28th ISET Annual Lecture

FOUNDATIONS FOR INDUSTRIAL MACHINES AND EARTHQUAKE EFFECTS

K.G. Bhatia
Center for Applied Dynamics
D-CAD Technologies, New Delhi

ABSTRACT

Improvement in manufacturing technology has provided machines of higher ratings with better tolerances and controlled behaviour. These machines give rise to considerably higher dynamic forces and thereby higher stresses and, in return, demand improved performance and safety leaving no room for failures. This paper highlights need for a better interaction between foundation designer and machine manufacturer to ensure improved machine performance. The paper also describes the design aids/methodologies for foundation design. Various issues related to mathematical modeling and interpretations of results are discussed at length. Intricacies of designing vibration isolation system for heavy-duty machines are also discussed. Influences of dynamic characteristics of foundation elements, viz., beams, columns, and pedestals etc. on the response of machine, along with some case studies, are also presented. The paper also touches upon the effects of earthquakes on machines as well as on their foundations. Use of commercially available finite element packages, for analysis and design of the foundation, is strongly recommended, but with caution.

KEYWORDS: Machine Foundation, Dynamic Response, Seismic Qualification, Design Aids, Vibration Isolation

INTRODUCTION

The dynamics of machine-foundation system is an involved task in itself and consideration of earthquake effects further adds to its complexity. The performance, safety and stability of machines depend largely on their design, manufacturing and interaction with environment. In principle machine foundations should be designed such that the dynamic forces of machines are transmitted to the soil through the foundation in such a way that all kinds of harmful effects are eliminated (Barkan, 1962; Bhatia, 1984, 2006, 2008; Major, 1980; Prakash and Puri, 1988; Srinivasulu and Vaidyanathan, 1980). In the past, simple methods of calculation were used, most often involving the multiplication of static loads by an estimated dynamic factor and the result being treated as an increased static load without any knowledge of the actual safety factor. Because of this uncertainty, the value of the adopted dynamic factor was usually too high, although practice showed that during operation harmful deformations did result in spite of using such excessive factors. This necessitated a deeper scientific investigation of dynamic loading. A more detailed study became urgent because of the development of machines of higher capacities (Bhatia, 1984).

Machines of higher ratings gave rise to considerably higher stresses thereby posing problems with respect to performance and safety. This called for development partly in the field of vibration technique and partly in that of soil mechanics. Hence new theoretical procedures were developed for calculating the dynamic response of foundations (Bhatia, 2006).

Based on the scientific investigations carried out in the last few decades it has been established that it is not enough to base the design only on the vertical loads multiplied by a dynamic factor, even if this factor introduces a dynamic load many times greater than the original one. It should be remembered that operation of the machines generates not only vertical forces, but also forces acting perpendicular to the axis; it is thus not enough to take into account the vertical loads only and to multiply those by a selected dynamic factor (Bhatia, 2006, 2008). It has also been found that the suitability of machine foundations depends not only on the forces to which they will be subjected to, but also on their behaviour, when

exposed to dynamic loads, which depends on the speed of the machine and natural frequency of the foundation. Thus a vibration analysis becomes necessary. Each and every machine foundation does require detailed vibration analysis providing insight into the dynamic behaviour of foundation and its components for satisfactory performance of the machine. The complete knowledge of load-transfer mechanism from the machine to the foundation and also the complete knowledge of excitation forces and associated frequencies are a must for the correct evaluation of machine performance.

All machine foundations, irrespective of the size and type of machine, should be regarded as engineering problems and their designs should be based on sound engineering practices. Dynamic loads from the machines causing vibrations must be duly accounted for to provide a solution, which is technically sound and economical. Though advanced computational tools are available for precise evaluation of dynamic characteristics of machine-foundation systems, their use in design offices, which was limited in the past, has now been found to be quite common. A machine-foundation system can be modeled either as a two-dimensional structure or as a three-dimensional structure.

For mathematical modeling and analysis, valid assumptions are made keeping in view the following:
- The mathematical model should be compatible with the prototype structure within a reasonable degree of accuracy.
- The mathematical model has to be such that it can be analysed with the available mathematical tools.
- The influence of each assumption should be quantitatively known with regard to the response of the foundation.

Vibration isolation techniques have also been used to reduce vibrations in the machines. Isolation leads to reduction in the transmissibility of the exciting forces from the machine to the foundation and vice-versa. Use of vibration isolation devices is one of the methods by which one can achieve satisfactory performance, which in turn can result in minimizing failures and reduce downtime on account of high vibrations. However, for equipment on elevated foundations, it is desirable to have support structure stiffness sufficiently higher than the overall stiffness of isolation system in order to get the desired isolation efficiency (Bhatia, 2008). The support structure, a 3-D elevated structural system, possesses many natural frequencies. The vibration isolation system, comprising the machine, inertia block and the isolation devices, also has six modes of vibration having specific stiffness values corresponding to each mode of vibration. It is of interest to note that the lateral stiffness of an elevated structure is very much lower than its vertical stiffness. If this lower (lateral) stiffness is comparable to the stiffness of isolators, it certainly affects the overall stiffness and thereby the response of the machine-foundation system. Hence, the lateral stiffness of the support structure must also be computed and considered while selecting the isolators. Finally it may be desirable to carry out detailed dynamic analysis of the complete system including the substructure.

MACHINE-FOUNDATION SYSTEM

The main constituents of a typical machine-foundation system are
- machine: rotary machines, reciprocating machines, impact machines;
- foundation: block foundations, or frame foundations; and
- support medium: soil continuum, or a soil-pile system, or a substructure that, in turn, is supported over the soil continuum or soil-pile system.

Dynamic forces are (i) internally generated forces by the machine itself, or (ii) externally applied forces (that are applied directly to the machine, or transmitted through the support medium/foundation).

Figure 1 shows the schematic of dynamics between various elements of a machine-foundation system. It is seen that all the three constituents of the machine-foundation system, viz., machine, foundation and soil, contribute to the frequency of the system. This system, when subjected to dynamic forces (whether internally generated, externally applied, or transmitted through the soil), results in response of the system.

