ANALYSIS OF RECIPROCATING MACHINE FOUNDATIONS RESTING ON PILES

A DISSERTATION

Submitted in partial fulfillment of the requirements for the award of the degree
of
MASTER OF TECHNOLOGY
in
EARTHQUAKE ENGINEERING
(With Specialization in Soil Dynamics)

By

M. BHARATHI

DEPARTMENT OF EARTHQUAKE ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)
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INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in this dissertation report entitled, **"ANALYSIS OF RECIPROCATING MACHINE FOUNDATIONS RESTING ON PILES"**, in the partial fulfillment of the requirements for the award of the degree of **MASTER OF TECHNOLOGY** in **EARTHQUAKE ENGINEERING**, with specialization in **SOIL DYNAMICS**, submitted in the Department of Earthquake Engineering, Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out for a period from July 2011 to June 2012 under the supervision of **Dr. Shyamal Mukerjee**, Assistant Professor and **Dr. Swami Saran**, Professor Emeritus, Department of Earthquake Engineering, IIT Roorkee.

The matter embodied in this report has not been submitted by me for the award of any other degree or diploma of this Institute or any other University/ Institute.

Date: 15th June, 2012.

Place: Roorkee

M. Bharathi

M. BHARATHI

CERTIFICATE

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

Dr. Swami Saran
Professor Emeritus
Department of earthquake Engineering
IIT Roorkee, Roorkee-247667 (INDIA)

S. Mukerjee

Dr. Shyamal Mukerjee
Associate Professor
Department of earthquake Engineering
IIT Roorkee, Roorkee-247667 (INDIA)

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M. Bharathi

Place: IIT Roorkee

Date: 15.06.12

M. BHARATHI

Department of Earthquake Engg.

ABSTRACT

Machine foundations are generally classified as special foundations. They require a detailed analysis of the foundation response to the dynamic load coming from the anticipated operation of the machines.

Reciprocating Machines includes engines and compressors with operating speed varying from 50 to 1000 rpm. The reciprocating machines are normally founded on blocks. Under unavoidable situations the reciprocating machines are founded on piles. Reciprocating machines resting on piles are analyzed with the help of solutions arrived from dynamic behavior of pile groups. The basic equations to study the dynamic behavior of piles and pile groups were developed by Novak. The solution given by Novak was complicated since it involves several constants. An attempt is made to simplify the procedure used to analyze the pile group subjected to dynamic load.

A machine foundation resting on pile group problem is selected such that the parameters used resemble the actual field conditions and analyzed for the dynamic conditions. To simplify the problem certain assumptions are made. MATLAB programs were developed for different modes of vibration and the machine foundation system was analyzed for varying parameters and hence the variation in the natural frequency and amplitude of the system were studied. The pile group system was also compared to the equivalent block foundation system to study the frequency and amplitude variation of both the systems.

The results obtained from the MATLAB programs were cross checked by manual calculations and charts were prepared to depict the variation of natural frequency and amplitude for different modes of vibration.

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LIST OF SYMBOLS

Notation	Description
α_A	Interaction factor for pile group
a	Length of base of foundation in m
A	Area of block foundation in m^2
A_h	Horizontal amplitude at bearing level in m
A_p	Area of cross section of pile in m^2
A_v	Vertical amplitude in m
A_x	Linear horizontal amplitude of the combined centre of gravity in m
A_z	Amplitude for vertical vibration in m
A_{ze}	Maximum amplitude in vertical vibration in m
A_ϕ	Rotational amplitude in radians around the combined centre of gravity in radians
b	Width of base of foundation in m
B_x	Mass ratio for sliding vibration
B_z	Mass ratio for vertical vibration
B_ϕ	Mass ratio for rocking vibration
B_ψ	Mass ratio for torsional vibration
$C_{\tau av}$	Average value of Co-efficient of elastic uniform shear in kN/m^3
C_u	Co-efficient of elastic uniform compression in kN/m^3
C_{uav}	Average value of Co-efficient of elastic uniform compression in kN/m^3
C_{uD}	Co-efficient of elastic uniform compression at the base of foundation in kN/m^3
C_{xf}	Damping of pile cap for translation motion in kN-s/m
C_{xf}	Damping of pile cap for rotational motion in kN-s/m
C_{xg}	Damping of pile group for translation motion in kN-s/m
C_{xgt}	Total damping of pile group and pile cap for translational vibration in kN-s/m
C_{xp}	Damping of single pile under translation motion in kN-s/m
$C_{x\phi p}$	Damping of single pile under coupled motion in kN-s/m
C_{zf}	Damping of pile cap for vertical vibration in kN-s/m
C_{zg}	Damping of pile group for rotational motion in kN-s/m

C_{zg}	Damping of pile group for vertical vibration in kN-s/m
C_{zgt}	Total damping of pile group and pile cap for vertical vibration in kN-s/m
C_{zp}	Damping of single pile under vertical vibration in kN-s/m
C_{τ}	Co-efficient of elastic uniform shear in kN/m^3
$C_{\tau D}$	Co-efficient of elastic uniform shear at the base of foundation in kN/m^3
C_{ϕ}	Co-efficient of elastic non-uniform compression in kN/m^3
$C_{\phi av}$	Average value of Co-efficient of elastic non-uniform compression in kN/m^3
$C_{\phi D}$	Co-efficient of elastic non-uniform compression at the base of foundation in kN/m^3
$C_{\phi gt}$	Total damping of pile group and pile cap for rotational vibration in kN-s/m
$C_{\phi p}$	Damping of single pile under rotational motion in kN-s/m
C_{ψ}	Co-efficient of elastic non-uniform shear in kN/m^3
$C_{\psi av}$	Average value of Co-efficient of elastic non-uniform shear in kN/m^3
$C_{\psi D}$	Co-efficient of elastic non-uniform shear at the base of foundation in kN/m^3
D	Embedment depth of the block
E_p	Modulus of elasticity of pile material kN/m^2
f_{w1}	Stiffness constant for vertical vibration
f_{w2}	Damping constant for vertical vibration
f_{x1}	Stiffness constant for translational vibration
f_{x2}	Damping constant for translational vibration
$f_{x\phi 1}$	Stiffness constant for coupled vibration
$f_{x\phi 2}$	Damping constant for coupled vibration
$f_{\phi 1}$	Stiffness constant for rotational vibration
$f_{\phi 2}$	Damping constant for rotational vibration
G_s	Shear modulus of soil in kN/m^2
h	Depth of foundation in m
h_e	Equivalent surcharge in m
I_p	Moment of inertia of pile cross section in m^4
K_x	Equivalent spring constant of the soil in sliding vibration in kN/m
K_{xf}	Stiffness of pile cap for translation motion in kN/m
K_{xg}	Stiffness of pile group for translation motion in kN/m
K_{xgt}	Total stiffness of pile group and pile cap for translational vibration in kN/m

K_{xp}	Stiffness of single pile under translation motion in kN/m
K_{xx}	Equivalent spring constant of the soil in coupled sliding vibration in kN/m
$K_{x\phi p}$	Stiffness of single pile under coupled motion in kN/m
K_z	Equivalent spring constant of the soil in vertical vibration in kN/m
K_{ze}	Equivalent spring stiffness of the embedded foundation in vertical vibration in kN/m
K_{zf}	Stiffness of pile cap for vertical vibration in kN/m
K_{zg}	Stiffness of pile group for rotational motion in kN/m
K_{zgt}	Total stiffness of pile group and pile cap for vertical vibration in kN/m
K_{zp}	Stiffness of single pile under vertical vibration in kN/m
K_{ϕ}	Equivalent spring constant of the soil in rocking vibration in kN/m
$K_{\phi e}$	Equivalent spring stiffness of the embedded foundation in rocking vibration in kN/m
$K_{\phi gt}$	Total stiffness of pile group and pile cap for rotational vibration in kN/m
$K_{\phi p}$	Stiffness of single pile under rotational motion in kN/m
K_{ψ}	Equivalent spring constant of the soil in torsional vibration in kN/m
L	Distance of combined centre of gravity above base in m
m	Mass of the block in kN
M_m	Mass moment of inertia of machine and foundation passing through the combined centre of gravity in kg-m^2
M_{mo}	Mass moment of inertia of machine and foundation about the axis of rotation passing through base in kg-m^2
M_{mz}	Mass moment of inertia of the machine and foundation about the axis of rotation
m_s	Apparent soil mass in kg
M_y	Moment acting in XZ plane kN-m
OS	Operating speed in rpm
Per. A	Permissible Amplitude in m
r_o	Equivalent radius in m
r_{oc}	Equivalent radius of pile cap in m
r_{ϕ}	Equivalent radius for rocking vibration in m
r_{ψ}	Equivalent radius for torsional vibration in m

S	Spacing between piles in m
S_{x1}	Stiffness constant of pile cap for translation motion
S_{x2}	Damping constant of pile cap for translation motion
S_{z1}	Stiffness constant of pile cap for vertical vibration
S_{z2}	Damping constant of pile cap for vertical vibration
$S_{\phi 1}$	Stiffness constant of pile cap for rotational motion
$S_{\phi 2}$	Damping constant of pile cap for rotational motion
v_s	Shear wave velocity in m/sec
W	Total weight of machine and block in kN
Wm	Weight of machine in kN
x_r	Distance of each pile from c.g. in m
Z_c	Height of centre of gravity of the pile cap above its base in m
γ_c	Density of concrete in kN/m^3
γ_s	Density of soil in kN/m^3
ξ_x	Damping ratio for translational vibration
ξ_ϕ	Damping ratio for rotational vibration
ω	Operating frequency of the machine in rad/s
ω_{n1}	Natural frequency of the machine in rad/s
ω_{n2}	Natural frequency of the machine in rad/s
ω_{nx}	Natural frequency of the machine in sliding vibration in rad/s
ω_{nz}	Natural frequency of the machine in vertical vibration in rad/s
$\omega_{n\phi}$	Natural frequency of the machine in rad/s
ω_{nxe}	Natural frequency for embedded block in sliding vibration in rad/sec
ω_{nze}	Natural frequency for embedded block in vertical vibration in rad/sec
$\omega_{n\phi e}$	Natural frequency for embedded block in rocking vibration in rad/sec
$\omega_{n\psi e}$	Natural frequency for embedded block in torsional vibration in rad/sec

1.1 GENERAL

Machine foundations require a special consideration because they transmit dynamic loads to soil in addition to static loads due to weight of foundation, machine and accessories. The dynamic load due to operation of the machine is generally small compared to the static weight of machine and the supporting foundation. In a machine foundation the dynamic load is applied repetitively over a very long period of time but its magnitude is small and therefore the soil behavior is essentially elastic, or else deformation will increase with each cycle of loading and may become unacceptable. The amplitude of vibration of a machine at its operating frequency is the most important parameter to be determined in designing a machine foundation, in addition to the natural frequency of a machine foundation soil system.

