REVIEW OF DESIGN OF MACHINE FOUNDATIONS IN NUCLEAR INDUSTRY

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ABSTRACT

The area of foundation dynamics is one of the fields of geotechnical engineering which is still under stages of development. This is due to the fact that a lot of parameters are involved in the analyses and design of foundations subjected to dynamic loading. During the past few decades a lot of models, both theoretical and experimental have been developed to predict these parameters with a certain degree of accuracy. The selection of any particular model requires thorough study of the parameters involved in the design. Till recently it has been the practice to design machine foundations mostly on the basis of empirical formulae. However with the recent development in the field of soil dynamics and machine foundation, design principles have gradually been developed for typical groups of machine foundations. After 1950, few foundation engineers started using vibration analysis usually based on theory of a surface load on elastic half space for analyzing the machine foundations. Elastic half space theory was refined in 1960’s and lumped mass approach was introduced. It has thus become imperative for the design engineers to know the various aspects of design and construction of machine foundation in order to achieve efficient and rational design. Extensive literature survey has been carried out for the design of machine foundations; various available methods have been discussed. Three methods have been selected namely Barkan’s model, elastic half space model and Dobry and Gazetas model for the present study. Comparative study of these methods has been presented for an example problem. Information on machine foundations subjected to blast loading has also been discussed briefly.

INTRODUCTION

Installation of heavy machinery has assumed increased importance after the industrial development in the country. Foundations of these machines have to be specially designed after considering the vibration characteristics of the load in addition to static loads. The properties of founding soil under dynamic conditions are also to be considered. Natural frequency of a machine foundation-soil system and the amplitude of motion of machine at its operating frequencies are important parameters to be determined in designing a machine foundation.

Establishing the design criteria is probably the most important step in the design process. For machine foundation, the criteria are generally described in terms of limiting values of acceleration, velocity, or displacement under the operating conditions. The vibration amplitude should be such as ‘to prevent serious damage to machinery’ and ‘not to be noticeable to persons’, etc [1].

Types of Machines in Nuclear Industry

Broadly the machines can be classified in the following two categories [1 – 2]:

(A1) Based on the Design Criteria of their Foundations:

(a) Impact machines, e.g., forging hammers, presses, etc. These machines produce impact loads. Their speeds of operation are usually 60-150 blows/minute, and dynamic load attains a peak in a short time and then practically dies out.
(b) Reciprocating machines, e.g., compressor, reciprocating engines, etc. These machines are having reciprocating masses as major moving parts which produce periodic unbalanced forces. The operating speeds of such machines are usually less than 600 rpm. For analysis of their foundations, the unbalanced forces can be considered to vary sinusoidally.
(c) Rotating machines, e.g., turbines, rotary compressors, etc. These machines are having rotating masses as major moving parts and they are high speed machines. The operating speeds of such machines are generally between 3000-10000 rpm.
(d) Other machines, e.g., generators, pump, etc.

(A2) Based on their Operating Frequency:

(a) Low frequency machines: These are the machines with operating speeds up to 1500 rpm. They comprise of large reciprocating engines, compressors, large blowers, etc.

(b) Medium frequency machines: These are the machines with operating speeds ranging between 1500-3000 rpm. They comprises of medium sized reciprocating engines such as diesel and gas engines, etc.

(c) High frequency machines: These are the machines with operating speeds more than 3000 rpm. They comprise of high speed internal combustion engines, electric motors, turbo generators, etc.

Types of Machine Foundations in Nuclear Industry

Based on their structural form, machine foundations may be classified as follows [2]:

(a) Block foundation: This consists of a pedestal of concrete on which the machine rests.

(b) Box or caisson type foundation: This consists of a hollow concrete block supporting the machinery on its top.

(c) Wall type foundation: This consists of a pair of walls which supports the machinery at their top.

(d) Framed type foundation: This consists of vertical columns that support a horizontal frame work at their top which forms the seat of machinery.