MODELING AND ANALYSIS

Every foundation designer should remember that he/she is dealing with machines weighing several tonnes and is required to design the foundations having dimensions of several meters but with amplitudes restricted to only a few microns. The designer, therefore, must clearly understand the assumptions,

approximations, and simplifications made during the modeling and must recognize their influence on the response. It is this aspect that makes modeling and analysis a very important part of design.
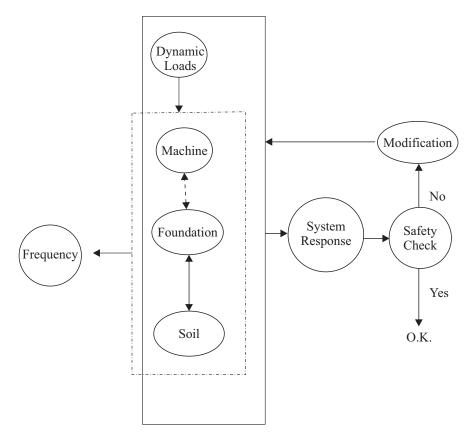

Fig. 1 Schematic diagram of a machine-foundation system subjected to dynamic loads

For the purpose of analysis, the machine-foundation system is represented by an appropriate mathematical model with the basic objective that the model should be compatible with the prototype. For each mathematical representation, a host of assumptions and approximations are made. The extent of complexity introduced in the mathematical model directly influences the reliability of results. In addition, simplifications/approximations are also introduced to meet the limitations of the analytical tools. In other words, mathematical representation not only depends on the machine and foundation parameters but also depends on the analysis tools.

1. Manual Computational Method

1.1 Block Foundations

For the machines on block foundations, it is good enough to use simple formulations (which are equations of motion considering block as a rigid body supported on an elastic medium, i.e., soil). Whereas majority of the machine and foundation aspects are well taken care of by these procedures, there are some aspects, as given below, that cannot be fully managed by these manual computational methods.

1.2 Foundation Eccentricity

If foundation eccentricity is higher than the permissible value, the vertical mode of vibration will no longer remain uncoupled from the lateral and rotational modes (Barkan, 1962; Bhatia, 2008). It is undoubtedly easy to write equations of motion for such uncoupled modes, but getting closed-form solutions for those equations is not that simple, and computations may turn out to be complex. Further, getting transient response history may be a tedious task, though it is possible to evaluate transient response at any of the defined frequencies.

It is therefore recommended to use finite element (FE) analysis, wherever feasible, in order to include all these aspects. Further, this gives improved reliability on account of lesser number of

approximations/assumptions. This also permits visualization of animated mode shapes, and viewing of response amplitude build-up and stress concentration locations.

1.3 Frame Foundations

The formulations used for manual computations cover only standard/ideal frames, i.e., frame beam is rectangular in cross-section having machine mass at its center. Analysis of a single portal frame is based on the premise that longitudinal beams of a frame foundation are flexible enough to permit transverse frames to vibrate independently (Barkan, 1962; BIS, 1992). These procedures are only for very ideal cases, and most of the real-life machine foundations do not fall under this category. Some of the aspects that cannot be suitably accounted for by the manual computational methods (Bhatia, 2008; Ramdasa et al., 1982) are

- haunches,
- machine mass at off-center locations of the beam,
- beams extended as cantilevers on one side/both sides of the frame beam,
- beams inclined in elevation supporting heavy machine mass,
- no frame beam at column locations,
- higher-order frame-column vibration frequencies,
- presence of solid thick deck within the frames, and
- depression/recess in the top deck.

Based on many design studies carried out by the author, it has been observed that

1. Variation in natural frequencies of a frame obtained manually compared to the FE method is of the order of 10% to 20% (Bhatia, 2008).
2. FE analysis confirms the presence of three-to-four additional frequencies between the first and second vertical modes as computed manually. These additional frequencies lie well within the operating range of the medium-RPM machines and may significantly contribute to the response.
3. In recognition of the higher reliability of the FE method, and the fact that manual computations give results that are in variance by 10% to 20% compared to the FE analysis, it has been suggested that no corrections need to be applied on account of either frame centerline dimensions or inclusion of haunches, etc.; all corrections put together will easily get absorbed by the available margins (Bhatia, 2008).

It is, therefore, recommended to use FE analysis with appropriate element types for the modeling of frame foundation. It is, however, recommended to use the manual analytical approach to evaluate free-vibration response for each frame to get a first-hand feeling of the frequency range of frames vis-à-vis the operating frequency and their sub- and super-harmonics.

2. Finite Element Method

Finite element method is the most commonly accepted analysis tool for the solution of engineering problems. Effective pre- and post-processing capabilities make modeling and interpretation of results simple. It is relatively easy to incorporate changes, if any, and to redo the analysis without much loss of time. Viewing of the animated mode shapes and dynamic response makes understanding of the dynamic behaviour of the machine foundation system relatively simpler. Design of machine foundation involves the consideration of machine, foundation and soil together as a system, subjected to applied or generated dynamic forces. Development of a specific FE-based package for the design of machine foundation is generally not feasible on account of (a) tight project schedules and (b) validation of results. Use of commercially available packages is more effective for design offices. There are many issues that need careful examination before finalizing the package, e.g., user friendliness, pre-processor capabilities (i.e., modeling capabilities), analysis capabilities, post-processor capabilities (related to the processing of results), etc., but the most important issue is the validation of results. Every package is a black box for the user and it has its associated limitations, some of which are explicit and some are implicit. Validation for some known sample cases, therefore, becomes a must before one accepts the results. The author has himself used many commercially available packages for the analysis and design of machine foundations during the course of his professional career. Finite element method enables the modeling of machine, foundation and soil in one go, which brings behaviour 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. In case soil is represented as continuum, it

is also modeled using the solid elements. In case soil is represented by equivalent springs, it could be modeled using spring elements or boundary elements. Modeling of each of the constituent is an art in itself and is briefly discussed below.

2.1 Machine

Machine is relatively rigid compared to the foundation and soil. It is considered contributing to the mass, only with its centre of gravity (CG) lying above the foundation level. While modeling the machine, the broad objective is to represent the machine in such a way that its mass is truly reflected, and CG of the overall mass of the model matches with that of the prototype. Thus, modeling of the machine with rigid links or rigid-beam elements is considered good enough. Machine mass is considered lumped at appropriate locations so as to correctly simulate the CG location. This should be cross-checked with the mass distribution given by the supplier/manufacturer.