1.1.1 Reciprocating Machines

The machines that produce periodic unbalanced forces (such as steam engines) belong to this category. These machines include steam, diesel and gas engines, compressors and pumps. The basic mechanism of a reciprocating machine consists of a piston that moves within a cylinder, a connecting rod, a piston rod and a crank. The crank rotates with a constant angular velocity. The operating speeds of such machines are usually less than 1000 rpm. For analysis of their foundations, the unbalanced forces can be considered to vary sinusoidally. [32]

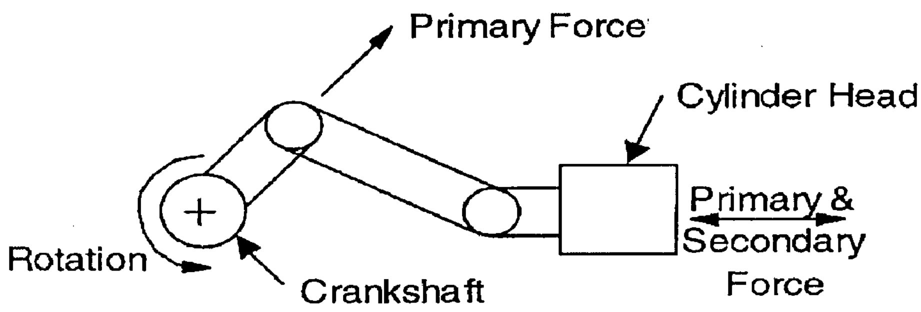


Fig. 1 Parts of a reciprocating machine

The dynamic forces developed by the reciprocating machines are much higher compared to those generated by the rotary machines. These dynamic forces are predominant along the piston axis and are generated at operating speed as well as at its first harmonic. Allowable limits of amplitude are higher for reciprocating machines compared to those for rotary machines. The system vibrates in all six degrees of freedom and thus requires computation of frequencies and amplitudes corresponding to all six degrees of freedom. [14]

1.1.2 Types of foundations [32]

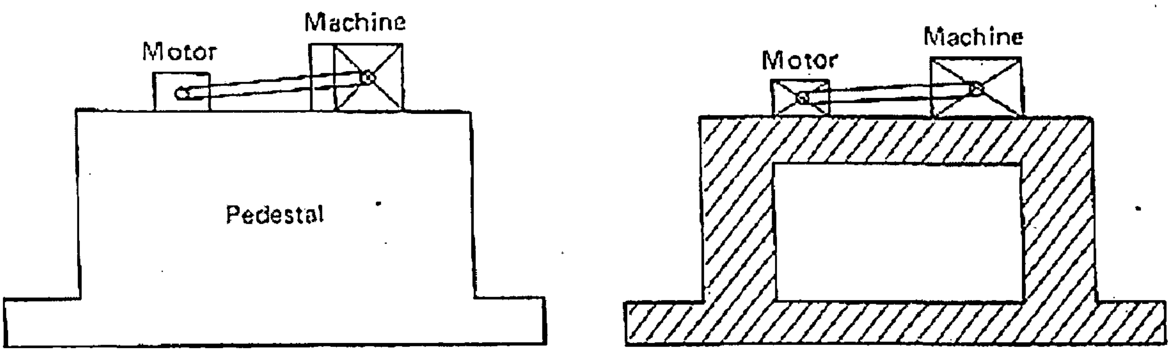
Reciprocating machines are very frequently encountered in practice. Usually the following two types of foundation are used for such machines:

i. Block type foundation

   The machine rests on a concrete block which rests on the soil. The depth of embedment of the block in the soil also plays a very significant role in calculating the stiffness and damping of the system.

ii. Box type foundation

   A hollow concrete block is used to support the machine. The mass of the block is less in this case and hence the natural frequency will be higher than the previous case.



(a) Block Type Foundation (b) Box Type Foundation

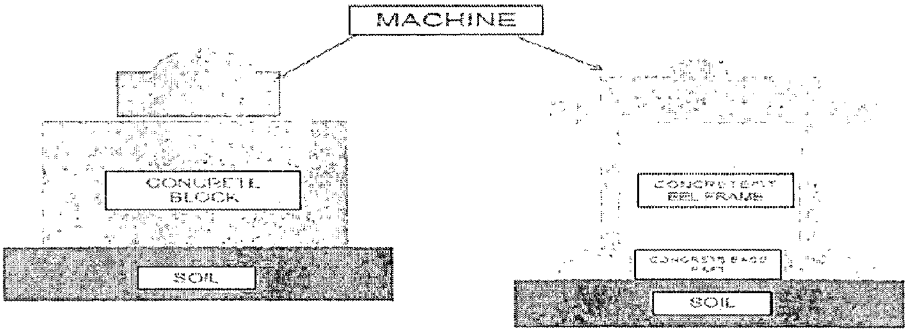
Fig.2 Types of foundations

1.1.3 Supports for foundations [4]

The reciprocating machines mounted on the foundation may rest either on soil or on piles.

i. Foundation resting on soil

The block supporting the machine rests on the soil. For an embedded foundation, the soil resistances are mobilized both below the base and on the sides. The additional soil reaction that comes into play on the sides may have significant influence on the dynamic response of embedded foundations. As a result of embedment, the natural frequency of the system increases and amplitude decreases.

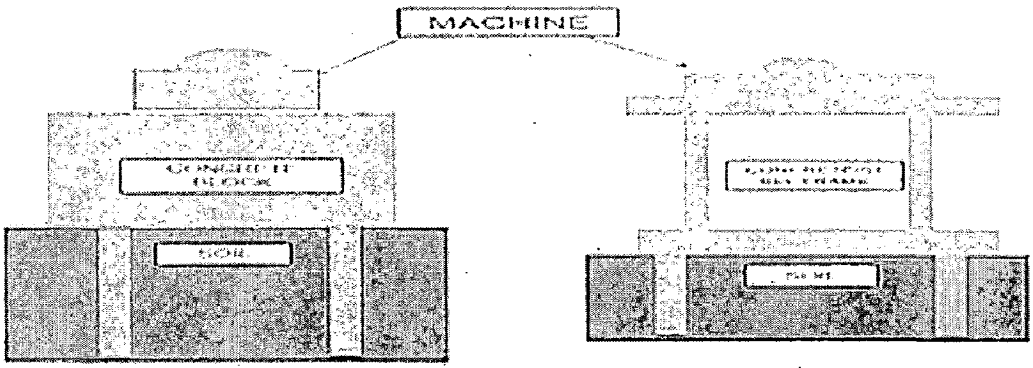


(b) Box Type (b) Frame Type

Fig.3 Foundations resting on soil

ii. Foundation resting on piles

In this case the blocks supporting the machinery rests on piles. The block plays the role of the pile cap for the pile group. The thickness of the pile cap i.e. the block should not be less than 600mm.



(a) Block supported by piles (b) Frame supported by piles

Fig.4 Foundations resting on piles

1.2 NEED FOR ANALYSIS

The necessity for developing effective and economical designs for pile supported foundations subjected to dynamic loads has become more important in recent years. The major users of vibratory equipment are large industrial plants, which are more frequently being located on marginal sites requiring piling for foundation support. A perfect theoretical solution to dynamic pile-soil interaction due to slippage and nonlinearity is difficult and therefore approximate methods need to be used.

1.3 OBJECTIVES

The main objectives of the study are as follows:

i. To present a simple approximate analytical procedure for analyzing dynamically loaded pile-supported machine foundations.
ii. To make the analysis of dynamically loaded pile group as simple as possible with accuracy.
iii. To study the frequency and amplitude variation among a pile group for different modes of vibration.
iv. To provide approximate relations between factors used in the dynamic analysis of piles with greater accuracy.

1.4 SCOPE OF THE STUDY

The present study includes the dynamic analysis of single piles and pile groups subjected to different modes of vibration. The machine foundation codes from different parts of the world have given its specifications for the design of block foundation. The codes do not provide any detailed specification for the design of machine foundation resting on piles. Moreover many research works have been carried out to study the dynamic behavior of piles and pile groups. But none of them is been suggested by the codes since they involve several design constants. There is no one such procedure to design the machine foundation resting on piles. The design charts available for the dynamic analysis of pile and its group is digitized to simple equations and they are used for the analysis of the machine foundation system resting on piles. The parameters involved in the system are varied and the variation in the frequency and amplitude are studied for the possible modes of vibration of the machine foundation system resting on piles.

1.5 OUTLINE OF THE THESIS

The work carried in this thesis has been presented in these chapters briefly described below:

- **Chapter 1:** Highlights the background, need, objectives and scope of work.
- **Chapter 2:** In this chapter brief description of machine foundation, effects of machine foundations resting on piles, review of the research towards the dynamic behavior of piles are discussed.
- **Chapter 3:** Presents the design principles of the machine foundation resting on piles for different modes of vibration.
- **Chapter 4:** The design charts developed for different modes of vibration for dynamic behavior of piles and interaction factors for pile groups under dynamic loading and the parameters involved are presented.
- **Chapter 5:** The problem selection, the parameters used and the analysis procedure has been discussed.
- **Chapter 6:** The results obtained for the considered problem and discussions about the various parameters involved are discussed.
- **Chapter 7:** Conclusions are drawn from the above study are explained in this chapter along with the scope for future work.

LITERATURE REVIEW

2.1 INTRODUCTION

Barkan [2], in his linear elastic weightless spring approach replaced soil by elastic springs. In developing the analysis the effects of damping and participating soil mass is neglected. Damping does not affect the natural frequency of the system appreciably, but it affects resonant amplitudes considerably. Since the zone of resonance is avoided in designing machine foundations, the effect of damping on amplitudes computed at operating frequency is also small. Hence neglecting damping may not affect the design appreciably, and if any that on the conservative side. Emprical methods have been suggested to obtain the soil mass participating in vibration.

