Analysis and Design of Framed and Block Machine Foundation

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Abstract - **Block machine foundations are used for machines which produce periodic and impulsive forces and which is operating at low speed i.e. low frequency. For Machine of rotating type and operating at high speed i.e. high frequency primarily framed machine foundation type is used. It may not be possible always to use above option for machine foundation due to local condition, in such cases any other system, which can be combination of above systems; can be used as support for machine foundation. Framed machine foundation are becoming of choice because it is space saving. Analysis and design of block and framed machine foundation is carried out manually for high speed rotary machine and their results are compared. For manual calculations MS excel sheets are prepared for both analysis of framed as well as block machine foundations. It is found that moments and forces in framed machine foundation are less than block machine foundation for high speed rotary machines. For manual calculation MS excel sheet prepared which saves time and arithmetic mistakes.**

keywords - **Block machine foundation, Framed machine foundation, Horizontal and vertical dynamic analysis**

I. INTRODUCTION

1.1 GENERAL

Machines are growth engines of the economy. Prime sectors of gross domestic product of country are Agriculture, Manufacturing and Industry, Defense, Electricity, Engineering, Infrastructure, Petroleum products and Chemicals, Pharmaceuticals, Textile, Pulp and Paper, Aviation, Construction, Hospitality etc. Each sector fulfills its demand by use of machine. Machines plays vital role in economy. Automation in every field has accelerated growth of economy which can possible only by use of machines. So the design of machine foundation has prime importance in our economy.

Use of machine since past few decades has been increasing rapidly and it is not only in industrial/rural areas but in small isolated/ rural areas also. Machines are installed in various establishments on large scale. Machines are supported by foundation. For safe operation of machine stable foundation is required. Machine foundation is very important as well as equally expensive component of any industrial set up. For analysis and design of machine foundation very few codes, guidelines, rules are available. Therefore machine foundation analysis and design is being done differently as per knowledge of designer. As far as machine foundation is considered uniformity in analysis and design is less and there are wide ranges of practices being followed in machine foundation analysis and design. Speedy industrial growth and high volume production requirement has increased the size of machines and are becoming huge and also the speed of machine is increasing, consequently dynamic effect of machine is also increasing.

Heavy equipment used in industries and machining tools have wide range of sizes, variable operating speeds, loads and different operating conditions. Hence foundations are designed considering the impulses (shocks) and dynamic loads (vibrations) resulting from operation of the machine. The machine foundation largely designed as thumb rule or done as per previously established design of machine in local area. Hence it is in mind of designer to design the machine foundation as block type foundation. In absence of proper and detailed guideline and procedure designer unnecessarily making machine foundation design heavy this inevitably makes it bulky and sometimes uneconomical. Construction of block type foundation is tedious and due to its heavy mass makes it difficult to modify and has very less space to accommodate other machine or its components.

Analysis and design of machine foundation is different in a way because it includes dynamic loads not only arising from earthquake but loads arise due to machine operation also which works along with static loads. The designer should be well aware about load transmission from machine and also dynamic behavior of supporting media. The analysis and design of machine foundation is complex. This field is not developed compared to development in other branches of engineering and technology. Primarily mechanical or electrical engineer is owner of machine because they design the machine for desired purpose as per requirement. And after that it becomes civil/structural engineer's responsibility to give firm support to machine. For effective use of machine within tolerance limit integrated approach of both civil and mechanical/electrical engineers is required from planning stage to execution stage for satisfactory performance of machine without causing harm to operator and other structural part.

Requirements of machine foundations:-

1. The first and foremost requirement of machine is that the foundation should be able to carry all superimposed load safely to the ground without causing crushing or developing cracks due to shear.
2. Centre of gravity of structure and combined C.G. of machine at plane should be as far as possible in a vertical line.
3. Resonance condition should not occur. Either natural frequency of the system should be much higher or lower than that of operating frequency.
4. The amplitude should be within permissible limit.
5. The settlement should be within limits.

Points to be considered while Planning machine foundation:-
1. The machine foundation should be separated from any building component; this can be achieved by placing expansion point surrounding to component which are adjacent to the machine system. This gap of expansion joint avoid transmission of the vibrations of the system hence proper damping material has to be placed in joint.
2. Machine foundation has to be at lower level than foundation of surrounding structure.

1.2 OBJECTIVES AND SCOPE

Basic objective of design of machine foundation are
1. The Stress on supporting media on which foundation rests should not be more than allowable stress.
2. Foundation has to be designed for Static load, dynamic load in horizontal and vertical direction, Earthquake forces, short-circuit moment, force due temperature change, loads induced due to shrinkage effect.
3. Natural frequency of the system has to be far away from machine operating speed and rotors critical speed.

