ANALYSIS FOR DESIGN OF A MACHINE FOUNDATION—A CRITICAL STUDY

A DISSERTATION

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requirements for the award of the degree
of
MASTER OF ENGINEERING
in
EARTHQUAKE ENGINEERING
(Specialization in Soil Dynamics)

By

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the dissertation entitled, " **ANALYSIS FOR DESIGN OF A MACHINE FOUNDATION - A CRITICAL STUDY** ", in partial fulfilment of the requirement for the award of degree of **MASTER OF ENGINEERING IN EARTHQUAKE ENGINEERING (SOIL DYNAMICS)**, submitted in the Department of Earthquqke Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out for a period of about six month in between, September 88' to March 89' under the supervision of Dr. Mani Kant Gupta, Professor, Department of Earthquake Engineering, University of Roorkee, Roorkee, India.

The matter embodied in this dissertation has not been submotted by me for the award of any other degree.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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A C K N O L E D G E M E N T S

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SYNOPSIS

For the design of machine foundations, the resonant frequency or natural frequency of the foundation - soil system and the amplitued fo vibration must be detrermined. A number of empirical and theortical methods are available to detrmine the dynamic response of machine foundations. out of these Two main approaches to this problem have been followed. The first approach is basedon a linear elastikc weight less spring theory (BARKAN'S APPROACH 1962) and second involves dynamic response of a footing resting on the surface of an elastic solid. Based upon theory, simplified Elastic half space analogs have been established by But superiority of one approach over the other is to be investigated.

So to find out the suitability of exact method for analysis of machine foundations comparison of both approaches is carried out with the half of computer programmes for comparison six practical cases have been studied two of these are foundations for low speed rotary machines and other are foundations, Supporting recprocating machines. The conclusion of study is that both method can be used for analysis of machine foundation because no remarkable trends are established in favour of any of the approach depending upon the reliablity of the data of soil dynamic properties satisfying the formulation of the approaches.

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List of Symbols

Symbols	Description
a	dimensionless frequency
A	area of footing
A_ϕ	angular amplitude of rocking vibration
A_ψ	angular amplitude of torsional vibration
Aprm	permissible amplitude of machine foundation
Ax	displacement amplitude of vibration in X, Y Z directions
AH1,AV1	absolute maximum value of amplitudes due to combination of vertical force and rocking moment (X-Z) plane
AH2,AV1	absolute maximum value of amplitudes due to combination of vertical force and rocking moment (Y-Z) plane
Bz	mass ratio for vertical vibration
Bx	mass ratio for horizantal vibration
B_ϕ	inertia ratio for rocking vibration
B_ψ	inertia ratio for torsional vibration
c_a	adhesion between soil and side of footing
c	viscous damping coeffecient
c_c	critical damping coeffecient
Cu	coefficient of uniform compression
C_τ	coefficient of uniform shear
C_ϕ	coefficient of nonuniform compression

C_φ	coefficient of nonuniform shear
ξ_z	damping ratio for vertical vibration
ξ_x	damping ratio for horizantal vibration
ξ_ϕ	damping ratio for rocking vibration
ξ_ψ	damping ratio for torsional vibration
$f_{1,2}$	stiffness and damping functions
fn	undamped natural frequency(hertz)
fnr	tschebotarrioff's reduced natural frequency
fnz	undamped natural frequency in vertical mode(hertz)
fnx,fny	undamped natural frequency in horizatal translational mode(hertz)
$fn\phi$	undamped natural frequency in rocking mode(hertz)
$fn\psi$	undamped natural frequency in torsional mode(hertz)
$fn_{1,2}$(X-Z)	undamped higher and lower coupled natural frequency in coupled sliding and rocking case(X-Z) plane(hertz)
$fn_{1,2}$(Y-Z)	undamped higher and lower coupled natural frequency in coupled sliding and rocking case(Y-Z) plane(hertz)
Ix,Iy,Iz	second moment of area with respect to axis of rotation.
Mmx.Mmy,Mmz	mass moment of Inertia with respect to axis of rotation.
kz	spring constant for vertical motion.
kx,ky	spring constant for horizontal motion.

k_ϕ	spring constant for rotational motion
k_ψ	spring constant for torsional motion.
m	mass of footing and machine
m'	apparent mass
Mx, My, Mz	amplitude of exciting moment about X, Y, and Z direction
r	radius of circular footing
ν	poisson ratio
ρ	mass density of foundation.

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CHAPTER 1

1. INTRODUCTION

Machine foundations which may be subjected to unbalanced dynamic forces and moments by the operation of machines, transmit dynamic loads to the soil below in addition to the static loads due to combined weight of the machine and the foundation. It is the consideration of the dynamic loads that distinguishes a machine foundation from an ordinary foundation and necessitates special design procedures. The foundations for the machines must therefore be designed to ensure stability under the combined effect of static and dynamic loads. For stability machine foundation should meet the following requirements-

For static loads

i) The foundation should be safe against shear failure.

ii) The foundation should not settle excessively.

For dynamic loads

i) There should be no resonance.

ii) The amplitudes of motion at the operating frequencies should not exceed the permissible value.

iii) The design should be such that the natural foundation-soil system will not be whole number multiple of the operating frequency of the machine to avoid resonance at higher harmonics.

iv) Vibration occasioned by the machine operation should not be annoying to person or ~~ur~~ harmful to other precision equipment or machines in the vicinity or to the adjoining structure.

Thus for vibration response of the machine-foundation-soil system,natural frequency and the amplitude are the two most important parameters to be determined from analysis in designing the foundation for any machine.

There are many type of machines and each may require a typical type of machine foundation.For example,for turbines frame type of foundation is more suited to provide enough space to house its accessories. For a reciprocating compressor a simple block type will suffice. Generally a single block type is adopted for reciprocating machines and low speed rotary machine. The basic form of reciprocating machine consists of a piston, piston rod, connecting rod and a crank.The operation of the reciprocating machine or the crank mechanism results in unbalanced force both in the direction of piston motion and perpendicular to it. The magnitude and direction of forces and moments will depend upon the number of cylinders in the machines, their size, piston displacements,and the direction of mounting. In low speed rotary machines, the exciting forces in vertical and horizontal direction generate due to unbalanced mass which has small eccentricity due to fact the axis of rotation and axis of center of mass do not coincide.

The natural frequency of foundation-soil- system is strongly influenced by the mass, depth of embeddment, stiffness and damping property of soil.A number of mathematical model are available to analyse the machine foundation soil system to obtain the natural frequency and amplitude which are used as design criteria.

A number of theoretical methods have been proposed for determination of dynamic response of foundation, resting on the soi surface, Which are as follows

a) empirical method by Pauw (1954)

b) Winkler-Vioget model considered by Barkan (1962)

c) Elastic half space approach by Reissner(1936), Quinlan (1953) and Sung (1953)

d) Simplified elastic half space analogs developed by Hseih(1962), Lysmer (1965)and Richart,Hall and Wood(1970).

e) Complaince-impedece function approach by Gazetas(1983)

The approaches adopted by various investigators to analyse the the embedded foundation can be classified into following categories:

a) Approximate methods,which considers the effect of the soil on the sides of the footing separately and include extension of the elastic half space method for the surface footing (Anandakrishna and Krishnaswamy, 1973;Barnov,1967; Berdugo and Novak, 1972;) and extension of the Barkan's approach by Prakash and Puri (1971,1972).

b) Rigorous methods, which include the finite element method with or without special energy absorbing boundaries (Dasgupta and Rao, 1978; and Lysmer, 1980), and the Boundary integral approach.

Out of these approaches there are two following main approaches which are used frequently.The first involves the Barkan's linear elastic weightless spring theory which assumes that soil can be replaced by linear identical weightless springs and footing rests on the surface of the ground.The second approach is based on the dynamic response of a footing on the surface of an elastic solid.

Scope of this study is to compare the elastic half space analogs with linear elastic weightless spring approach and to find out the superiority of one method over the other through some practical field cases.In computing the response, the analytical procedures have some complex formulae, especially in case of combined sliding and rocking. If large number of cases are to be compared or to be calculated for finding out the response, the computer programmes of these approaches will provide help in simplifying the computation procedure.So to compare these methods six cases of different machine foundations are being considered in present work.Out of these six cases, four cases are of reciprocating machines and two are from low speed rotary machines.After computing the responses in different modes of vibration depending upon the unbalanced exciting forces comparisons are made between natural frequencies and amplitudes in each case.After comparisons of these approaches the conclusion is that both approaches can be used depending upon the reliable data of dynamic soil property.

CHAPTER 2

2. LITERATURE REVIEW

In the past, machine foundations were frequently designed by thumb rule without any analysis of the expected vibration amplitude. For instance, one such design rule called for a machine foundation of a total weight equal to at least three to five times the weight of supported machine(s).

Following the pioneering experimental studies carried out by the German Degbo in the early 1930s,a number of following empirical analyses procedure were developed:

Tschebotarioff (1954) Obtained an approximate correlation between the contact area of the machine foundation and a variable that he termed the 'reduced natural frequency', f_{nr}. The reduced natural frequency is defined as the product of the natural frequency and the square root of the contact pressure.

$$f_{nr} = f_n \ (W/A)^{1/2} \qquad \text{......(2.1)}$$

The correlation may be used to determine the natural frequency (f_n), in terms of the total weight of machine plus foundation (W) and the contact area (A).Since the natural frequency of a machine- foundation-soil system depends upon the rigidity of the soil,it is insufficient to describe the supporting soils simply as sands or plastic clays. It is for this reason that Tschebotarioff's correlation is of rather limited applicability.

Alpan (1961) made use of Tschebotarioff's data to develop an expression for natural frequency, the form of which could also be developed theoretically.

$$f_n = \frac{a}{W^{1/2}} A^{1/4} \quad \text{.....(2.2)}$$

where

f_n is natural frequency in cycles/min.

W is the weight of machine and foundation in kgf

A is contact area in m^2

a = 39,000 for peats

= 69,000 for plastic clays

= 82,000 for sands

= 111,000 for sandstones.

Hertwig, Fruh and Lorenz (1933) developed the concept of a mass of soil,sometimes called an apparent mass which vibrates in sympathy with an oscillating footing.If this concept is incorporated into the expression for natural frequency (W_n) of a mass spring system, the following is obtained for translational modes of vibration

$$W_n^2 = k / (m + m') \qquad \text{......(2.3)}$$

where

k is the appropriate spring constant

m is the mass of machine and footing

m' is the apparent mass of soil

Pauw (1954) developed an analysis considering that the effective zone of soil beneath the vibrating footing is a truncated pyramid extending to infinite depth.The plan shape of this truncated pyramid at any depth z is rectangular with sides ($2c + \alpha z$) and ($2d + \alpha z$) where 2c and 2d are the dimensions of the rectangular footing on which the machine rests. For vertical vibrations the spring constant is determined as the surface load divided by the corresponding elastic surface deflection of the pyramid. The apparent mass is evaluated by equating the kinetic energy of the truncated pyramid to the energy of a mass, the apparent mass, of soil vibrating with an amplitude equal to the surface displacement.

Rao and Nagaraj (1960) have suggested a slight variation to pauw's method. The spring constant k_z is determined by means of pauw's method. The soil participating in the vibration is assumed to be that enclosed within the γ lbf/ft.^{2}

Pressure bulb where γ lbf/ft.^{3} is the unit weight of the soil.

Vertical Vibration

Reissner (1936) developed a solution for the evaluation of the dynamic response of a vibrating center footing on the surface of soil mass, assuming that the soil mass could be represents by an elastic half space,he developed an expression for the vertical displacement (z) of the center of a circular footing (radius r) under vertical force Fo

$$Z = \frac{Fo}{Gr} (f_1 + i f_2) \exp (iwt) \quad \text{.....(2.4)}$$

where

Fo = amplitude of the externally applied force which remains constant as the frequency w varies.

G = shear modulus of the elastic half space

a = wr (f/g)

p = density of the half space material

f1 , f2 = dimension less function of poission's Ratio and frequency ratio)

Shekhter (1998), Sung (1953), Quinlan (1953) and Arnold, Bycroft and Warburton (1955),extended the work of Reissner who developed expressions for the center and average footing displacement with three assumed constant stress distributions. These three stress distributions were

(a) Uniform, as assumed by Reissner

(b) Parabolic with zero stress at circumference of the footing

(c) Rigid base, the same as that obtained for purely static loading of rigid footing.

It was found that the dynamic responses were different for the three assumed stress distributions. The maximum amplitude increased and the resonant frequency decreased as the load tends to become more concentrated near the center of footing.

Hsieh (1962) developed a solution for the vibration response of a rigid circular footing on an elastic half space, based upon the work of Reissner and Arnold. Bycroft and Warburton first considered the vibration of a weight less circular disk and then developed the equation of motion for a footing having a total mass m considering vertical vibration.

$$m\ddot{z} + (G\rho)^{1/2} r^2 F2 \dot{z} + G r F1 z = Fo \exp(iwt) \quad ..(2.5)$$

Which is identical in form to equation of motion for a damped mass spring system.

Awojobi and Grootenhuis (1965) and Robertson (1966) presented a dynamic solution by means of integral equations.Awojobi and Grootenhuis solution has been presented for a zero value poission's ratio. For other value of poissons'ratio they have presented an approximate solution which they acknowledge in satisfactory only for small values of the frequency factor a the Robertson solution is in he form of a power series which in applicable for values of the frequency factor,(a) less than unity.

Lysmer and Richart (1966) have shown that the elastic half space model behaves similarly to a damped mass spring system. They developed a equation of motion for vertical vibration. From which it can be recognized that

$$\text{damping coefficient } c_z = \{3.4r^2(G\ )^{1/2}\}/(1-v) \quad ..(2.6)$$

$$\text{spring constant } k_z = 4Gr/(1-v) \quad ..(2.7)$$

Barkan (1962) developed another expression for the spring Constant which is given by the following equation

$k_x = Cu\ A$ ..(2.8)

where

Cu is the coefficient of elastic uniform compression, A area of circular footing.

<u>Horizontal Sliding Vibration</u>

Hall (1967) has demonstrated that if the motion is described by a mass spring dashpot analogy, a solution in approximate agreement with the half space solution may be obtained.

Arnold, Byocraft and Warburton (1955) and Bycroft (1956) presented the solution for the horizontal translation of a rigid circular disk on an elastic half spaces. Based upon these solution **Hseish** developed a solution which he expressed in the form given in equation (2.5)

Gladwell(1968) has developed a dynamic solution to the equation of motion for a weightless rigid circular footing resting on an elastic solid, in which the assumption of stress distribution beneath the footing did not here to be mode. The solution was carried out by means of integral equations and has been presented in power series.

Bycroft (1956) has developed an expressions for the spring constant for studing motion to be used with the lumped parameter model.

$$K_x = \frac{32\ (1-2)\ Gr}{(7-8v)} \qquad ..(2.9)$$

Barkan (1962) has also developed an expressions for spring constant for sliding vibration as follows.

$$K_x = C_\tau A. \qquad ..(2.10)$$

Where C is the coefficient of elastic uniform shear

Barkan has found experimentally that the ratio of cu to C_τ that is,the coefficient uniform shear varies from 1.22 to 2.40 for design calculation he has tentatively suggests a value of 2.

Rocking vibration

Arnold, Bycroft & Warburton (1955) & Bycroft (1956) have developed is solution for the purely rocking vibration of rigid circular footing resting upon an elastic solid in which assume at the stress distribution beneath the footing in same as that produced by corresponding static moment they have expressed angular amplitude of vibration A as follows

$$A = \frac{M}{Gr^3} \left(\frac{f_1^2 + f_2^2}{(1+b'a^2 f_1)^2) + (b\, a^2 f^2)} \right)^{1/2} \quad ..(2.11)$$

b is the inertia ratio defined as $b = I/fr^5$, I is mass moment of inertia of the footing with respect to axis of rotation

f_1 & f_2 are function of poisson's ratio and fequency factor a.

Moore (1975) developed a numerical solution for all values of poisson ratio which involves numerical integration of the expressions given by Arnold Bycroft,& warburton for the angular displacement .

Gladwell(1968) has developed a dynamic solution by mean of integral equations for the vibration of weightless circular footing on the surface of an elastic solid

Hall (1967) has found agreement between the Bycroft half space solution and solution based upon the mass-spring dashpot analogy by using the static spring constant for a rigid circular footing

$$k = \frac{8\,Gr^3}{3\,(1-v)} \qquad ..(2.12)$$

Barkan(1962) has developed an expression for spring constant which he has expressed in the following form

$$K = C_\phi I_\theta \qquad ..(2.13)$$

where

C_ϕ is the coeffeient of elastic non uniform compression

I_θ is the second moment area of the footing about the axis of rotation

Barkan has found experimentally that the ratio of the coeffecient of elastic nonuniform compression (C_ϕ) to the coeffecient of uniform compression (C_u), varies from 1.02 to 2.73 with an average value of about 1.73. **Richart Hall & Woods (1970) and Tstoyich et al.(1947)** suggested that the ratio of Cu to C_ϕ can be assumed equal to 2.

TORSIONAL VIBRATION

Reissner & Sagochi(1944) & Arnold Bycroft and Warburton (1955) have presented solution for the torsional vibration of a rigid circular footing on an elastic half space,in which they assumed,there was a linear variation in displacement from the center to the cirumference of the footing this corresponds to the assumption that the shear stresses varies from zero at the center to infinity at the circumference. **Reissner & sagochi (1944)** have also developed as expression for the spring constant, which may be used in lumped parameter model.

$$K = \frac{16}{3} G r^3 \qquad ..(2.13)$$

Weissmann (1971) has modified the Reissner-Sagochi approach to torsional vibrations by taking slip between the foundation and soil into account. He has developed simplified expressions for determination of resonant frequency and the spring constant

Barkan (1962) developed the expression for spring constant which is given by

$$k = C_\psi J \qquad ..(2.14)$$

where c_ψ in the coefficient of elastic non uniform shear J in the polar moment of inertia of contact area of circular footing.

Coupled Rocking & sliding Vibration

Barkan (1962), who assumed that the foundation soil could be characterized by the coeffecient of elastic non uniform shear,damping being ignore By solving deferent coupled equations of motion he developed following frequency equation

$$w^4 - \frac{I_o(w_\phi^2 + w_x^2)}{I_c} w^2 + \frac{w_\phi^2 w_x^2 I_o}{I_c} = 0 \quad ..(2.15)$$

where

w is the natural frequency of coupled Rocking & sliding vibration

I_0 - mass moment of inertia of machine foundation with respect to axis passing through center of gravity of Base constant area and at right angle to plane of vibration

w_x is natural frequency for purely solving vibration

w_ϕ is the natural frequency for purely rocking vibration

Hall(1967) solved the coupled rocking & sliding vibration response of a rigid circular footing on the surface of soil where which is idealized as an elastic half space. Hall developed a solution in the form of four simultaneous equations.

EFFECT OF FOUNDATION EMBEDMENT

Kaldjian(1969) predicted the effect of embedment on the vertical vibration of circular footing using finite element solution. He presented his solution in terms of the ratio of the spring constant for vertical loading of a rigid footing at the surface. In part of this analysis the sides of the footing were assumed to adhere to the surrounding soil

Lysmer and Kuhlemeyer (1969) carried out a dynamic finite element analysis using an energy absorbing boundary to show the effect of embedment of a rigid circular footing on the response to vertical vibration.

Novak(1970) demonstrated experimentally the effect of embedment on the vertical & horizontal vibration response of circular footing.The results confirm qualitatively the theoretically findings.