Whether it is a block foundation or a frame foundation, lumping of the machine mass at the top level of the foundation is not desirable, as this will result in mismatch of the CG of the machine mass (in the vertical direction) of the model with that of the prototype. Figure 2(a) shows such a lumping for a typical block foundation (Bhatia, 2006, 2008). Such a representation does affect the mass moment of inertia and thereby the natural frequencies and the response. It is therefore essential that the CG of the machine mass in vertical direction must be matched with that of the prototype, as given by the manufacturer. Machine mass should be lumped at an appropriate level above the foundation, as shown in Figure 2(b). Similar concept should be used for modeling the bearing pedestals.

For advanced modeling, it is desirable to model the rotor and stator independently. The rotor is represented using a set of beam elements with corresponding section and material properties that represent the variation of rotor section along the machine axis, whereas the stator is modeled using the rigid links, with stator mass lumped at appropriate locations, such that the CG of mass matches with that provided by the supplier. Rotor support at the bearing locations should be modeled with the corresponding stiffness and damping properties offered by the bearings (Bhatia, 2008). Such a model is as shown in Figure 2(c). The bearing pedestals, however, are modeled as the rigid links.

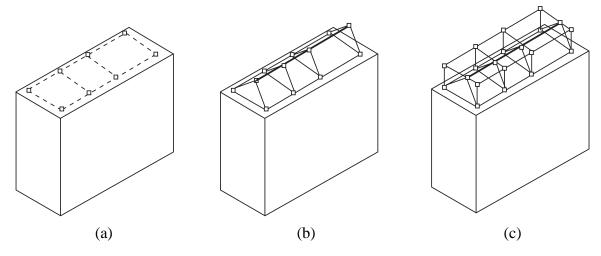(a)   (b)   (c)

Fig. 2 Modeling of machine with foundation: (a) machine mass lumped at the foundation top, (b) machine masses lumped at the CG level of the machine, (c) rotor and stator modeled separately—masses lumped at the respective CG levels

2.2 Foundation

Block Foundation: A foundation block is a solid mass made of reinforced cement concrete (RCC) with required openings, depressions, raised pedestals, cutouts, bolt pockets, and extended cantilever projections. Solid elements are good enough for modeling a foundation block. A coarse mesh for the block and relatively finer mesh in the vicinity of openings, pockets, and cutouts is considered sufficient. Solid model and FE mesh of a typical foundation block are shown in Figure 3. Generally speaking, 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, while improvement in the results may only be marginal. Choice of element size is fairly subjective as it is problem-dependent. It is, therefore, not possible to specify firm guidelines regarding the choice of right element size that will be applicable to all types of problems. The judgment of optimum mesh density, however, would emerge after experience.
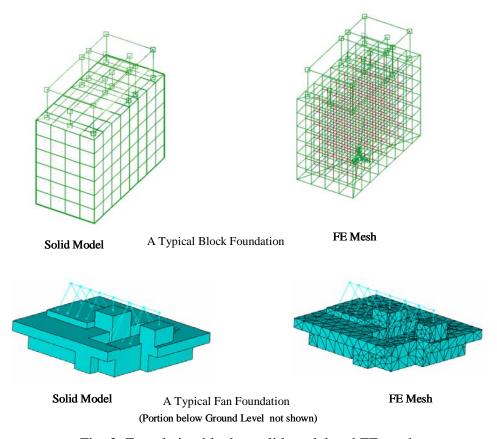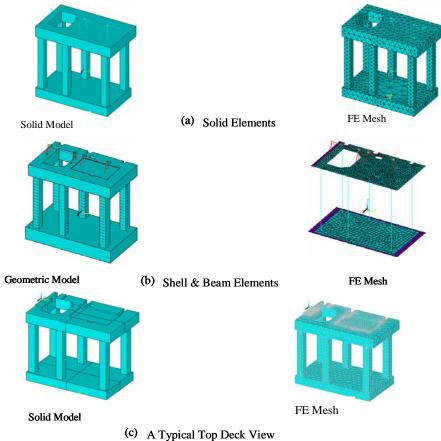

Solid Model   A Typical Block Foundation   FE Mesh

Solid Model   A Typical Fan Foundation   FE Mesh
(Portion below Ground Level not shown)

Fig. 3 Foundation block—solid model and FE mesh

Frame Foundation: A frame foundation comprises base raft, set of columns (which is equal to the number of frames), and top deck consisting of (longitudinal and transverse) beams and slabs. The top deck is made of RCC with required openings, depressions, raised pedestals, cutouts, bolt pockets and extended cantilever projections. In certain cases, haunches may also be provided between the columns and the top deck. There are many ways of representing the model of a frame foundation. One can model using the beam elements, shell elements, solid elements, or a combination of all of these. Models with the solid elements as well as beam and shell elements are shown in Figures 4(a) and 4(b) respectively. Each modeling style, however, will have associated limitations. For example, while modeling using the solid elements, one may not be able to get the bending moments and shear forces in the columns, beams and slabs, which are needed for the structural design of these members. When it is possible to get the bending moments and shear forces in the flexural members like beams, columns, slabs, etc., the modeling would not permit inclusion of the effects like haunches, depressions, cut-outs, raised blocks, projections, etc., as shown in Figure 4(c). It may be noted that a FE mesh of frame foundation with all the openings, pockets, cutouts, notches, etc., though feasible, is basically undesirable. It may unnecessarily add to the problem size and, thereby, to the computational time without any significant gain in the results. Only those elements that contribute significantly to the stiffness and mass, like large openings, sizeable depressions, etc., must be accounted for and modeled in detail, whereas the elements like pockets, small notches, etc. could easily be ignored while modeling. Since modeling of the top deck and base raft by the shell element is done at their mid-surface locations, it usually results in increased column heights, thus making the system more flexible than the prototype. Necessary modifications therefore are necessary to overcome this deficiency. Similar is the case while modeling the machine. Use of the rigid links is recommended to cover up such deficiencies. Here again, a coarse mesh for the foundation in general, and relatively finer mesh in the vicinity of openings, depressions, raised pedestals, pockets, and cutouts is considered adequate. The judgment of optimum mesh density, however, would emerge only after experience.

Solid Model   (a)   Solid Elements   FE Mesh

Geometric Model   (b)   Shell & Beam Elements   FE Mesh

Solid Model   FE Mesh

(c)   A Typical Top Deck View
Openings, notches, cutouts, pockets etc.

