil dynamic system given by [10]:

$\omega_{nx} = \sqrt{(k_x / M_t)}$ rad/s (15)

k_x is the soil stiffness in the lateral direction given according to Gazetas by [1]:

$k_x = 8GRC_x(L/B) / (2-\nu)$ (16)

where:

G = soil modulus of rigidity

C_x is a correction factor in the lateral direction depending only on the foundation ratio L/B as indicated by Barken [24]. The author fitted the following third order polynomial to Barken's data with an 0.99977 correlation coefficient:

$C_x=1.026129841805-0.04249420017(L/B)+0.011028882116(L/B)^2-0.000512405066(L/B)^3$ (17)

(viii) ***Soil isolation efficiency in the vertical direction, C_8:***

The isolation efficiency in the vertical direction is defined as:

$C_8 = 100(1-TR_z)$ (18)

where TR_z is the vibration transmissibility in the vertical direction given by:

$$TR_x = \left\{ \frac{1 + (2\zeta_z r_z)^2}{(1 - r_z^2)^2 + (2\zeta_z r_z)^2} \right\}^{0.5} \quad (19)$$

R_z is the frequency ratio in the lateral direction:

$R_z = \omega/\omega_{nz}$ (20)

ω_{nz} is the vertical natural frequency of the foundation-soil dynamic system given by [10]:

$\omega_{nz} = \sqrt{(k_z / M_t)}$ rad/s (21)

k_z is the soil stiffness in the vertical direction given according to Gazetas by [1]:

$k_z = 4GRC_z(L/B) / (1-\nu)$ (22)

C_z is a correction factor in the vertical direction. The author fitted the following fourth order polynomial to Barken's data with an 0.9998 correlation coefficient:

$$C_z=0.968339145184-0.044979844242(L/B)+0.033221840858(L/B)^2-0.004676759709(L/B)^3+0.000208628044(L/B)^4 \quad (24)$$

(ix) Vibration velocity in the lateral direction, C_9:

It is recommended by the Building Department of the Government of Hong Kong that the vibration velocity in lateral or vertical directions not to exceed 15 mm/s [25]. Therefore, this and the next constraint is set on vibration velocity of the foundation.

The vibration velocity in the lateral direction for the rotating unbalance excited vibrations is given by:

$$C_9 = (\omega m e r_x^2/M_t) / \sqrt{\{(1 - r_x^2)^2 + (2\zeta_x r_x)^2\}} \quad (25)$$

(x) Vibration velocity in the vertical direction, C_{10}:

The vibration velocity in the vertical direction for the rotating unbalance excited vibrations is given by:

$$C_{10} = (\omega m e r_z^2/M_t) / \sqrt{\{(1 - r_z^2)^2 + (2\zeta_z r_z)^2\}} \quad (26)$$

3 Constraints Limits

The optimization problem in hand is a constrained one on both foundation dimensions and functional constraints. The upper and lower limits used in this optimal design problem are as follows:

(i) Foundation dimensions limits (depend on machine dimensions for L and B):

$$\left.\begin{array}{l} 2 \le L \le 10 \text{ m} \\ 1 \le B \le 5 \text{ m} \\ 0.5 \le H_f \le 6 \text{ m} \end{array}\right\} \quad (27)$$

(ii) Functional constraints limits:

$1 \le C_1 \le 10$

$0 \le C_2 \le 2$

$0 \le C_3 \le$ allowable bearing capacity

$0 \le C_4 \le 25$ mm

$0 \le C_5 \le$ Allowable vibration amplitude mm

$0 \le C_6 \le$ Allowable vibration amplitude mm

Minimum isolation efficiency $\le C_7 \le 100$ %

Minimum isolation efficiency $\le C_8 \le 100$ %

$0 \le C_9 \le 15$ mm/s

$0 \le C_{10} \le 15$ mm/s

4 Allowable Vibration Amplitudes

The limit of the peak vibration amplitude for machinery foundations is function of the vibration frequency [21]. The vibration limit – frequency is presented in a graphical form. To suit computer-aided application of the foundation design, this relation is defined by a power model in the form [16]:

$$A = 112.429489135742\ f^{(-1.9699963312149)} \quad \text{mm}$$

Where f is the vibration frequency in Hz.

5 Minimum Isolation Efficiency

The isolation efficiency is a key factor in controlling the vibrations transmitted to surrounding during machine operation. This is a famous known problem facing contracting companies. To help in solving this problem, The lower limit of the isolation efficiency constraint is left adjustable to examine the effect of its level of the foundation design.

The range used for the minimum isolation efficiency is: 71 to 87 94 %.

6 Optimal Foundation Design

The objective function given by Eq.1 has to be minimized subject to 10 functional constraints given by Eqs.2, 3, 4, (6 and 7), 8, 10 , 12, 18, 25 and 26, and the design variables constraints in Eq.27. The MATLAB optimization toolbox is used to perform this task [26, 27].