Novak and Berdugo (1972) presented an approximate analytical solution for vertical vibration. Their approach is based upon **Barnovs (1967)** assumption that the soil underlying the base of the footing in an elastic half space and independent elastic layers. Expressions were developed for frequency dependent (K_z) & frequency dependent damping coeffecient (C_z) as follows.

$$K_z = Gr \left(C1 + \frac{G_s}{G} \frac{H}{r} S_1 \right) \quad ..(2.16)$$

$$C_z = \frac{Gr}{W} \left(C_2 + \frac{G_s}{G} \frac{H}{r} S_2 \right) \quad ..(2.17)$$

G is the shear modular of the soil beneath the footing

G_s is the shear modular of the back fill or soil layer

f_s is mass density of the side layer soil

r is the radius of footing

H is the depth of embeddment of footing

C_1,C_2 are functions of the dimensionless frequency

S_1 S_2 are function of the dimensionless frequency

Ananandkrishnan & krishnaswamy (1973) developed another analytical solution for the effect of embeddment on vertical vibration response of footing. They used a lumped parameter model and assumed that the force exerted on the vertical sides of embedded footing could be represented by Coulomb friction damping. The parameter used in the model are :

damping coefficient $c_z = \{3.4 r_2 (G)_{1/2}\}/(1-v)$

spring constant $k_z = 4Gr/(1-v)$

natural frequency $w_z = (k_z/m)^{1/2}$

damping ratio $cz/cc = 0.425/((1-v)/4b)^{1/2}$

damping force $F = (0.5\ ko\ H^2 f G \mu_f + CaH) lp$

where

Ko = coeffecient of earth pressure at rest

ρ = mass density of the soil

μ_f = coeffecient of kinematic friction

g = acceleration due to gravity

Ca = adhesion

lp = resistive length of embedded footing

Ramiah et.al (1977) examined the effect of embeddment on vertical vibration response of footings using the Mindlin's equations they developed expressions for stiffness at various embeddment depths.

The level of agreement between observed resonant frequency and amplitude and those predicted by the Ramiah et al. technique in variable and more comparison are necessary while the disagreement between the various theories described above have yet to be resolved,the general trends of the effect of embeddment in increasing resonant frequency & decreasing amplitude clearly established.These general have also been confirmed by experiment observation as there of Gupta(1972), Erden & stoke (1975) saran et al. (1981).

Kaldjian (1971), evaluated the increase in torsional stiffness of circular footing at various depths of embeddment,using an elastic finite element solution and assuming no slip on the contact surfaces.

Novak and Sachs(1973) have examined the case of torsional vibration of embedded footing using similar assumption as those made by Novak and Berdugo(1972) for vertical vibration.

LAYERING AND NON HOMOGENEITY

Awojobi (1972) has developed an approximate solution for the vertical vibration response of a circular footing on the surface of an incompressible soil for which the shear modulus increases with depth with a zero value at the ground surface. He found that the footing response was nearly the same as a footing on an elastic half space with a shear modulus the same as that of the non homogeneous soil at depth equal to the footing radius.

Johnson et al. (1975) and **Chikanagappa (1981)** examined the effects of layer thickness and embeddment depth on the stiffness for various vibration modes using an finite element solution and mindlin's equation respectively. He found that the effects both decreasing layer thickness and increasing depth of embeddment is to raise the stiffness.The vertical vibration response of a circular footing on the

Bycroft (1956) and by **Warburton (1957)**evaluated the surface of an elastic layer which is underlain by rigid base.

They presented curves showing the effects of an elastic layer on the resonant frequency of the footing were presented by Warburton for two values of poisson's ratio.

Gazetas and Rosset (1979) have developed a solution for the vertical vibration response of a strip footing on the surface of linearly hysteric,elastic soil layer overlying rock. The method is based on a direct solution of the wave equation in turn of displacements. the authors found that the presence of a thin layer tends to increase the resonant and amplitude compared with the half space values.

Kagwa and Kraft (1981) examined the effect of soil layering on vertical vibration response by parametric study, in which the soil deposits was idealized by a two layer system, the bottom layer being treated as a half space.

Kreizek et al. (1972) examined the response of embedded strip footing to coupled rocking and sliding vibrations. they used a lumped parameter model to simulate the elastic half space in which the footing is embedded. They found that the resonant frequency increases substantilly as the depth of embedment increases,approximately doubling that for a surface foundation as the foundation becomes enbedded to a depth equal to one half its width. Embedment also significantly decreases the peak vibration amplitude,being about one fourth the value for a surface footing when the foundation is embedded to one half its width.

Beredugo and Novak (1972) developed an approximate analytical solution for the coupled rocking and sliding vibration response of embedded circular footings. They developed expressions for frequency dependent stiffnesses and damping coefficients and after making some simplifications.

Urlich and Kuhlemeyer (1973) developed a finite element solution for the coupled rocking and sliding response of footings embedded in an elastic half space .

lysmer (1978) illustrated the effect of side contact with embedded footing. He found out that complete removal of side contact of an embedded footing the resonance frequency in torsional vibration decreases but the amplitude increases significantly.

Bhaskaran nair (1979) has developed an analytical method for the evaluation of the torsional vibration response of an embedded footing. The considered the internal damping of the soil and assumed that a coulomb frictional fore acted on the contact surfaces of the footing the mathematical model assumed in the analysis and the differential equation of motion is.

$$I_\theta \ddot{\theta} + c_\theta \dot{\theta} + (C_i/w) + k_\theta \theta \pm M_f \Theta = M \cos wt \quad ..(2.17)$$

C_i = internal damping coeffecient

$M_{f\theta}$ = frictional moment

M = amplitude of exciting moment

L = horizontal moment arm of eccentric masses from of rotation

Arnold,Bycroft and Warburton (1955) and Bycroft (1956) examined the effect of layering on the resonant frequency for torsional vibrations. They fond that the presence of rigid boundary underlying an elastic layer produces stiff-ening effect which in creases the resonant frequency and layers also tends to in crease the maximum vibration amplitude of the footing.

Gazetas(1983) developed the concepts which is associated with the definition, physical interpretation and use of the dynamic impedance functions of foundations are elucidated and the available analytical/numerical methods for their evaluation are discussed.Groups of crucial dimensionless problem parameters related to the soil profile and the foun-dation geometry are identified and their effects on the response are studied. Results are presented in the form of simple formulae and dimensionless graphs for both the static and dynamic parts of impedances,pertaining to surface and embedded foundations having circular,srip,rectangular or arbitrary plan shape and supported by three types of idealized soil profiles: the halfspace, the stratum-over-bedrock and the layer-over-halfspace. Consideration is given to the effects of inhomogeneity, anisotropy and non- linearity of soil. The various results are synthesized in a case study referring to the response of two rigid massive foundations, and practical recommendations are made on how to inexpensively predict the response of foundations supported by actual soil deposits.

DISCUSSION

Out of these methods, Simplified Elastic Half Space Analogs and Bakan's approach based on Winkler-Vioget mathematical model are very much popular for design and analysis of machine foundation. In westeren countries elastic half space approach is used for design while in Russia Barkan's approach is popular. In India both approaches are frequently used. but superiority of one approach over the other is debatable.

CHAPTER 3

3. ANALYTICAL APPROACHES

3.1 GENERAL

The comparison of different cases are carried out by the follwing approaches:

i) Elastic Half Space Approach

ii) Linear Elastic Weightless Spring Approach

In the elastic half space method, analog has been established(Richart et al. (1975) as spring dashpot system. Both the spring and dashpot coefficient are defined in terms of the elastic constants of the foundation.

In linear elastic weighhtless spring approach, the analysis may be carried out by a single equivalent mass supported by a perfactly elastic system - the soil being replaced by linear weightless spring. The damping of soil foundation system has been neglected. Such a system has six degree of freedom and has thus six natural frequencies.

3.2 STEP BY STEP FORMULATION OF BOTH APPROACHES ACCORDING TO PROGRAMMES

3.2.1 Elastic half space approach:

This approach is based on following assumptions:

1) soil mass is elastic, homogeneous and isotropic

2) footing is resting on soil surface

3) Base contact area of the footing is circular.

Based on these assumption following are the steps to compute the responses of the foundation.

i)Equivalent radius - Equivalent radius of rectangular foundation can be determined by equalizing the area of the foundation to equivalent area of a circular footing in translation mode. In rocking mode of vibration,for equivalent radius,the moment of inertia of given footing should be same asthat of an equivalent circular footing.so

For translation

$$r_{ox} = r_{oy} = r_{oz} = (A/\pi)^{1/2}$$

For rocking vibration

$$r_{oo} = (4I_x/\pi)^{1/4} \quad \text{or} \quad (4I_y/\pi)^{1/4}$$

For torsional vibration

$$r_o = (2I_z/\pi)^{1/4}$$

ii) Determination of mass ratio, spring constant, and damping factors—these value can be calculated by **table 3.1**

iii) Natural Frequencies and Amplitude of Vibration in Uncoupled Modes

for vertical vibrations

natural frequency

$$w_{nz} = (k_z/m)^{1/2}$$

damped amplitude

$$A_z = P_z/\{k_z[(1-(w/w_{nz})^2)^2)+(2\xi_z w/w_{nz})^2]^{1/2}\}$$

for torsional vibration

natural frequency

$$w_n = (k_\psi/M_{mz})^{1/2}$$

damped amplitude

$$A = M_z/\{k_\psi[(1-(w/w_n)^2)^2)+(2\xi_\psi w/w_n)^2]^{1/2}\}$$

iv) Natural Frequencies and Amplitude of Vibrations in Coupled modes.

sliding natural frequency

$$w_{nx} = (k_x/m)^{1/2}$$

rocking natural frequency

$$w_{n\phi} = (k_\phi/M_{m\phi})^{1/2}$$

Undamped coupled natural frequencies can be obtained by

$$w_{n1,2}^2 = [w_{nx}^2+w_{n\phi}^2 \pm \{(w_{n\phi}^2+w_{nx}^2)^2-4\gamma w_{n\phi}^2\ w_{nx}^2)^{1/2}\}]/(2\gamma)$$

$$\gamma = \frac{m_m}{m_{mo}}$$

Damped Amplitude due to moment M_y

$$A_x = \{M_y\ [(w_{nx}^2)^2+(2\xi_x w_{nx})^2]^{1/2}\}/\{M_m\ \#(w^2)\}$$

Rocking damped amplitude due to moment M_y

$$A_\phi = \{M_y\ [(w_{nx}^2-w^2)^2+(2\xi_x w_{nx} w)^2]^{1/2}\}/\{M_m\ \#(w^2)\}$$

where

$$\#(w^2) = [\{w^4-w^2/\gamma\ (\{w_{n\phi}^2+w_{nx}^2\}-4\xi_x\xi_\phi w_{nx}\ w_{n\phi})\ +w_{nx}^2\ w_{n\phi}^2/\gamma\}^2$$
$$+4(\xi_x w_{nx}\ w/\ (w_{n\phi}^2-w^2)\ +\xi_\phi w_{n\phi}\ w/\gamma(w_{nx}^2-w^2))^2]^{1/2}$$

Damped amplitude for motion occasioned by an applied force P acting at the centre of gravity of the foundation may be obtained from equation

$$A_x=\{P_x/(m\ M_m\ \#w^2)\}\ [(-M_m\ w^2+k_\phi+L^2\ k_x)\ +\ 4w^2\{\xi_\phi(k_\phi\ M_{mo})^{1/2}$$
$$+L^2\xi_x(k_x\ m)^{1/2}\}^2]^{1/2}$$

$$A_\phi=\{P_x L/(M_m\ \#w^2)\}\ \{w_{nx}(w_{nx}^2+4\xi_x w^2)^{1/2}\}$$

Amplitude in Y-Z plane can be find out similarly as in case of X-Z plane.

Table 3.1 Mass or Inertia Ratio B, Damping Factor ξ, and Spring Constant k for Rigid Circular Footing on a Semi-Infinite Elastic Half-Space

Mode of Vibration (1)	Mass (or inertia) ratio (2)	Damping factor (3)	Spring Constant (4)*
Vertical	$B_z = \frac{(1-\nu)}{4}\frac{m}{\rho r_o^3}$	$\xi_z = \frac{0.425}{B_z}$	$k_z = \frac{4Gr_o}{1-\nu}$
Sliding	$B_x = \frac{(7-8\nu)}{32(1-\nu)}\frac{m}{\rho r_o^3}$	$\xi_x = \frac{0.2875}{B_x}$	$k_x = \frac{32(1-\nu)}{7-8\nu} Gr_o$
Rocking	$B_\phi = \frac{3(1-\nu)}{8}\frac{M_{mo}}{\rho r_o^5}$	$\xi_\phi = \frac{0.15}{(1+B_\phi)\sqrt{B_\phi}}$	$k_\phi = \frac{8Gr_o^3}{3(1-\nu)}$
Torsional	$B_\psi = \frac{M_{mz}}{\rho r_o^5}$	$\xi_\psi = \frac{0.5}{1+2B_\psi}$	$k_\psi = \frac{16}{3} Gr_o^3$

3.2.2 LINEAR ELASTIC WEIGHTLESS SPRING APPROACH

In linear elastic weightless spring approach the assumption are as follows -

1. The foundation block is infinitely rigid as compare to the soil.

2. The soil underlying is weightless.

3. The soil can be simulated by linear elastic spring .

4. Damping in the soil beneath a foundation may be neglected.

5. the foundation is resting on the surface of soil.

These assumptions make it possible to represent the foundation soil with an equivalent mass-spring system in which the mass represents the foundation and machine and the spring represents the elasticity of the soil.For different mode of vibration theresponse can be calculated from the following steps-

i) Uncoupled modes. Vertical oscillations and torsional vibrations occur independently of any other vibration. The natural frequencies and corresponding amplitudes can be determined with the help of following equations:

b) rocking natural frequency

$$w_{n\phi} = [(C\phi Iy - WL)/M_{mo}]^{1/2}$$

Where C and Co are coefficients of uniform shear and non-uniform compression respectively and approximatly equal to 0.5 times and 2 times the coefficient of uniform compression.

c) coupled natural frequencies can be determined by following expression:

$$w_{n1,2}{}^2 = [w_{nx}{}^2 + w_{n\phi}{}^2 +- \{(w_{n\phi}{}^2 + w_{nx}{}^2)^2 - 4w_{n\phi}{}^2 w_{nx}{}^2)^{1/2}\}]/(2\gamma)$$

The amplitudes of vibration can be computed with the following equations:

$$Ax = [(C_\tau AL^2 + C\phi I - WL - Mm\ w^2)Fx + (C_\tau AL)My]/\#(w^2)$$

and

$$Ao = [(C_\tau AL)Fx + (C_\tau A - m\ w^2)\ My]/\#(w^2)$$

in which

Ax= linear horizontal amplitude of the combined center of gravity

$A\phi$= the rotational amplitude in radians around the centre of gravity.

Where

$$\#(w^2) = m\ Mm(w_{n1}{}^2 - w^2)\ (w_{n2}{}^2 - w^2)$$

The natural frequencies and amplitude of vibration should be compared with operating speed and permissible amplitudes, respectively, to cheque the foundation size

Vertical vibrations

a) natural frequency

$$w_{nz}=(C_u\ A/m)^{1/2}$$

where Cu is a coefficient of uniform compression and it is determined by following expression:

$$Cu=(2.26G)/\{(1-v)\ (A)^{1/2}\}$$

If area of the foundation is greater than 10 m2, Cu is determined for area equal to 10 m^2.

b) Undamped amplitude

$$Az= Pz/[m(w_{nz}{}^2-w^2)]$$

Torsional vibration

a) natural frequencies

$$w_{n\psi}= \{(C\psi I_z)/M_{mz}\}^{1/2}$$

Where C is the coeffecient of nonuniform shear and equal to 0.75 times the coeffecient of uniform compression.

b) Undamped amplitude

$$A= M_z/[M_{mz}(w_{n\psi}{}^2-w^2)$$

ii) Combined rocking and sliding

Sliding and rocking are coupled mode of vibration. The natural frequencies are determined as follows:

a) sliding natural frequency

$$w_{nx}= (C_\tau A/m)^{1/2}$$

selected is adequate. the natural frequency of the foundation soil system should be at least 30% away from the operating speed of the machine. the amplitude of vibration should be smaller than the limiting values of amplitude specified by manufacturer.

3.3 THE COMPUTER PROGRAMMES

The programme for linear elastic weightless spring approach calculates the undamped natural frequencies and undamped amplitudes of vibration of a rigid-block-type foundation for different modes of vibration. The damped amplitudes can not be calculated by this approach because damping is not considered by Barkàn.But the elastic half space analogs consideres the damping, so the program for this approach calculates not only the natural frequencies and undamped amplitudes but also the damped amplitudes of vibrations of foundation.

In computer programmes there are four following cases-

i) vertical vibrations along Z axis occasioned by a force P_z

ii) torsional vibrations about Z axis occasioned by a moment M_z

iii) translation along X axis and rotation about Y axis, occasioned by a force P_y and a moment M_y

iv) translation along Y axis and rotation about X axis, occasioned by a force P_y and a moment M_x

Each case has two options in which each option calculates the undamped amplitude and damped amplitude repectively.So, the elastic half space analogs' program and the other program of Barkan's approach have eight and four options respectively. The input quantities used in the programs are as following-

W= weight of the foundation block including weight of the machine in tons

A= area of the foundation block in contact with the soil in m2

l= height of the combined centre of gravity of the machine and the foundation above the base in m.

l_x= maximum distance of the point where horizontal amplitude is to be calculated from the axis of rocking and measured parallel to X-axis in m.

l_y= maximum distance of the point where horizontal amplitude is to be calculated from the axis of rocking and measured parallel to Y-axis in m.

R= maximum horizontal distance of the point from Z-axis where horizontal amplitude occasioned by torsional vibration is to be calculated

G= dynamic shear modulus in t/m^2

v= poisson's ratio

I_x= moment of inertia of the area of the foundation about an axis passing through its centroid and parallel to X axis in m^4.

I_y = moment of inertia of the area of the foundation about an axis passing through its centroid and parallel to Y axis in m^4.

I_z = polar moment of inertia about Z-axis in m^4.

M_{mx}= mass moment inertia of the foundation and machine about an axis passing through combined centre of gravity and parallel to Y axis in t-m/sec^2.

M_{my}= mass moment inertia of the foundation and machine about an axis passing through combined centre of gravity and parallel to X axis in t-m/sec^2.

M_{mz}= polar mass moment of inertia of the foundation about a vertical axis passing through its center of gravity (Z-axis) in t-m/sec^2.

P_x= horizontal unbalanced force (X-axis) in tons

P_y= horizontal unbalanced force (Y-axis) in tons

Pz= Vertical unbalanced force (Z-axis) in tons

M_x= vertical moment causing rotation about X-axis in t-m

M_y= horizontal moment causing rotation about Y axis in t-m.

M_z= torsional moment about Z axis.

= unit weight of soil in t/m^3.

QPA= allowable soil pressure in t/m^2

N= operating speed of machine in rpm

H= height of top of the foundation above the center of gravity of the system.

The listing of the programmes is being presented in APPENDIX A and APPENDIX B.