Block type foundations are used for reciprocating type of machines, low frequency rotary machines, and machines producing impulsive and periodic forces at low frequency [1, 3]. Block type foundations resting on springs or suitable elastic pads are generally suggested for medium frequency machines; where massive block foundations are used, small contact surfaces and suitable isolation pads are desirable to lower the natural frequencies [1].

Framed type foundations are used for medium to high frequency rotary machines, and machines producing impulsive and periodic forces at medium to high frequency [4]. Turbo machinery requires framed type foundations which accommodate the necessary auxiliary equipment between the columns [4].

Certain machines such as lathes, which induce very little dynamic force, may be bolted directly to the floor without special foundations [3].

Design Criteria for Machine Foundations [5]

Criteria under static loads are as follows: (i) it should be safe against shear failure, and (ii) it should not settle excessively, i.e., settlement should be within permissible limit.

Criteria under dynamic loads are as follows [1, 3 – 4]:

(a) There should be no resonance. It means that, natural frequency of machine-foundation system should be far away from the operating frequency of the machine. Criteria for different machines are as follows:

(i) For reciprocating machines: The ratio of operating frequency of machine to natural frequency of machine-foundation system should be between 0.4 – 1 which would result in over tuned design and less mass of foundation. When this is not possible, the ratio should be more than 1.5 which would result in under tuned design and more mass of foundation. In case of under tuned design, the resonance amplitude should be less than the permissible limits.

(ii) For rotary machines of low frequency: The ratio of operating frequency of machine to natural frequency of machine-foundation system should preferably be less than 0.8 which would result in over tuned design and less mass of foundation. The natural frequency of any foundation should not preferably be within 20 percent of the operating frequency of the machine.

(iii) For rotary machines of medium to high frequency: The fundamental natural frequency of the machine-foundation system (f_n) shall be at least 20 % away from the operating frequency of machine (f_m), i.e., $f_n < 0.8 \cdot f_m$ or $f_n > 1.2 \cdot f_m$. However, frequency separation of 50% is preferable.

(b) The displacement amplitudes of motion at operating frequencies should not exceed the safe limit. The safe limit 'to avoid damage to machinery' is as specified by the manufacturer and 'to avoid damage to structures, discomfort to persons, excessive settlements to foundation, etc.' is 0.2 mm.

(c) The vibration must not be annoying to the persons working in the factory or be damaging to other precision machines. The nature of vibrations that are perceptible, annoying, or harmful depends on the frequency of vibration and amplitude of motion.

Objectives

There is no unique method available for the analyses and design of machine foundations. Methods available for analyses and design include empirical methods, Barkan's method, elastic half space method, Dobry and

Gazetas method, etc. The objective of the present study is to compare analyses and design results obtained for an example problem of a machine foundation based on Barkan's method, Elastic half space method and Dobry & Gajetas method.

METHODS OF ANALYSIS OF A MACHINE FOUNDATION

(B1) Empirical Method [6]

These methods are based on the experimental data collected from practice. The recognized empirical method has been proposed by Tschebotarioff [6], who presented following relationships given by Eq. (1) for the preliminary designs of foundations when the soil parameters are not readily available. This method may be used to check the occurrence of resonance.

$$f_n = \frac{f_{nr}}{\sqrt{q_0}}; \quad q_0 = \frac{W}{A_f} \tag{1}$$

where, f_n and f_{nr} = natural frequency and reduced natural frequency of machine-foundation system, respectively; A_f = contact area of machine foundation; W = weight of foundation.

(B2) Linear Elastic Weightless Spring Method (Barken's Method) [7]

This method has been proposed by Barkan [7], wherein founding soil has been considered as a linear elastic weightless spring for small amplitudes of strain. It is assumed that certain mass of soil vibrates along with the foundation. This method ignores the effect of damping. It has been shown that the apparent mass of soil participating in the foundation vibrations does not normally exceed 23 percent of the combined mass of machine and foundation [7]. Thus, the error in calculation of natural frequency is less than 10 percent. Because of its simplicity and fairly close prediction of the true foundation behaviour, the method has been adopted by IS codes [1, 3].