In the elastic half space method, the machine foundation is analyzed as a vibrating mechanical oscillator with a circular base resting on the surface of ground. The ground is assumed to be an elastic, homogenous, isotropic, semi-infinite body, which is referred to as an elastic half space. This approach was apparently more rational, but relatively more complicated.

Many analytical and semi analytical methods have been developed over the time to study the dynamic response of piles. Some of the methods are as follows: [31]

i. Sub-grade Reaction Method
ii. Lumped Mass Idealization Method
iii. Novak's Continuum Approach
iv. Equivalent Cantilever Approach

Though the response of pile foundations subjected to dynamic loading [21] has been studied by several methods, Novak's Continuum approach or Novak's plane strain model [20] is widely used in practice. This pioneering works included the radiation damping in the analysis and offered a good insight into the behavior of piles under dynamic loads. Many researchers (Novak and Nogami [24], Novak and El Sharnouby [18]) used the Novak's plane strain model to determine the impedance functions for both vertical and horizontal vibrations. Novak and Aboul-Ella [24] investigated the impedance functions of piles in layered media. Novak [17] has suggested the stiffness and damping values of pile groups subjected to different modes of vibration.

With the emergence of the new rather abstract theories for dynamic pile analysis, it became necessary to verify their validity by means of experiments. The full scale forced vibration tests in the field were conducted for both vertical and horizontal vibrations by many investigators [16]. Field experiments with small prototype single piles and group of piles were conducted by Novak and Grigg [19] and Han and Novak [8] subjected to strong horizontal and vertical excitations. A series of dynamic tests were conducted with a group of 102 closely spaced piles for vertical, horizontal and torsional mode of vibrations by El Sharnouby and Novak [29] and the experimental results were evaluated to determine if the theories available could predict the behavior of the test pile group. Chadrasekaran [5] in his solution for pile subjected to lateral vibrations idealized the soil pile system as a discretized mathematical model.

The pile group is expressed as a sub-grade reaction where the coefficients are defined in terms of pile group stiffnesses, but expressed in the same form as coefficient of sub-grade reaction. These coefficients are calculated by making piling assumptions and selecting the size of the foundation according to the British Standards [6].

Embedment substantially affects the response in that it increses the resonant frequencies and reduces the resonant amplitudes. This affect is much more pronounced in coupled motion than in vertical translation. [22].

The theoretical and experimental research into dynamic behavior of piles and pile groups by Novak and Sheta suggest the following [23]

i. Dynamic behavior of piles is strongly affected by the variation of soil stiffness with depth and the lack of bond between the pile and soil.
ii. Plane strain soil reactions facilitate dynamic analysis of piles and gives satisfactory results.
iii. Dynamic characteristics of pile groups differ considerably from static characteristics and are more frequency dependent than characteristics of single piles.

iv. Stiffness and damping of pile groups can either be reduced by pile soil pile interaction or increased depending on frequency, spacing between piles and the weakened zone around the piles.

v. There is a need for experimental research into dynamic behavior of pile groups and the examination of simplified approaches.

Coming to the effect of material non linearity of soil, B K Maheswari, [13] have suggested that

i. Material nonlinearity reduces both the real and imaginary parts of the dynamic stiffness but the reduction in the real part is comparatively larger. Due to nonlinearity, the equivalent damping ratio of the soil pile system increases. The effect of nonlinearity on the real part of the dynamic stiffness is not much changed with frequency of excitation.

ii. In general, effect of nonlinearity was greater for a single pile, compared to 2x2 pile group. It appears that group effect diminishes the effects of nonlinearity.

Recent studies on the dynamic behavior of piles are done by Manna and Baidya [15]. The analytical investigation is carried out using plane strain model of Novak to validate the dynamic test results of piles. The dynamic tests were carried out on model reinforced concrete single pile and 2 x 2 pile groups. Frequency versus amplitude curves of piles were experimentally established in the field for different intensities of excitation, different static loads on piles, and different contact conditions of the pile cap with the soil. Important parameters that influence the dynamic soil-pile interaction for both single and pile group are studied for the investigation.

2.2 SURVEY ON CODES:

A survey is done on the codes of various countries on machine foundation and found out that the procedure for the design of machine foundation supported on piles or its specifications is not available in them. This is due to fact that there are several parameters on which the design of pile foundations supporting the machines depends upon.

2.2.1 AMERICAN [1]

ACI 351 -3R -04

Foundations for dynamic equipment

Clause 2.3.7 Any of the previously mentioned foundation types may be supported directly on soil or on piles. Piles are generally used where soft ground conditions result in low allowable contact pressures and excessive settlement for a mat-type foundation. Piles use end bearing, frictional side adhesion, or a combination of both to transfer axial loads into the underlying soil. Transverse loads are resisted by soil pressure bearing against the side of the pile cap or against the side of the piles. Various types of piles are used including drilled piers, auger cast piles, and driven piles.

2.2.2 SAUDI [28]

SAES – Q – 007

Foundations and supporting structures for heavy machinery

Clause 8.1 A geotechnical investigation shall be carried out in accordance with SAES-A-113 to determine soil and groundwater conditions based on a sufficient number of boring results and in-situ and laboratory testing. Foundation adequacy for static bearing capacity and settlement considerations shall be checked. In addition, effect of dynamic loading on foundation soil shall be investigated. If necessary, treatment of the in-situ foundation soils to improve their condition shall be considered. In-situ or laboratory testing to establish appropriate dynamic parameters of the foundation soils, whether in-situ treated or untreated, or compacted fill, shall be carried out. If a requirement for piles is established, appropriate dynamic parameters for the piles shall be determined.

2.2.3 GERMAN [7]

DIN 4024

Part 1 ***Flexible structures that supports machines with rotating elements*** [For framed type (Flexible) foundations]

i. Machine support
ii. Table foundation
iii. Spring foundation
iv. Slab foundation
v. Platform foundation

Part 2 ***Rigid foundations for machinery subjected to periodic vibration*** [For block type (Rigid) foundations]

i. Foundation block
ii. Foundation box
iii. Supporting ground
    - Soil
    - Material similar to soil
    - Piles
    - Spring elements
    - Other elastic materials

2.2.4 INDIAN [10]

IS 2974

Part 1 Foundation for reciprocating type machines

Part 2 Foundations for impact type machines (hammer foundations)

Part 3 Foundations for rotary type machines (medium and high frequency)

Part 4 Foundations for rotary type machines of low frequency

Part 5 Foundations for impact type machines other than hammer (forging and stamping press, pig breaker, elevator and hoist towers)

IS 2974 Part 1Clause: 5.4.4 Supporting foundation blocks on end-bearing or friction piles shall be considered in cases where there is need to make a significant change in frequency in one or more modes of vibration or dead loads. Pile caps where used as a foundation block shall be of such a size as to meet all design criteria, and be not less than 60cm thick.

Requirements:

i. When pressure on the soil under the block exceeds the permissible bearing pressure.
ii. When a foundation is found to be subject to resonance, or when an increase in the mass of the block is either unduly wasteful in material or ineffective due to the danger of resonance in other modes
iii. When a block foundation is low tuned by one mode and high tuned by other and desirable or specified frequency ratios cannot be maintained simultaneously.

iv. When the amplitudes of movement of a block foundation are in excess of their permissible values.

v. Piled foundation shall be used when a raft foundation is liable to suffer a differential settlement exceeding the permissible limit

vi. Piles may be used to minimize the effect of ground borne vibration on surrounding foundation and equipment.

Evaluation of Pile Soil Stiffness:

Pile Soil Stiffness factors both in vertical and horizontal modes of vibrations shall preferably be determined by conducting in situ test on piles. In cases, where it becomes difficult to conduct this test, the values can be taken from some standard publications. The centre of gravity of the system, that is, foundation and machine shall be located within 5 percent of the length of foundation to concerned axis with respect to the centre of gravity of the pile group.

Design considerations:

i. Pile-soil stiffness factors both in vertical and horizontal modes of vibration shall be determined by conducting in situ dynamic tests on piles. For preliminary design however the computative method of estimation of pile-soil stiffness can be adopted.

ii. Usually in situ dynamic tests are conducted on single pile with free head condition. In actual practice the pile shall be used in a group with pile heads largely restrained by the pile cap. Allowance shall be made for these factors in evaluation of pile-soil stiffness to be adopted for design. Failure to take account of these factors will lead to error in estimating stiffness of the system.

iii. After evaluating the pile-soil stiffness, the design shall be carried out in the same way as for the block foundation resting directly on soil.

2.2.5 BRITISH [6]

CP 2012

The stiffness is calculated by

i. Longitudinal and lateral in situ loading tests on actual piles
ii. Spring stiffness from the geometrical and material configuration of the pile group.

Three rules by British Standards

i. Mass of foundation > Mass of the plant

   Usually Mass of foundation = 3 to 5 * Mass of the plant

ii. 5% Rule

   Plan geometric centre of foundation is within 5% of centre of mass

   This is to ensure even distribution of stress of soil and even distribution of settlement. Even distribution of force to a set of pile is desirable. Stiffness attracts force. Even distribution of force can be achieved by applying the force to the centre of stiffness.

iii. Width of foundation = Min (Centre of crank shaft of the machine to the bottom of foundation)

   This is to ensure the stability against overturning.

   Overturning calculation is important.

2.2.6 ISO [12]

1S0 10816 (7 parts)

Evaluation of machine vibration by measurements on non-rotating parts

Part 1: General guidelines

Part 2: Land-based steam turbines and generators in excess of 50 mw with normal operating speeds of 1500 rpm, 1800 rpm, 3000 rpm AND 3600 rpm

Part 3: Industrial machines with nominal power above 15kw AND NOMINAL speeds between 120rpm AND 15000rpm when measured in situ

Part 4: Gas turbine sets with fluid-film bearings

Part 5: Machine sets in hydraulic power generating and pumping plants

Part 6: Reciprocating machines with power ratings above 100kw

Part7: Rotodynamic pumps for industrial applications, including measurements on rotating shafts

Evaluation of response of the machine foundation system is done based on the type of fault, zone and the type of alarm according to the provisions.