CHAPTER 4

4. ANALYSIS OF DIFFERENT CASE STUDIES

Comparisons are made among the responses for different modes of vibration, computed by linear weightless spring theory and simplified elastic half space analog. For this purpose six practical cases have been selected, in which four cases belong to reciprocating machines and two cases are covered from the category of rotary machines of low speed. Study of these cases are as follows:

4.1 CASE 1 (FOUNDATION OF A TWO-STAGE SINGLE CYLINDER COMPRESSOR): Fig 1 shows the both side views of the loading diagram of machine foundation system.
(Ref. MAJOR A. (1980). "DYNAMICS IN CIVIL ENGG. "ANALYSIS AND DESIGN." VOL.2)

Technical data of this compressor are:

machine weights:	compressor	11.5 ton
	motor	1.0 ton
	driving gear	0.9 ton
	total weight of machine	13.4 ton

Operating speed of machine **N** = 290 rpm

Permissible amplitude of foundation **Aprm** = 0.2 mm

Generating forces and generating moment acting on the

foundation:

vertical generating force acting upward	-Pz = -10.24 ton
vertical generating force acting downward	Pz = 7.78 ton
horizontal generating force	Py = 2.04 ton
moment in the plane XZ	+My = 6.41 t-m
	-My = - 8.45 t-m
moment in the plane YZ	+Mx = + 9.80 t-m
	-Mx = - 9.80 t-m
Rotational moment about the Z axis	-Mz = - 1.67 t-m
	+Mz = + 1.67 t-m

Dynamic characteristics of the soil

type of soil	stiff,rich clay
dynamic shear modulus of the soil	G = 8437.40 t/m2
allowable soil pressure	QPA = 15 t/m2

Geometrical data used in the calculations

base area of the foundation	A = 17.4 m2
weight of the foundation block	W2 = 153.1 ton
the height of the combined center of, gravity from the bottom of the foundation	L = 2.26 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation are:

mass moment of inertia about X axis	Mmx = 36.00 t-m-sec2
mass moment of inertia about Y axis	Mmx = 69.40 t-m-sec2

mass moment of inertia about Z axis   Mmz = 57.00 t-m-sec2

4.1.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.1 below:

S.NO	Frequency	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_{nz}	15.288	13.301
2	$f_{n\psi}$	13.604	17.713
3	f_{nx}	10.810	12.070
4	$f_{n\phi y}$	11.930	10.970
5	$f_{n1}(x-z)$	22.567	22.873
6	$f_{n2}(x-z)$	8.567	8.686
7	f_{ny}	10.810	12.070
8	$f_{n\phi x}$	6.910	7.520
9	$f_{n1}(y-z)$	22.937	25.433
10	$f_{n2}(y-z)$	6.042	6.609

table 4.1

4.1.2 Computation of amplitudes in different modes of vibration: amplitudes computed from the programmes are given in table-4.2 below

S.No	amplitude	linear elastic weightless spring approach (undamped)	elastic half approach (damped)
1	A_z	0.073 mm	0.095 mm
2	A_ψ	$4.58 * 10^{-6}$ rad	$2.3 * 10^{-6}$ rad
3	A_x	0.030 mm	0.007 mm
4	$A_{\phi 1}$	$1.18 * 10^{-5}$ rad	$1.41 * 10^{-5}$ rad
5	A_y	0.47 mm	0.198 mm
6	$A_{\phi 2}$	$1.54 * 10^{-4}$ rad	$1.04 * 10^{-4}$ rad

table 4.2

4.1.3 Computation of maximum amplitudes: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in table 4.3 below

S.No	amplitude	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH1	0.054 mm	0.0318 mm
2	AV1	0.080 mm	0.1350 mm
3	AH2	0.739 mm	0.379 mm
4	AV2	0.520 mm	0.250 mm

table 4.3

The comments are as follows:

1. The maximum value of amplitudes computed by Barkan's approach and simplified elastic half space analogs are 0.739 mm and 0.379 mm in vertical direction respectively which is caused by combined action of force Pz and moment My. These amplitudes are more than the permissible amplitude of 0.2 mm.,prescribed by the manufacturer.So this case needs a modified geometry of foundation.

The maximum natural frequency calculated by Both approaches are 22,937 h_z and 25.433 H_z in coupled mode (Y-Z plane), and minimum frequencies are 6.91 H_z and 7.52 H_z. which are close to the operating frequency of machine (4.83H_z), hence there is chance of resonance.

2. Table 4.1 shows that natural frequency computed by elastic half space is less than natural frequency computed by Barkan's approach in vertical mode of vibration by 13% and more in case of torsional (Z-axis), and in coupled modes (Y-Z plane) by 30%, 10.8% and 9.38% respectively. Both approaches compute the same natural frequencies in coupled mode when sliding in taking place along X axis and Rocking occurs about Y-axis.

3. Amplitude calculated by elastic half space is more than Barkan's approach computations, in vertical mode by 30% and less in torsional, translational (X & Y axis) and in Rocking mode (X-axis) by 49.78%, 76.67%, 57.87% and 32.46% respectively (table 4.2)

4.2 CASE 1 WITH MODIFIED GEOMETRY

Geometrical data used in the calculations

base area of the foundation A = 23.2 m2

weight of the foundation block W2 = 102.0 ton

the height of the combined center of,

gravity from the bottom of the foundation L = 1.27 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation are:

mass moment of inertia about X axis Mmx = 26.7 t-m-sec2 mass moment of inertia about Y axis   Mmx = 40.63t-m-sec2

mass moment of inertia about Z axis   Mmz = 44.60 t-m-sec2

4.2.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.4 below

S.NO	Frequency	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_{nz}	21.204	17.169
2	$f_{n\psi}$	19.184	23.635
3	f_{nx}	14.99	15.58
4	$f_{n\phi y}$	22.29	19.79
5	$f_{n1}(x-z)$	29.510	27.256
6	$f_{n2}(x-z)$	13.721	13.702
7	f_{ny}	14.99	15.58
8	$f_{n\phi x}$	17.88	17.20
9	$f_{n1}(y-z)$	27.505	27.493
10	$f_{n2}(y-z)$	12.541	12.694

table 4.4

4.2.2 Computation of amplitudes in different modes of vibration: amplitudes computed from the programmes are given in table-4.5 below:

S.No	amplitude	linear elastic weightless spring approach (undamped)		elastic half space approach (damped)	
1	A_z	0.05	mm	0.0769	mm
2	A_ψ	$2.7*10^{-5}$	rad	$1.69*10^{-6}$	rad
3	A_x	0.010	mm	0.006	mm
4	$A_{\phi 1}$	$7.5*10^{-6}$	rad	$9.3*10^{-6}$	rad
5	A_y	0.0568	mm	0.048	mm
6	$A_{\phi 2}$	$2.4*10^{-4}$	rad	$2.55*10^{-5}$	rad

table 4.5

4.2.3 Computation of maximum amplitudes: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in table 4.6

S.No	amplitude	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH1	0.016 mm	0.014 mm
2	AV1	0.128 mm	0.104 mm
3	AH2	0.075 mm	0.066 mm
4	AV2	0.101 mm	0.128 mm

table 4.6

The observations are as follows.

1. The maximum natural frequency calculated by both approaches are 27.505 Hz & 27.493 Hz and minimum frequencies are 12.541 & 12.694 Hz (table 4.4), which are not close to the operating frequency (4.83 Hz). So now there in no chance of resonance.

The maximum amplitude computed by both approaches are 0.128 mm(table 4.6) in different modes but these value are less than permissible value of 0.2 mm.

2. From table 4.4 it is clear that frequencies calculated by both approaches are nearly equal in coupled modes. But calculation shows negative variation of 19.02% in vertical mode and positive variation of 23.2% in torsional mode in favour of elastic half space approach.

3. The amplitude calculated by elastic half space method are greater than the Barkan's approach computations in vertical, rocking (Y) and sliding mode (Y- direction) by 53.8%, 24% and 6.24% respectively, and less in torsional (Z-axis), Rocking (X- direction) and sliding mode (X-direction) by 93%, 40% and 15.64% respectively.

4.3 CASE 2: RAWMILL FAN FOUNDATION

(Ref. RANJAN.G. et. al. (1986). " PERFORMANCE STUDY OF TWO INDUSTRIAL FAN FOUNDATIONS" 8th SYMPOSIUM ON EARTHQUAKE ENGG.".

FIG 2 shows the raw mill fan foundation in which the axes chosen for analysis are also marked. the foundation rests on a bed rock at a depth of 3.75 m below the finished floor level. The flexibility of the block and the stiffness of the filled up soil above the bed rock level have both been neglected, being of secondary significance.

Technical data of this RAWMILL FAN FOUNDATION are:

machine weights:
- fan = 8.0 ton
- motor = 4.0 ton
- shaft bearing = 7.5 ton
- rotating part = 3.6 ton

operating speed of machine **N** = 1487 rpm

Permissible amplitude of foundation **Aprm** = 0.04-0.6 mm

Generating forces and generating moment acting on the foundation:

vertical generating force acting downward P_z = 0.57 ton

horizontal generating force P_x = 0.57 ton

moment in the plane XZ M_y = 2.1785 t-m

Dynamic characteristics of the soil

dynamic shear modulus of the soil G = 11250 t/m2

allowable soil pressure QPA = 25 t/m2

Geometrical data used in the calculations

base area of the foundation A = 18.087 m^2

weight of the foundation block

including the weight of machine W = 191.48 ton

the height of the combined center of,

gravity from the bottom of the foundation L = 3.078 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation is:

mass moment of inertia about Y axis Mmx = 85.86 t-m-sec2

4.3.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.7 below

S.NO	element	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_{nz}	16.780	14.462
2	f_{nx}	11.86	13.12
3	$f_{n\phi y}$	4.982	5.52
4	$f_{n1}(x-z)$	22.366	24.776
5	$f_{n2}(x-z)$	4.694	5.201

table 4.7

4.3.2 Computation of amplitudes in different modes of vibration:

amplitudes computed from the programmes are given in table-4.8 below:

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	Az	- 0.002 mm	0.00154 mm
2	Ax	0.0016 mm	0.0068 mm
3	$A_{\phi 1}$	$3.43 * 10^{-6}$ rad	$1.8 * 10^{-6}$ rad

table 4.8

4.3.3 Computation of maximum amplitudes: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in table 4.9below

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH1	0.00820 mm	0.0047 mm
2	AV1	0.00825 mm	0.0120 mm

table 4.9

Obsevations are as follows:

1. The maximum amplitude calculated by the Barkan's approaches and linear elastic weightless spring theory are. 00825 mm and .012 mm respectively (table 4.9) which are less than the permissible range of amplitude ie.0.04 mm to 0.6 m m.

The operating frequency of machine is 24.78 Hz. which is close to the higher frequencies of the natural frequencies calculated by Barkan's approach (22.366 Hz) and Elastic Half Space approach (24.746 Hz),(table 4.7), So this may produce large vibration but it has been already predicted that maximum amplitudes are less than permissible amplitude.

2. Frequency in vertical mode computed by Elastic Half Space approach is less than the computation of first approach by 13.81% frequency are more in coupled mode (Y-Z plane) case by 10.6 and 10.8 percent(table 4.7).

3. Amplitude calculated by Elastic Half Space approach are less by 23% and 47.2% in case of vertical and Rocking mode but it is more in case of sliding mode by 250% . Although the absolute value of amplitudes are very small(table 4.8).

4.4 CASE 3: PREHEATER FAN FOUNDATION

(Ref. same as in Case 2)

The preheater fan foundation is shown in Fig 3,with the x,y,z-axis marked in the figure.Bed rock is 3.30 m below the finished floor level. The monolithically cast foundation block has been considered to consist of three parts A, B, and C for the purpose of analysis.

Technical data of this PREHEATER FAN FOUNDATION are:

machine weights:	fan	= 10.0 ton
	motor	= 10.5 ton

shaft bearing = 8.8 ton

rotating parts = 6.1 ton

operating speed of machine **N** = 600 rpm

Permissible amplitude of foundation **Aprm** = 0.08-0.12 mm

Generating forces and generating moment acting on the foundation:

vertical generating force acting downward Pz = 0.40 ton

horizontal generating force Px = 0.40 ton

moment in the plane XZ My = 1.4672 t-m

Dynamic characteristics of the soil

dynamic shear modulus of the soil G = 11250 t/m^2

allowable soil pressure QPA = 25 t/m^2

Geometrical data used in the calculations

base area of the foundation A = 21.02 m^2

weight of the foundation block

including the weight of machine W = 270.66 ton

the height of the combined center of,

gravity from the bottom of the foundation L = 2.78 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation is:

mass moment of inertia about Y axis M_{mx} = 100.885 t-m-sec2

4.4.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.10 below

S.NO	element	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_{nz}	15.218	12.620
2	f_{nx}	10.76	11.46
3	$f_{n\phi y}$	5.34	5.707
4	$f_{n1}(x-z)$	20.628	21.986
5	$f_{n2}(x-z)$	4.916	5.253

table 4.10

4.1.2 Computation of amplitudes in different modes of vibration: amplitudes computed from the programmes are given in table-4.11 below:

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	Az	0.0027 mm	0.0035 mm
2	Ax	0.0083 mm	0.035 mm
3	$A_{\phi 1}$	$1.55*10^{-6}$ rad	$2.28*10^{-6}$ rad

4.4.3 Computation of maximum amplitudes: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in 4.12

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH1	0.00126 mm	0.041 mm
2	AV1	0.00279 mm	0.0079mm

table 4.12

Following are the obsevations:

1. The maximum amplitude calculated by Barkan and Elastic Half Space approaches are 0.0126mm & 0.041mm (table 4.12), which occur in translational direction. These amplitudes are very much less than the range of permissible amplitude (.08 to 0.12 mm).
The operating frequency of preheater fan foundation is 10 Hz and the closest value to this frequency is 12.629 Hz in vertical mode which is computed by Elastic Half Space approach whereas Barkan's approach computed this frequencies as 15.218 Hz(table 11).

2. This case shows the same type of variations in natural frequency as in case of Rawmill fan foundation. The frequency in vertical mode computed by Elastic Half Space is less by 17.01% and more in coupled mode by 6.58% and 6.85% respectively. These variations are very small and can be considered as insignificant.

3. The variation in amplitude shows very different trend as compare to the case of natural frequencies which coincide with the previous case of Rawmill Fan Foundation. In each mode the amplitudes calculated by Elastic Half Space approach exceeds the Barkan's approach computations by 27.73%, 320%, and 47.09%, respectively. Although the values are very small.

4.5 CASE 4- COMPRESSOR FOUNDATION : (Ref: Prakosh. S. (1981). "SOIL DYNAMICS" McGRAW HILL - NEW YORK.)

Fig 4 shows the loading diagram and design diagram of the compressor foundation.

Technical data of this FOUNDATION are:

machine weights: compressor = 10.0 ton

motor = 3.5 ton

Total 13.5 ton

operating speed of machine **N** = 600 rpm

Permissible amplitude of foundation **Aprm** = 0.2 mm

Generating forces and generating moment acting on the foundation:

vertical generating force acting downward Fz = 4.243 ton

horizontal generating force Px = 0.00 ton

moment in the plane XZ My = 4.589 t-m

Dynamic characteristics of the soil

dynamic shear modulus of the soil G = 3750 t/m^2

allowable soil pressure QPA = 8 t/m^2

Geometrical data used in the calculations

base area of the foundation A = 26.4 m^2

weight of the foundation block

including the weight of machine W = 68.22 ton

the height of the combined center of,

gravity from the bottom of the foundation L = 0.61 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation is:

mass moment of inertia about Y axis   Mmx = 22.054 t-m-sec2

4.5.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.13 below

S.NO	element	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_{nz}	19.613	15.375
2	f_{nx}	13.86	13.96
3	$f_{n\phi y}$	28.07	23.73
4	$f_{n1}(x-z)$	30.152	25.724
5	$f_{n2}(x-z)$	13.648	13.608

table 4.13

4.5.2 Computation of amplitudes in different modes of vibration: amplitudes computed from the programmes are given in table-4.14 below:

S.No	element	linear elastic weightless spring approach (undamped)		elastic half space approach (damped)	
1	Az	0.0540	mm	0.0551	mm
2	Ax	0.0088	mm	0.0075	mm
3	$A_{\phi 1}$	$6.90*10^{-6}$	rad	$7.00*10^{-6}$	rad

table 4.14

4.5.3 Computation of maximum amplitudes: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in 4.15

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH1	0.0543 mm	0.078 mm
2	AV1	0.018 mm	0.0170 mm

table 4.15

The comments and comparisons are as follows:

1. The operating frequency of machine is 10 Hz. The closest values computed by Barkan's approach and elastic half space approach are the 13.60 Hz and 13.648 Hz respectively which are the lower frequencies of coupled mode.So it is clear that the natural frequencies are not close to the operating frequency, hence there is no possibility of resonance.

The maximum amplitude calculated by both approach are .078 mm & .0543 mm (vertical direction) which are very much less than the permissible amplitude of 0.2 mm.

2. The lower frequency of coupled mode calculated by both approaches are approximately equal but Elastic Half Space approach computation shows less value of frequencies in vertical and coupled mode for higher frequency. So Barkan's computations exceed by 21.6% and 17.21% in the two above mentioned modes.

3. The Rocking (Y- direction) and vertical amplitudes computed by both approach are nearly equal but there is positive difference of 14.7710% in sliding mode (X - direction) in favour of Barkan's approach computation. But these variation in very small and can be neglected.

4.6 CASE 5: FOUNDATION FOR A RECIPROCATING COMPRESSOR (Ref: Puri. V. k. et. al. (1987). "FOUNDATION FOR MACHINES : ANALYSIS AND DESIGN". WILLEY SERIES. IN. Geo. tech. Eng

Fig 5 (a and b) show the section and plan view of the reciprocating compressor foundation. The following data are supplied.

1. Machine data

operating speed of the compressor	= 405 rpm
weight of the compressor	= 9 ton
height of the center of gravity of compressor above its base	= 0.5 m
operating speed of motor	= 1470 rpm
weight of the motor	= 2.0 ton
height of the center of the gravity of the motor	= 0.5 m
bearing level of the compressor above its base	= 0.5 m

UNBALANCED FORCES AND MOMENT OCCASIONED BY THE OPERATION OF COMPRESSOR

Horizontal primary force	= $P_x' = P_y' = 0$
Horizontal secondary force	= $P_x'' = P_y'' = 0$
Vertical primary force	= $P_z' = 0.165$ ton
Vertical secondary force	= $P_z'' = 0.40$ ton
Horizontal primary moment	= $M_z' = 0.105$ t.m.
Horizontal secondary moment	= $M_z'' = 0$
Vertical primary moment	= $M_x' = 1.75$ t-m
vertical secondary moment	= $M_x'' = 0.45$ t-m

Permissible amplitude

(peak to peak) = 0.025 mm

2. Soil Data

Dynamic shear modulus of soil = 8076 t/m^2

allowable soil pressure = 25 t/m^2

3. Geometrical data used in the calculations

base area of the foundation A = 17.4 m2

weight of the foundation block

including the weight of machine W = 141.524 ton

the height of the combined center of,

gravity from the bottom of the foundation L = 1.0299 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation are:

mass moment of inertia about X axis Mmx = 60.7416t-m-sec2

mass moment of inertia about Z axis Mmz = 77.7185t-m-sec2

4.6.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.16 below

S.NO	element	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_{nz}	26.945	18.191
2	$f_{n\psi}$	29.022	29.915
3	f_{ny}	19.05	16.51
4	$f_{n\phi x}$	38.33	28.66
5	$f_{n1}(y-z)$	44.177	33.452
6	$f_{n2}(y-z)$	18.496	15.826

table 4.16

4.6.2 Computation of absolute maximum amplitude : amplitudes computed from the programmes are given in table-4.17 below:

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	A_z	0.0053 mm	0.001 mm
2	A_φ	$7.6 * 10^{-8}$ rad	$6.7 * 10^{-6}$ rad
3	A_y	0.0006 mm	0.0084 mm
4	$A_{\phi 1}$	$5.15 * 10^{-7}$ rad	$7.8 * 10^{-7}$ rad

table 4.17

4.6.3 Computation of maximum amplitude: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in 4.18

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH2	0.00178 mm	0.0026 mm
2	AV2	0.002 mm	0.0037 mm

table-4.18

the observations are as follows:

1. The lowest frequencies from both approach computation are 18.496 Hz and 15.826 Hz. And the operating frequency is 6.75 Hz which is very less than the computed value of frequencies. So there in no chance of resonance.