7 Case Study

A 150 kW motor-centrifugal pump unit has the parameters:

- Speed: 1800 rev/min.
- Total mass: 500 kg
- Rotor mass: 300 kg
- Overall length: 2 m
- Overall width: 0.60 m
- Residual unbalance: 12 kgmm

The silty soil has the properties [28-33]:

- Plasticity index: 0.5 %
- Poisson's ratio: 0.34
- Cohesion: 12.9 kN/m²
- Unit weight: 16.3 kN/m²
- Friction angle: 32 degrees
- Shear modulus: 44 MN/m²
- Shear strength: 30 kN/m²

Foundation density: 2400 kg/m³
Design factor of safety: 3

Requirements: The foundation dimensions supporting the motor-pump unit for the stated silt soil properties.

Minimum foundation dimensions: The machine dimensions set the minimum length and width of the foundation at 2 and 1 m respectively.

Optimization results: The optimization results is presented graphically against the minimum isolation efficiency:

- Foundation dimensions and mass: Figs.1 and 2.

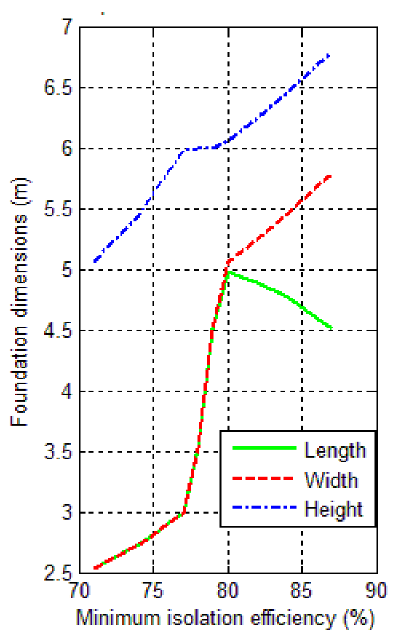

Fig.1 Optimal foundation dimensions.

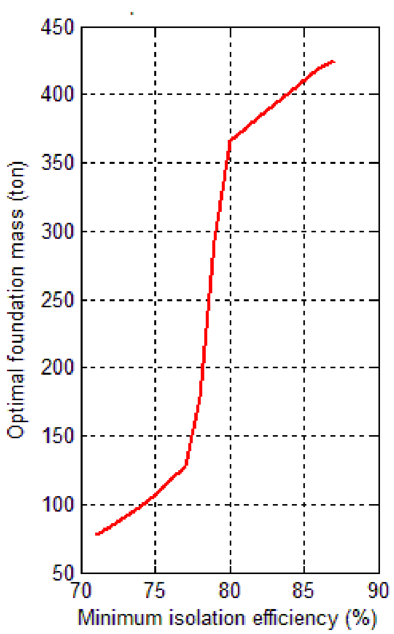

Fig.2 Optimal foundation mass.

- Soil stress at foundation interface and elastic settlement : Figs.3 and 4.

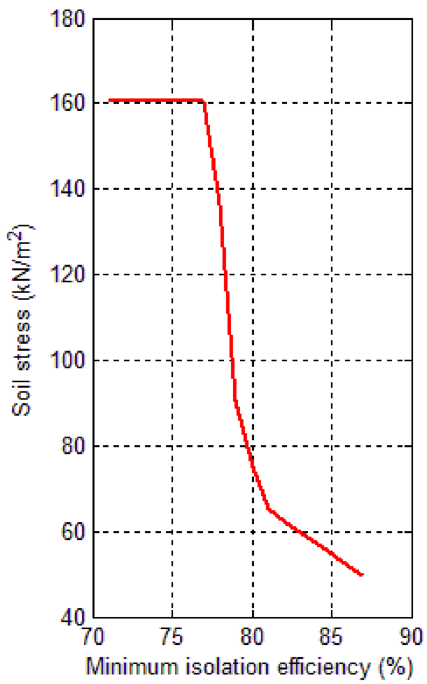

Fig.3 Optimal soil stress at foundation interface.

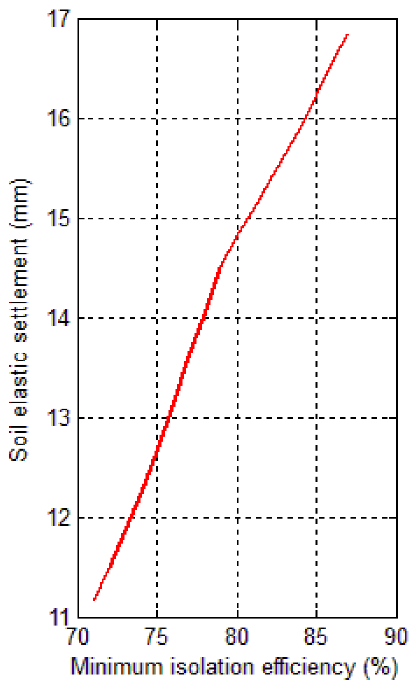

Fig.4 Optimal soil elastic settlement.