2.3 SUMMARY

Regarding evaluation of stiffness and damping of pile-supported foundations, general observations, as reported in the literature, are as under:

i. Elastic resistance of pile to vertical loads changes with lapse of time i.e. the elastic resistance offered by a fresh driven pile to vertical loads is different than the resistance offered by it after lapse of some time.
ii. Elastic resistance of pile to vertical loads changes with increase in length of pile.
iii. Elastic resistance of pile to lateral loads primarily depends upon its cross-section and its fixation length and any increase in length of pile beyond fixation length has no influence on its lateral resistance. The fixation length of a pile is the length of pile in the soil, where it is assumed fixed when subjected to lateral loads. This is generally of the order of 1 to 1.5m for all piles.
iv. Dynamic stiffness of a single pile is generally found to be greater than its static stiffness.
v. Both stiffness and damping of pile have been found to be frequency dependent i.e. these vary with change in frequency. The reliability of response using frequency independent stiffness and damping values, in dynamic domain, would therefore be questionable.
vi. Damping increases with increase in pile length.
vii. Embedment of pile cap results in increased stiffness and damping of the pile group. However its quantification is not yet established.
viii. Damping of group of pile is more frequency dependent than that for a single pile.
ix. Dynamic group effect of piles differs considerably from static group effect.
x. Frequency dependence of stiffness and damping of pile group could safely be ignored for translational and rocking modes of vibration.
xi. Rocking and translational stiffness of individual pile could safely be ignored while evaluating dynamic response of group of piles.
xii. Elastic resistance of each pile in a group is a function of pile spacing. Inter-influence of piles is observed to be quite significant. The elastic resistance of each pile increases with the increase in the pile spacing and decreases with the decrease in pile spacing. When the pile spacing becomes sufficiently large, the elastic resistance of each pile in a group approaches the resistance of a single pile.

xiii. The combined stiffness, for a group of n piles, is not the linear summation of individual stiffness of n piles.

xiv. The effective stiffness of a single pile (in a group of piles) is its individual stiffness multiplied by an influence factor that depends upon the ratio of pile spacing s to its diameter d.

In light of the above:

i. Any single approach for dynamic response of pile supported machine foundation systems as the reliability of dynamic properties of group of piles derived from that of single pile should be recommended.

ii. Notwithstanding the above, it is recommended that Elastic Resistance of a Pile, to both vertical and lateral loads, must necessarily be determined from pile test.

iii. Most of the approaches suggested in the literature are good enough for R&D purposes and may not be suitable for industry.

iv. The ground reality is that the industry cannot wait till validated solutions are available.

v. It has to continue with the designs with the best available practical approaches or solutions such that the machine performance is acceptable.

vi. The designer should be able to complete the task in a specified time schedule with a good level of confidence in his design.

FOUNDATIONS FOR RECIPROCATING MACHINES

3.1 INTRODUCTION

Reciprocating machines can be founded on blocks or on piles. In this chapter the behavior of reciprocating machines resting on blocks and on piles is discussed in detail. It helps us to understand the behavior of the whole machine foundation system when it has different support conditions. Therefore, its necessary for understanding the parametric variation with the two different types of foundation.

3.2 RECIPROCATING MACHINE ON BLOCK FOUNDATION

Block type or box type of foundations are used for reciprocating machines. Here, the basic assumptions are made for analysis of the whole machine foundation system. It includes that the foundation block is considered to have only inertial properties and lack elastic properties and the soil is considered to have only elastic properties and lack properties of inertia. A rigid block being a problem of six degrees of freedom has six natural frequencies. The natural frequency is determined in a particular mode and compared with the operating frequency. Similarly, amplitude is worked out in a particular mode and compared with the permissible amplitude.

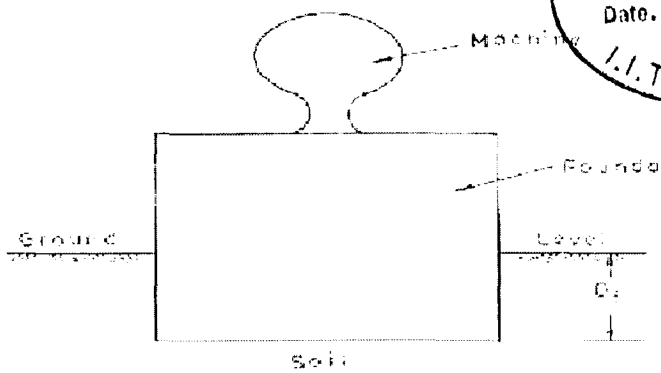


Fig.5 Block Foundation

3.3 RECIPROCATING MACHINE ON PILE FOUNDATION

The introduction of pile in a soil stratum makes the system stiff. Due to this the natural frequency and the amplitudes of motion are affected. In all vibration problems, resonance needs to be avoided. Therefore, the natural frequency of the structure soil system is required for analysis and design. For machine foundation application [30], piles are provided in the following cases:

i. When soil is weak in bearing capacity to withstand pressures due to both static and dynamic loads.
ii. When significant loss of soil strength is postulated under dynamic loads on account of critical soil and water table conditions.
iii. When it is required to increase natural frequency of the machine foundation system.
iv. When dynamic amplitudes are required to be reduced.
v. When it is required to stiffen the support system on account of seismic consideration.

The selection of pile type, pile size, pile depth, number of piles etc. is an involved task and is accomplished using standard pile design procedures based on soil data and the load data (static and dynamic loads). In certain cases, selection of pile type, pile size, pile depth, number of piles etc. becomes a tricky issue and for all practical purposes may turn out to be a difficult task. In either case, evaluation of dynamic characteristics of piles is a complex task and suffers with many associated uncertainties. [9]

A machine foundation block itself serves as rigid pile cap that connects piles at the top. Evaluation of dynamic characteristics of a single pile, in itself, is a difficult task and evaluation of dynamic characteristics of a group of piles connected by a rigid pile cap becomes complex and calls for many assumption resulting in added levels of uncertainties.

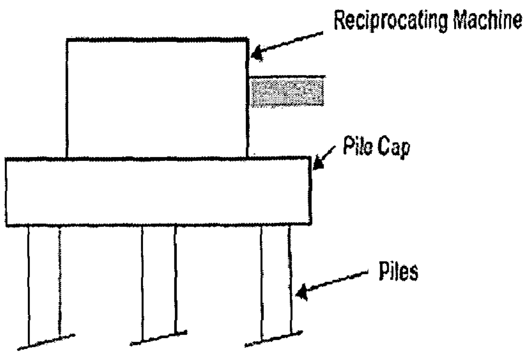


Fig.6 Reciprocating machine resting on piles

Regarding Pile Supported Machine Foundations, [25]

i. Understanding of Dynamic behavior of Group of Piles is still in its Infancy.
ii. Evaluation of dynamic characteristics of piles is a complex task and suffers with many associated uncertainties.
iii. As the reliability of dynamic characteristics of group of piles is faced with many questions, so shall be the status of computed dynamic response.

The stiffness and damping of piles under various modes of vibration were computed by two different analytical approaches

i. Novak's frequency independent solutions with static interaction factor for parabolic soil profile
ii. Novak's complex frequency dependent analytical solutions with dynamic interaction factor approach for layered media.

Designing foundations with piles for vibrating machinery is a difficult task for the simple reason that practical design methods are not readily available or published in codes of practice. When designing a foundation with piles, the method of design is not explicitly given by the code. Therefore, a simple method to determine the stiffness and damping of pile group subjected to different modes of vibration is to be used to design the foundation on piles. The procedure to calculate the stiffness and damping of the pile group subjected to different modes of vibration is discussed in detail in the next chapter.

4.1 INTRODUCTION

Reciprocating machines are normally supported on block type of foundation but under unavoidable situations they are founded on piles. In this chapter the different modes of vibration and the types of analysis used are discussed in brief. Therefore, from the different types of analysis a suitable method is selected to analyze and design the problem. The analysis is carried out and the variation of the natural frequency and the amplitude of the machine foundation system is studied.

4.2 DIFFERENT MODES OF VIBRATION

The machine foundations are subjected to three translational and three rotational modes of vibration. [32]

i.	Translation along vertical axis	-	Vertical vibration
ii.	Translation along longitudinal axis	-	Longitudinal or Sliding vibration
iii.	Translation along lateral axis	-	Lateral or Sliding vibration
iv.	Rotation about vertical axis	-	Yawing motion
v.	Rotation about longitudinal axis	-	Rocking vibration
vi.	Rotation about lateral axis	-	Pitching vibration

The vibratory modes may be 'decoupled' or 'coupled'. Of the six modes, translation along vertical axis and rotation around vertical axis can occur independently of any other motion and are called decoupled modes. But the translation along the longitudinal or lateral and the corresponding rotations always occur together and are called coupled modes. [3]

Hence the dynamic analysis of the machine foundations subjected to coupled sliding and rocking motion passing through the common centre of gravity of machine and foundation becomes must.

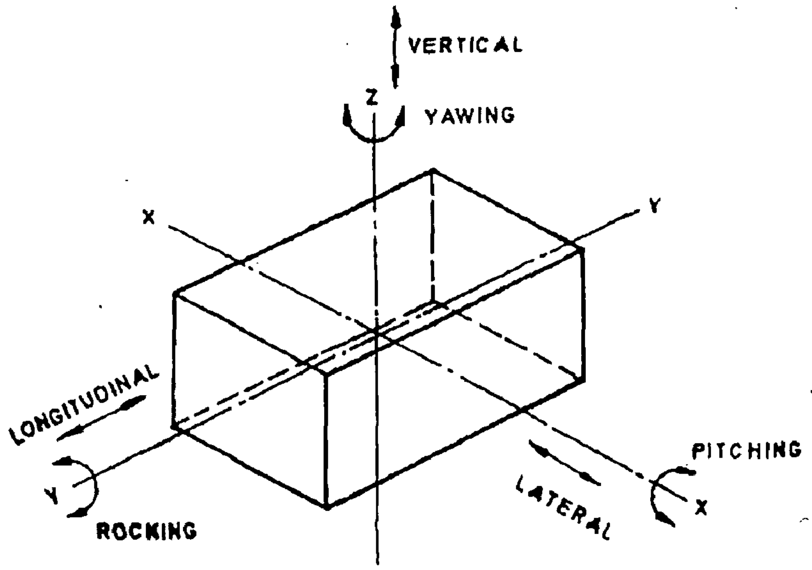


Fig.7 Different modes of vibration [10]

4.3 METHODS OF ANALYSIS [11]

The method of analysis of the reciprocating machine resting on block and on the pile is entirely different from each other. The analysis of the reciprocating machines is done with the help of the following theories developed. For designing the machine foundations the various parameters involved are to be studied thoroughly, where analysis plays a very important role.