Soil spring constants in different modes of vibrations are estimated by using relationships given by Eq. (2).

$$K_z = C_z \cdot A_f;\ K_\tau = C_\tau \cdot A_f;\ K_\varphi = C_\varphi \cdot I_{x\,or\,y};\ K_\psi = C_\psi \cdot I_z \tag{2}$$

where, K_z, K_τ, $K\varphi$ and K_ψ = soil spring constants in vertical, horizontal, rocking and torsional modes of vibrations, respectively; for soils C_z = coefficient of elastic uniform compression (vertical mode); C_τ = coefficient of elastic uniform shear (horizontal mode); C_φ = Coefficient of elastic non uniform compression (rocking mode); C_ψ = coefficient of elastic non uniform shear (torsional mode); $I_{x\,or\,y\,or\,z}$ = moment of inertia of contact area with respect to the axis of rotation passing through the centroid of the area. Having determined one of the soil constant C_z from the in situ soil test, such as, cyclic plate load test, other soil constants shall be evaluated approximately by using the relationships, given by Eq. (3) [7].

$$C_\tau = 0.5 \cdot C_z;\ C_\varphi = 2 \cdot C_z;\ C_\psi = 0.75 \cdot C_z \tag{3}$$

Natural frequencies of vibrations for soil-foundation system and amplitudes of motion for foundation are determined by the relationships given in the reference [1].

(B3) Elastic Half Space Method

For dynamically loaded foundations supported directly on soils it has been found that the theory of foundations supported by the elastic half space provides the key for determining satisfactory values of damping and spring constants for a given foundation soil system. This theory idealizes the machine foundation as a vibratory mechanical oscillator with a circular base resting on the surface of ground. The soil is assumed to be homogeneous, isotropic, elastic, semi infinite material characterized by three properties namely shear modulus, G, Poisson's ratio, υ, mass density, ρ_m [8]. The footing has been represented by an oscillating mass which produces a periodic vertical pressure uniformly distributed over a circular area on the surface of the half space. This method provides a dimensionless solution for the steady motion amplitudes of a footing over a wide frequency range including the resonance condition. Theory for evaluating the dynamic response of a vibrating footing has been proposed by Lysmer and Richart [9]. The most important result of this study was establishing the bridge between the elastic half space theory and the mass-spring-dashpot system and providing values for the damping and spring constants.

Lysmer and Richart [9] proposed a simplified mass-spring-dashpot analog known as Lysmer's analog for calculating the response of a rigid circular footing subjected to vertical vibrations. They defined the displacement function, *F*, and modified mass ratio, B_z, for the vertical vibration of rigid circular footing by Eq. (4).

$$F = \frac{4 \cdot f_n}{1-\upsilon} = F_1 + i \cdot F_2;\ B_z = \frac{(1-\upsilon) \cdot b}{4} = \frac{(1-\upsilon) \cdot m}{4 \cdot \rho_m \cdot r_o^3} \tag{4}$$

where υ = Poison's ratio of soil; F_1 and F_2 = components of displacement function; *b* = dimensionless mass ratio; m = mass of foundation; r_o = radius of circular footing.

By using the values of *F* and B_z, Lysmer and Richart [9] developed the response curves for variation of spring constant and effective damping as a function of non-dimensional frequency ratio. Based on the analyses of response curves, they discovered that constant values of spring constant and effective damping could be used. They proposed static value of spring constant, K_z, and damping constant, c_z, by Eq. (5).

$$K_z = \frac{4 \cdot G \cdot r_o}{1-\upsilon};\ c_z = \frac{3.4 \cdot r_o^2 \cdot (\rho_m \cdot G)^{0.5}}{1-\upsilon} \tag{5}$$