   The basic criterion to avoid resonance in system is, machine foundation should have natural frequency, either much higher or much lower than that of operating frequency of the machine. Based on relation between natural frequency of system and operating frequency of the machine there are two cases. One is under tuned system and the other is over tuned system.

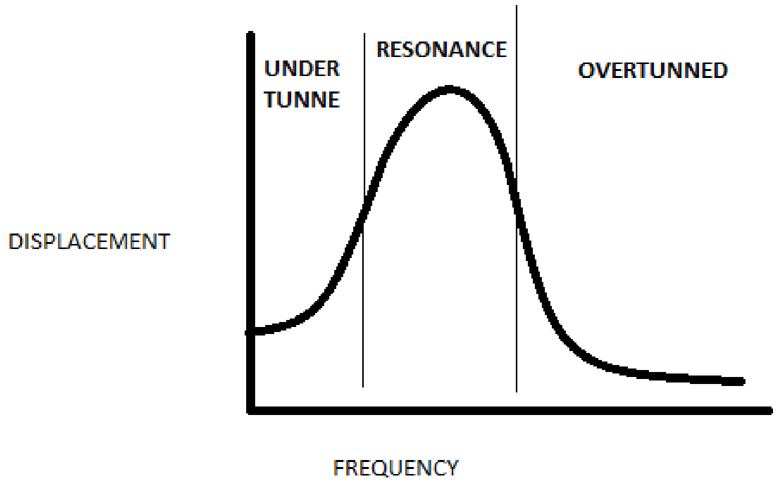

Figure 1: Machine Foundation Tunning

   If we plot frequency in x-axis and displacement in Y axis, typical variation will be as shown in figure 1. Resonance occurs in middle portion as shown in above figure for the frequency. If we keep operating frequency of the machine far away from middle portion, either in first portion or in third machine foundation will be safe. So, we can have very high value of operating frequency than natural frequency or very low value of operating frequency than the natural frequency of the machine and foundation system, to take care of no resonance criteria.
   When natural frequency is less than operating frequency then system is called undertunned.
   When natural frequency is higher than operating frequency then system is called overtunned.
4. The amplitude of vibration should be within prescribed limits for safe operation. Generally the limits of amplitude for famed machine foundation for vibration are 0.02 mm and 0.04 mm for vertical vibration and horizontal vibration respectively for high speed machines. For low speed machine amplitude for vibration are 0.04 mm and 0.07 mm for vertical vibration and horizontal vibration respectively.
5. Any kind of load arising due to eccentric loading of any part on foundation which causes torsional moment in member should be accounted in the machine foundation design.

Following points considered while arriving worst loading combination:
Vertical and horizontal loads do not occur at the same time hence they should not be combined while calculation worst loading combination.

1.3 AIM OF PROJECT

Design of machine foundation includes calculation of various loads transferred by the machine which act simultaneously on foundation, so every load has equal importance while calculation is being done, hence due care has to be taken for evaluation of forces. For any design work basic understanding of various forces acting on design element should be known.

The specific aims of the project are;

1. Analysis and design of framed machine foundation and comparing with block foundation.
2. Analysis and design of block machine foundation and comparing with framed foundation.
3. Developing MS excel sheet for analysis and design of framed and block machine foundation.