4.3.1 Analysis of Block Foundation

The following two methods are commonly used for analyzing a machine supported by a block.

4.3.1.aLinear Elastic Weightless Spring Approach

Barkan proposed this method by replacing the soil with elastic springs. The effect of damping and the participating soil mass is neglected. The machine foundation soil system is idealized as a mass spring system for different modes of vibration.

4.3.1.bElastic Half-Space Method

Richart proposed this method where he assumed the ground to be an elastic, homogenous, isotropic, semi-infinite body. Richart's method was more complicated since it involves dimensionless parameters i.e. the mass ratio and the dimensionless frequency.

Elastic Half Space Analogs

It can be used to determine the values of equivalent soil springs and damping, then make use of theory of vibrations to determine the response of the foundation. The equivalent soil spring and damping values depends upon

(i) Type of soil and its properties
(ii) Geometry and layout of the foundation
(iii) Nature of the foundation vibrations occasioned by unbalanced dynamic loads.

In the above two methods, the effect of side soil resistance is not considered i.e.thefoundation is assumed to rest on the ground surface.

For an embedded block foundation, the soil resistances are mobilized both below and on the sides. This additional soil reaction has some significant influence on the dynamic response of embedded foundations. The embedded block foundation has been represented by equivalent spring stiffness for different modes of vibration.

4.3.2 Analysis of Pile Foundation

Basically, there are two types of analysis of the dynamic behavior of pile group and they are adopted to analyze and design the reciprocating machine supported on the pile group:

4.3.2.a Pseudo-Static Analysis

In this approach,approximate values of horizontal and vertical seismic co-efficient, are adopted and equivalent seismic forces are calculated to design the pile foundation for structures located in seismic regions. When these equivalent seismic forces are added to the static forces, the pile foundation is subjected to eccentric inclined load.

4.3.2.b Dynamic Analysis

In this method, the pile is subjected to sinusoidally varying dynamic force which is modeled as a single degree of freedom system. Here, the soil was assumed to be composed of independent infinitesimally thin horizontal layers of infinite extent which could be considered as a generalized Winkler material possessing inertia and dissipates energy.

4.4 DESIGN OF FOUNDATIONS[11]

The most important parameters in the design of machine foundation are the natural frequency of the machine foundation soil system and the amplitude of motion of the machine at its operating frequency. For the design of machine foundation, the values of permissible amplitudessuggested by Bureau of Indian Standards for the foundations of different types of machines are

Table 1:Permissible Amplitude for Foundations for Different Machines

S. No.	Type of Machine	Permissible Amplitude in mm
1	Reciprocating Machines	0.2
2	Hammer	
	(a) For foundation block	1.0 to 2.0
	(b) For anvil	1.0 to 3.0
3	Rotary Machines	
	(a) < 1500 rpm	0.2
	(b) 1500 to 3000 rpm	0.4 to 0.6 (Vertical) 0.7 to 0.9 (Horizontal)
	(c) >3000 rpm	0.2 to 0.3 (Vertical) 0.4 to 0.5 (Horizontal)

The trial size of the foundation is assumed and the amplitudes are calculated for different modes of vibration. Thus, to limit the amplitude within the permissible values several iterations are carried out and finally the size of the foundation system is obtained.

DYNAMIC BEHAVIOUR OF BLOCK AND PILE FOUNDATIONS

5.1 DYNAMIC BEHAVIOUR OF BLOCK FOUNDATION [32]

5.1.1 Linear Weightless Spring Approach

Barkan has given the analysis of block foundation for different modes of vibration. He introduced the coeffiecients i.e. the soil parameters which yield the spring stiffness of soil in various modes of vibration.

(i) Vertical Vibration

$$\omega_{nz} = \sqrt{\frac{C_u A}{m}} \tag{5.1}$$

$$A_z = \frac{F_z}{m(\omega_{nz}^2 - \omega^2)} \tag{5.2}$$

(ii) Coupled Rocking and Sliding

$$\omega_{nx} = \sqrt{\frac{C_\tau A}{m}} \tag{5.3}$$

$$\omega_{n\phi} = \sqrt{\frac{C_\phi I - WL}{M_{mo}}} \tag{5.4}$$

$$I = \frac{b * a^3}{12} \tag{5.5}$$

$$M_m = \frac{m}{12} * (b^2 + h^2) \tag{5.6}$$

$$M_{mo} = M_m + (m * L^2) \tag{5.7}$$

$$r = \frac{M_m}{M_{mo}} \tag{5.8}$$

$$\omega_{n1,2}^2 = \frac{1}{2r}\left[(\omega_{nx}^2 + \omega_{n\phi}^2) \pm \sqrt{(\omega_{nx}^2 + \omega_{n\phi}^2)^2 - 4r\omega_{nx}^2\omega_{n\phi}^2}\right] \tag{5.9}$$

$$\Delta\omega^2 = mM_m(\omega_{n1}^2 - \omega^2)(\omega_{n2}^2 - \omega^2) \tag{5.10}$$

$$A_x = \frac{(C_\phi I - WL + C_\tau AL^2 - M_m\omega^2)F_x + (C_\tau AL)M_y}{\Delta\omega^2} \tag{5.11}$$

$$A_\phi = \frac{(C_\tau AL)F_x + (C_\tau A - m\omega^2)M_y}{\Delta\omega^2} \tag{5.12}$$

$$A_v = A_z + \frac{a}{2}A_\phi \tag{5.13}$$

$$A_h = A_x + h'A_\phi \tag{5.14}$$

5.1.2 Elastic Half-Space Approach

Initially the problem of vibration of single oscillating force acting at a point on the surface of an elastic half space was studied by Lamb (1904). Later in 1936 Reissner developed the analysis for the problem of vibration of a uniformly loaded flexible circular area by integrating Lamb's solution for a point load (Fig.). Later on Richart developed an analytical approach as follows for different modes of vibration.

(i) Vertical Vibration

$$r_o = \sqrt{\frac{A}{\pi}} \tag{5.15}$$

$$B_z = \frac{1-\mu}{4}\frac{m}{\rho r_o^3} \tag{5.16}$$

$$K_z = \frac{4Gr_o}{1-\mu} \tag{5.17}$$

$$\omega_{nz} = \sqrt{\frac{K_z}{m}} \tag{5.18}$$

$$A_z = \frac{F_z}{K_z\left[\left(1-\left\{\frac{\omega}{\omega_{nz}}\right\}^2\right)^2 + \left(2\xi_z\frac{\omega}{\omega_{nz}}\right)^2\right]^{1/2}} \tag{5.19}$$

(ii) Coupled Rocking and Sliding

$$r_{ox} = \sqrt{\frac{A}{\pi}} \tag{5.20}$$

$$K_x = \frac{32(1-\mu)Gr_o}{7-8\mu} \tag{5.21}$$

$$B_x = \frac{7-8\mu}{32(1-\mu)}\frac{m}{\rho r_o^3} \tag{5.22}$$

$$\xi_x = \frac{0.2875}{\sqrt{B_x}} \tag{5.23}$$

$$\omega_{nx} = \sqrt{\frac{K_x}{m}} \tag{5.24}$$

$$r_{o\phi} = \left(\frac{ab^3}{3\pi}\right)^{\frac{1}{4}} \tag{5.25}$$

$$K_\phi = \frac{8Gr_o^3}{3(1-\mu)} \tag{5.26}$$

$$B_\phi = \frac{3(1-\mu)}{8}\frac{M_{mo}}{\rho r_o^5} \tag{5.27}$$

$$\xi_\phi = \frac{0.15}{(1+B_\phi)\sqrt{B_\phi}} \tag{5.28}$$

$$\omega_{n\phi} = \sqrt{\frac{K_\phi}{M_{mo}}} \tag{5.29}$$

$$\omega_{n1,2}^2 = \frac{1}{2r}\left[\left(\omega_{nx}^2 + \omega_{n\phi}^2\right) \pm \sqrt{\left(\omega_{nx}^2 + \omega_{n\phi}^2\right)^2 - 4r\omega_{nx}^2\omega_{n\phi}^2}\right] \tag{5.30}$$

$$\Delta\omega^2 = \left[\begin{array}{c}\left\{\omega^4 - \omega^2\left[\frac{\left(\omega_{nx}^2 + \omega_{n\phi}^2\right)}{r} - \frac{4\xi_x\xi_\phi\omega_{nx}\omega_{n\phi}}{r}\right] + \frac{\left(\omega_{nx}^2\omega_{n\phi}^2\right)}{r}\right\}^2 + \\ 4\left\{\left(\frac{\xi_x\omega_{nx}\omega}{r}\left(\omega_{n\phi}^2 - \omega^2\right)\right) + \left(\frac{\xi_\phi\omega_{n\phi}\omega}{r}\left(\omega_{nx}^2 - \omega^2\right)\right)\right\}^2\end{array}\right]^{1/2} \tag{5.31}$$

$$A_{x1} = \frac{F_x\left[\left(-M_m\omega^2 + K_\phi + K_xL^2\right)^2 + \omega^2\left(C_\phi + C_xL^2\right)^2\right]^{1/2}}{mM_m\Delta\omega^2} \tag{5.32}$$

$$A_{\phi1} = \frac{F_xL\omega_{nx}[\omega_{nx}^2 + 4\xi_x\omega^2]^{1/2}}{M_m\Delta\omega^2} \tag{5.33}$$

$$A_{x2} = \frac{M_yL[(\omega_{nx}^2)^2 + 2\xi_x\omega_{nx}\omega]^{1/2}}{M_m\Delta\omega^2} \tag{5.34}$$

$$A_{\phi2} = \frac{M_y[(\omega_{nx}^2 - \omega^2)^2 + (2\xi_x\omega_{nx}\omega)^2]^{1/2}}{M_m\Delta\omega^2} \tag{5.35}$$