Relatively little energy is dissipated in to the elastic-half-space in rocking mode of vibration, thereby resulting in low damping [10]. Modes of vibration in horizontal translation are associated with relatively high damping as is the case for mode of vibration in vertical translation, thereby resulting in high damping [10]. Therefore, in lumped parameter analog, the spring and damping constants are constants and are frequency independent. But for footings on elastic-half-space, K_z and c_z are frequency dependent. In this manner, it was possible to replace the elastic-half-space by a two parameter model. For the lumped parameter model system, K_z and c_z values from Eq. (5) can be inserted in to dynamic equilibrium equation to get the solution. The spring constants (K_τ, K_z, K_φ and K_ψ), the mass ratios (B_τ, B_z, B_φ and B_ψ), and the damping ratios (D_τ, D_z, D_φ and D_ψ) for horizontal, vertical, rocking and torsional modes of vibration, respectively are given by Eq. (6) – (8) [8].

$$K_\tau = \frac{32 \cdot (1-\upsilon) \cdot G \cdot r_o}{(7-8 \cdot \upsilon)};\ K_z = \frac{4 \cdot G \cdot r_o}{(1-\upsilon)};\ K\varphi = \frac{8 \cdot G \cdot r_o^3}{3 \cdot (1-\upsilon)};\ K_\psi = \frac{16 \cdot G \cdot r_o^3}{3} \tag{6}$$

$$B_\tau = \frac{(7-8 \cdot \upsilon) \cdot m}{32 \cdot (1-\upsilon) \cdot \rho_m \cdot r_o^3};\ B_z = \frac{(1-\upsilon) \cdot m}{4 \cdot r_o^3};\ B_\varphi = \frac{3 \cdot (1-\upsilon) \cdot I_\varphi}{8 \cdot \rho_m \cdot r_o^3};\ B_\psi = \frac{I_\psi}{\rho_m \cdot r_o^3} \tag{7}$$

$$D_\tau = \frac{0.288}{\sqrt{B_\tau}};\ D_z = \frac{0.425}{\sqrt{B_z}};\ D_\varphi = \frac{0.15}{(1+B_\varphi) \cdot \sqrt{B_\varphi}};\ D_\psi = \frac{0.5}{(1+2 \cdot B_\psi)} \tag{8}$$

where, I_φ and I_ψ = mass moment of inertia of the footing about centre of rotation in rocking mode and torsional mode, respectively. It is noted that the stiffness and damping values obtained from the above models are static and independent of geometry of foundation and frequency of loading.

(B4) Dobry and Gazetas Method [11]

The stiffness and damping values obtained from Eq. (6) – (8) are static and frequency independent. It has been found that these values are not static, but are dependent on geometry of foundations, aspect ratio, *L/B*, and frequency of loading. Here *L* and *B* are the length and breadth of footing, respectively. In elastic half space model, every shape is converted to equivalent circular shape which leads to erroneous results for higher values of aspect ratio. The method proposed by Dobry and Gazetas [11] attempts to rectify these errors.

In this method, rectangular shape is used as the reference shape. Every shape is converted to equivalent rectangular shape. The advantage of rectangular shape is that it gives a better representation of the footing than the circular shape. Dobry and Gazetas [11] made an extensive literature survey for methods to compute the spring and damping values. They plotted the spring and damping values from several sources as a function of non-dimensional frequency ratio, and produced a series of best fit curves. Predicted vibrations from these curves were in very good agreement with the measured values [12]. By using the curve fit values, they computed the static spring values after making corrections for the shape of the footing. They proposed the values for a footing of length 2*L* and breadth 2*B*. They proposed multiplication of frequency dependent factors with static spring and damping values to get dynamic values.