Maximum amplitude calculation show the maximum value of amplitude are .002mm and .00337 respectively which are very far from the permissible amplitude (0.2mm).

2. In vertical and in coupled mode natural frequency calculated by Barkan's approach are greater than the other approach computations by 32, 24.27 and 14.4 percent. but less in case of torsional mode by 3% which is insignificant.

3. The variations of amplitudes in case of vertical, sliding (Y- direction) and Rocking mode (X- direction) are positive in case of elastic half approach by 88%, 40% and 57% and negative in torsional mode by 11.84%.

4.7 CASE 6: FOUNDATION FOR A SIX CYLINDER DIESEL ENGINE (Ref. MAJORA. (1980) " DYNAMICS IN CIVIL ENGG: ANALYSIS AND DESIGN " VOL 2.

The detailed figure of a 5400 HP six cylinder diesel engine is shown in fig 6.

SITE: Upto depth of 4.0 m there is medium sand, with a layer of sandy gravel below. The ground- water table is at a considerable depth and is consequently not dangerous from the point of view of the propagation of vibration. The coefficient of uniform compression(Cu) of the soil is 8000 t/m^2. Corresponding to this value of Cu, the dynamic shear modulus G comes out equal to 7500 t/m^2.

The operating speed of the machine is N = 125 rpm. The foundation should therefore be designed to have a natural frequency exceeding once or even twice the operating speed. this is necessary because the second harmonic frequency of the mass forces is twice as high as the operating speed.

Design data supplied by the manufacturer are:

machine weights:	engine	= 263.0 ton
	generator	= 54.00 ton
	total	= 317.0 ton

Permissible amplitude of foundation **Aprm** = 0.2 mm

Generating forces and generating moment acting on the foundation:

moment about Z-axis	Mz =	12.0	t-m
horizontal generating force	Px =	0.00	ton
moment in the plane XZ	My =	4.589	t-m

Dynamic characteristics of the soil

dynamic shear modulus of the soil	G = 7500 t/m²
allowable soil pressure	QPA = 20 t/m²

Geometrical data used in the calculations

base area of the foundation	A = 26.4 m²
weight of the foundation block including the weight of machine	W = 68.22 ton
the height of the combined center of, gravity from the bottom of the foundation	L = 0.61 m

The mass moment of inertia related to the orthogonal coordinate systems passing through the common center of gravity of machine and foundation are:

mass moment of inertia about Y axis	Mmx = 2450.0 t-m-sec2
mass moment of inertia about Z axis	Mmz = 2296.9 t-m-sec2

4.7.1 Computation of natural frequencies in different modes of vibration: frequencies computed from the programmes are given in table-4.19 below

S.NO	element	linear elastic weightless spring approach (Hz)	elastic half space approach (Hz)
1	f_n	12.091	10.065
2	f_{nx}	9.31	6.660
3	$f_{n\phi y}$	14.46	8.490
4	$f_{n1}(x-z)$	18.387	11.301
5	$f_{n2}(x-z)$	8.650	5.919

4.7.2 Computation of amplitudes in different modes of vibration:

amplitudes computed from the programmes are given in table-4.20 below:

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	A_ψ	$9.3*10^{-7}$ rad	$1.3*10^{-6}$ rad
2	Ax	0.0075 mm	0.0088 mm
3	$A_{\phi 1}$	$7.00*10^{-6}$ rad	$6.90*10^{-6}$ rad

table 4.20

4.7.3 Computation of maximum amplitudes: Absolute maximum value of amplitude caused by vertical force and rocking moment are given in 4.21

S.No	element	linear elastic weightless spring approach (undamped)	elastic half space approach (damped)
1	AH1	0.00660 mm	0.0086 mm
2	AV1	0.00576 mm	0.0170 mm

table 4.21

Comparisons between the approaches for different modes of vibration are as follows:

1. The maximum frequencies calculated by both approaches are 18.387 Hz and minimum frequencies are 8.650 Hz and 5.919 Hz. The operating frequency of machine 125 rpm or 2.08 Hz which in very much less than computed value of minimum frequencies Hence these is no possibility of resonance.

The maximum amplitudes calculated by both approaches are .0066 mm and .017mm which is not close to the permissible limit of amplitude (0.2 mm).

2. The frequencies calculated by elastic half space approach are less than the calculations of Barkan's approach in torsional (Z-direction) and coupled mode (Y-Z plane) by 16.75%, 38.5% and 31.57%.

3. The amplitudes calculation shows positive variation of 39.78% to 200% in favour of elastic half space approach in vertical and ocking (Y-direction) mode. and negative variation of 26% in case of sliding mode (x-direction).

4.7 Disscussion

The data presented above is reworked to obtain table 4.22 and 4.23 where relative difference(in perchantage) calculated by elastic half space approach with respect to Barkan's approach for frequencies and amplitudes,in different cases and comparisons are made between computed amplitudes by both approaches with permissible amplitude respectively.

Undamped natural frequency due to vertical excitation , calculated by elastic half space approach is less in each case by about from 12% to 32% in different cases with respect to Barkan's approach. Similar variations are predicted in coupled modes of vibration in X-Z plane where higher and lower natural frequency of coupled mode,in elastic half space approach, are less with respect to Barkan's approach by 0% to 38.5% and 0% to 31.57% respectively.But in case of coupled vibration (Y-Z plane), higher values of frequencies are indicated by elastic half space in computing the higher and lower natural frequencies of coupled mode.This increase varies from 6.58% to 10.64% and 6.85% to 10.80% respectively.

FOR AMPLITUDES, elastic half space approach calculates more value in vertical and rocking mode in each case with respect to Barkan's approach except case 2, where 23% decrease is predicted in vertical mode and the range of positive variations are 0% to 88% and 0% to 200% respectively.

there is a variation of -3% to -49.78% in amplitudes, calculated by elastic half space approach in torsional case with respect to Barkan's approach.So less values of torsional amplitude are calculated by elastic half space approach as compare to Barkan's approach. In case of sliding along X , Y direction and rocking about X-direction,amplitudes vary from -76.67% to 40%, -57.87% to 350% and -47.2% to 47.09% respectively. The comparisons of absolute maximum amplitude computed by both approaches with permissible limit of amplitudes in different cases is shown in table 4.23.

Maximum amplitudes calculated in case 1, 2(horizontal), 3, 4, 5 and 6 by elastic half space approach are much closer to the permissible amplitudes but in case of 1(mod) and 2(vertical case)

Barkan's amplitudes are much closer to the permissible value. In 1983, S.Prakash analyzed a case history of Reciprocating Compressor, from this case history Barkan's approach calculation are much closer to the permissible amplitude.

So from these interpretation of results it is clear that there is no definite and remarkable trend to signify the the superiority of one approach over the other. Both approaches have their own merits and demerits. In western countries simplified elastic half space analogs are used to design the machine foundation whereas Barkan's approach is used to analyze the machine foundations in Russia. Foundations designed by these methods have been working satisfactorily in the field. So any of the two approaches can be used to analyse the machine foundation.

Table 4.22

element	case 1	case 1(mod)	case 2	case 3	case 4	case 5	case 6
fnz	-12.99	-19.02	-13.81	-17.01	-21.6	-32.	-
fnΦ	30.00	23.20	-	-	-	3.00	-16.75
fn1(x-z)	0	-6.7	-	-	-17.21	-24.27	-38.5
fn2(x-z)	0	0	-	-	0	-14.10	-31.57
fn1(y-z)	10.88	0	10.64	6.58	-	-	-
fn2(y-z)	9.38	0	10.80	6.85	-	-	-
Az	30.13	53.8	-23.00	27.23	0	88.00	39.78
Aψ	-49.78	-3.0	-	-	-	-11.84	-
Ax	-76.67	-40.0	-	-	-14.77	40.00	-26.0
Aφ1	19.49	24.0	-	-	0	51.00	200.0
Ay	-57.87	-15.64	350	320	-	-	-
Aφ2	-32.46	6.25	-47.2	47.09	-	-	-

- sign indicates that less value is calculated in elastic half space approach than the Barkan's approach.

+ sign indicates that in elastic half space approach more value is calculated with respect to the Barkan's approach table-4.23

cases	direction	Barkan's approach	Elastic Half space approach	Permissible amplitudes
1	horizontal	0.739mm	**0.379mm**	0.2mm
	vertical	0.52 mm	**0.25 mm**	
1(mod)	horizontal	**0.075mm**	0.066mm	0.2mm
	vertical	**0.128mm**	0.104mm	
2	horizontal	0.00825mm	**0.012mm**	0.04-0.06 mm.
	vertical	**0.0082 mm**	0.0047mm	
3	horizontal	0.012 mm	**0.041mm**	0.08 -0.12 mm.
	vertical	0.0028 mm	**0.0078mm**	
4	horizontal	0.018 mm	0.017 mm	0.2mm
	vertical	0.0543 mm	**0.078 mm**	
5	horizontal	0.00178mm	**0.0026mm**	0.0125mm
	vertical	0.002 mm	**0.0037mm**	
6	horizontal	0.0066 mm	**0.0086mm**	0.2mm
	vertical	0.00576mm	**0.017 mm**	

In table 2.23 highlighted values signify that amplitudes are much closer to the permissible limit of amplitude.

CHAPTER 5

5. CONCLUSIONS

From the studies carried out for different cases no precise, definite and remarkable trend can be established for superiority of one approach over the other. Both approaches, elastic half space approach and linear elastic weightless spring approach, are used frequently to design the machine foundation, In western countries elastic half space approach is used whereas Russians design the machine foundation by Barkan's approach.Post-constrution behavior of Machine foundations which are designed by these approaches are satisfactory.So these approaches can be used depending upon the reliability of data of soil dynamic properties, i.e dynamic shear modulus, coefficient of uniform compression, poisson's ratio,damping ratio etc.

SCOPE OF FURTHER STUDY

Several case studies should be carried out for practical cases of machine foundations and a definite trend should be developed to analyse the different machine foundations by a particular approach.

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FIGURES

APPENDIX

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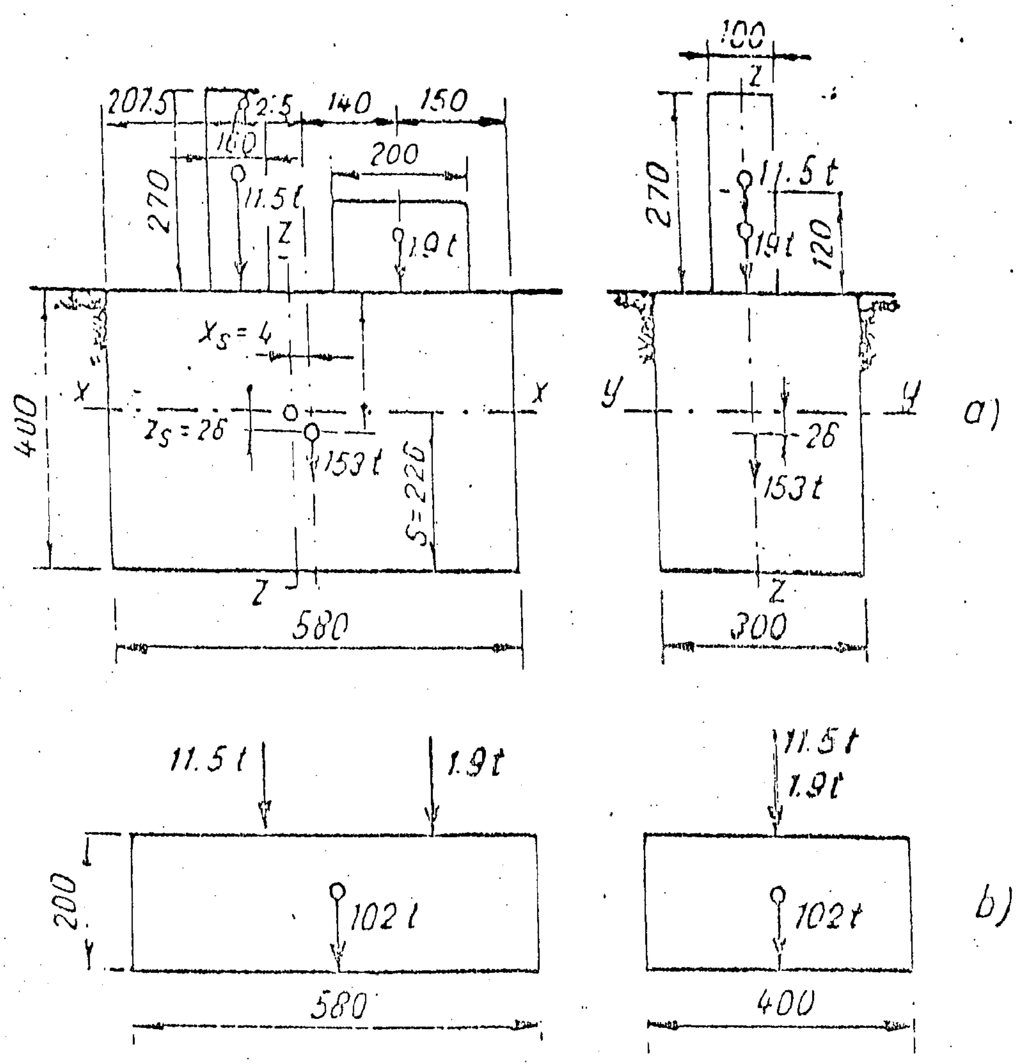


Fig. 1 FOUNDATION OF TWO STAGE SINGLE CYLINDER COMPRESSOR a – proposed b – modified

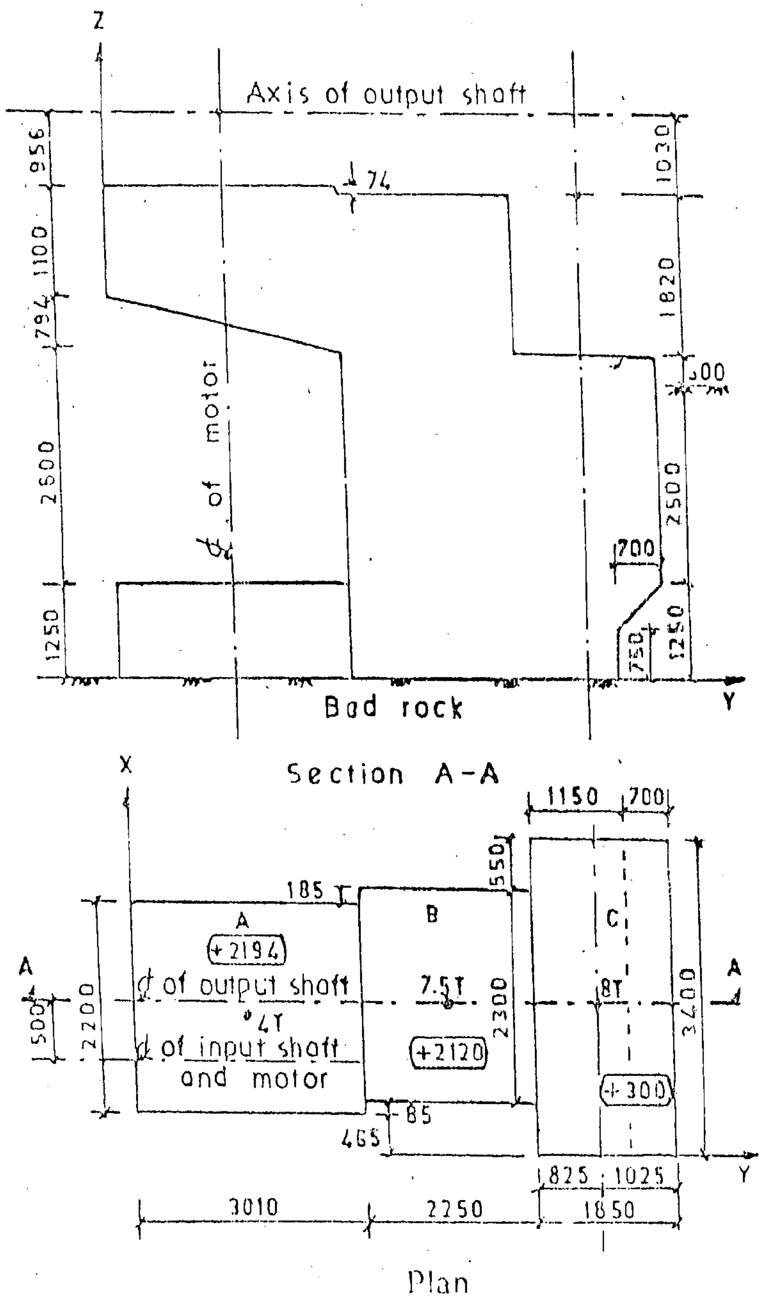


Fig.2 - Rawmill fan foundation

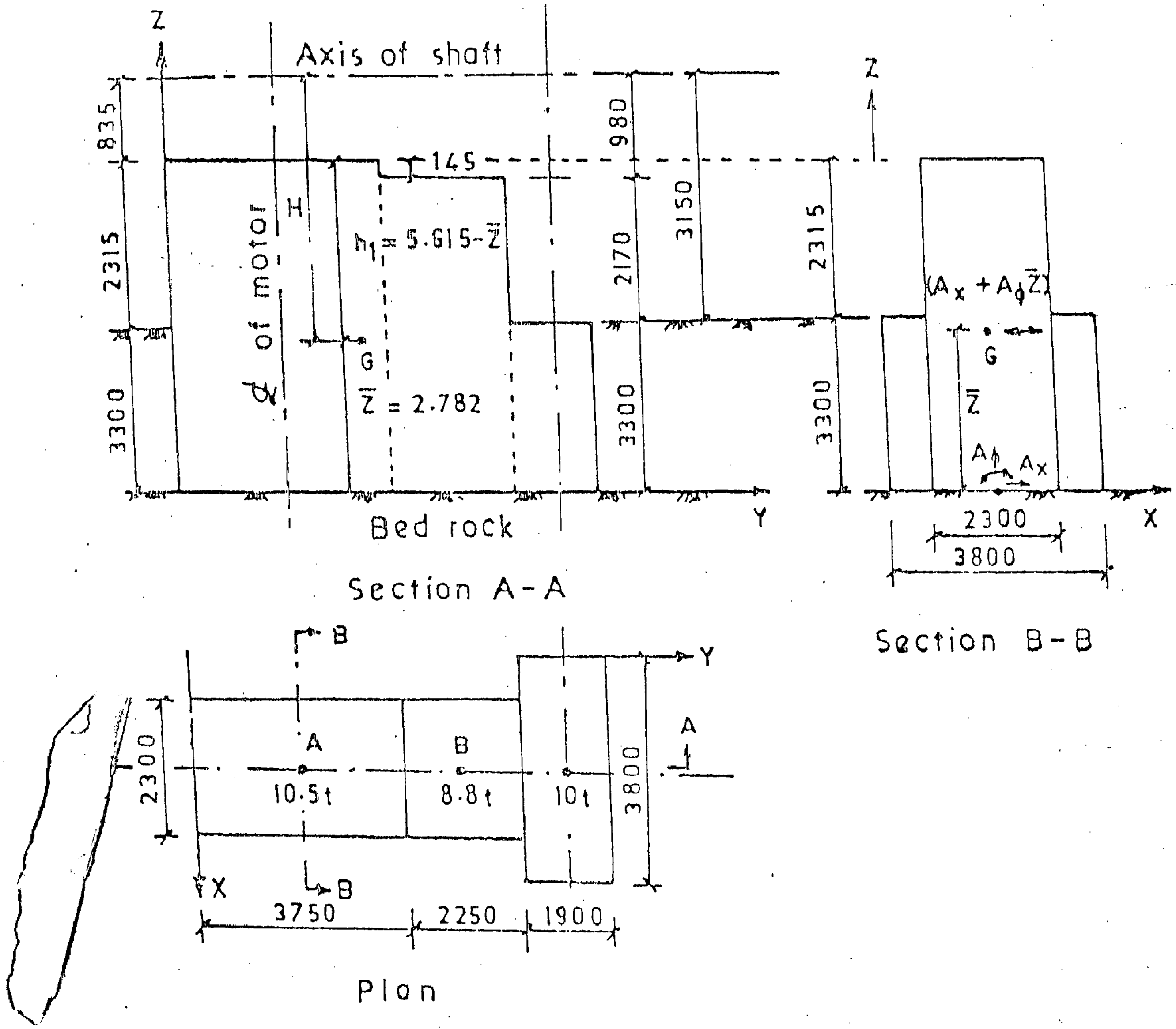
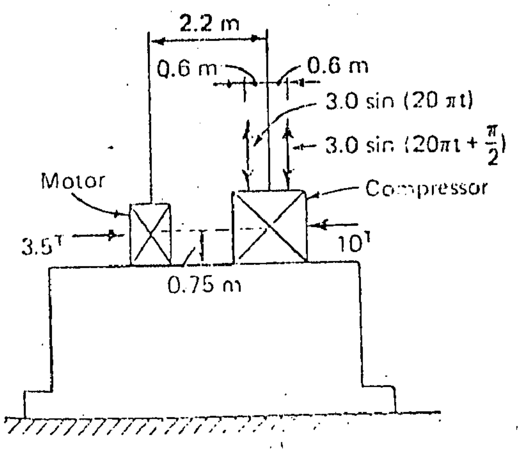