II. LITERATURE REVIEW

- **Patel Utkarsh S., Mangukiya Siddharth H., Miyani Ankit L., Patel Hardik A., Vora V., Dr. Sevelia Jigar K.** in their paper on topic "Dynamic Analysis Of Foundation Supporting Rotary Machine", covered study of dynamic behavior of a foundation structure for blower type machine subjected to forces due to operation of the blower. Two different types of foundations block foundation and hollow type foundation for Rotary type blower has been studied in the paper. For modeling they have two configurations. First is hollow block foundation with piles: In this model they have considered hollow block foundation with piles of size 3m X1.2mX 0.6m. They have done rubble filling of 2.8m and width 0.8m. The foundation has been supported by soil spring as per structural subgrade modulus of soil. Second model is table mounted block foundation: This type of model is adopted when good soil strata are available up to great depth below level of foundation. In this model as machine rested on RCC walls. They have done modeling and analysis in commercially available STAAD Pro software package.
- **P.M. Shimpale** and his colleague in the paper covered basic definitions of vibrations, periodic motion, period, cycle, frequency, degrees of freedom etc., types of machine such as block type, box or caisson type , wall type, framed type, non-rigid type etc., general requirements of machine foundations, modeling and result. The paper covers topic to analyze machine foundation subjected to vibrations as Block Type Foundation, Frame Type Foundation using commercially available finite element method Ansys software package.
- **Jayarajan P., Kouzer K.M.** in the paper "Dynamic Analysis Of Turbo-Generator Machine Foundations", have covered a detailed procedure for the finite element modeling of foundation with supporting soil and dynamic analysis of turbo-generator foundations. They have modeled a frame foundation base raft, set of columns and top deck consisting of (longitudinal and transverse) beams and slabs. The top deck is consisting of openings, depressions, raised pedestals, and extended cantilever projections. Conceptual model of a turbine foundation resting on a bottom raft supported by soil is presented in the paper. The super structure is modeled as usual a space frame where the beams and columns are idealized as beam elements having six degrees of freedom at each node. But for modeling a turbine foundation frame there is a difference with normal building frames where the beams and columns are modeled at their center lines. In the case of Turbine foundations , as the columns are of large dimensions (1500-2000mm) and design bending moment in beams are required at the face of columns, the beam column junction consist of three nodes instead of one connected by rigid links. The mathematical model for the superstructure complicated features such as haunches, depressions, raised blocks etc. which increases the problem size without any significant gain in the accuracy of results are avoided. 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. are ignored while modeling. To demonstrate the analysis procedures, an example problem of a turbo-generator foundation is modeled and analyzed on commercially available SAP2000 software which provides effective computational environment to perform various types of analysis.
- **Shamsher Prakash, Vijay K. Puri,** presented paper on "Foundations For Vibrating Machines", in which they have discussed the methods of analysis for determining the response of foundations subjected to vibratory loads. The paper also presents a brief discussion of the predicted and observed response of machine foundations. The paper also presents a brief discussion of the predicted and observed response of machine foundations .Analogs based on the elastic half-space solutions are used for their simplicity. The soil stiffness is considered frequency independent for design of machine foundations. They have discussed types of machine foundations, degrees of freedom of a rigid block foundation in detail as; a) translation along Z axis, b) translation along X axis, c) translation along Y axis, d) rotation about Z axis, e) rotation about X axis f) rotation about Y axis. As per author the problem of a rigid block foundation resting on the ground surface, may therefore be represented in a reasonable manner by a spring-mass-dashpot system. The spring is the equivalent soil spring which represents the elastic resistance of the soil below the base of the foundation. The dashpot represents the energy loss or the damping effect. For coupled modes of vibration, as for combined rocking and sliding, two degree-of-freedom model is used as discussed in the paper.

III. DESIGN METHODOLOGY

Analysis of framed machine foundation:

For the dynamic analysis of framed foundations, there are three methods are available which are, the "resonance method" developed by Rausch in Germany, the "amplitude method" introduced by Barkan in the U.S.S.R. and the "combined method" coined by Major in Hungary. The brief introductions to these three methods are given below. There are advantages and disadvantages to these methods which are discussed as follows.

For dynamic analysis using resonance method, the main necessity is that the foundation including frame system should be out of tune with the machine. This means that the natural frequency of the foundation with its framework should differ by at least 20% from the operating frequency of the machine.

Also it has been noticed that there are various drawback in resonance method as given below.

a. A check on resonance does not guarantee adequate design if, for example, the natural frequency of the foundation is considerably lower than the operating speed (i.e., if the foundation is under-tuned). Actual observations have shown that in case of under- tuned foundations, even though the natural frequency is well away from the operating speed (which means that the resonance conditions would be satisfied) excessive vibration is still noticed every time the machine speed passes through the natural frequency value during acceleration and deceleration stages.

b. It has also been found in some cases that although the natural frequency of the foundation is close to the operating speed of machine (which means that there is theoretically a possibility of resonance), no damage is caused to the foundation. In such cases, although resonance might have occurred, the resulting amplitudes are so small that it does not damage the structure.

C. For the analysis of frequencies, a single spring-mass system is suggested. This is an over-simplification of the real system.

The basic objection to the resonance method is that it does not predict the extent of damage to the foundation, since the determination of amplitudes is omitted. This has led to the adoption of the amplitude method developed by Barkan. to this method, the fundamental requirement is that the amplitude of foundation under forced vibrations should not exceed a certain permissible value. Based on various investigations, different permissible amplitudes are prescribed for different machines.

The method is based on a system with two degrees of freedom, which is an obvious improvement over the resonance method. The method, however, neglects the fact that the amplitudes increase during acceleration and deceleration stages (in case of under-tuned foundations). Actual observations showed that the amplitudes computed by this method are smaller than those actually measured on under-tuned foundations. According In fact, the resonance method and the amplitude method are complimentary. This gave rise to the third method, known as "combined method", also termed the "extended resonance method". According to this method, while the possibility of resonance is investigated, the amplitudes should also be determined. In the case of under-tuned foundations, the maximum dynamic effects that occur during acceleration and deceleration stages are also considered in design.