Fig. 4 Frame foundation—solid element model and shell-beam model
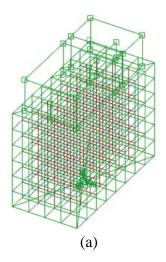
2.3 Soil

2.3.1 Soil Modeling

Use of the FE analysis has become the state of art for the design of machine foundations. There are many ways of mathematical representation of the soil. We limit our discussion here only to two ways that are common in the design office practices for the FE analysis and design of foundations.

<u>Soil Represented by a Set of Equivalent Springs</u>: Two types of representations are commonly used in the FE modeling of the foundation:

a) The soil is represented by a set of three translational springs and three rotational springs, attached at the CG of the base, as shown in Figure 5(a). This kind of representation yields results (i.e., frequencies and amplitudes) that are found to be in close agreement with the manual computations (Barkan, 1962; Bhatia, 1981, 2006, 2008; Prakash and Puri, 1988).

b) The soil is represented by a set of three translational springs, attached at each node at the base of the foundation in contact with the soil, as shown in Figure 5(b). This kind of representation provides an upper bound to the overall rotational stiffness offered by the soil about the X-, Y-, and Z-axes (Bhatia, 2008).

<u>Soil Represented as Continuum</u>: Soil domain in true sense is an infinite domain, and for analysis purposes, it becomes necessary to confine it to a finite domain when soil is considered as continuum (Bhatia, 2008; Prakash, 1981). The broad issues that need to be addressed are

a) the extent of the soil domain to be considered for the modeling; and

b) whether to consider soil domain only below the foundation base (in which case the foundation is not embedded) or to consider the foundation embedded into the soil domain.
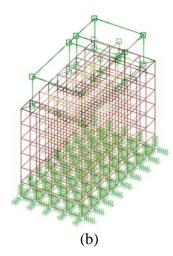
(a)   (b)

Fig. 5 Various methods of soil representation for FE modeling: (a) soil represented by a set of three translational springs, k_x, k_y, k_z, and three rotational springs, k_θ, k_ψ, k_ϕ, applied at the CG of the base of the foundation; (b) soil represented by a set of three translational springs, k_x, k_y, k_z, applied at each node in contact with the soil at the foundation base

2.3.2 Extent of Soil Domain

For FE modeling, it is well known that a narrow domain with fixed boundaries is not likely to represent a realistic soil behaviour, whereas a very large domain would result in an increased problem size. It is, therefore, necessary to find an optimum value that reflects the realistic behaviour of soil without significant loss in accuracy. Different designers adopt their own practices based on the rule of thumb, while deciding on the extent of soil domain to be modeled with the foundation. The extent of soil domain has been found to vary from three to eight times the width of the foundation, to be provided on all the five sides of the foundation. It is to be noted that such a consideration is good enough for academic purposes only. In a real industrial situation, no foundation could remain isolated from other equipment/structure foundations within this finite soil domain. In other words, many other equipment/structure foundations would exist within the range of three to eight times the dimension of the foundation in each *X*-, *Y*-, and *Z*-direction. Thus, in the author's opinion, the computed behaviour of a foundation as a stand-alone foundation is likely to differ with the actual one. It is also true that the modeling of all the equipment and structure foundations of a project in one single go is neither feasible nor necessary (Bhatia, 2008). Here too, a mesh consisting of the solid elements is good enough. As the soil domain is very large compared to the foundation, a relatively coarser mesh of the soil is considered to be adequate. Refinement of the mesh size may be adopted, if considered necessary, for specific cases. The choice of element size remains subjective.

The precise decision on the extent of soil domain still remains a question mark. Even the academicians have provided no definite answer to this issue. It is also true that a practicing engineer, in view of his/her tight time schedule, can neither afford to search for the optimum domain size nor ignore the problem. In the author's considered opinion, soil domain equal to three to five times the lateral dimensions in plan on either side of the foundation and five times along the depth should work out to be reasonably good. The finite soil domain is modeled along with the foundation block using the FE idealization. Appropriate soil properties in terms of the elastic modulus/shear modulus and Poisson's ratio are assigned to the soil. If the soil profile indicates the presence of layered media, appropriate soil properties are assigned to the respective soil layers, with variation in soil properties along the length, width, and depth of the soil domain.

2.3.3 Unembedded and Embedded Foundations

While modeling soil along with the foundation, two cases arise:

i)   Soil domain is modeled below the foundation up to three to five times the width of the foundation along the length, breadth, and depth of the foundation. This makes the foundation not embedded into the soil, as shown in Figure 6(a).

ii) Soil domain is modeled right from the ground level encompassing the foundation up to three to five times the width of the foundation along the length, breadth, and depth of the foundation. This makes the foundation embedded into the soil, which is a realistic situation. This representation is shown in Figure 6(b).
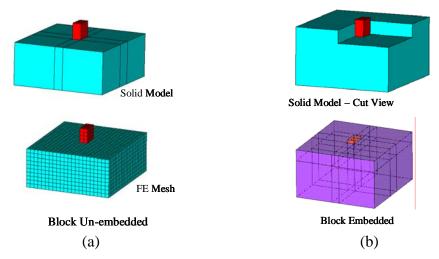

Fig. 6 Various methods of soil representation for FE modeling: (a) soil represented by a continuum below the foundation base, extending three times the width of the foundation along the length and the width and five times the depth of the foundation along the depth; (b) soil represented by a continuum starting from the ground level, extending three times the width of the foundation along the length and the width and five times the depth of the foundation along the depth

To investigate as to how each method of soil representation compares with others, free-vibration analysis of a typical block foundation is performed using each method of soil representation having same/compatible soil properties (Bhatia, 2008):

- Case-1: The soil is represented by a set of six springs attached at the CG of the base of the foundation.
- Case-2: The soil is represented by a set of three springs attached at each node in contact with the soil at the base of the foundation. In total 45 nodes are considered in contact with the soil. Translational stiffness at each node is therefore 1/45 of k_x, k_y, k_z as given above.
- Case-3: The soil is represented as continuum below the foundation base level, i.e., the foundation is not embedded. The soil domain considered is 10 m on all the five sides of the foundation.
- Case-4: The soil is represented as continuum right from the ground level all around the foundation, i.e., the foundation is embedded. Here again, the soil domain considered is 10 m on all the four sides (in plan) of the foundation. The ground level is considered at 0.75 m below the top of the block. The soil domain along depth is taken as (10 + 3 =) 13 m from the ground level.