Fig. 3 - Preheater fan foundation



LOADING DIAGRAM OF RECIPROCATING COMPRESSOR

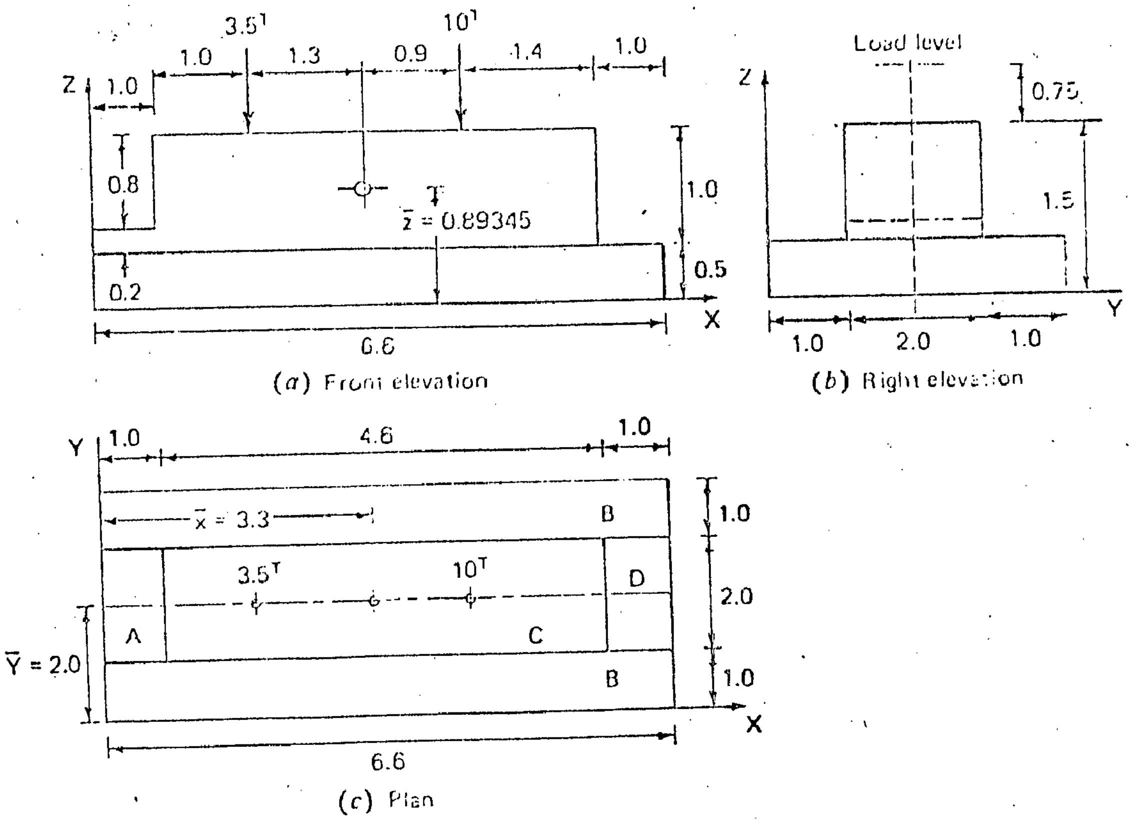


Fig. 4 DESIGN DIAGRAM OF RECIPROCATING COMPRESSOR

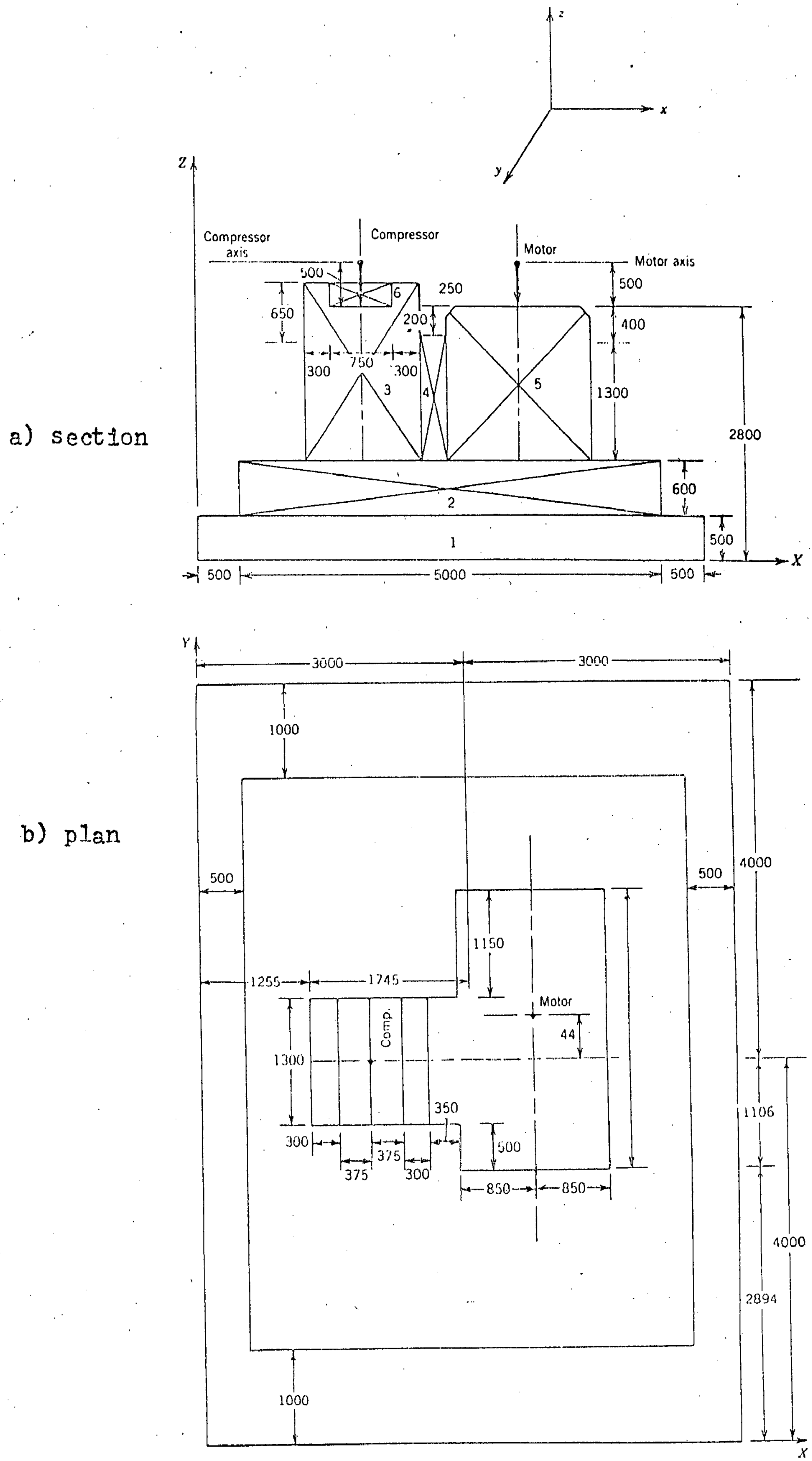


Fig. 5 DESIGN DIAGRAM OF RECIPROCATING COMPRESSOR

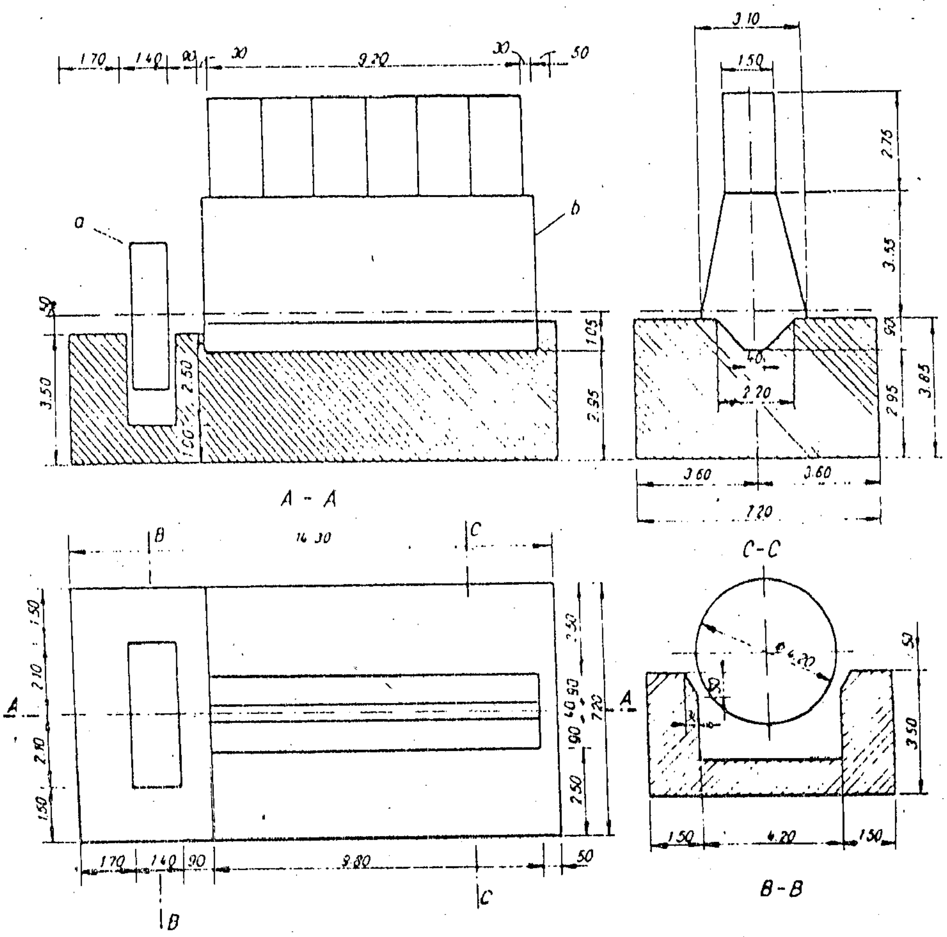


Fig. 6 ARRANGEMENT FOR SIX CYLINDER DIESEL ENGINE AT ITS FOUNDATION
a) generator b) engine