$$A_x = A_{x1} + A_{x2} \tag{5.36}$$

$$A_\phi = A_{\phi1} + A_{\phi2} \tag{5.37}$$

$$A_v = A_z + \frac{a}{2}A_\phi \tag{5.38}$$

$$A_h = A_x + h'A_\phi \tag{5.39}$$

5.1.3 Embedded Block Foundation Approach

(i) Vertical Vibration

$$K_{ze} = C_{uD}A + 2C_{\tau av}(bD + aD) \tag{5.40}$$

$$h_e = \frac{h\gamma_c}{\gamma_s} \tag{5.41}$$

$$S = \frac{\alpha h_e}{b} \tag{5.42}$$

$$m_s = \frac{\gamma b^3 C_m}{\alpha g} \tag{5.43}$$

$$\omega_{nze} = \sqrt{\frac{K_{ze}}{m + m_s}} \tag{5.44}$$

$$A_{ze} = \frac{F_e}{(m + m_s)(\omega_{nze}^2 - \omega^2)} \tag{5.45}$$

(ii) Coupled Rocking and Sliding

$$K_{xe} = C_{\tau D}A + 2C_{uav}bD + 2C_{\tau av}aD \tag{5.46}$$

$$M_{mxs} = \frac{\gamma b^5 C_i^x}{12\alpha g} \tag{5.47}$$

$$\omega_{nxe} = \sqrt{\frac{K_{xe}}{m + m_s}} \tag{5.48}$$

$$K_{\phi e} = C_{\phi D}I - WL + \frac{C_{\phi av}b(16D^3 - 12hD^2)}{24} + 2C_{\phi av}I_o + C_{\tau av}\frac{Dba^2}{2} \tag{5.49}$$

$$I = \frac{b * a^3}{12} \tag{5.50}$$

$$I_o = \frac{a * D^3}{3} \tag{5.51}$$

$$\omega_{n\phi e} = \sqrt{\frac{K_{\phi e}}{M_{mo} + M_{mos}}} \tag{5.52}$$

$$K_{xx} = C_{\tau D}A + 2C_{uav}bD + 2C_{\tau av}aD \tag{5.53}$$

$$K_{x\phi} = C_{\phi av}b(D^2 - 2DL) - C_{\tau D}AL \tag{5.54}$$

$$I_y = \frac{D * a^3}{12} + \frac{a * D * b^2}{4} \tag{5.55}$$

$$K_{\phi\phi} = C_{\phi D}I + C_{\tau D}AL^2 - WL + 2C_{\psi av}I_y + C_{\tau av}\frac{bDa^2}{2} + \frac{2C_{\phi av}(L^3 + (D - L)^3)}{3} \tag{5.56}$$

$$K_{\phi x} = -\left[C_{\tau D}AL + 2C_{uav}bD\left(L - \frac{D}{3}\right) + 2C_{\tau av}aD(L - \frac{D}{3})\right] \quad (5.57)$$

$$A_{x1} = \frac{\{K_{\phi\phi} - (M_m + M_{mxs})\omega^2\}F_x}{\{K_{xx} - (m + m_s)\omega^2\}\{K_{\phi\phi} - (M_m + M_{mxs})\omega^2\} - K_{\phi x}K_{x\phi}} \quad (5.58)$$

$$A_{\phi 1} = \frac{-K_{\phi x}F_x}{\{K_{xx} - (m + m_s)\omega^2\}\{K_{\phi\phi} - (M_m + M_{mxs})\omega^2\} - K_{\phi x}K_{x\phi}} \quad (5.59)$$

$$A_{x2} = \frac{-K_{x\phi}M_y}{\{K_{xx} - (m + m_s)\omega^2\}\{K_{\phi\phi} - (M_m + M_{mxs})\omega^2\} - K_{\phi x}K_{x\phi}} \quad (5.60)$$

$$A_{\phi 2} = \frac{\{K_{xx} - (m + m_s)\omega^2\}M_y}{\{K_{xx} - (m + m_s)\omega^2\}\{K_{\phi\phi} - (M_m + M_{mxs})\omega^2\} - K_{\phi x}K_{x\phi}} \quad (5.61)$$

$$A_x = A_{x1} + A_{x2} \quad (5.62)$$

$$A_\phi = A_{\phi 1} + A_{\phi 2} \quad (5.63)$$

$$A_v = A_z + \frac{a}{2}A_\phi \quad (5.64)$$

$$A_h = A_x + (h - L)A_\phi \quad (5.65)$$

5.2 DYNAMIC BEHAVIOUR OF SINGLE PILE [32]

5.2.1 Single Pile Subjected To Vertical Vibration

Novak and Sharnouby [18] have developed the following solutions to calculate the stiffness and damping constant of a single pile subjected to vertical vibration.

$$r_o = \sqrt{\frac{A}{\pi}} \quad (5.66)$$

$$K_{zp} = (E_pA/r_o)*f_{w1} \quad (5.67)$$

$$C_{zp} = (E_pA/v_s)*f_{w2} \quad (5.68)$$

f_{w1} and f_{w2} are parameters which depend on

(i) Type of pie whether end bearing or friction

(ii) Pile slenderness

(iii) E_p/G_s

(iv) Variation of G_s with depth.

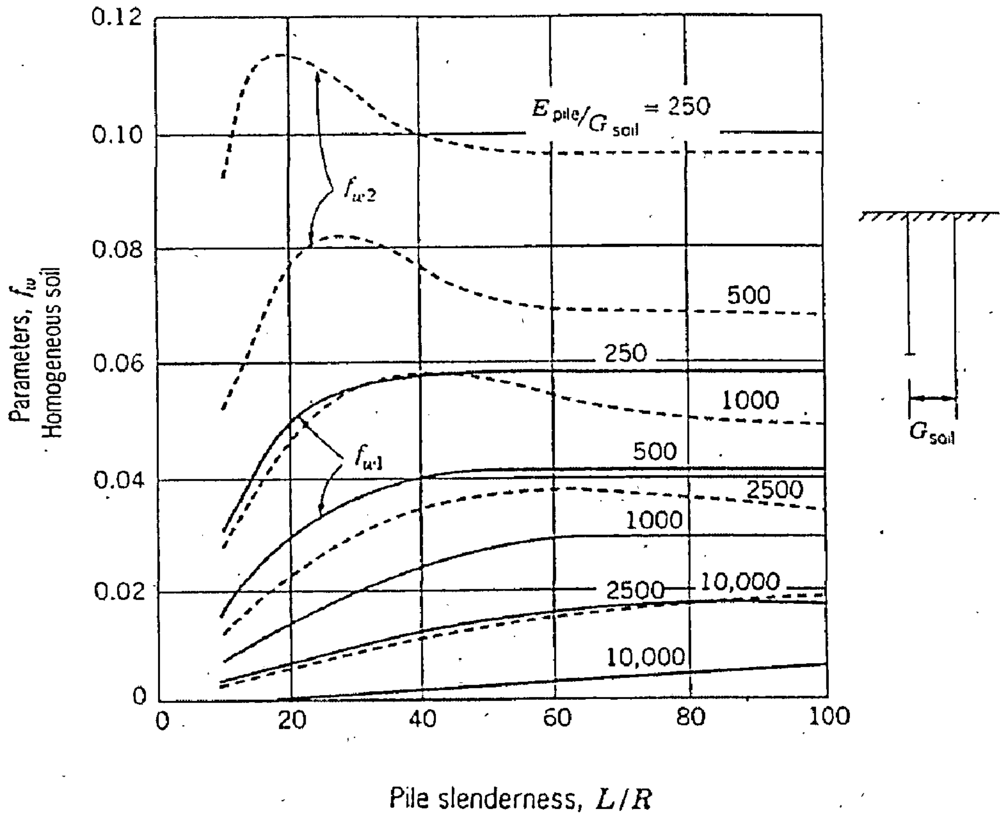


Fig.8 Chart for friction pile with constant profile for vertical vibration [32]

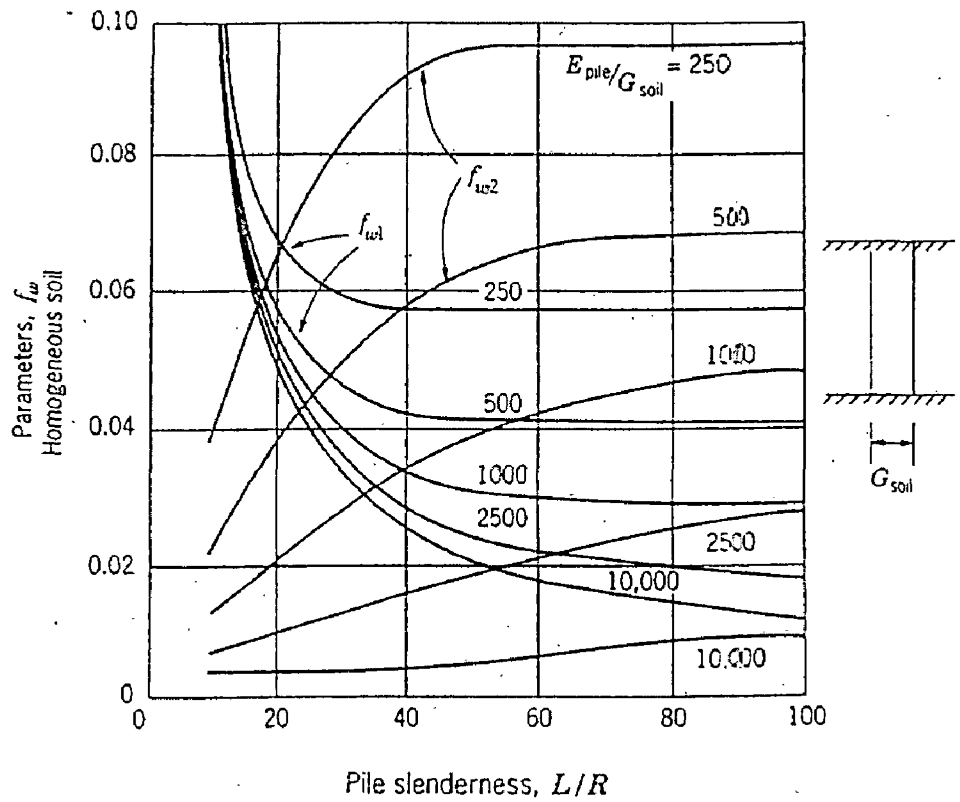


Fig.9 Chart for end bearing pile with constant profile for vertical vibration [32]