    The data considered is as under:
- foundation block dimensions (along the *Z*-, *X*-, *Y*-axes): $4 \times 2 \times 3.75$ m;
- coefficient of uniform compression: $C_u = 4.48 \times 10^4$ kN/m³;
- soil spring stiffness (translational): $k_y = 35.84 \times 10^4$ kN/m, $k_x = k_z = 17.97 \times 10^4$ kN/m;
- soil spring stiffness (rotational): $k_\theta = 95.5 \times 10^4$ kN-m/rad (about the *X*-axis), $k_\psi = 44.8 \times 10^4$ kN-m/rad (about the *Y*-axis), $k_\phi = 23.9 \times 10^4$ kN-m/rad (about the *Z*-axis);
- $\rho_{soil} = 1.8$ t/m³, $\nu_{soil} = 0.33$, $E_{soil} = 89{,}218$ kN/m²; and
- $\rho_{conc} = 2.5$ t/m³; $\nu_{conc} = 0.15$; $E_{conc} = 2 \times 10^7$ kN/m².

    Modal frequencies are listed in Table 1. The comparison reveals interesting observations as follows:

a) The translational mode frequencies for Case-3 and Case-4, i.e., when soil is considered as continuum, are much lower than those obtained for Case-1 and Case-2.

b) Discrepancies in rotational frequencies of Case-3 and Case-4 are also significant in comparison with those of Case-1 and Case-2.

c) For Case-2, both linear as well as rotational frequencies are marginally lower than those for Case-1.

For block foundations, since soil flexibility is a controlling parameter that governs the response of the foundation, the author recommends only the use of modeling as in Case-1 and Case-2. In view of the above observations, modeling of soil as continuum is not recommended for the block foundations. Designers, however, may take their own need-based decisions.

Table 1: Modal Frequencies (in Hz)

	Soil Representation Type	**Predominant Mode Direction**					
		X	**Y**	**Z**	**Θ_X**	**Θ_Y**	**Θ_Z**
1	Soil represented by six springs (three linear and three rotational) at the CG of the foundation base	15.4	10.9	15	5.6	9.4	3.62
2	Soil represented by three equivalent linear springs at the foundation base at each node in contact with the soil	15.2	11	14	4.9	8.9	3.24
3	Soil continuum—foundation considered as not embedded	5.16	6.8	6.1	7	7.6	6.97
4	Soil continuum—foundation considered as embedded	6.52	5.96	6.3	7	7.3	7.23

Whichever modeling criteria are finally chosen by the designer, it is strongly recommended that validation of the FE results with the manual computations must be done for very simple problems using the same modeling criteria, before those are adopted for the actual design. Such a caution is essential as one often tends to feel that whatever results are obtained by using a computer code are bound to be correct.

PARAMETERS INFLUENCING VIBRATION

Foundation parameters that influence the vibrations of a machine-foundation system are mainly (i) overall foundation size, (ii) depth of embedment, (iii) sizes of the foundation members like columns, beam, deck slab, cantilever projections, etc., (iv) dynamic soil parameters or dynamic soil-pile properties, and (v) dynamic forces, both internally generated as well as externally applied. The three constituents, viz., machine, foundation and soil, contribute to the frequencies of the system. When the system is subjected to dynamic forces (whether internally generated, externally applied, or transmitted through the soil), we get response of the system. If the response is well within the prescribed limits, it is fine; otherwise, it calls for modifications in the system till the response achieved becomes satisfactory. Such a statement is qualitative and its implementation requires complete knowledge of each constituent and experience to precisely identify the modification. At the design stage it is possible to play with the parameters of each constituent to bring down the response under the control limits. However, if such a check/modification is not implemented at the design stage, it may not be that simple to apply desired modifications after the foundation is cast and the machine is placed in position. In either case it may be desirable to know the uncertainties associated with each constituent before one even attempts the design or its modification. An effort is made to broadly identify these uncertainties and address those as given below.

1. Uncertainties Associated with Soil Parameters

There are two distinct types of uncertainties: (i) those associated with the evaluation of dynamic soil parameters; and (ii) those associated with the modeling of soil.

1.1 Dynamic Soil Parameters

It is seen very often that there is a marked variation in the evaluated soil data when evaluation is done by different agencies (Bhatia, 2008). It becomes extremely difficult to precisely choose design dynamic

soil properties from the so-called soil evaluation reports. Such a scenario is practically true for every project site. Level of uncertainty becomes even higher when selecting the dynamic stiffness properties of a group of piles, for application to a machine-foundation system, from the single-pile test. This aspect of soil is also not quantifiable from the point of view of the machine-foundation design. For the design purposes, the author therefore recommends that higher frequency margins of the foundation be kept vis-à-vis the machine operating speed.

1.2 Soil Mass Participation

It is a reality that part of the soil mass vibrates along with the foundation (Barkan, 1962; Bhatia, 2006, 2008; Bhatia and Sinha, 1977; Prakash and Puri, 1988). Some of the issues that need to be addressed are as follows:

- What is the extent of the soil that vibrates with the foundation?
- Does the vibrating soil mass depend upon the mode of vibration?
- Does it have any influence on the soil stiffness and damping?
- Can these aspects be quantified?

There are various opinions expressed by different authors regarding the soil mass participation. According to some, the mass of the soil moving with the foundation varies with the dead load, exciting force, base contact area, mode of vibration, and the type of soil. According to other authors, the size of the participating mass of soil is related to a bulb-shaped stress distribution curve under the effect of uniformly distributed load. Till date no concrete formulation is available giving quantification of the soil mass participation for different types of soils, and what is lacking is perhaps the validation of the results. It is generally the view that soil mass participation will increase the overall effective mass of the machine-foundation system and will thereby tend to reduce the natural frequency. Here again, this aspect of soil is not quantifiable from the point of view of machine-foundation design. For the design purposes, the author therefore recommends (Bhatia, 2008):

a) for under-tuned foundations, soil mass participation to be ignored; and
b) for over-tuned foundations, frequency margin to be increased by additional 5%, i.e., natural frequencies to be kept away from the operating speed by 25% instead of the normal 20%.