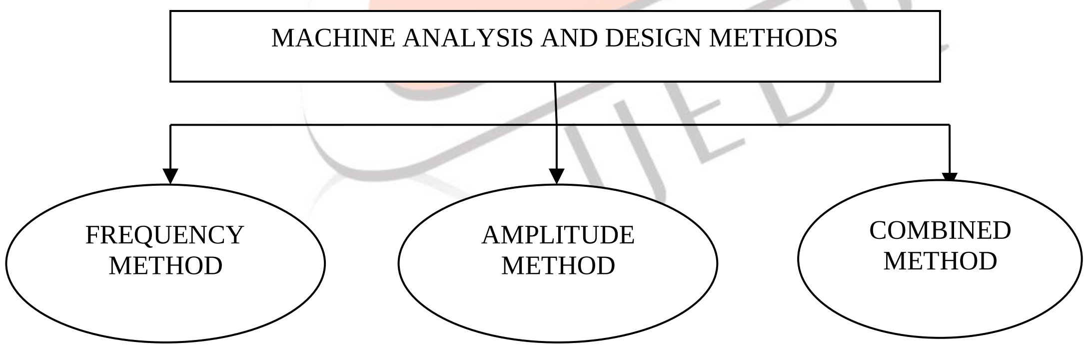

Figure 2: Framed Machine foundation analysis Methods

All the methods mentioned above are shown in figure 2. For purpose of dynamic analysis, each cross-frame of the foundation may be considered independently. It has been found from practical observations that the resonant range of the first natural frequency is wide and this gradually narrows down for the second and higher-order frequencies. This led to the belief that dangerous resonance at higher frequencies is remote and that only the fundamental natural frequency may be considered for checking the occurrence of resonance and for the determination of amplitudes.

Combined method:-

A summary of the various stages in computation based on combined method mentioned above is given in the figure 3.
Loading diagram provided by machine manufacturer or mechanical engineer gives magnitude and point of application of load and its direction including stationary and rotating.

1. Construction loads:- Construction load act only while erection/assembling of machine, the construction loads should not be considered to act with dynamic loads. Construction load are generally taken as uniformly distributed load as 1000kg/m2 to 3000 kg/m2.
2. Dynamic loads:-There are two types of dynamic loads.

a. Periodic load which is developed by rotation of imperfectly balanced rotor

b. Non periodic i.e. irregular loads, these are impulsive shock like in nature. The shock which is in form of couple known as short circuit moments short circuit force=M=RDN/3000 where, R is wt of rotor, D is dia of casing in m, N is frequency of rotation in rpm.

3. Temperature and shrinkage loads:-Differential temperature of 20 degrees assumed between upper slab and raft. For shrinkage of the upper slab relative to base slab a temperature fall of 10 degree c may be assumed.
4. Earthquake force