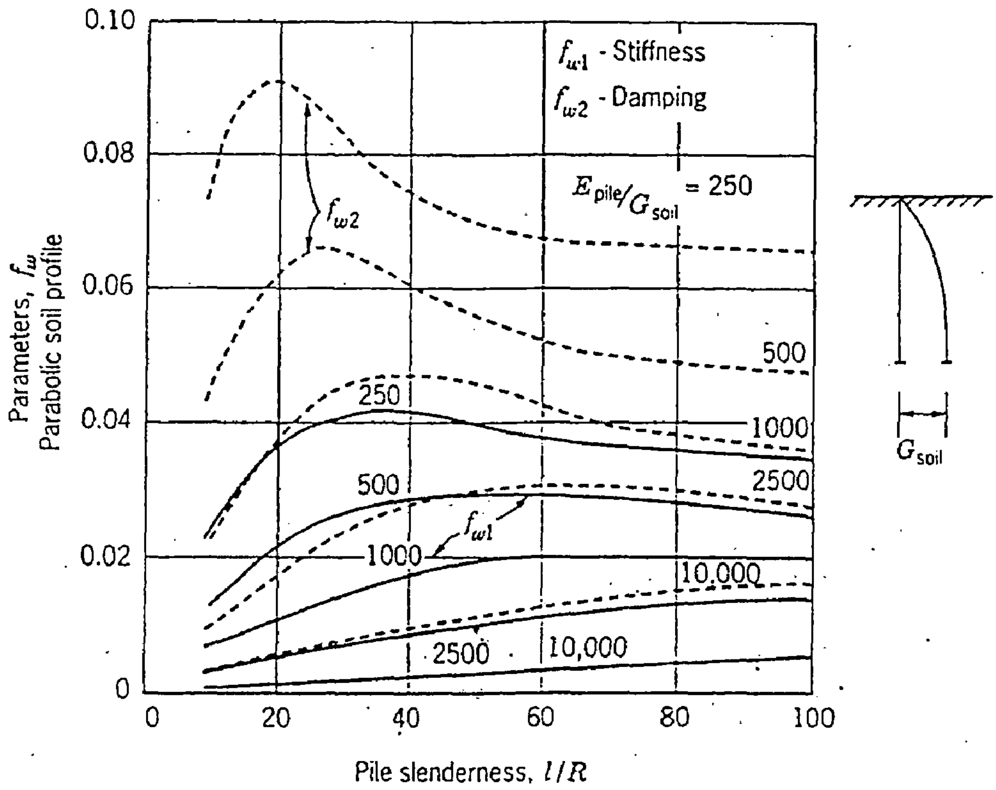


Fig.10 Chart for friction pile with varying profile for vertical vibration [32]

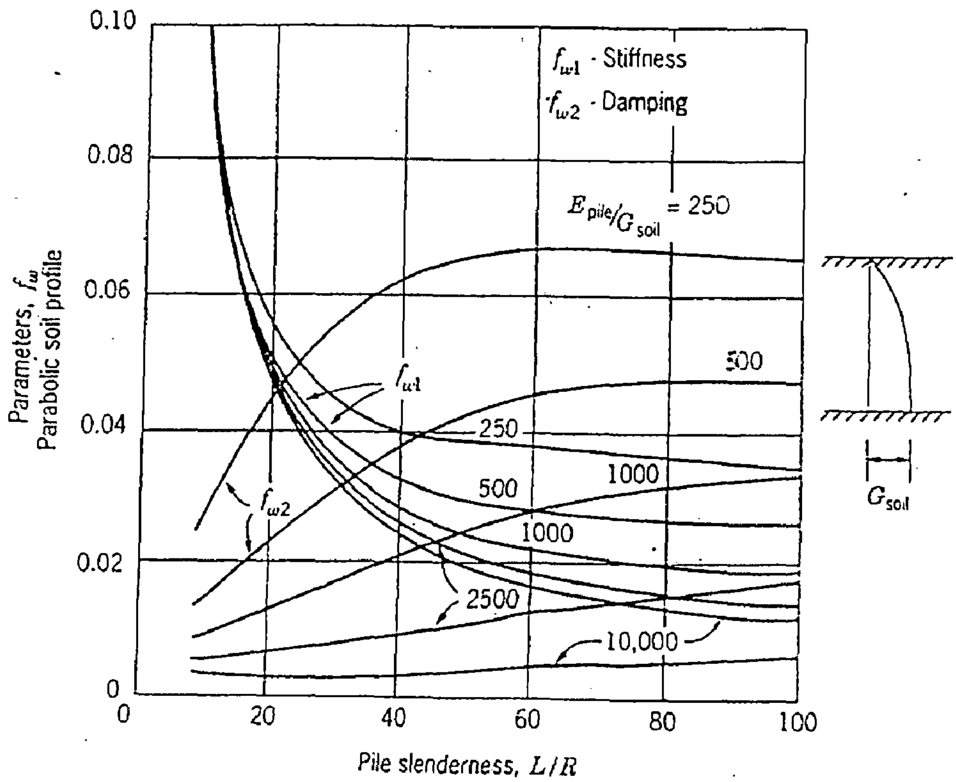


Fig.11 Chart for end bearing pile with varying profile for vertical vibration [32]

5.2.2 Single Pile Subjected To Translation Motion

Novak [20] gave the solution for constant soil modulus and later on Novak and Sharnouby [18] extended the solutions to varying soil modulus for translation motion.

$K_{xp} = (E_p I_p / r_o^3)*f_{x1}$ (5.69)

$C_{xp} = (E_p I_p / r_o^2 v_s)*f_{x2}$ (5.70)

f_{x1} and f_{x2} are parameters which depend on

(i) Poisson's ratio
(ii) Pile slenderness
(iii) E_p/G_s
(iv) Variation of G_s with depth
(v) Type of support of pile head.

5.2.3 Single Pile Subjected To Rotational Motion

Novak [20] gave the solution for constant soil modulus and later on Novak and Sharnouby [18] extended the solutions to varying soil modulus for rotational motion.

$K_{\phi p} = (E_p I_p / r_o)*f_{\phi 1}$ (5.71)

$C_{\phi p} = (E_p I_p / v_s)*f_{\phi 2}$ (5.72)

$f_{\phi 1}$ and $f_{\phi 2}$ are parameters which depend on

(i) Poisson's ratio
(ii) Pile slenderness
(iii) E_p/G_s
(iv) Variation of G_s with depth.

5.2.4 Single Pile Subjected To Coupled Motion

Novak [20] gave the solution for constant soil modulus and later on Novak and Sharnouby [18] extended the solutions to varying soil modulus for coupled motion.

$K_{x\phi p} = (E_p I_p / r_o^2)*f_{x\phi 1}$ (5.73)

$C_{x\phi p} = (E_p I_p / r_o v_s)*f_{x\phi 2}$ (5.74)

$f_{x\phi 1}$ and $f_{x\phi 2}$ are parameters which depend on

(i) Poisson's ratio
(ii) Pile slenderness
(iii) E_p/G_s
(iv) Variation of G_s with depth.

Table 2: Constants for various modes of vibration of piles [32]

ν	Stiffness Parameters					Damping Parameters			
	E_{pile}/G_{soil}	$(f_{\phi 1})$	$(f_{x\phi 1})$	(f^{*}_{x1})	(f^{p}_{x1})	$(f_{\phi 2})$	$(f_{x\phi 2})$	(f^{*}_{x2})	(f^{p}_{x2})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Homogeneous Soil Profile									
0.25	10,000	0.2135	-0.0217	0.0042	0.0021	0.1577	-0.0333	0.0107	0.0054
	2,500	0.2998	-0.0429	0.0119	0.0061	0.2152	-0.0646	0.0297	0.0154
	1000	0.3741	-0.0668	0.0236	0.0123	0.2598	-0.0985	0.0579	0.0306
	500	0.4411	-0.0929	0.0395	0.0210	0.2953	-0.1337	0.0953	0.0514
	250	0.5186	-0.1281	0.0659	0.0358	0.3299	-0.1786	0.1556	0.0864
0.4	10,000	0.2207	-0.0232	0.0047	0.0024	0.1634	-0.0358	0.0119	0.0060
	2,500	0.3097	-0.0459	0.0132	0.0068	0.2224	-0.0692	0.0329	0.0171
	1000	0.3860	-0.0714	0.0261	0.0136	0.2677	-0.1052	0.0641	0.0339
	500	0.4547	-0.0991	0.0436	0.0231	0.3034	-0.1425	0.1054	0.0570
	250	0.5336	-0.1365	0.0726	0.0394	0.3377	-0.1896	0.1717	0.0957
Parabolic Soil Profile									
0.25	10,000	0.1800	-0.0144	0.0019	0.0008	0.1450	-0.0252	0.0060	0.0028
	2,500	0.2452	-0.0267	0.0047	0.0020	0.2025	-0.0484	0.0159	0.0076
	1000	0.3000	-0.0400	0.0086	0.0037	0.2499	-0.0737	0.0303	0.0147
	500	0.3489	-0.0543	0.0136	0.0059	0.2910	-0.1008	0.0491	0.0241
	250	0.4049	-0.0734	0.0215	0.0094	0.3361	-0.1370	0.0793	0.0398
0.4	10,000	0.1857	-0.0153	0.0020	0.0009	0.1508	-0.0271	0.0067	0.0031
	2,500	0.2529	-0.0284	0.0051	0.0022	0.2101	-0.0519	0.0177	0.0084
	1000	0.3094	-0.0426	0.0094	0.0041	0.2589	-0.0790	0.0336	0.0163
	500	0.3596	-0.0577	0.0149	0.0065	0.3009	-0.1079	0.0544	0.0269
	250	0.4170	-0.0780	0.0236	0.0103	0.3468	-0.1461	0.0880	0.0443

5.3 GROUP ACTION OF PILES UNDER DYNAMIC LOADING [32]

5.3.1 Vertical Vibration

Novak and Grigg [19] gave the solutions for calculating the stiffness and damping of piles in a pile group, whereas, the constants for embedded pile cap was given by Novak and Beredugo [17].