1.3 Effect of Embedment

All machine foundations are invariably embedded partly into the ground. Many authors have studied this effect and have made varying observations (Barkan, 1962; Bhatia, 2008; Prakash, 1981; Richart et al., 1970; Srinivasulu and Vaidyanathan, 1980; Swami, 1999). Some have reported that embedment causes an increase in the natural frequency, and some have reported that it causes a reduction in amplitudes. By and large, it has been generally agreed that embedment tends to reduce the dynamic amplitudes. The reduction in the amplitudes could be on account of change in stiffness, change in damping, change in soil mass participation, or their combinations. Here again, this aspect of soil is not quantifiable from the point of view of machine-foundation design for all types of soils. For design purposes, the author recommends that it will be on the safe side to ignore the embedment effect while computing the dynamic response.

1.4 Soil Damping

Damping is an inherent property of soil and its influence on forced vibration response is significant during the resonance or near-resonance conditions (Barkan, 1962; Bhatia, 2008; Richart et al., 1970). Different soils exhibit different damping properties, depending upon their soil composition and other characteristic parameters. In the case of embedded foundations, the depth of embedment also influences the damping properties. Soil damping comprises (a) geometrical damping, and (b) material damping. While geometrical damping represents the energy radiated away from the foundation, material damping represents the energy lost within the soil due to the hysteretic effects.

In the context of machine-foundation design, the contribution of geometrical damping to rocking modes of vibration has been reported to be of low order compared to the translational and torsional modes of vibration. Damping in the soil has been observed to be both strain- and frequency-dependent. Same soil exhibits different damping characteristics at different strain levels and similar is the variation with the frequency of excitation. In other words, soil damping not only depends upon the stress, strain, or contact pressure distribution but also on the frequency of vibration. Representation of frequency-dependent soil damping has not found appropriate place in the design industry for real-life design problems (Bhatia,

2008). On the other hand, representation in the form of equivalent viscous damping has found larger acceptability.

It has to be remembered that damping plays a role only during resonance. If one is able to avoid the resonance of foundation with the machine excitation frequencies at the design stage itself, the significance of damping could be felt only during the transient resonance. In the author's opinion, considering strain- and frequency-dependent geometrical or radiation damping in design office practices is not only difficult but inconvenient too. The commonly available mathematical tools with the industry, in general, are not geared to accommodate this type of damping. Further, the use of high-end analytical tools is not recommended for design purposes in view of tight project schedules. In the absence of any specified data for the damping value of a site, the damping coefficient equal to 8% to 10%, i.e., $\zeta = 0.08$ to 0.1 could safely be considered for computing the response at resonance.

2. Uncertainties Associated with Foundation Parameters

Elastic Modulus: The basic question is whether to use the static elastic modulus or dynamic elastic modulus of concrete for design. Some authors and codes of practices recommend the use of dynamic elastic modulus, whereas some suggest the use of static elastic modulus of concrete. The difference is of the order of about 20%. As the dynamic elastic modulus is strain-dependent, and since stresses developed in the foundation during the normal operating conditions are relatively of lower order of magnitude, the author recommends the use of static elastic modulus for dynamic analysis and design (Bhatia, 2008).

Cold Joints, Cracks at Beam Column Interface and Honeycombs: At times cold joints and honeycombs are encountered in the super-structure of a frame foundation. In addition, cracks have also been witnessed at the beam-column interface. Such cracks have a tendency to result in lower stiffness and thereby lower frequencies. Epoxy or cement grout is used for the repair of such cracks. Loss of stiffness on account of this phenomenon is well known but this still remains unquantifiable. In view of this uncertainty, it is recommended to keep slightly higher margins for the over-tuned foundations.

3. Uncertainties Associated with Machine Parameters

Dynamic forces furnished by machine suppliers, at times, contain a fictitious multiplying factor that results in very large dynamic forces (Barkan, 1962; Bhatia, 2006, 2008). This not only makes the life of designer miserable but also adversely affects the reliability of design. It is, therefore, desirable for the designer to evaluate the dynamic forces in line with the balance quality grade of the rotor and to cross-check the same with the given machine data. In addition, phase angle of the dynamic forces pertaining to different rotors may be 180^0 degree out of phase as shown in Figure 7.

When the forces are 180^0 out of phase, i.e., $\phi_1 = \phi$ and $\phi_2 = 180 - \phi$, the total maximum reaction along the *Y*-axis will be $F_{1y} - F_{2y} = F_1 - F_2$ (for $\sin\phi = 1$), and the total maximum reaction along the *X*-axis will also be $F_{1x} - F_{2x} = F_1 - F_2$ (for $\cos\phi = 1$). In addition, the unbalance forces will give rise to two couples with reference to the moment at any point, say at Bearing 1 (at the distance *a*, along the *Z*-axis, from the center of Rotor 1). The maximum value of this moment about the *Y*-axis is $M_\psi = F_{2x}(L + a) - F_{1x}a$ and about the *X*-axis is $M_\theta = F_{2y}(L + a) - F_{1y}a$.

This phenomenon is common to practically most of the machines. Thus, the rotational modes of vibration of the foundation get excited and may significantly contribute to the enhanced response. Thus, it is clear that though the generated unbalance forces have components only in the *X*- and *Y*-directions, these will also generate moments about the *Y*- and *X*-axes. Hence it becomes obvious that it is not enough to compute amplitudes for the vibration modes in the *Y*- and *X*-translations; amplitudes must also be computed for the rocking (about the *X*-axis) as well as the torsional modes (about the *Y*-axis) for the moments thus generated.

VIBRATION ISOLATION SYSTEM

In machine-foundation design, the term 'isolation' refers to a reduction in the transmission of vibration from machine to the foundation and vice-versa. In other words, it means control of transmission of dynamic forces from machine to the foundation, and thereby to the adjoining structures and equipment,

or from the adjoining structures and equipment to the machine through its foundation (Bhatia, 2008; Bhatia and Sinha, 1977; Prakash, 1981; Singh and Bhatia, 1989; Srinivasulu and Vaidyanathan, 1980).
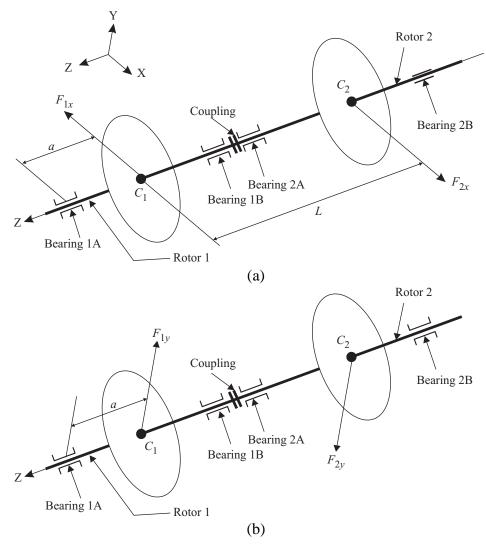

Fig. 7 Machine having two rotors with unbalanced forces out of phase in each rotor: (a) *X*-component of unbalanced force 180^0 out of phase; (b) *Y*-component of unbalanced force 180^0 out of phase

Principle of Isolation: Whether dynamic excitation is applied at the mass and the force is transmitted at the base of the foundation, or dynamic excitation is applied at the base of the foundation and the force is transmitted at the mass, the transmitted force should be the least. The ratio of the transmitted force to the excitation force is termed as transmissibility ratio (*TR*). A plot of transmissibility ratio versus frequency ratio is shown in Figure 8.