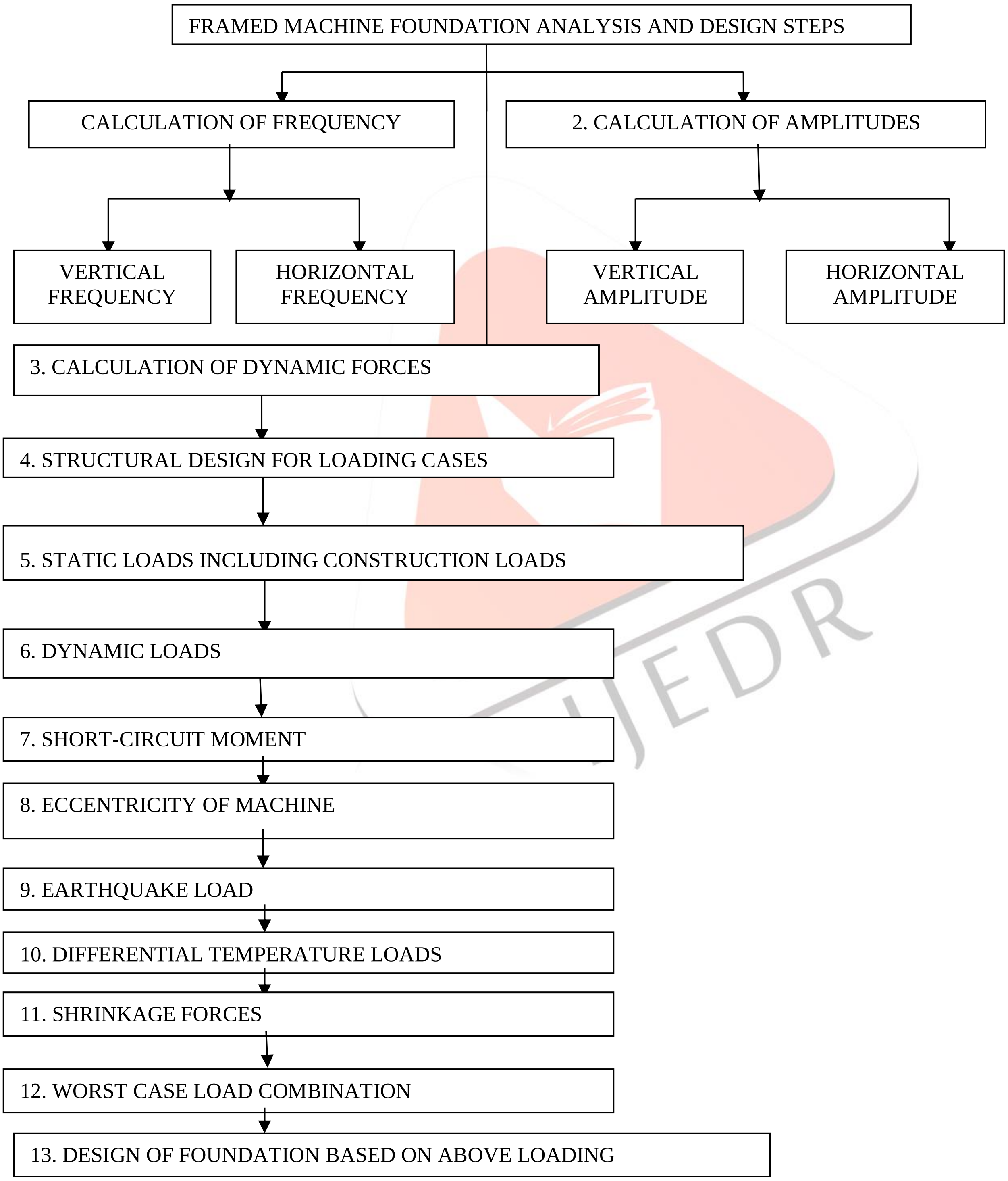

Figure 3: The flowchart of Analysis and Design of framed machine foundation.

For calculation of worst case combinations following points to be considered:-

1. As construction load act only while erection/assembling of machine, the construction loads should not be considered to act with dynamic loads.
2. Vertical and horizontal dynamic loads should not be considered simultaneously.
3. Since the effects of temperature and shrinkage are mutually opposite in nature, they may not be considered together while evaluating the moments.
4. The effect of earthquake and dynamic forces from the machinery may be considered together.

Analysis of block machine foundation

Design Steps:

A) Static analysis

a) Weight of Machine

b) Weight of Foundation Top slab on which machine rests=

Total Static Weight(Wt) = Weight of machine + Weight of Foundation Top slab on which machine rests

Stress Due to structure should be less than Safe stress value of support soil.

Dynamic Load

Horizontal Force= 0.2 *static load

Dynamic moment about at base= Horizontal Force *Height

Calculate Stress at base due to dynamic moment

B) Dynamic Analysis= This foundation is primarily analyzed for vertical vibrations

Calculate Base area provided

Height of assembly

Calculate Effective spring constant kz=

$kz = Cz \times Af$

Af= area of foundation

Cz=Coefficient of elastic uniform compression

Calculate total mass of foundation.

Vertical natural frequency in cpm i.e. cycle per minute =

$$\sqrt{\frac{kz}{m}}$$

Calculate Frequency difference

Frequency difference should be more than 20%

Amplitude Check=

Calculate unbalanced force

$$(P) = \frac{Wt}{g} * St * Wm^2$$

Calculate Dynamic factor

$$\mu = \frac{Fn^2}{Fm^2} - Fn^2$$

Static equivalent force=

$$F = 6 * \mu * p$$

Calculate Amplitude

$$Y = \left(\frac{P}{K}\right) * \mu$$

Amplitude should be less than Amplitude limit 0.5mm

Moment calculations:-

$$Moment = \frac{(Wm \pm FD) * L}{8}$$

Steel requirement calculated from above moments.

IV. DESIGN CALCULATIONS

Analyze and design framed machine foundation for machine which is rotating at 1500 rpm and having weight of 14.715 kN with rotor weight of 4.905kN and supported on 4 legs.

Figure 4 shows top horizontal frame arrangement i.e. plan at top level.