The stiffness and damping values obtained from the lumped parameter model are based on a perfectly elastic soil with zero material damping. The damping assumed by this model is geometric damping which is due to dissipation of waves. However, the assumption of soil as an elastic material is not wholly correct. Experimental evidence indicates that even at very small strains soil exhibits a material (or hysteretic damping) which is mainly due to the friction between the soil and the material. Material damping correction has been done in the dynamic stiffness and damping values. The elastic half space method of analysis considered the footing resting on the ground surface without taking into consideration of embedment correction factors; Dobry and Gazetas [11] considered embedment correction factors in their model. Dynamic spring constants ($K_{\tau x}$, $K_{\tau y}$, K_z, $K_{\varphi x}$, $K_{\varphi y}$ and K_ψ) for sliding along X and Y directions, vertical, rocking about X and Y directions, and torsional modes of vibration, respectively for rectangular and circular base are given by Eq. (9) – (10) [11, 13 – 14]. Here *X* and *Y* directions are along length and breadth of the footing, respectively.

$$K_x = K_y - \frac{0.21 \cdot L \cdot G}{(0.75-\upsilon)\cdot(1-\frac{B}{L})};\ K_y = \frac{S_y \cdot 2 \cdot L \cdot G}{(2-\upsilon)};\ K_z = \frac{S_z \cdot 2 \cdot L \cdot G}{(1-\upsilon)} \ \text{(Rectangular Base)} \tag{9a}$$

$$K_{\varphi x} = \frac{S_{\varphi x} \cdot I_x^{0.75} \cdot G}{(1-\upsilon)\cdot\left(\frac{B}{L}\right)^{-0.25}};\ K_{\varphi y} = \frac{S_{\varphi y} \cdot I_y^{0.75} \cdot G}{(1-\upsilon)};\ K_\psi = S_\psi \cdot G \cdot I_z^{0.75} \ \text{(Rectangular Base)} \tag{9b}$$

$$K_x = \frac{8 \cdot G \cdot B}{(2-\upsilon)};\ K_y = K_x;\ K_z = \frac{4 \cdot G \cdot B}{(1-\upsilon)};\ K_{\varphi x} = \frac{8 \cdot G \cdot B^3}{3\cdot(1-\upsilon)};\ K_{\varphi y} = K_{\varphi x};\ K_\psi = \frac{16 \cdot G \cdot B^3}{3} \ \text{(Circular Base)} \tag{10}$$

where, S_y, S_z, $S_{\varphi x}$, $S_{\varphi y}$ and S_ψ = factors that are described in the reference [11]; I_x, I_y and I_z = plan moment of inertia of footing about *X*, *Y* and *Z* directions, the direction *Z* being along the height of the footing.

CRITICAL APPRAISAL OF EXISTING METHODS

The empirical method (Section B1) can be used for preliminary design purposes and it can only be used to check the occurrence of resonance which in itself is not adequate for a satisfactory design. The method does not provide the criteria of checking the design with respect to permissible displacement. Due to its simplicity, it is widely used worldwide.

In linear elastic weightless spring (Section B2), damping is ignored and the amplitude of motion at resonance approaches infinity. According to Barkan [7], damping has only a slight effect upon the calculated natural frequency, and if the operating and the natural frequencies are well apart, the effect of damping on amplitudes can be neglected. Barkan’s method gives no useful information on the amplitude of motion at frequencies near resonance as it ignored damping. This method gives useful results only for the undamped frequency of vibration.

The elastic-half-space theory (Section B3) includes the dissipation of energy throughout the half-space by geometrical damping. This theory permits calculation of finite amplitude of vibration at the resonant frequency. Since the elastic-half-space theory is an analytical procedure, certain mathematical simplifications have been introduced. The footing is assumed to rest on the surface of elastic half-space and to have simple geometrical area of contact, usually circular but occasionally rectangular or a long strip. The analytical solution serves as a useful guide for evaluation of the dynamic response of simple footings undergoing single mode of vibration. The consideration of soil as an elastic-half-space has further advantages in application of solutions from Geophysics to problems of wave propagation in soils and of isolation of foundation. Also the solution permits extension of the theoretical studies to problems of the refraction and diffraction of waves in soils by geometrical discontinuities. Consequently, theories based on the concepts of elastic media have engineering value.