Isolation Efficiency: Isolation efficiency η is given as $\eta = (1-TR)$. It is clear from this equation that lesser the transmissibility ratio, better is the isolation efficiency η. A plot of isolation efficiency versus frequency ratio is shown in Figure 9.

Isolation Requirements: Generally speaking, for machine-foundation applications one would be interested in the isolation above 85%; otherwise the very purpose of isolation gets defeated. In view of this, let us view the isolation plot for $\eta > 80\%$, which obviously means that $\beta > 2$, as shown in Figure 9. It is noticed from the plot that even for zero damping, one requires $\beta = 3$ for $\eta = 88\%$ and $\beta = 5$ for $\eta = 96\%$. This gives an impression that one can achieve as high isolation as desired just by increasing the frequency ratio. In reality, this impression, however, does not hold any ground. It is evident from Figure 9 that there is hardly any appreciable gain in η for $\beta > 6$, which corresponds to $\eta = 97\%$. This implies

that one can, at best, aim for the isolation efficiency of about $\eta = 97\%$, knowing that the presence of damping in isolators, if any, shall reflect in a reduction of η. It is obvious that higher the value of η, higher will be β and lower will be the frequency of isolation system, $f\,(=\,\omega/\beta)$. It is also known that lower the value of f, lower will be the stiffness of the isolation system, k, and that this lower stiffness would result in higher static deflection δ under the self-weight of the system. A plot of isolator system frequency versus static deflection of isolator is shown in Figure 10.

Fig. 8 Transmissibility ratio (*TR*) versus frequency ratio (β)
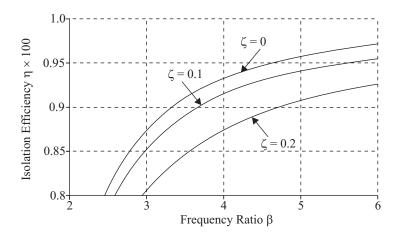
Fig. 9 Isolation efficiency η ($> 80\%$) versus frequency ratio β (> 2)
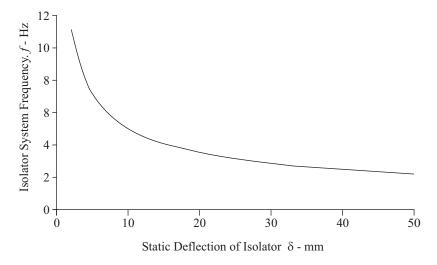
Fig. 10 Isolator system frequency f versus static deflection of isolator unit, δ

Inertia Block: Inertia block, generally made of RCC, is provided to support the machine. It is made heavy enough (with mass two to three times that of the machine) so as to keep the overall centroid in a stable position. It should be rigid enough so as to have its natural frequencies much above the machine speed and its harmonics.

Isolators: These are commercially available devices (as per the required specifications) to be installed between the inertia block and the support system. There are many types of isolators available commercially. We limit our discussions here to only two types: (a) mechanical isolators (spring type with or without damping), and (b) sheet/pad type isolators (cork, rubber sheets, etc).

Selection of Isolator: It is totally dependent on the machine excitation frequency, target isolation efficiency, and the overall mass of machine plus the mass of inertia block. There are many ways one can arrive at the specification for the required isolators. A typical machine system supported on isolators is shown in Figure 11.
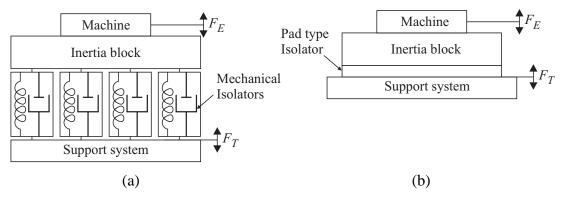

Fig. 11 Machine foundation isolation system: (a) mechanical isolators; (b) sheet/pad type isolators

EARTHQUAKE EFFECTS

Significant damage to machinery has been reported for many earthquake occurrences the world over. Majority of this damage, however, pertains to static electrical/mechanical equipments, and only in rare cases damage is reported for rotating electrical/mechanical equipments. In the context of machine-foundation systems, earthquakes not only influence the foundation but also the machine. Earthquake forces get transmitted from ground to the machines through their foundations.

In the absence of any specific code for earthquake-resistant design of machine-foundation systems, it is recommended to use the provisions of IS 1893 (Part 4) (BIS, 2005). The horizontal seismic coefficient A_h should be computed as per Clause 8.3 of these provisions. Unlike other structures, the author recommends that the vertical seismic coefficient be considered same as the horizontal seismic coefficient in the applications to machine-foundation systems.

Unlike the buildings and structures where ductility plays an important role in bringing down the design seismic coefficient, there is practically no provision for ductility in the design of machine foundation systems. Thus, even controlled damages to the foundations are not permitted. Hence, the seismic coefficient for a machine-foundation system should be computed using the reduction factor $R = 3$, as applicable to the ordinary moment resisting frames (refer Table 3 of IS 1893 (Part 4) (BIS, 2005)). Since the importance factor assigned to a machine varies with the machine functionality or use in the plant cycle, it is recommended to use the same value as that assigned to the industrial structures but not less than 1.5 (refer Table 2 of IS 1893 (Part 4) (BIS, 2005)).