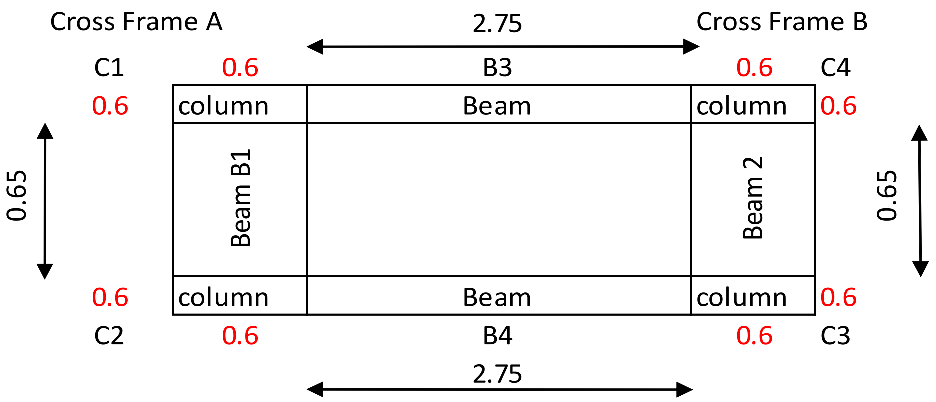

Figure 4: Column and Beam frame arrangement at top level (i.e. Plan at top level).

Framed foundation consists of two cross frames and two longitudinal frame. Beam and column sizes are given in table 1.

Table 1: Beam and column sizes

Beam	Width(m)	Depth(m)	Column	Width(m)	Depth(m)
B1	0.6	0.6	C1	0.6	0.6
B2	0.6	0.6	C2	0.6	0.6
B3	0.6	0.6	C3	0.6	0.6
B4	0.6	0.6	C4	0.6	0.6

Figure 5 shows elevation of beam and column of framed foundation.

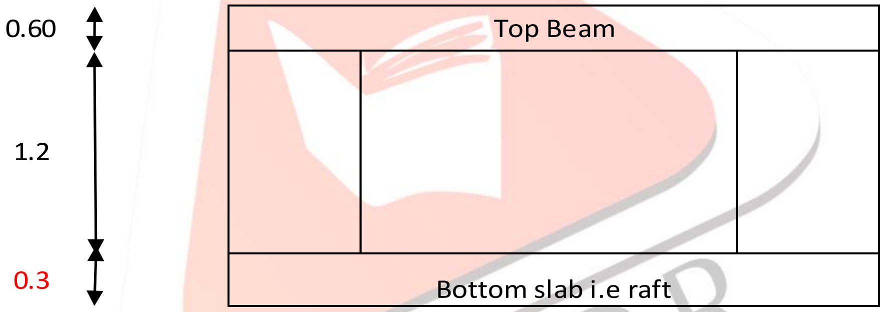

Figure 5: Longitudinal section of framed machine foundation

Figure 6 shows plan at foundation level column of framed foundation.

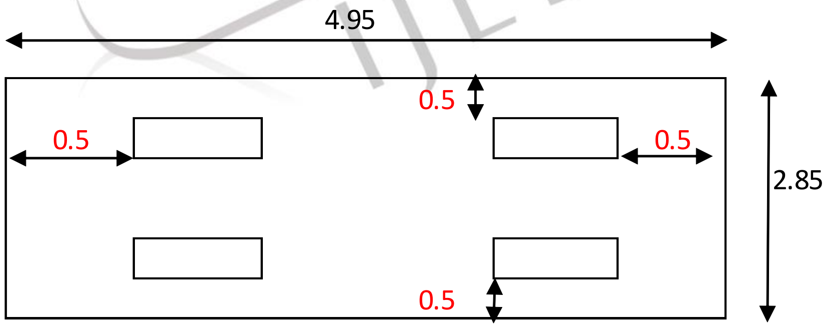

Figure 6: Plan at raft level

Detailed stepwise calculations are carried out as per design methodology mentioned in section III for framed as well as block machine foundation. For block machine foundation size of block is 3.95m X 1.85m and height is 1.8m.

V. RESULTS

Basic objective is to analyse and design block and framed machine foundation and compare their results for high frequency rotating machine and to develop MS excel sheet for Framed and block machine foundation results of which are discussed below

Framed machine foundation

Natural Frequency Calculations:- Vertical Frequencies of cross frames for given machine loading and frame is found as 12266 cpm and horizontal frequency of system 3708cpm which satisfies no resonance condition, as there is difference of more than 20% between machine operating frequency of 1500 rpm and natural frequency of system.