- Vibration maximum peak amplitudes and isolation efficiencies: Figs.5 and 6.

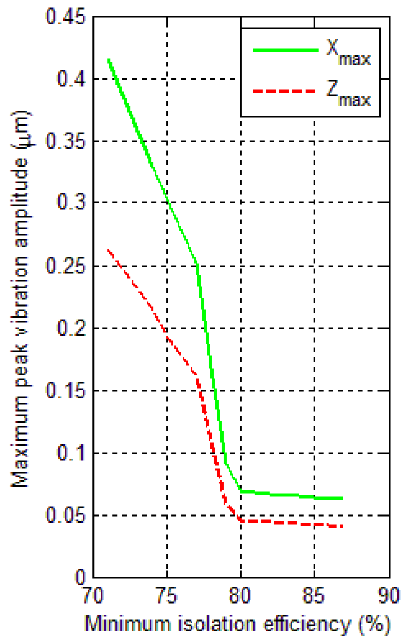

Fig.5 Optimal vibration peak amplitude of the foundation.

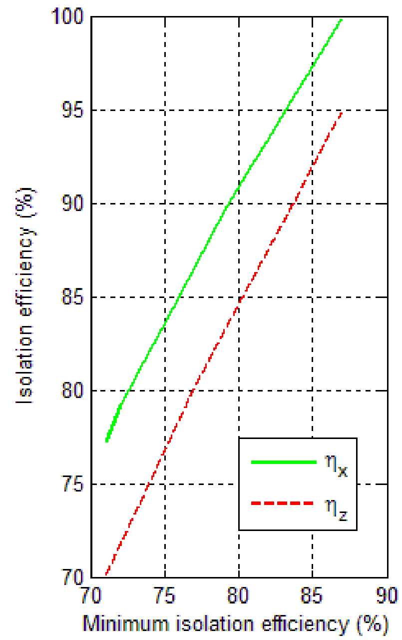

Fig.6 Optimal vibration isolation Efficiencies.

- Vibration peak velocities: Fig.7.

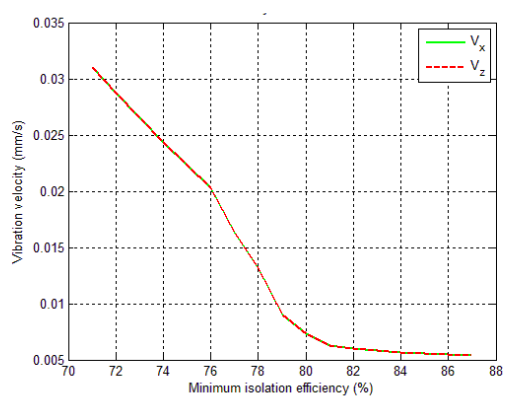

Fig.7 Optimal vibration peak velocities.

8 Conclusions

- Optimization is a powerful technique which leads to successful machinery foundation design fulfilling all the required objectives in case of machinery foundations subjected dynamic loads.
- All the design constraints are simultaneously considered without any trial work .
- Recommendations on soil bearing capacity, foundation relative dimensions , foundation maximum vibrations and isolation efficiency are all considered.
- Isolation efficiency is a very important parameter in foundation design since it controls the vibration and noise induced vibrations of surrounding structures.
- 10 functional constraints were considered increasing the level of the foundation performance and effectiveness associated with a specific dynamic machine.
- The minimum isolation efficiency is used to direct the design giving the structural engineer a chance to compromise between cost and performance.
- The minimum isolation efficiency range considered was from 71 % to 87 % (lower limit).
- The optimal foundation mass range was from 77.8 to 425 ton.
- The vertical soil stress at the foundation interface ranged from 50 to 160.6 kN/m^2.
- The elastic settlement ranged from 11.2 to 16.8 mm.
- The maximum peak vibration amplitude in the lateral direction ranged from 0.063 to 0.415 μm.
- The maximum peak vibration amplitude in the vertical direction ranges from 0.041 to 0.263 μm.
- The isolation efficiency in the lateral direction ranged from 77.2 to 99.8 %.
- The isolation efficiency in the vertical direction ranged from 70.1 to 94.9 %.
- The peak vibration velocity in the lateral and vertical directions ranged from 0.0054 to 0.0287 mm/s.
- All the functional constraints were within the pre-assigned limits.

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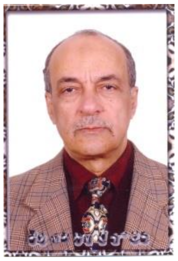
Biography



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