Dynamic interaction between the machines, their foundations, and the soil during the earthquakes is of prime importance. It must be borne in mind that there are no codal provisions to avoid failures of machine-foundation systems during earthquakes. Air gap (or clearance) between the rotor and stator could be as low as 1 to 2 mm and could also be as high as tens of millimeters. The basic objective is that there should not be any rubbing of rotor with the stator. This makes the seismic qualification of machine-foundation systems a shade different from that of the other structural systems. It is recommended to use

the same mathematical model (i.e., the same FE model) as that used for the dynamic analysis of the machine-foundation system under consideration. As mentioned earlier, it must be ensured that the machine is modeled along with the foundation and that its masses are lumped at appropriate centroid locations. It is not only desirable but essential to model the rotor and stator separately. This helps in ensuring the safety against rotor-stator rubbing.

In the event of foundation design requiring structural changes on account of seismic safety, the entire dynamic computations need to be redone. This includes free-vibration analysis, and the analyses for forced-vibration response and transient response, in addition to the analysis for seismic safety.

CONCLUDING REMARKS

This paper is based on the long experience (of about 3 decades) of the author on design, testing and troubleshooting of machine-foundation systems. Salient observations may be made as given below:

1. Generally speaking, machine-foundation design has been associated with the civil engineering discipline. Whether it is a soil specialist or structure specialist, depending upon his/her specialization, the designer studies and analyses all the data connected to his/her specialization and takes the rest of the data as a black box. This is neither desirable nor adequate. This paper recommends a higher level of interaction amongst all the concerned disciplines, which should result in an improved machine performance.

2. The paper highlights various issues related to the mathematical modeling of machine, foundation and soil. The gray areas have been specifically highlighted. The influence of various assumptions and simplifications on the response has also been discussed.

3. From the point of view of dynamic response, limitations of the manual methods of computation have been discussed. It is observed that not only the dynamic behaviour of foundation as a whole but also its elements, viz., beams, columns, pedestals, etc., show strong influence on the machine response.

4. Necessary design aids/methodologies for the modeling and analysis of machine foundations, including various issues related to the mathematical modeling, are provided. Basics of the vibration isolation system for heavy-duty machines are also described.

5. The paper also touches upon the effects of earthquakes on machines as well as on their foundations in view of the reported damages for many industrial systems. Use of commercially available finite element packages, for the analysis and design of foundations, is strongly recommended, but with some caution.

ACKNOWLEDGEMENTS

REFERENCES

1. Barkan, D.D. (1962). "Dynamics of Bases and Foundations", McGraw-Hill Book Company, New York, U.S.A.

2. Bhatia, K.G. (1981). "Soil Structure Interaction Effects on the Response of 210 MW TG Frame Foundation", Proceedings of the International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, St. Louis, U.S.A., Vol. 1, pp. 319–322.

3. Bhatia, K.G. (1984). "Machine Foundation in Power Plant and Other Industries—Case Studies", Proceedings of the International Conference on Case Histories in Geotechnical Engineering, St. Louis, U.S.A., Vol. 2, pp. 775–779.

4. Bhatia, K.G. (2006). "Machine Foundation Design—A State of the Art", Journal of Structural Engineering, SERC, Vol. 33, No. 1, pp. 69–80.

5. Bhatia, K.G. (2008). "Foundations for Industrial Machines—A Handbook for Practising Engineers", D-CAD Publishers, New Delhi.

6. Bhatia, K.G. and Sinha, K.N. (1977). "Effect of Soil-Structure Interaction on the Behaviour of Machine Foundations", Proceedings of the International Symposium on Soil-Structure Interaction, Roorkee, pp. 399–404.

7. BIS (1979). "IS: 2974 (Part IV)-1979—Indian Standard Code of Practice for Design and Construction of Machine Foundations, Part IV: Foundations for Rotary Type Machines of Low Frequency (First Revision)", Bureau of Indian Standards, New Delhi.

8. BIS (1980). "IS: 2974 (Part II)-1980—Indian Standard Code of Practice for Design and Construction of Machine Foundations, Part II: Foundations for Impact Type Machines (Hammer Foundations) (First Revision)", Bureau of Indian Standards, New Delhi.

9. BIS (1982). "IS: 2974 (Part I)-1982—Indian Standard Code of Practice for Design and Construction of Machine Foundations, Part I: Foundation for Reciprocating Type Machines (Second Revision)", Bureau of Indian Standards, New Delhi.

10. BIS (1987). "IS: 2974 (Part 5)-1987—Indian Standard Code of Practice for Design and Construction of Machine Foundations, Part 5: Foundations for Impact Machines other than Hammer (Forging and Stamping Press, Pig Breaker, Drop Crusher and Jolter) (First Revision)", Bureau of Indian Standards, New Delhi.

11. BIS (1992). "IS 2974 (Part 3): 1992—Indian Standard Design and Construction of Machine Foundations—Code of Practice, Part 3: Foundations for Rotary Type Machines (Medium and High Frequency) (Second Revision)", Bureau of Indian Standards, New Delhi.

12. BIS (2005). "IS 1893 (Part 4): 2005—Indian Standard Criteria for Earthquake Resistant Design of Structures, Part 4: Industrial Structures Including Stack-like Structures", Bureau of Indian Standards, New Delhi.

13. Major, A. (1980). "Dynamics in Civil Engineering—Analysis and Design, Vols. I–IV", Akadémiai Kiadó, Budapest, Hungary.

14. Prakash, S. (1981). "Soil Dynamics", McGraw-Hill Book Company, New York, U.S.A.

15. Prakash, S. and Puri, V.K. (1988). "Foundations for Machines: Analysis and Design", John Wiley & Sons, New York, U.S.A.

16. Ramdasa, K., Singh, A.K. and Bhatia, K.G. (1982). "Dynamic Analysis of Frame Foundation Using FEM", Proceedings of the 7th Symposium on Earthquake Engineering, Roorkee, Vol. 1, pp. 411–416.

17. Richart Jr., F.E., Hall Jr., J.R. and Woods, R.D. (1970). "Vibrations of Soils and Foundations", Prentice-Hall, Englewood Cliffs, U.S.A.

18. Singh, A.K. and Bhatia, K.G. (1989). "Base Isolation of Equipment and System", Bulletin of Indian Society of Earthquake Technology, Vol. 26, No. 4, pp. 39–48.

19. Srinivasulu, P. and Vaidyanathan, V. (1980). "Handbook of Machine Foundations", Tata McGraw-Hill Publishing Company, New Delhi.

20. Swami, S. (1999). "Soil Dynamics and Machine Foundation", Galgotia Publications Private Limited, New Delhi.