Amplitude Calculations:- Vertical amplitude of the system is found out as 0.06 µm which is well within limit of 40 µm (0.04mm) and horizontal amplitude of 0.46 µm which is within limit of 70 µm (0.07mm) for machines with operating speeds less than 3000rpm.

Figure 7a and 7b shows moment diagram of cross frame ABCD. M_A is moment at end A. M_B is moment at point B and M_P is maximum moment.

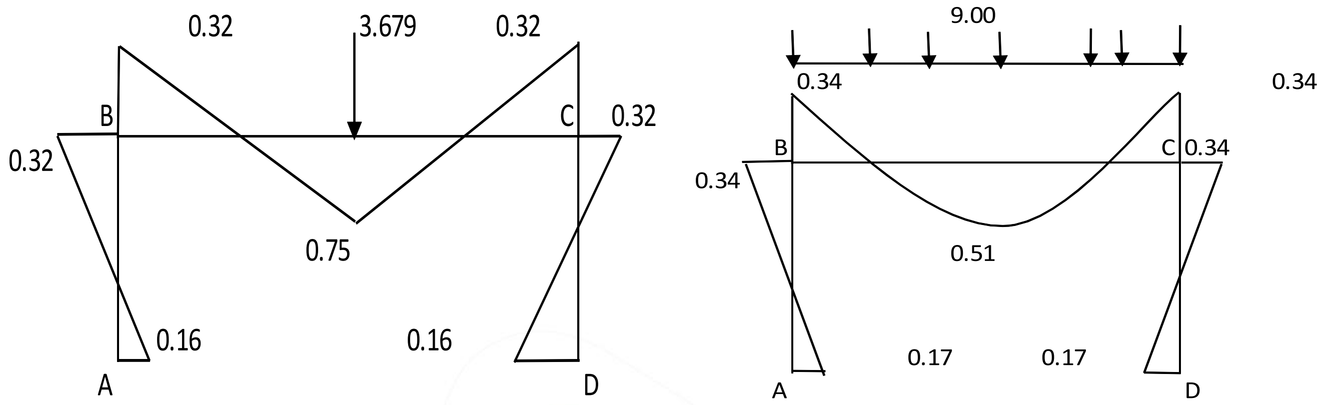

Figure 7 a) Moment diagram due to concentrated static load b) Moment diagram due to uniformly distributed load

Table 2 gives bending moments of cross frames for framed foundation.

Table 2: Bending moments (kNm) of cross frame

sr. no.	Moments due to	M_A	M_B	M_P
1	Concentrated static load	0.160	-0.320	0.750
2	Distributed static load	0.170	-0.340	0.510
3	Vertical dynamic load	±0.220	±0.440	±0.987
4	Horizontal dynamic load	±1.800	±1.420	±0.000
5	Earthquake	±1.870	±1.480	±0.000
6	Differential temperature	81.680	-45.380	-45.380
7	Shrinkage	-40.840	22.690	22.690
	Maximum=	85.680	24.930	24.937
	Minimum=	-44.180	-48.940	-45.107

Table 3 gives bending moments of longitudinal frames for framed foundation.

Table 3: Bending moments (kNm) of longitudinal frame

sr. no.	Moments due to	M_A	M_B	M_P
1a)	Self weight	3.228	-6.455	5.428
1 b)	superimposed loads	0.609	-1.218	1.772
2	Construction loads	2.111	-4.222	3.55
3	Short circuit load	±2.453	±1.226	0.000
4	Longitudinal Dynamic load	±1.131	±0.652	0.000
5	Vertical dynamic load	±0.330	±0.660	±0.940
6	Earthquake load	±1.554	±0.896	0.000
7	Differential temperature	29.381	-9.180	-9.180
8	Shrinkage	-14.691	4.590	4.590
	Maximum=	39.34	-0.30	15.34
	Minimum=	-16.97	-19.64	-5.53

Soil Pressure diagram for machine foundation=

Figures 8 shows pressure distribution diagram for supporting media.