It has been shown that the vertical vibration of a rigid circular footing on the elastic-half-space could be represented quite satisfactorily by the lumped parameter, mass-spring-dashpot system if the spring and damping constants were chosen correctly [8 – 10]. There is already wealth of literature available concerning the solutions for lumped parameter systems, but it has always been a problem to determine representative values for the lumped mass, spring and dashpot. It followed that the lumped parameter system equivalent to elastic-half-space model could be used to represent the motion of rigid foundations. This method is widely used for the analysis of machine foundations even though it is not considering the non-linearity of soil. But the effects of the non-linearity of soil on the foundation response may be insignificant in the design of machine foundations, because after few cycles of operations, the soil behavior essentially approaches that of linear elasticity for small amplitude of motion. The lumped mass is chosen as the mass of the foundation and supporting machinery.

In lumped parameter method equivalent to elastic–half-space theory, the values suggested for spring and damping constants are static and frequency independent. The assumption of frequency of spring and damping constant is valid for low frequency only. Material damping was not considered in this method. The order of internal damping is of the order of 0.05. For vibration in translatory modes, geometrical damping overshadows the internal damping. For rocking and torsion mode of vibration, geometrical damping is small and for rocking in particular, these two damping terms may be of the order of same magnitude. In this case, internal damping is important and should be considered. The value of geometric damping obtained shall be considered as first approximation, because the theory treats footings resting on the surface of the elastic half space where as actual foundations are often partially embedded.

Dobry and Gazetas (section B4) multiply static spring and damping constant with frequency dependent parameters to get the dynamic values. Then they corrected the dynamic values for material damping and got the final values. They used rectangular shape as the basic reference shape and other shapes were converted in to equivalent circular shape. They paid proper attention to the embedment of the footing. In general, partial embedment reduces the amplitude of motion at resonance peaks and increases the value of resonant frequency. This indicates an increase in the effective spring constant and a probable increase in the effective damping ratio. More significant effect on stiffness is for rocking and sliding modes of vibration.

After discussing all the methods, it can be concluded that Dobry and Gazetas method [11] is the most rational method and it can be used for the foundations with moderate to high aspect ratios and high operating frequency. Considerations in various methods are summarized in Table 1.

Table 1: Considerations in various methods of analysis of machine foundation

Sr. No.	Methods	Considerations
1	Empirical Method [6]	Criteria of checking with respect to permissible displacement are not present.
2	Barkan's Method [7]	Damping is ignored, amplitude of motion at resonant frequency not available
3	Elastic Half Space Method [8 – 10]	Basic foundation shape is circular. Foundation resting on elastic half space. Spring and damping constants are static and frequency independent. Material/internal damping is not considered.
4	Dobry and Gazetas Method [11]	Basic foundation shape is rectangular. Foundation resting on elastic half space. Spring and damping constants are dynamic and frequency dependent. Material/internal damping is considered. Embedment of foundation is considered.

EXAMPLE PROBLEM OF A MACHINE FOUNDATION

Example – For uncoupled vibrations, obtain the amplitudes for a base having the following properties: length of base = 24 ft; breadth of base = 12 ft; height of base = 1 ft; mass of foundation = 1.342 k.sec^2/ft; internal damping of soil = 0.05 (estimated); soil density = 0.00388 k.s^2/ft^4; G = 5000 ksf; poisson's ratio = 0.333 (estimated); starting and ending RPM of machine for vertical vibration = 900 and 1900; RPM increment = 200; operating RPM of machine = 2000; force amplitude: F_z = 20 kips; F_x = F_y = 10 kips; moment amplitude: M_x = 15kft; M_y = 20kft; M_z = 25kft; Starting and ending RPM for vibration other then vertical vibration = 900.