APPENDIX-A

```
C        COMPUTER PROGRAM FOR DESIGN OF A BLOCK FOUNDATION FOR
C        DIFFERENT MODES OF VIBRATION USING ELASTIC HALF SPACE
C        ANALOG(RAJEEV)
      IMPLICIT REAL(A-Z)
      INTEGER I
      CHARACTER*14 FILOP
      DATA CASE1,CASE2,CASE3,CASE4/0.,0.,0.,0./
      DATA NOP1,NOP2,NOP4,NOP5,NOP6,NOP7,NOP8/
     1  0.,0.,0.,0.,0.,0./
      DATA Y/'Y'/
   50       WRITE(*,*)'I/P O/P-DATA/FILE NAME'
      READ(*,*)FILEOP
  915   FORMAT(A14)
        OPEN (UNIT=1,FILE='R1.DAT',STATUS='OLD')
        OPEN (UNIT=2,FILE='R1.OUT',STATUS='NEW')
      WRITE(*,*)'I/P PROBLEM TITLE(I)'
      READ(*,6669) (TITLE(I),I=1,120)
      WRITE(2,668) (TITLE(I),I=1,120)
 6668   FORMAT(10X,'TITLE=',120A1,/,/,/,72('*'),//)
 6669   FORMAT(120A1)
      WRITE(*,*) 'DO YOU WANT CASE 1(TRANSLATION-Z)?'
      READ(*,914)Q
  914   FORMAT(A1)
      IF(Q.EQ.Y) CASE1=1.0
      WRITE(*,*) 'DO YOU WANT CASE 2(TORSIONAL-Z)?'
      READ(*,914)Q
      IF(Q.EQ.Y) CASE2=1.
      WRITE(*,*) 'DO YOU WANT CASE 3(TRANSLATION-X,ROTATION-Y)?'
      READ(*,914)Q
      IF(Q.EQ.Y) CASE3=1
      WRITE(*,*) 'DO YOU WANT CASE 4(TRANSLATION-Y,ROTATION-X)?'
      READ(*,914)Q
      IF(Q.EQ.Y) CASE4=1.
C        ************************************************************
      IF(CASE1.EQ.1)THEN
      WRITE(*,*)'***********CASE1***********'
      WRITE(*,*)' DO YOU WANT THE UNDAMPED CASE?'
      READ(*,914)Q
      IF(Q.EQ.Y)NOP1=1.0
      WRITE(*,*)' DO YOU WANT THE DAMPED CASE?'
      READ(*,914)Q
      IF(Q.EQ.Y)NOP2=1.0
      END IF
      IF(CASE2.EQ.1)THEN
      WRITE(*,*)'***********CASE2***********'
        WRITE(*,*)'DO YOU WANT THE UNDAMPED CASE?'
      READ(*,914)Q
        IF(Q.EQ.Y)NOP3=1.0
      WRITE(*,*)' DO YOU WANT THE DAMPED CASE?'
      READ(*, 914)Q
      IF(Q.EQ.Y)NOP4=1.0
        END IF
        IF(CASE3.EQ.1)THEN
      WRITE(*,*)'***********CASE3***********'
      WRITE(*,*)' DO YOU WANT THE UNDAMPED CASE?'
      READ(*,914)Q
        IF(Q.EQ.Y)NOP5=1.0
      WRITE(*,*)' DO YOU WANT THE DAMPED CASE?'
        READ(*,914)Q
        IF(Q.EQ.Y) NOP6=1.0
        END IF
        IF(CASE4.EQ.1)THEN
        WRITE(*,*)'************CASE4************'
        WRITE(*,*)' DO YOU WANT THE UNDAMPED CASE?'
        READ(*,914)Q
        IF(Q.EQ.Y)NOP7=1.0
        WRITE(*,*)' DO YOU WANT THE DAMPED CASE?'
        READ(*,914)Q
        IF(Q.EQ.Y)NOP8=1.0
```

```
C       ******TYPE*******
        WRITE(2,1144)
 1144   FORMAT(15X,15('*'),'INPUT VARIBLES:',15('*'),/72('*'),///)
        WRITE(*,*)'I/P A'
      READ(*,*)A
      WRITE(*,*)'I/P W'
      READ(*,*)W
      WRITE(2,1155) A,W
         READ(*,*)N
        WRITE(*,*)'I/P QPA'
      READ(*,*) QPA
      WRITE(2,1112) GAMMA,G,N,QPA
 1112   FORMAT(
      1  1X,'UNIT WEIGHT OF THE SOIL,               GAMMA=',F10.4,1X,'t/m3',
      2  1X,'DYNAMIC SHEAR MODULAS,                     G=',F10.2,1X,'t/m2',
      3  1X,'OPERATING SPEED OF MACHINE,                N=',F10.2,1X,'rpm',/
      4  1X,'ALLOWABLE SOIL PRESSURE,                 QPA=',F10.2,1X,'t/m2',
C     *********TYPE1 **************
      IF(CASE1.EQ.1.0.OR.CASE3.EQ.1.0.OR.CASE4.EQ.1.0)THEN
      WRITE(*,*)'I/P NU'
      READ(*,*) NU
      WRITE(2,1955) NU
 1955   FORMAT(
      1  1X,'POISSONS RATIO,                            NU=',F10.3/)
      END IF
C         *********TYPE2*************
      IF(CASE4.EQ.1.0)THEN
      WRITE(*,*)'I/P IX'
      READ(*,*) IX
      WRITE(*,*)'I/P MX'
      READ(*,*)MX
      WRITE(*,*)'I/P MMX'
      READ(*,*)MMX
      WRITE(*,*)'I/P PY'
      READ(*,*)PY
      WRITE(*,*)'I/P LY'
      READ(*,*)LY
      WRITE(2,1166) IX,MX,MMX,PY,LY
 1166       FORMAT(
      1  1X,'MOMENT OF INERTIA,                         IX=',F10.4,1X,'m4.',/,
      2  1X,'UNBALANCED MOMENT,                         MX=',F10.4,1X,'t-m.',/
      3  1x,'POLAR MASS MOMENT OF INERTIA,             MMX=',F10.4,1X,'t-m.sec
      3  ',/,
      4  1X,'UNBALANCED FORCE,                          PY=',F10.4,1X,'t.',/,
      5  1X,'MAXIMUM DISTANCE OF THE POINT',/,
      6  1X,'FROM THE AXIS OF ROCKING(HORIZONTAL),LY=',F10.4,1X,'m.',/)
      END IF
C     *******TYPE6*********
      IF(CASE4.EQ.1.0.OR.CASE3.EQ.1.0)THEN
      WRITE(*,*)'I/P L'
      READ(*,*)L
      WRITE(*,*)'I/P HH'
      READ(*,*)HH
      WRITE(2,1177)L,HH
 1177       FORMAT(
      1  1X,'HEIGHT OF THE CENTRE OF GRAVITY,        L=',F10.4,1X,'m.'
      2  1X,'HEIGHT OF THE TOP OF THE FOUNDATION,    H=',F10.4,1X,'m.'
      END IF
C     ********TYPE3*********
      IF(CASE3.EQ.1.0)THEN
      WRITE(*,*)'I/P IY'
      READ(*,*)IY
      WRITE(*,*)'I/P MY'
      READ(*,*) MY
      WRITE(*,*)'I/P MMY'
      READ(*,*)MMY
      WRITE(*,*)'I/P PX'
      READ(*,*)PX
```

```
      WRITE(*,*)'I/P LX'
      READ(*,*)LX
      WRITE(2,1188) IY,MY,MMY,PX,LX
 1188      FORMAT(
     1   1X,'MOMENT OF INERTIA,                           IY=',F10.4,1X,'m4.',/,
     2   1X,'UNBALANCED MOMENT,                           MY=',F10.4,1X,'t-m',/,
     3   1X,'POLAR MASS MOMENT OF INERTIA,               MMY=',F10.4,1X,'t-m.sec
     3   1X,'UNBALANCED FORCE,                            PX=',F10.4,1X,'t.',
     5   1X,'MAXIMUM DISTANCE OF THE POINT',/,
     6   1X,'FROM THE AXIS OF ROCKING(HORIZONTAL),LX=',F10.4,1X,'m.'/)
      END IF
C     ************TYPE 4**********
      IF (CASE2.EQ.1.0)THEN
      WRITE(*,*)'I/P IZ'
      READ(*,*)IZ
      WRITE(*,*)'I/P MZ'
      READ(*,*)MZ
      WRITE(*,*)'I/P MMZ'
      READ(*,*) MMZ
      WRITE(*,*)'I/P R'
      READ(*,*)R
      WRITE(2,1100) IZ,MZ,MMZ,R
 1100      FORMAT(
     1   1X,'MOMENT OF INERTIA                            IZ=',F10.4,1X,'m4.',/,
     2   1x,'UNBALANCED MOMENT,                           MZ=',F10.4,1X,'t-m.'/,
     3   1x,'POLAR MASS MOMENT OF INERTIA                MMZ=',F10.4,1X,'t-m.sec
     $   ',//,
     4   1X,'MAXIMUM HORIZANTAL DISTANCE(TORSION),R=',F10.4,1X,'m.',/)
      END IF
C         ********TYPE5*************
      IF(CASE1.EQ.1.0)THEN
      WRITE(*,*)'I/P PZ'
      READ(*,*)PZ
      WRITE(2,1111)PZ
 1111      FORMAT(
    1   1X,'UNBALANCED FORCE,                             PZ=',F10.4,1X,,'t.',/)
C     *******NOPT=1  UNDAMPED AMPLITUDE
C     *******NOPT=2    DAMPED AMPLITUDE
      GA=9.81
      ZZ=3.141592654
      IF(CASE1.EQ1.0)
      ROZ=SQRT(A/ZZ)
      KZ=4.*G*ROZ/(1.-NU)
          OMGNZ=SQRT(KZ*GA/W)
          FNZ=OMGNZ/(2*ZZ)
      OMEGA=2*ZZ*N/60
      BZ=(1.-NU)*W/(4.*(ROZ**3)*GAMMA)
      ZETAS=0.425/SQRT(BZ)
      IF(NOP1.EQ.0) GO TO 123
      AA=PZ/(KZ*(1.-(OMEGA/OMGNZ)**2))
      AZ=AA*1000
      WRITE(2,13) ROZ,KZ,OMGNZ,FNZ,AZ
   13      FORMAT(///,20X,'********UNDAMPED VERTICAL CASE******',///,
     1   5X,'EQUIVALENT RADIUS,                          ROZ=',F10.3,1X,'m.',/,
     2   5X,'EQUIVALENT SPRING,                           KZ=',F15.5,1X,'t/m',/,
     3   5X,'NATURAL FREQUENCY,                        OMGNZ=',F10.3,1X,'rad/s'
     4   ,/,
     4   5X,'NATURAL FREQUENCY,                          FNZ=',F10.3,1X,'HZ.',/,
     5   5X,'VERTICAL AMPLITUDE,                          AZ=',F15.9,1X,'mm.',/)
      IF(NOP2.EQ.0)
      PIN=OMEGA/OMGNZ
      AAD=PZ/(KZ*SQRT((1.-(PIN)**2)**2+(2*ZETAS*PIN)**2))
      AZD=AAD*1000
      WRITE(2,14) ROZ,BZ,KZ,ZETAS,OMGNZ,FNZ,AZD
   14    FORMAT(///,20X,'********DAMPED VERTICAL CASE*********',///,
     1   5X,'EQIVALENT RADIUS,                    ROZ=',F10.3,1X,'m',/,
     2   5X,'MASS RATIO,                           BZ=',F10.3,/,
     3   5X,'EQUIVALENT SPRING,                           KZ=',F15.5,1X,'t/m',/,
     4   5X,'DAMPING FACTOR,                           ZETAZ=',F10.3,/,
     5   5X,'NATURAL FREQUENCY (UNDAMPED),             OMGNZ=',F10.3,1X,'rad/s',
     6   5X,'NATURAL FREQUENCY (UNDAMPED),               FNZ=',F10.3,1X,'HZ.',/,
     7   5X,'VERTICAL AMPLITUDE,                         AZD=',F15.9,1X,'mm.',/)
```

```
C.......................NOPT=3     UNDAMPED AMLITUDE
C      .....................NOPT=4     DAMPED    AMLITUDE
  124     IF(CASE2.EQ.0)
          ROSI=(2*IZ/ZZ)**0.25
          KSI=(16.*G*ROSI**3.)/3
          OMEGA=2*ZZ*N/60
          OMGNSI=SQRT(KSI/MMZ)
          FNSI=OMGNSI/(2*ZZ)
          IF(NOP3.EQ.0)
          ASI=MZ/(KSI*(1.-(OMEGA/OMGNSI)**2.))
          WRITE(2,15) ROSI,KSI,OMGNSI,FNSI,ASI
   15     FORMAT(///,20X,'**********UNDAMPED TORSIONAL CASE**********'//,
     1    5X,'EQUIVALENT RADIUS.                          ROSI=',F10.3,1X,'m.',/,
     2    5X,'EQUIVALENT SPRING,                           KSI=',F15.5,1X,'t/m',/,
     3    5X,'NATURAL FREQUENCY,                        OMGNSI=',F10.3,1X,'rad/s',
     3    /,
     4    5X,'NATURAL FREQUENCY,                          FNSI=',F10.3,1X,'HZ',/,
     5    5X,'TORSIONAL AMPLITUDE,                         ASI=',F15.9,'rad.',/)
  125     IF(NOP4.EQ.0) GO TO 126
          BSI=MMZ*GA/(GAMMA*ROSI**5)
          ZETASI=0.5/(1.+2.*BSI)
          ASID=MZ/(KSI*SQRT((1.-(OMGA/OMGNSI)**2)**2+
     1    (2.*ZETASI*OMEGA/OMGNSI)**2.))
          WRITE (2,16) ROSI,BSI,KSI,ZETASI,OMGNSI,FNSI,ASID
   16     FORMAT(///,20X,'*********DAMPED TROSIONAL CASE***********',//,
     1    5X,'EQUIVALENT RADIUS,                          ROSI=',F10.3,1X,'m.',/,
     2    5X,'INERTIA RATIO,                               BSI=',F10.3,/,
     3    5X,'EQUIVELENT SPRING,                           KSI=',F15.5,1X,'t/m',/,
     4    5X,'DAMPING FACTOR,                           ZETASI=',F10.3,1X,/,
     5    5X,'NATURAL FREQUENCY (UNDAMPED)              OMGNSI=',F10.3,1X,'rad/s'
     5    ,/,
     6    5X,'NATURAL FREQUENCY (UNDAMPED)                FNSI=',F10.3,1X,'HZ',/,
     7    5X,'TORSIONAL AMPLITUDE,                        ASID=',F15.9,'rad.',/)
C         **************CASE3*******************************************
C         ******TRANSLATION ALONG X-AXIS AND ROTATION ABOUT Y-AXIS*****
C         ***********NOPT=5 UNDAMPED AMPLITUDE
C         ***********NOPT=6   DAMPED AMPLITUDE
  126     IF(CASE3.EQ.0)
      ROX=SQRT(A/ZZ)
      ROPHIY=(IY*4/ZZ)**0.25
      MMOY=MMY+((W/GA)*L**2)
      BPHIY=(3.*(1.-NU)*MMOY*GA)/(8*GAMMA*ROPHIY**5)
      RIY=MMY/MMOY
      KX=32*(1.-NU)*G*ROX/(7-8*NU)
      KPHIY=(8*G*ROPHIY**3)/(3*(1-NU))
      OMGNX=SQRT(KX*GA/W)
      ONPHIY=SQRT(KPHIY/MMOY)
      W3=SQRT(((OMGNX**2+ONPHIY**2)/RIY)**2.-4.*(OMGNX**2)*(ONPHIY**2)
      1   /RIY)
      W6=(OMGNX**2+ONPHIY**2)/RIY
      X7=(W6+W3)/2.
      X8=(W6-W3)/2.
      ON1=SQRT(X7)
      ON2=SQRT(X8)
      FN1=ON1/(2*ZZ)
      FN2=ON2/(2*ZZ)
          WRITE(*,*) FN1,FN2
      OMEGA=2*ZZ*N/60
      IF(NOP5.EQ.0)
      Y5=(OMEGA**4-(OMEGA**2)*((ONPHIY**2+OMGNX**2)/RIY)+OMGNX**2*
      1   ONPHIY**2/RIY)
      DELTA=ABS(Y5)
      M=W/GA
      PINA=(PX*L*OMGNX**2)/(DELTA*MMY)
      MURA=(PX/M*MMY)*(-MMY*OMEGA**2+KPHIY+L**2*KX)/DELTA
      AO=(MY/MMY)*(OMGNX**2/DELTA)+MURA
          AX=AO*1000
          APHI1=(MY/MMY)*((OMGNX**2-OMEGA**2)/DELTA)+PINA
          WRITE(*,*) APHI1
      WRITE(2,17) ROX ,ROPHIY,BPHIY,KX,KPHIY,OMGNX,ONPHIY,ON1,FN1
      1   ON2,FN2,AX,APHI1
   17     FORMAT(//,15X,'*****UNDAMPED SLIDING AND ROCKING CASE*******
```

```
     1    **********',//,35X,'*****X-Z PLANE******',//,
     2    5X,'EQUIVELENT RADIUS,                          ROX=',F12.3,1X,'m.',/,
     3    5X,'EQUIVELENT RADIUS,                       ROPHIY=',F12.3,1X,'m.',/,
     4    5X,'MASS RATIO,                               BPHIY=',F10.3,/,
     5    5X,'EQUIVELENT SPRING,                           KX=',F15.5,1X,'t/m',/,
     6    5X,'EQUIVELENT SPRING,                        KPHIY=',F15.5,1X,'t/m',/,
     7    5X,'NATURAL FREQUENCY,                        OMGNX=',F10.3,1X,'rad/s'
     8    ,/,
     8    5X,'NATURAL FREQUENCY,                       ONPHIY=',F15.5,1X,'rad/s'
     2    ,/,
     9    5X,'COUPLED NATURAL FREQUENCY,                  ON1=',F10.3,1X,'rad/s'
     9    ,/,
     @    5X,'COUPLED NATURAL FREQUENCY,                  FN1=',F10.3,1X,'HZ.',/,
     #    5X,'COUPLED NATURAL FREQUENCY,                  ON2=',F10.3,1X,'rad/s'
     #    ,/,
    $    5X,'COUPLED NATURAL FREQUENCY,                   FN2=',F10.3,1X,'HZ.',/,
     %    5X,'SLIDING AMPLITUDE,                           AX=',F15.9,1X,'mm',/,
     &    5X,'ROCKING AMPLITUDE,                         APHI=',F15.9,1X,'rad',/)
 127      IF(NOP6.EQ.0)
      BX=((7-8*NU)*W)/(32*GAMMA*(ROX**3)*(1-NU))
      ZETAX=.2785/(SQRT(BX))
      ZIPHIY=0.15/((1.+BPHIY)*SQRT(BPHIY))
      U1=(ONPHIY**2+OMGNX**2-4.*ZIPHIY*ZETAX*OMGNX*ONPHIY)/RIY
      U2=(OMEGA**4-OMEGA**2*U1+OMGNX**2*ONPHIY**2/RIY)**2
      U3=(ZETAX*OMGNX*OMEGA*(ONPHIY**2-OMEGA**2)/RIY)
      U4=ZIPHIY*ONPHIY*OMEGA*(OMGNX**2-OMEGA**2)/RIY
      U5=4*(U3+U4)**2
      DELETE=SQRT(U2+U5)
      M=W/GA
      PIN=(PX/M*MMY)*((-MMY*OMEGA**2+KPHIY+L**2*KX)**2+4*OMEGA**2*(ZI
      1   PHIY*(SQRT(KPHIY*MMYO))+L**2*ZETAX*SQRT(KX*M))**2)**0.25/DELETE
      MUR=(PX*L/MMY)*SQRT(OMGNX**2+4*ZETAX*OMEGA**2)*OMGNX/DELETE
      AXX=(MY/MMOY)*(SQRT(OMGNX**4+4*ZETAX**2*OMGNX**2)/DELETE)+PIN
      AXD=AXX*1000
       APHIDI=(MY/MMY)*(SQRT((OMGNX**2-OMEGA**2)**2+(2*ZETAX*OMGNX*OMEGA
      1  )**2)/DELETE)+MUR
      WRITE(2,18) ROX,ROPHIY,BX,BPHIY,KX,KPHIY,ZETAX,ZIPHIY,OMGNX,
      1   ONPHIY,ON1,FN1,ON2,FN2,AXD,APHIDI
  18      FORMAT(///,20X,'******DAMPED SLIDING AND ROCKING CASE*******
      1   ****',//,37X,'*****************X-Z PLANE***********',//,
      2   5X,'EQUIVELENT RADIUS,                      ROX=',F10.3,1X,'m.',/,
      3   5X,'EQUIVELENT RADIUS,                   ROPHIX=',F10.3,1X,'m.',/,
      4   5X,'MASS RATIO,                              BX=',F10.3,/,
      5   5X,'INERTIA RATIO,                        BPHIY=',F10.3,/,
      6   5X,'EQUIVELENT SPRING,                       KX=',F15.5,1X,'t/m',/,
      7   5X,'EQUIVELENT SPRING,                    KPHIY=',F15.5,1X,'t/m',/,
      8   5X,'DAMPING FACTOR,                       ZETAX=',F10.3,/,
      9   5X,'DAMPING FACTOR,                      ZIPHIY=',F10.3,/,
      #   5X,'NATURAL FREQUENCY,                    OMGNX=',F10.3,1X,'rad/s',/,
      $   5X,'UNDAPMED NATURAL FREQUENCY,          ONPHIY=',F10.3,1X,'rad/s',/,
      @   5X,'COUPLED NATURAL FREQUENCY,              ON1=',F10.3,1X,'rad/s',/,
      !   5X,'COUPLED NATURAL FREQUENCY,              FN1=',F10.3,1X,'HZ.',/,
      +   5X,'COUPLED NATURAL FREQUENCY,              ON2=',F10.3,1X,'rad/s',/,
      &   5X,'COUPLED NATURAL FREQUENCY,              FN2=',F10.3,1X,'HZ.',/,
      %   5X,'SLIDING AMPLITUDE,                      AXD=',F15.9,1X,'mm.',/,
      -   5X,'ROCKING AMPLITUDE,
C         *******TRANSLATION ALONG Y-AXIS AND ROTATION ABOUT X-AXIS*****
C         *******NOPT=7     UNDAMPED AMPLITUDE********
C         *********NOPT=8        DAMPED AMPLITUDE********
 131      IF(CASE4.EQ.0)
      ROY=SQRT(A/ZZ)
      ROPHIX=(IX*4/ZZ)**0.25
      MMOX=MMX+((W/GA)*L**2)
      BPHIX=(3.*(1.-NU)*MMOX*GA)/(8*GAMMA*ROPHIX**5)
      RIX=MMX/MMOX
      KY=32*(1.-NU)*G*ROY/(7-8*NU)
      KPHIX=(8*G*ROPHIX**3)/(3*(1-NU))
          OMGNY=SQRT (KY*GA/W)
          ONPHIX=SQRT(KPHIX/MMOX)
          X3=((ONPHIX**2+OMGNY**2)/RIX)**2
          X4=((4*(OMGNY**2)*(ONPHIX**2))/RIX)
          X5=SQRT(X3-X4)
```

```
      X6=(OMGNY**2+ONPHIX**2)/RIX
      X7=(0.5)*(X6+X5)
      X8=(0.5)*(X6-X5)
      ON1=SQRT(X7)
      ON2=SQRT(X8)
      FN1=ON1/(2*ZZ)
      FN2=ON2/(2*ZZ)
      OMEGA=2*ZZ*N/60.
      WRITE (*,*) OMGNY,ONPHIX
      IF(NOP5.EQ.0) GO TO 427
      Y4=(OMEGA**4-OMEGA**2*
     1 (ONPHIX**2+OMGNY**2)/RIX+(OMGNY**2*ONPHIX**2/RIX))
      DELTA=ABS(Y4)
      ATA=(PY/(M*MMX))*((-MMX*OMEGA**2+KPHIX+L**2*KY)/DELTA)
      ATAV=(PY*L*OMGNY**2)/(MMX*DELTA)
      AQ=(MX/MMX)*(OMGNY**2/DELTA)+ATA
      AY=AQ*1000
      APHI2=(MX/MMX)*((OMGNY**2-OMEGA**2)/DELTA)+ATAV
      WRITE(2,77)ROY,ROPHIX,BPHIX,KY,KPHIX,OMGNY,ONPHIX,ON1,FN1
     1 ON2,FN2,AY,APHI2
 77   FORMAT(/,20X,'*********UNDAMPED SLIDING AND ROCKING CASE****'
     1 ,/,25X,'****Y-Z PLANE****',/,
     2 5X,'EQUIVELENT RADIUS,                        ROY=',F12.3,1X,'m.',/,
     3 5X,'EQUIVELENT RADIUS,                     ROPHIX=',F12.3,1X,'m.',/,
     4 5X,'MASS RATIO,                             BPHIX=',F10.3,/,
     5 5X,'EQUIVELENT SPRING,                         KY=',F15.5,1X,'t/m',/,
     6 5X,'EQUIVELENT SPRING,                      KPHIX=',F15.5,1X,'t/m',/,
     7 5X,'NATURAL FREQUENCY,                      OMGNY=',F10.3,1X,'rad/s'
     8 5X,'NATURAL FREQUENCY,                     ONPHIX=',F10.3,1X,'rad/s'
     9 5X,'COUPLED NATURAL FREQUENCY,                ON1=',F10.3,1X,'rad/s'
     * 5X,'                                          FN1=',F10.3,1X,'HZ',/,
     $ 5X,'COUPLED NATURAL FREQUENCY,                ON2=',F10.3,1X,'rad/s
     & 5X,'                                          FN2=',F10.3,1X,'HZ',/,
     & 5X,'SLIDING AMPLITUDE,                         AY=',F15.9,1X,'mm.',/,
     @ 5X,'ROCKING AMPLITUDE,                      APHI2=',F15.9,1X,'rad.',/
427   IF(NOP8.EQ.0)
    BY=((7-8*NU)*W)/(32*GAMMA*(ROY**3)*(1-NU))
      ZETAY=.2785/(SQRT(ABS(BY)))
      ZIPHIX=0.15/((1.+BPHIX)*SQRT(BPHIX))
     U1=(ONPHIX**2+OMGNY**2)/RIX-(4.*ZIPHIX*ZETAY*OMGNY*ONPHIX/RIX)
    U2=((OMEGA**4)-(OMEGA**2*U1)+(OMGNY**2*ONPHIX**2/RIX))**2
     U3=(ZETAY*OMGNY*OMEGA*(ONPHIX**2-OMEGA**2)/RIX)
     U4=ZIPHIX*ONPHIX*OMEGA*(OMGNY**2-OMEGA**2)/RIX
    DELETE=SQRT(U2+U5)
    SUK=(PY*L/MMX)*OMGNY*((OMGNY**2+4*ZETAY*OMEGA**2)**0.5)/DELETE
     SU=(PY/(M*MMX))*(((-MMX*OMEGA**2+KPHIX+L**2*KY)**2+4*OMEGA**2*(ZI
    1 HIX*SQRT(KPHIX*MMOX)+L**2*ZETAY*SQRT(KY*M))**2)**0.5)/DELETE
    AQD=(MX/MMX)*(SQRT(OMGNY**4+(4*ZETAY**2*OMGNY**2))/DELETE)+SU
    AYD=AQD*1000
    APHIDE=(MX/MMX)*(SQRT((OMGNY**2-OMEGA**2)**2+(2*ZETAY*OMGNY*
    1 OMEGA)**2)/DELETE)+SUK
    WRITE(2,58) ROY,ROPHIX,BY,BPHIX,KY,KPHIX,ZETAY,ZIPHIX,OMGNY,
    1 ONPHIX,ON1,FN1,ON2,FN2,AYD,APHIDE
     FORMAT(/,20X,'********DAMPED SLIDING AND ROCKING CASE******'
     1 ,/,25X,'*******Y-Z PLANE******',/,
     2 5X,'EQUIVELENT RADIUS,              ROY=',F10.3,1X,'m',/,
     3 5X,'EQUIVELENT RADIUS,           ROPHIX=',F10.3,1X,'m.',/,
     4 5X,'MASS RATIO,                      BY=',F10.3,/,
     5 5X,'INERTIA RATIO,                BPHIX=',F10.3,/,
     6 5X,'EQUIVELENT SPRING,               KY=',F15.5,1X,'t/m',/,
     7 5X,'EQUIVELENT SPRING,            KPHIX=',F15.5,1X,'t/m',/,
     8 5X,'DAMPING FACTOR,               ZETAY=',F10.3,/,
     9 5X,'DAMPING FACTOR,              ZIPHIX=',F10.3,/,
     # 5X,'NATURAL FREQUENCY,            OMGNY=',F10.3,1X,'rad/s',/,
     $ 5X,'UNDAPMED NATURAL FREQN       ONPHIX=',F10.3,1X,'rad/s',/,
     @ 5X,'COUPLED NATURAL FREQUENCY,      ON1=',F10.3,1X,'rad/s',/,
     ! 5X,'COUPLED NATURAL FREQUENCY,      FN1=',F10.3,1X,'HZ',/,
     + 5X,'COUPLED NATURAL FREQUENCY,      ON2=',F10.3,1X,'rad/s',/,
     & 5X,'COUPLED NATURAL FREQUENCY,      FN2=',F10.3,1X,'HZ.',/,
     6 5X,'SLIDING AMPLITUDE,              AYD=',F15.9,1X,'mm.',/,
     7 5X,'ROCKING AMPLITUDE,           APHIDE=',F15.9,1X,'rad',/
C     ************************************************************
```

```
      WRITE(2,7901)
 7901       FORMAT(///,72('*'),/,72('*'),///)
      IF(NOP2.EQ.1.0.OR.NOP4.EQ.1.0.OR.NOP6.EQ.1.0.OR.NOP8.EQ.1.0)THEN
C     ********************TOTAL DAMPED AMPLLITUDE****************
C     MAX.HORIZANTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
      ASID=ASID*R*1000
C        MAX.VERTICAL AMPLITUDE DUE TO PZ AND (PX+MY)
      AVD1=AZD+LX*APHIDI*1000
C        MAX.VERTICAL AMPLITUDE DUE TO PZ AND (PY+MX)
         AVD2=AZD+LY*APHIDE*1000
C        MAX HORIZANTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND MY
         AHD1=AXD+APHIDI*HH*1000
C        MAX HORIZANTAL AMPLITUDE DUE TO COMBINED ACTION OF PY AND MX
      AHD2=AYD+APHIDE*HH*1000
      WRITE(2,2234) ASID,AHSID,AVD1,AVD2,AHD1,AHD2
 2234    FORMAT(20X,'***************TOTAL DAMPED AMPLITUDE***********',/,
     @   5X,'MAX TORSIONAL AMPLITUDE,              ASID=',F15.9,1X,'rad.',/
     1   5X,'MAX HORIZANTAL AMPLITUDE,(TORSIONAL)AHSID=',F15.9,1X,'mm.',/
     2   5X,'MAX VERTICAL AMPLITUDE, (PZ,PX+MY)   AVD1=',F15.9,1X,'mm.',/,
     3   5X,'MAX VERTICAL AMPLITUDE,  (PZ,PY+MX)   AVD2=',F15.9,1X,'mm.',/,
     4   5X,'MAX HORIZONTAL AMPLITUDE,(PX AND PY) AHD1=',F15.9,1X,'mm.',/
     5   5X,'MAX HORIZONTAL AMPLITUDE,(PY AND MX) AHD2=',F15.9,1X,'mm.'/,
          END IF
        IF (NOP1.EQ.1.0.OR.NOP3.EQ.1.0.OR.NOP5.EQ.1.0.OR.NOP7.EQ.1.0)THEN
C        ****************************************************************
C        **************TOTAL UNDAMPED AMPLITUDE**************************
C        MAX HORIZONTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
         AHSI=ASI*R
C        MAX VERTICAL DUE TO PZ AND PX+MY
         AVI=AZ+APHI1*LX*1000
C        MAX VERTICAL AMPLITUDE DUE TO PZ AND PY+MX
         AV2=AZ+APHI2*LY*1000
C        MAX HORIZONTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND  MY
         AH1=AX+APHI1*HH*1000
C        MAX HORIZONTAL MPLITUDE DUE TO COMBINED ACTION OF PY AND MX
         AH2=AY+APHI2*HH*1000
         WRITE(2,2567)ASI,AHSI,AV1,AV2,AH1,AH2,
 2567    FORMAT(20X,'**********TOTAL UNDAMPED AMPLITUDE**********',//,
     #   5X,'MAX TORSIONAL AMPLITUDE,              ASI=',F15.9,1X,'RAD',//,
     1   5X,'MAX HORIZONTAL AMPLITUDE,(TORSIONAL)AHSI=',F15.9,1X,'mm.',/,
     2   5X,'MAX VERTICAL AMPLITUDE,(PZ,PX+MY)    AV1=',F15.9,1X,'mm.',//,
     3   5X,'MAX VERTICAL AMPLITUDE,(PZ,PY+MX)    AV2=',F15.9,1X,'mm.',//,
     4   5X,'MAX HORIZONTAL AMPLITUDE,(PX,MY)     AH1=',F15.9,1X,'mm.',//,
     5   5X,'MAX HORIZONTAL AMPLITUDE,(PY,MX)     AH2=',F15.9,'mm.',//)
       *****************************************************************
C      ***COMPARISON OF ACTUAL SOIL PRESSURE WITH ALLOWABLE SOIL PRESSURE
C      ACTUAL SOIL PRESSURE
       IF(QPA.LE.QP) GO TO 4455
         WRITE (2,4445) QP,QPA
 4445    FORMAT(68('*'),//,
     1   5X,'SOIL PERSSURE,QP='F10.4,1X,'t/m.sg.'1X,'AND SMALLER THAN
     2   ',/,5X,'THE ALLOWABLE SOIL PRESSURE QPA=',
     3   F10.4,1X,'t/m.sg.',//,68('*'))
 4455    WRITE(2,4466) QP,QPA
 4466    FORMAT(68('*'),//,
     1   5X,'SOIL PRESSURE,QP=',F10.4,1X,'T\M2.',1X,'AND MORE THAN',//,
     2   5X,'THE ALLOWABLE SOIL PRESSURE QPA=',F10.4,1X,'T\M2.',//,
     3   68('*,*'))
         STOP
         END
```