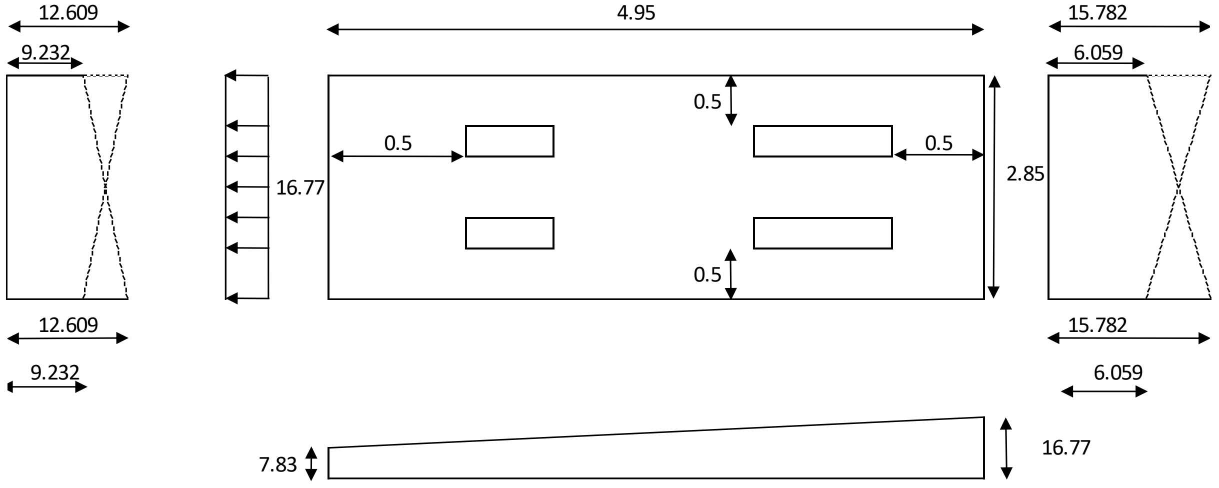

Figure 8: Pressure distribution diagram

Design of Raft
Figure 9 shows loading on raft

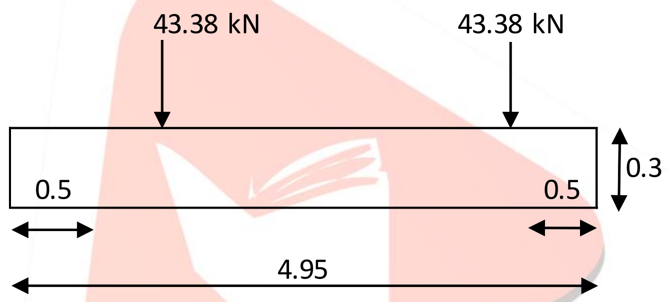

Figure 9: Loading on raft

Block machine foundation
Natural Frequency Calculations: Vertical natural frequency is 64.51 sec-1 and machine Operating frequency is 157.08sec-1 Frequency difference in percentage is 58.93%. As there is difference of more than 20% between machine operating frequency and natural frequency of system hence no resonance occurs.
Amplitude Calculations: Amplitude of the system is found out as 0.027mm which is well within limit of 0.5mm.
Moments Calculations: Moment in longitudinal direction is found as 84.215Knm and in Transverse dir is 179.8Knm.

Moment and forces in block foundation are more than framed machine foundation for given machine. Frequency and amplitudes are well within limit for framed machine foundations and are less than block foundations.

VI. CONCLUSIONS

Though block machine foundations are widely used for machine. Due to availability of commercial software, machine foundations should be modeled and designed as framed machine foundation. While using commercially available software one should not blindly follow the result: manual calculations to be done carefully to avoid any mistakes while using input on software. Calculation of analysis of framed machine foundation manually is tedious task so development of MS excel is very helpful. MS excel is installed on every PC and various applications are freely available for mobile to run MS excel.

1. Moment and forces in block foundation are more than framed machine foundation for given machine. Moment for framed machine foundations is 5.07 kNm while for block foundation is 84.2 kNm. So for high speed rotary machine framed machine foundation should be used. Also soil maximum stress due to foundation for block foundation is 75.4 kN/m^2 and for framed foundation is 16.77 kN/m^2. Soil stresses are more due to block foundation as compared to framed foundation.
2. Frequency and amplitudes are well within limit for framed machine foundations and are less than block foundations. Amplitude of block foundation is 0.027mm i.e. 27 μm and for framed foundation is 0.5 μm. Therefore framed machine foundations are preferred over block foundations for high speed rotary machines.
3. Developed MS excel sheet for analysis and design of framed and block machine foundation makes manual analysis and design easy, saves time as manual calculation on paper takes entire day and with help of MS excel program it takes 2 hours to do manual calculations. It can be used for various weights of rotary machine. Iterations for no resonance and amplitude criteria can be done quickly.

6.2 SCOPE FOR FUTURE WORK

1. Present MS excel is prepared for 2 X2 cross and longitudinal frame. Excel sheet can be extended for 2 longitudinal and 3 cross frame and 2 longitudinal and 3 cross frame and so on.
2. Earthquake forces are calculated from seismic coefficient method. More advanced method can be applied while calculating seismic forces.

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