This example has been solved by Barkan's method, elastic-half-space method and Dobry and Gazetas method (Sections B2 – B4). The estimated amplitude from each method for various modes of vibration has been studied and comparison has been done. As the stiffness and damping properties of the soil influenced the amplitudes of vibrations, the amplitudes of vibration are considered as the major parameter for comparison. Amplitudes are given in Table 2.

Table 2: Estimated amplitudes from various methods

Amplitudes of Vibration	Barkan's Method (Section B2)	Elastic Half Space Method (Section B3)	Dobry & Gazetas Method (Section B4)
A_z	0.00105 inch	0.000489 inch	0.00065447 inch
A_x	0.00091 inch	0.00045 inch	0.00046337 inch
A_y	0.00091 inch	0.00045 inch	0.00046036 inch
A_{rx}	0.00000266 rad	0.00000154 rad	0.00000193 rad
A_{ry}	0.000000888 rad	0.0000007654 rad	0.00000065 rad
A_{rz}	0.0000009 rad		0.00000085 rad
Note: Notations have their usual meanings.			

As the Barkan's method (Section B2) neglects the damping, it gives high values of amplitudes. On the other hand, the linear variation of parameters considered in the elastic half space method (Section B3) may overestimate the particular parameter say damping, thus it gives low values of amplitudes. The realistic values may be somewhere between the values estimated by the above two methods. Dobry and Gazetas methods (Section B4) give realistic values of amplitudes.

MACHINE FOUNDATION SUBJECTED TO BLAST LOADING

Blast is another source of vibration for machine foundations. Analyses should be performed if machine foundation is subjected to blast induced vibration. Blast loading may arise from quarry blasting, construction blasting, terrorist attack etc. The machine as well as the foundation should not get damaged by the blast. Acceleration time histories in three directions caused by blast are used to generate force time histories for design of machine foundation. The most intense ground accelerations are observed at the ground surface. Hence, it is selected as the final design acceleration time-history.

A better understanding is required to protect foundation systems and to prevent massive damage. Response to machine foundations subjected to blast loading is a very complex problem. It involves understanding of blast wave propagation, ground particle vibration parameters e.g. acceleration, velocity, displacement and their respective frequencies. Characteristics of blast waves, parameters affecting foundation responses, soil modeling, and dynamic soil structure interaction under blast loadings are the major concerns. Responses of foundations depend on blast characteristics, blast geometry, properties of surrounding soil and properties of the structure itself. Blast induced liquefaction, damage to foundation systems, effects of rock joints on blast induced shock wave propagation, soil modeling to simulate the stress wave propagation and damage assessment of structures are also areas of concern.

Blast induce excitation has been evaluated by carrying out an extensive ground vibration monitoring program [15]. Initial blast monitoring of production blasts was carried out at the proposed turbine location, and final design acceleration time-history was developed. The ground accelerations due to blasting were measured and recorded for three directions simultaneously. This acceleration-time history was used to calculate the force-time histories that would be experienced by the proposed foundation. Acceleration intensity and force amplitudes were found to be highest in the longitudinal direction and lowest in the transverse direction. As a wide range of frequencies is observed in the forcing function, the stiffness and damping of the foundation system should be calculated over that range. Response of centre of gravity of machine foundation system to blast load as well as operating load has been evaluated. The maximum total combined responses to normal operating loads and blast loading in all translational directions were calculated checked with the permissible limits [15].

CONCLUSIONS

The designs using analytical solutions suggested by Dobry and Gazetas method is more rational as compared to the same proposed by Barkan's method. The assumption of frequency independence of soil stiffness and damping values is valid for low frequency only. The stiffness and damping values are dependent on geometry of foundation, aspect ratio and frequency of loading. The equivalent circular shape becomes a poor model for higher values of aspect ratios which leads to erroneous results. The use of rectangular shape as the basic reference shape gives a better representation of the footing other than circular shape. At very small strains, soil exhibits material damping and it should be considered in the calculation of spring and damping constants as considered by Dobry & Gazetas [11]. The machine sensitive in nature or foundation near blast source should be designed to resist blast loading.

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