APPENDIX-B

```
C        COMPUTER PROGRAM FOR DESIGN OF A BLOCK FOUNDATION FOR
C        DIFFERENT MODES OF VIBRATION USING LINEAE ELASTIC
```

```
      WRITE(2,7901)
 7901      FORMAT(///,72('*'),/,72('*'),///)
      IF(NOP2.EQ.1.0.OR.NOP4.EQ.1.0.OR.NOP6.EQ.1.0.OR.NOP8.EQ.1.0)THEN
C     ********************TOTAL DAMPED AMPLLITUDE*****************
C     MAX.HORIZANTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
      ASID=ASID*R*1000
C        MAX.VERTICAL AMPLITUDE DUE TO PZ AND (PX+MY)
      AVD1=AZD+LX*APHIDI*1000
C        MAX.VERTICAL AMPLITUDE DUE TO PZ AND (PY+MX)
         AVD2=AZD+LY*APHIDE*1000
C        MAX HORIZANTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND MY
         AHD1=AXD+APHIDI*HH*1000
C        MAX HORIZANTAL AMPLITUDE DUE TO COMBINED ACTION OF PY AND MX
      AHD2=AYD+APHIDE*HH*1000
      WRITE(2,2234) ASID,AHSID,AVD1,AVD2,AHD1,AHD2
 2234    FORMAT(20X,'***************TOTAL DAMPED AMPLITUDE***********',/,
      @  5X,'MAX TORSIONAL AMPLITUDE,              ASID=',F15.9,1X,'rad.',/
      1  5X,'MAX HORIZANTAL AMPLITUDE,(TORSIONAL)AHSID=',F15.9,1X,'mm.',/
      2  5X,'MAX VERTICAL AMPLITUDE, (PZ,PX+MY)   AVD1=',F15.9,1X,'mm.',/,
      3  5X,'MAX VERTICAL AMPLITUDE, (PZ,PY+MX)   AVD2=',F15.9,1X,'mm.',/,
      4  5X,'MAX HORIZONTAL AMPLITUDE,(PX AND PY) AHD1=',F15.9,1X,'mm.',/
      5  5X,'MAX HORIZONTAL AMPLITUDE,(PY AND MX) AHD2=',F15.9,1X,'mm.'/,
           END IF
        IF (NOP1.EQ.1.0.OR.NOP3.EQ.1.0.OR.NOP5.EQ.1.0.OR.NOP7.EQ.1.0)THEN
C        ****************************************************************
C        *************TOTAL UNDAMPED AMPLITUDE***************************
C        MAX HORIZONTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
         AHSI=ASI*R
C      . MAX VERTICAL DUE TO PZ AND PX+MY
         AVI=AZ+APHI1*LX*1000
C        MAX VERTICAL AMPLITUDE DUE TO PZ AND PY+MX
         AV2=AZ+APHI2*LY*1000
C        MAX HORIZONTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND  MY
         AH1=AX+APHI1*HH*1000
C        MAX HORIZONTAL MPLITUDE DUE TO COMBINED ACTION OF PY AND MX
         AH2=AY+APHI2*HH*1000
         WRITE(2,2567)ASI,AHSI,AV1,AV2,AH1,AH2,
 2567    FORMAT(20X,'**********TOTAL UNDAMPED AMPLITUDE***********',//,
      #  5X,'MAX TORSIONAL AMPLITUDE,              ASI=',F15.9,1X,'RAD',//,
      1  5X,'MAX HORIZONTAL AMPLITUDE,(TORSIONAL)AHSI=',F15.9,1X,'mm.',/,
      2  5X,'MAX VERTICAL AMPLITUDE,(PZ,PX+MY)     AV1=',F15.9,1X,'mm.',//,
      3  5X,'MAX VERTICAL AMPLITUDE,(PZ,PY+MX)     AV2=',F15.9,1X,'mm.',//,
      4  5X,'MAX HORIZONTAL AMPLITUDE,(PX,MY)      AH1=',F15.9,1X,'mm.',//,
      5  5X,'MAX HORIZONTAL AMPLITUDE,(PY,MX)      AH2=',F15.9,'mm.',//)
       **************************************************************
C      ***COMPARISON OF ACTUAL SOIL PRESSURE WITH ALLOWABLE SOIL PRESSURE
C      ACTUAL SOIL PRESSURE
       IF(QPA.LE.QP) GO TO 4455
         WRITE (2,4445) QP,QPA
 4445    FORMAT(68('*'),//,
      1  5X,'SOIL PERSSURE,QP='F10.4,1X,'t/m.sq.'1X,'AND SMALLER THAN
      2  ',/,5X,'THE ALLOWABLE SOIL PRESSURE QPA=',
      3  F10.4,1X,'t/m.sq.',//,68('*'))
 4455    WRITE(2,4466) QP,QPA
 4466    FORMAT(68('*'),//,
      1  5X,'SOIL PRESSURE,QP=',F10.4,1X,'T\M2.',1X,'AND MORE THAN',//,
      2  5X,'THE ALLOWABLE SOIL PRESSURE QPA=',F10.4,1X,'T\M2.',//,
      3  68('*,*'))
         STOP
         END
```

APPENDIX-B

```
C        COMPUTER PROGRAM FOR DESIGN OF A BLOCK FOUNDATION FOR
C        DIFFERENT MODES OF VIBRATION USING LINEAE ELASTIC
C        WEIGHTLESS SPRING APPROACH(RAJEEV)
      IMPLICIT REAL(A-Z)
      INTEGER I
      CHARACTER*1 Q,Y,TITLE(120)
      CHARACTER*14 FILOP
      DATA CASE1,CASE2,CASE3,CASE4/0.,0.,0.,0./
      DATA Y/'Y'/
      WRITE(*,*)'I/P O/P-DATA/FILE NAME'
      READ(*,915)FILEOP
         OPEN (UNIT=1,FILE='R1.DAT',STATUS='OLD')
         OPEN (UNIT=2,FILE='R2.OUT',STATUS='NEW')
      WRITE(*,*)'I/P PROBLEM TITLE(I)'
      READ(*,6669) (TITLE(I),I=1,120)
 6668    FORMAT(10X,'TITLE=',120A1,/,/,/,72('*'),//)
 6669    FORMAT(120A1)
      WRITE(*,*) 'DO YOU WANT CASE 1(TRANSLATION-Z)?'
      READ(*,914)Q
  914    FORMAT(A1)
      IF(Q.EQ.Y) CASE1=1.0
      WRITE(*,*) 'DO YOU WANT CASE 2(TORSIONAL-Z)?'
      READ(*,914)Q
      IF(Q.EQ.Y) CASE2=1.
      WRITE(*,*) 'DO YOU WANT CASE 3(TRANSLATION-X,ROTATION-Y)?'
      READ(*,914)Q
      IF(Q.EQ.Y) CASE3=1
      WRITE(*,*) 'DO YOU WANT CASE 4(TRANSLATION-Y,ROTATION-X)?'
      READ(*,914)Q
      IF(Q.EQ.Y) CASE4=1
C        ***********************************************
C        VARIABLE INPUT SECTION
C        ************************************************
C        ******TYPE*******
         WRITE(2,1144)
 1144    FORMAT(15X,15('*'),'INPUT VARIBLES:',15('*'),/72('*'),///)
         WRITE(*,*)'I/P A2'
      READ(*,*)A2
      WRITE(*,*)'I/P W'
      READ(*,*)W
      WRITE(2,1155) A2,W
 1155    FORMAT(
     1   1X,'AREA OF THE FOUNDATION,                A2=',F10.4,1X,'sq.m.',
     5   /,
     2   1X,'WEIGHT OF THE FOUNDATION',/,
     3   1X,'(INCLUDING WEIGHT OF THE MACHINE),    W=',F10.4,1X,'t.'/)
         WRITE(*,*)'I/P GAMMA'
         READ(*,*)GAMMA
         WRITE(*,*)'I/P G'
         READ(*,*)G
         WRITE(*,*)'I/P N'
         READ(*,*)N
      WRITE(*,*)'I/P QPA'
      READ(*,*) QPA
      WRITE(*,*)'I/P NU'
      READ(*,*) NU
         WRITE(2,1112) GAMMA,G,N,QPA,NU
 1112    FORMAT(
     1   1X,'UNIT WEIGHT OF THE SOIL,          GAMMA=',F10.4,1X,'t/m3.',
     8   /,
     2   1X,'DYNAMIC SHEAR MODULAS,                G=',F10.2,1X,'t/m2.',
     7   /,
     3   1X,'OPERATING SPEED OF MACHINE,           N=',F10.2,1X,'rpm',/,
     4   1X,'ALLOWABLE SOIL PRESSURE,            QPA=',F10.2,1X,'t/m2.',
     6   /,
     5   1X,'POISSONS RATIO,                      NU=',F10.3/)
C        ********TYPE2************
      IF(CASE4.EQ.1.0)THEN
      WRITE(*,*)'I/P IX'
```

```
      READ(*,*)  IX
      WRITE(*,*)'I/P MX'
      READ(*,*)MX
      WRITE(*,*)'I/P MMX'
      READ(*,*)MMX
      WRITE(*,*)'I/P PY'
      READ(*,*)PY
      WRITE(*,*)'I/P LY'
      READ(*,*)LY
      WRITE(2,1166) IX,MX,MMX,PY,LY
 1166       FORMAT(
     1   1X,'MOMENT OF INERTIA,                          IX=',F10.4,1X,'m4',/,
     2   1X,'UNBALANCED MOMENT,                          MX=',F10.4,1X,'t-m.',/,
     3   1X,'POLAR MASS MOMENT OF INERTIA,              MMX=',F10.4,1X,'t-m.sec2'
     %   ,/,
     4   1x,'UNBALANCED FORCE,                           PY=',F10.4,1X,'t.',/,
     5   1X,'MAXIMUM DISTANCE OF THE POINT',/,
     6   1X,'FROM THE AXIS OF ROCKING(HORIZ.),           LY=',F10.4,1X,'m.',/)
          END IF
C     *******TYPE6*********
      IF(CASE4.EQ.1.0.OR.CASE3.EQ.1.0)THEN
      WRITE(*,*)'I/P L'
      READ(*,*)L
      WRITE(*,*)'I/P HH'
      READ(*,*)HH
      WRITE(2,1177)L,HH
 1177       FORMAT(
     1   1X,'HEIGHT OF THE CENTRE OF GRAVITY,        L=',F10.4,1X,'m.',/,
     2   1X,'HEIGHT OF THE TOP OF THE FOUNDATION, H=',F10.4,1X,'m.',/)
      END IF
C     ********TYPE3*********
      IF(CASE3.EQ.1.0)THEN
      WRITE(*,*)'I/P IY'
      READ(*,*)IY
      WRITE(*,*)'I/P MY'
      READ(*,*) MY
      WRITE(*,*)'I/P MMY'
      READ(*,*)MMY
      WRITE(*,*)'I/P PX'
      READ(*,*)PX
      WRITE(*,*)'I/P LX'
      READ(*,*)LX
      WRITE(2,1188) IY,MY,MMY,PX,LX
 1188       FORMAT(
     1   1X,'MOMENT OF INERTIA,                           IY=',F10.4,1X,'m4.',/,
     2   1X,'UNBALANCED MOMENT,                           MY=',F10.4,1X,'t-m',/,
     3   1X,'POLAR MASS MOMENT OF INERTIA,              MMY=',F10.4,1X,'t-m.sec2
     &   ',/,
     4   1X,'UNBALANCED FORCE,                              PX=',F10.4,1X,'t.',/
     5   1X,'MAXIMUM DISTANCE OF THE POINT',/,
     6   1X,'FROM THE AXIS OF ROCKING(HORIZ.),            LX=',F10.4,1X,'m.'/)
      END IF
C     ************TYPE 4**********
      IF (CASE2.EQ.1.0)THEN
      WRITE(*,*)'I/P IZ'
      READ(*,*)IZ
      WRITE(*,*)'I/P MZ'
      READ(*,*)MZ
      WRITE(*,*)'I/P MMZ'
      READ(*,*) MMZ
      WRITE(*,*)'I/P R'
      READ(*,*)R
      WRITE(2,1100) IZ,MZ,MMZ,R
 1100       FORMAT(
     1   1X,'MOMENT OF INERTIA                            IZ=',F10.4,1X,'m4.',/,
     2   1X,'UNBALANCED MOMENT,                           MZ=',F10.4,1X,'t-m.'/,
     3   1X,'POLAR MASS MOMENT OF INERTIA               MMZ=',F10.4,1X,'t-m.sec2
     6   ',/,
     4   1X,'MAXIMUM HORIZANTAL DISTANCE(TORSION), R=',F10.4,1X,'m.',/)
      END IF
C        ********TYPE5************
      IF(CASE1.EQ.1.0)THEN
```

```
      WRITE(*,*)'I/P PZ'
      READ(*,*)PZ
      WRITE(2,1111)PZ
 1111      FORMAT(
     1   1X,'UNBALANCED FORCE,                          PZ=',F10.4,1X,,'t.',/)
      END IF
C     **********************************
C         *********TYPE 7***************
          IF(CASE1.EQ.1.0.OR.CASE2.EQ.1.0.OR.CASE3.EQ.1.0.OR.CASE4.EQ.1.0)
          IF(A2.GT.A1)CU=(1.13*(2*G)/(1-NU))/SQRT(A1)
          IF(A2.LE.A1)CU=(1.13*(2*G)/(1-NU))/SQRT(A2)
          WRITE(2,6000) CU
 6000     FORMAT(
     1    1X,'COEFF OF UNIF COMPRESSION,           CU=',F10.4,1X,'t/m3',/)
          END IF
C         ********************************
C     **********CASE1***************
C     *******TRANSLATION ALONG Z-AXIS
      GA=9.81
      IF(CASE1.EQ.0) GO TO 124
          KZ=CU*A2
          OMGNZ=SQRT(KZ*GA/W)
          FNZ=OMGNZ/(2*ZZ)
      OMEGA=2*ZZ*N/60
      AA=PZ/(KZ*(1.-(OMEGA/OMGNZ)**2))
      AZ=AA*1000
      WRITE(2,13) KZ,OMGNZ,FNZ,AZ
   13      FORMAT(///,20X,'********UNDAMPED VERTICAL CASE******',///,
     2    5X,'EQUIVALENT SPRING,                    KZ=',F15.5,1X,'t/m',/,
     3    5X,'NATURAL FREQUENCY,                 OMGNZ=',F10.3,1X,'rad/s',
     4    5X,'NATURAL FREQUENCY,                   FNZ=',F10.3,1X,'HZ.',/,
     5    5X,'VERTICAL AMPLITUDE,                   AZ=',F15.9,1X,'mm.',/)
C       ***************************************************************
C       .......................CASE TWO...............................
C       .......................TORSIONAL VIBRATION ABOUT Z-AXIS.........
4    IF(CASE2.EQ.0) GO TO 126
          CSHI=0.75*CU
          KSI=CSHI*IZ
          OMEGA=2*ZZ*N/60
          OMGNSI=SQRT(KSI/MMZ)
          FNSI=OMGNSI/(2*ZZ)
          ASI=MZ/(KSI*(1.-(OMEGA/OMGNSI)**2.))
          WRITE(2,15) CSHI,KSI,OMGNSI,FNSI,ASI
   15     FORMAT(///,20X,'**********UNDAMPED TORSIONAL CASE**********'//,
     1    5X,'COEFF.OF NON UNIF.SHEAR             CSHI=',F10.4,1X,'t/m3',/,
     2    5X,'EQUIVALENT SPRING,                   KSI=',F15.5,1X,'t/m',/,
     3    5X,'NATURAL FREQUENCY,                OMGNSI=',F10.3,1X,'rad/s',
     6    /,
     4    5X,'NATURAL FREQUENCY,                  FNSI=',F10.3,1X,'HZ.',/,
     5    5X,'TORSIONAL AMPLITUDE,                 ASI=',F15.9,'rad.',/)
C         **************CASE3*****************************************
C         ******TRANSLATION ALONG X-AXIS AND ROTATION ABOUT Y-AXIS*****
  126     IF(CASE3.EQ.0) GO TO 131
      CTAX=0.5*CU
      CPHIY=2*CU
      MMOY=MMY+((W/GA)*L**2)
      RIY=MMY/MMOY
      KX=CTAX*A2
      KPHIY=CPHIY*IY-W*L
      OMGNX=SQRT(KX*GA/W)
      ONPHIY=SQRT(KPHIY/MMOY)
      W3=((OMGNX**2+ONPHIY**2)/RIY)**2.
          W4=((4.*(OMGNX**2)*(ONPHIY**2))/RIY)
          W5=SQRT(W3-W4)
      W6=(OMGNX**2+ONPHIY**2)/RIY
      X7=(W6+W5)/2.
      X8=(W6-W5)/2.
      ON1=SQRT(X7)
      ON2=SQRT(X8)
      FN1=ON1/(2*ZZ)
      FN2=ON2/(2*ZZ)
          WRITE(*,*) ON1,ON2,MMY
```

```
      OMEGA=2*ZZ*N/60
        M=W/GA
        Y5=M*MMY*(ON1**2-OMEGA**2)*(ON2**2-OMEGA**2)
        WRITE(*,*) OMEGA,Y5
        DELTA=ABS(Y5)
        WRITE (*,*) DELTA
        MURA=PX*(KX*L)/DELTA
        AQ=(MY/DELTA)*(KX*L)+PX*((KPHIY+KX*L**2)-(MMY*OMEGA**2))/DELTA
        AX=AQ*1000
        APHI1=(MY/DELTA)*(KX-M*OMEGA**2)+MURA
      WRITE(2,17) CTAX,CPHIY,KX,KPHIY,OMGNX,ONPHIY,ON1,FN1,
     1  ON2,FN2,AX,APHI1
   17   FORMAT(//,15X,'*****UNDAMPED SLIDING AND ROCKING CASE***,
     1  **********',//,35X,'*****X-Z PLANE******',//,
     2  5X,'COEFF.OF UNIFORM SHEAR,                   CTAX=',F10.4,1X,'t/m3',/,
     3  5X,'COEFF.OF NONUNIFORM COMP.,               CPHIY=',F10.4,1X,'t/m3',/,
     4  5X,'EQUIVELENT SPRING,                          KX=',F15.5,1X,'t/m',/,
     5  5X,'EQUIVELENT SPRING,                       KPHIY=',F15.5,1X,'t/m',/,
     6  5X,'NATURAL FREQUENCY,                       OMGNX=',F10.3,1X,'rad/s',
     +  /,
     7  5X,'NATURAL FREQUENCY,                      ONPHIY=',F10.3,1X,'rad/s',
     @  /,
     8  5X,'COUPLED NATURAL FREQUENCY,                 ON1=',F10.3,1X,'rad/s',
     1  /,
     @  5X,'COUPLED NATURAL FREQUENCY,                 FN1=',F10.3,1X,'HZ.',/,
     #  5X,'COUPLED NATURAL FREQUENCY,                 ON2=',F10.3,1X,'rad/s',
     %  /,
     $  5X,'COUPLED NATURAL FREQUENCY,                 FN2=',F10.3,1X,'HZ.',/,
     %  5X,'SLIDING AMPLITUDE,                          AX=',F15.9,1X,'mm.',/,
     &  5X,'ROCKING AMPLITUDE,                       APHI1=',F15.9,1X,'rad',/)
  128 CONTINUE
C       *********************CASE 4****************************************
C       *******TRANSLATION ALONG Y-AXIS AND ROTATION ABOUT X-AXIS******
  131   IF(CASE4.EQ.0) GO TO 431
      CTAY=0.5*CU
      CPHIX=2*CU
      MMOX=MMX+((W/GA)*L**2)
      RIX=MMX/MMOX
        KY=CTAY*A2
      KPHIX=CPHIX*IY-W*L
        OMGNY=SQRT (KY*GA/W)
        ONPHIX=SQRT(KPHIX/MMOX)
        X3=((ONPHIX**2+OMGNY**2)/RIX)**2
        X4=((4*(OMGNY**2)*(ONPHIX**2))/RIX)
        X5=SQRT(X3-X4)
        X6=(OMGNY**2+ONPHIX**2)/RIX
        X7=(0.5)*(X6+X5)
        X8=(0.5)*(X6-X5)
        ON1=SQRT(X7)
        ON2=SQRT(X8)
        FN1=ON1/(2*ZZ)
        FN2=ON2/(2*ZZ)
        OMEGA=2*ZZ*N/60.
        M=W/GA
        Y4=M*MMX*(ON1**2-OMEGA**2)*(ON2**2-OMEGA**2)
        DELTA=ABS(Y4)
        ATAV=PY*((KPHIX+KY*L**2)-(MMX*OMEGA**2))/DELTA
        ATA=PY*(KY*L)/DELTA
        AQ=(MX/DELTA)*(KY*L)+ATAV
        AY=AQ*1000
        APHI2=(MX/DELTA)*(KY-M*OMEGA**2)+ATA
        WRITE(2,77) CTAY,CPHIX,KY,KPHIX,OMGNY,ONPHIX,ON1,FN1,ON2,
     #  FN2,AY,APHI2
   77   FORMAT(//,15X,'*********UNDAMPED SLIDING AND ROCKING CASE*****
     1  ****',//,35X,'....Y-Z PLANE.....',//,
     2  5X,'COEFF.OF UNIFORM SHEAR,                   CTAY=',F10.4,1X,'t/m3',/,
     3  5X,'COEFF.OF NONUNIF.COMP.,                  CPHIX=',F10.4,1X,'t/m3',/,
     4  5X,'EQUIVELENT SPRING,                          KY=',F15.5,1X,'t/m',/,
     6  5X,'EQUIVELENT SPRING,                       KPHIX=',F15.3,1X,'t/m',/,
     7  5X,'NATURAL FREQUENCY,                       OMGNY=',F10.3,1X,'rad/s',
     +  /,
     8  5X,'NATURAL FREQUENCY,                      ONPHIX=',F10.3,1X,'rad/s',
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     -    /,
     9    5X,'COUPLED NATURAL FREQUENCY,         ON1=',F10.3,1X,'rad/s',
     %    /,
     #    5X,'COUPLED NATURAL FREQUENCY,         FN1=',F10.3,1X,'HZ.',/,
     $    5X,'COUPLED NATURAL FREQUENCY,         ON2=',F10.3,1X'rad/s',/,
     %    5X,'COUPLED NATURAL FREQUENCY,         FN2=',F10.3,1X,'HZ.',/,
     &    5X,'SLIDING AMPLITUDE,                  AY=',F15.9,1X,'mm.',/,
     @    5X,'ROCKING AMPLITUDE,               APHI2=',F15.9,1X,'rad.'//)
  431     CONTINUE
C         ************************************************************
       WRITE(2,7901)
 7901      FORMAT(///,72('*'),/,72('*'),///)
          IF(CASE1.EQ.1.0.OR.CASE2.EQ.1.0.OR.CASE3.EQ.1.0.OR.CASE4.EQ.1.0)
     1    THEN
C         **************TOTAL UNDAMPED AMPLITUDE**************************
C         MAX HORIZONTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
          AHSI=ASI*R
C         MAX VERTICAL DUE TO PZ AND PX+MY
          AVI=AZ+APHI1*LX*1000
C         MAX VERTICAL AMPLITUDE DUE TO PZ AND PY+MX
          AV2=AZ+APHI2*LY*1000
C         MAX HORIZONTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND  MY
          AH1=AX+APHI1*HH*1000
C         MAX HORIZONTAL MPLITUDE DUE TO COMBINED ACTION OF PY AND MX
          AH2=AY+APHI2*HH*1000
          WRITE(2,2567)ASI,AHSI,AV1,AV2,AH1,AH2,
 2567     FORMAT(20X,'**********TOTAL UNDAMPED AMPLITUDE***********',//,
     #    5X,'MAX TORSIONAL AMPLITUDE,                ASI=',F15.9,1X,'RAD',/
     1    5X,'MAX HORIZONTAL AMPLITUDE,(TORSIONAL)AHSI=',F15.9,1X,'mm.',/
     7    /,
     2    5X,'MAX VERTICAL AMPLITUDE,(PZ,PX+MY)    AV1=',F15.9,1X,'mm.',/
     6    /,
     3    5X,'MAX VERTICAL AMPLITUDE,(PZ,PY+MX)    AV2=',F15.9,1X,'mm.',/
     &    /,
     4    5X,'MAX HORIZONTAL AMPLITUDE,(PX,MY)     AH1=',F15.9,1X,'mm.',/
     @    /,
     5    5X,'MAX HORIZONTAL AMPLITUDE,(PY,MX)     AH2=',F15.9,'mm.',//)
          END IF
C        ****************************************************************
C        ***COMPARISON OF ACTUAL SOIL PRESSURE WITH ALLOWABLE SOIL PRESSURE
C        ACTUAL SOIL PRESSURE
          QP=W/A2
          IF(QPA.LE.QP) GO TO 4455
          WRITE (2,4445) QP,QPA
 4445     FORMAT(68('*'),//,
     1    5X,'SOIL PERSSURE,QP='F10.4,1X,'t/m.sq.'1X,'AND SMALLER THAN
     2    ',/,5X,'THE ALLOWABLE SOIL PRESSURE QPA=',
     3    F10.4,1X,'t/m.sq.',//,68('*'))
          GO TO 1477
 4455     WRITE(2,4466) QP,QPA
 4466     FORMAT(68('*'),//,
     1    5X,'SOIL PRESSURE,QP=',F10.4,1X,'T\M2.',1X,'AND MORE THAN',//,
     2    5X,'THE ALLOWABLE SOIL PRESSURE QPA=',F10.4,1X,'T\M2.',//,
     3    68('*,*'))
 1477     STOP
          END
```

I

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      WRITE(2,7901)
 7901      FORMAT(///,72('*'),/,72('*'),///)
      IF(NOP2.EQ.1.0.OR.NOP4.EQ.1.0.OR.NOP6.EQ.1.0.OR.NOP8.EQ.1.0)THEN
C     ******************TOTAL DAMPED AMPLLITUDE****************
C     MAX.HORIZANTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
      ASID=ASID*R*1000
C         MAX.VERTICAL AMPLITUDE DUE TO PZ AND (PX+MY)
      AVD1=AZD+LX*APHIDI*1000
C         MAX.VERTICAL AMPLITUDE DUE TO PZ AND (PY+MX)
          AVD2=AZD+LY*APHIDE*1000
C         MAX HORIZANTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND MY
          AHD1=AXD+APHIDI*HH*1000
C         MAX HORIZANTAL AMPLITUDE DUE TO COMBINED ACTION OF PY AND MX
      AHD2=AYD+APHIDE*HH*1000
      WRITE(2,2234) ASID,AHSID,AVD1,AVD2,AHD1,AHD2
 2234     FORMAT(20X,'***************TOTAL DAMPED AMPLITUDE***********',/,
     @    5X,'MAX TORSIONAL AMPLITUDE,                 ASID=',F15.9,1X,'rad.',/,
     1    5X,'MAX HORIZANTAL AMPLITUDE,(TORSIONAL)AHSID=',F15.9,1X,'mm.',/,
     2    5X,'MAX VERTICAL AMPLITUDE, (PZ,PX+MY)  AVD1=',F15.9,1X,'mm.',/,
     3    5X,'MAX VERTICAL AMPLITUDE, (PZ,PY+MX)  AVD2=',F15.9,1X,'mm.',/,
     4    5X,'MAX HORIZONTAL AMPLITUDE,(PX AND PY) AHD1=',F15.9,1X,'mm.',/,
     5    5X,'MAX HORIZONTAL AMPLITUDE,(PY AND MX) AHD2=',F15.9,1X,'mm.'/,
           END IF
         IF (NOP1.EQ.1.0.OR.NOP3.EQ.1.0.OR.NOP5.EQ.1.0.OR.NOP7.EQ.1.0)THEN
C         ******************************************************************
C         **************TOTAL UNDAMPED AMPLITUDE****************************
C         MAX HORIZONTAL AMPLITUDE DUE TO TORSIONAL VIBRATION
          AHSI=ASI*R
C         MAX VERTICAL DUE TO PZ AND PX+MY
          AVI=AZ+APHI1*LX*1000
C         MAX VERTICAL AMPLITUDE DUE TO PZ AND PY+MX
          AV2=AZ+APHI2*LY*1000
C         MAX HORIZONTAL AMPLITUDE DUE TO COMBINED ACTION OF PX AND  MY
          AH1=AX+APHI1*HH*1000
C         MAX HORIZONTAL MPLITUDE DUE TO COMBINED ACTION OF PY AND MX
          AH2=AY+APHI2*HH*1000
          WRITE(2,2567)ASI,AHSI,AV1,AV2,AH1,AH2
 2567     FORMAT(20X,'**********TOTAL UNDAMPED AMPLITUDE***********',//,
     #    5X,'MAX TORSIONAL AMPLITUDE,                 ASI=',F15.9,1X,'RAD',//,
     1    5X,'MAX HORIZONTAL AMPLITUDE,(TORSIONAL)AHSI=',F15.9,1X,'mm.',/,
     2    5X,'MAX VERTICAL AMPLITUDE,(PZ,PX+MY)    AV1=',F15.9,1X,'mm.',//,
     3    5X,'MAX VERTICAL AMPLITUDE,(PZ,PY+MX)    AV2=',F15.9,1X,'mm.',//,
     4    5X,'MAX HORIZONTAL AMPLITUDE,(PX,MY)     AH1=',F15.9,1X,'mm.',//,
     5    5X,'MAX HORIZONTAL AMPLITUDE,(PY,MX)     AH2=',F15.9,'mm.',//)
       ***************************************************************
C      ***COMPARISON OF ACTUAL SOIL PRESSURE WITH ALLOWABLE SOIL PRESSURE
C      ACTUAL SOIL PRESSURE
       IF(QPA.LE.QP) GO TO 4455
          WRITE (2,4445) QP,QPA
 4445     FORMAT(68('*'),//,
     1    5X,'SOIL PERSSURE,QP='F10.4,1X,'t/m.sg.'1X,'AND SMALLER THAN
     2    ',/,5X,'THE ALLOWABLE SOIL PRESSURE QPA=',
     3    F10.4,1X,'t/m.sg.',//,68('*'))
 4455     WRITE(2,4466) QP,QPA
 4466     FORMAT(68('*'),//,
     1    5X,'SOIL PRESSURE,QP=',F10.4,1X,'T\M2.',1X,'AND MORE THAN',//,
     2    5X,'THE ALLOWABLE SOIL PRESSURE QPA=',F10.4,1X,'T\M2.',//,
     3    68('*,*'))
          STOP
          END
```