$$K_{zg} = \frac{\sum_1^n K_{zp}}{\sum_1^n \alpha_A} \quad (5.75)$$

$$C_{zg} = \frac{\sum_1^n C_{zp}}{\sum_1^n \alpha_A} \quad (5.76)$$

$$K_{zf} = G_s D S_{z1} \quad (5.77)$$

$$C_{zf} = D r_{oc} S_{z2} \sqrt{G_s \rho} \quad (5.78)$$

$$K_{zgt} = K_{zg} + K_{zf} \quad (5.79)$$

$$C_{zgt} = C_{zg} + C_{zf} \quad (5.80)$$

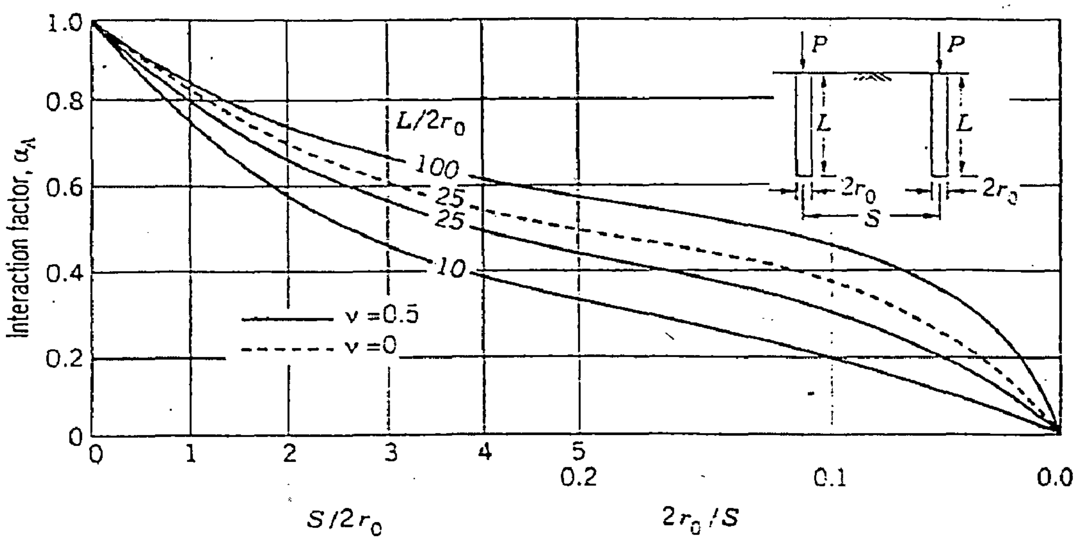


Fig.12 Interaction factor for pile groups under vertical vibration [32]

5.3.2 Translation Motion

$$K_{xg} = \frac{\sum_1^n K_{xp}}{\sum_1^n \alpha_A} \quad (5.81)$$

$$C_{xg} = \frac{\sum_1^n C_{xp}}{\sum_1^n \alpha_A} \quad (5.82)$$

$$K_{xf} = G_s D S_{x1} \quad (5.83)$$

$$C_{xf} = D r_{oc} S_{x2} \sqrt{G_s \rho} \quad (5.84)$$

$$K_{xgt} = K_{xg} + K_{xf} \quad (5.85)$$

$$C_{xgt} = C_{xg} + C_{xf} \quad (5.86)$$

Table 3: Constants of pile cap for translation motion [32]

Poisson's Ratio υ	Validity Range	Constant Parameter
0.00	$0 < a_0 < 1.5$	$\bar{S}_{x1} = 3.6$ $\bar{S}_{x2} = 8.2$
0.25	$0 < a_0 < 1.5$	$\bar{S}_{x1} = 4.0$ $\bar{S}_{x2} = 9.1$
0.40	$0 < a_0 < 1.5$	$\bar{S}_{x1} = 4.1$ $\bar{S}_{x2} = 10.6$

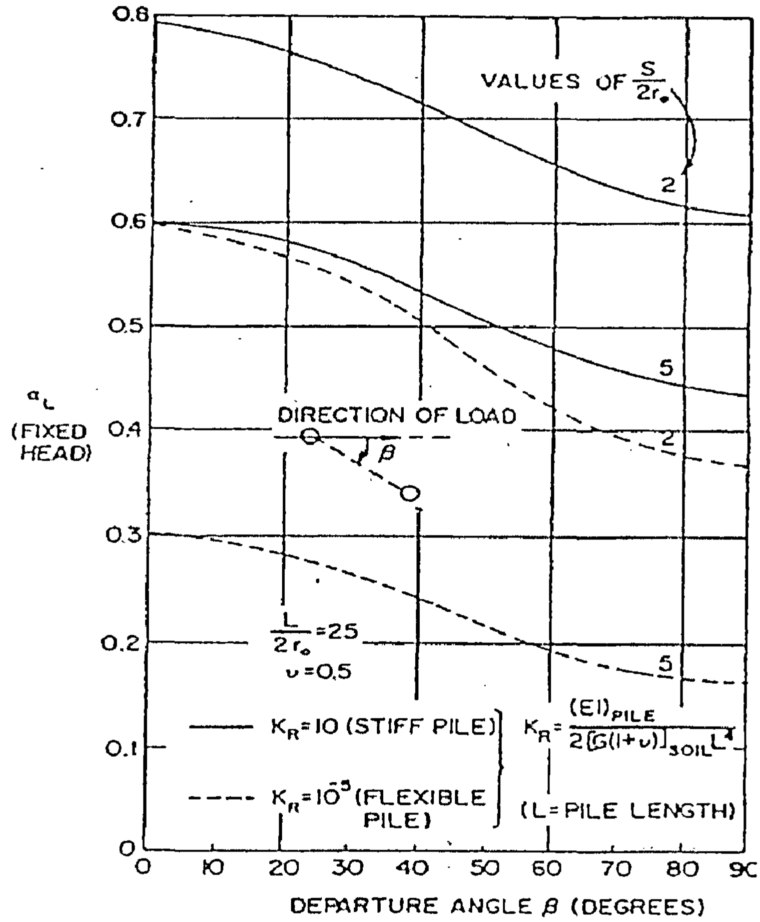


Fig.13 Interaction factor for pile group under translation motion [32]

5.3.3 Rotational Motion

$$K\phi_g = \Sigma_1^n\left(K_{\phi p} + K_{zp}x_r^2 + K_{xp}Z_c^2 - 2Z_cK_{x\phi p}\right) \quad (5.87)$$

$$C\phi_g = \Sigma_1^n\left(C_{\phi p} + C_{zp}x_r^2 + C_{xp}Z_c^2 - 2Z_cC_{x\phi p}\right) \quad (5.88)$$

$$K\phi f = G_s r_{oc}^2 D S_{\phi 1} + G_s r_{oc}^2 D\left[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_0}\right)^2 - \left(\frac{Z_c}{r_0}\right)\right] S_{x1} \quad (5.89)$$

$$C\phi f = \delta r_{oc}^4\sqrt{\frac{G_s\gamma}{g}}\left\{S_{\phi 2} + \left[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_0}\right)^2 - \delta\left(\frac{Z_c}{r_0}\right)\right] S_{x2}\right\} \quad (5.90)$$

$$K_{\phi gt} = K_{\phi g} + K_{\phi f} \quad (5.91)$$

$$C_{\phi gt} = C_{\phi g} + C_{\phi f} \quad (5.92)$$

5.3.4 Coupled Motion

Undamped natural frequencies in coupled rocking and sliding are given by

$$\omega_{n1,2}^2 = \frac{1}{2r}\left[\left(\omega_{nx}^2 + \omega_{n\phi}^2\right) \pm \sqrt{\left(\omega_{nx}^2 + \omega_{n\phi}^2\right)^2 - 4r\omega_{nx}^2\omega_{n\phi}^2}\right] \quad (5.93)$$

$$\Delta\omega^2 = \left[\begin{array}{c}\left\{\omega^5 - \omega^2\left[\frac{\left(\omega_{nx}^2+\omega_{n\phi}^2\right)}{r} - \frac{4\xi_x\xi_\phi\omega_{nx}\omega_{n\phi}}{r}\right] + \frac{\left(\omega_{nx}^2\omega_{n\phi}^2\right)}{r}\right\}^2 + \\ 4\left\{\left(\frac{\xi_x\omega_{nx}\omega}{r}\left(\omega_{n\phi}^2 - \omega^2\right)\right) + \left(\frac{\xi_\phi\omega_{n\phi}\omega}{r}\left(\omega_{nx}^2 - \omega^2\right)\right)\right\}^2\end{array}\right]^{1/2} \quad (5.94)$$

Where,

$$\omega_{nx} = \sqrt{\frac{K_{xgt}}{m}} \quad (5.95)$$

$$\omega_{n\phi} = \sqrt{\frac{K_{\phi gt}}{M_{mo}}} \quad (5.96)$$

$$r = \frac{M_m}{M_{mo}} \quad (5.97)$$

$$\xi_x = \frac{C_{xg}}{2\sqrt{K_{xgt}m}} \quad (5.98)$$

$$\xi_\phi = \frac{C_{\phi g}}{2\sqrt{K_{\phi gt}M_{mo}}} \quad (5.99)$$

$$A_{x1} = \frac{F_x\left[\left(-M_m\omega^2+K_\phi+K_xL^2\right)+\omega^2\left(C_\phi+C_xL^2\right)^2\right]^{1/2}}{mM_m\Delta\omega^2} \quad (5.100)$$

$$A_{\phi 1} = \frac{F_xL\omega_{nx}\left[\omega_{nx}^2+4\xi_x\omega^2\right]^{1/2}}{M_m\Delta\omega^2} \quad (5.101)$$

$$A_{x2} = \frac{M_yL\left[\left(\omega_{nx}^2\right)^2+2\xi_x\omega_{nx}\omega\right]^{1/2}}{M_m\Delta\omega^2} \quad (5.102)$$

$$A_{\phi 2} = \frac{M_y\left[\left(\omega_{nx}^2-\omega^2\right)^2+\left(2\xi_x\omega_{nx}\omega\right)^2\right]^{1/2}}{M_m\Delta\omega^2} \quad (5.103)$$

$$A_x = A_{x1} + A_{x2} \quad (5.104)$$

$$A_\phi = A_{\phi 1} + A_{\phi 2} \quad (5.105)$$

5.4 DESIGN CHARTS

The design charts already available for the dynamic analysis of pile group are more complicated and involves several constants and ratios. The following table shows the factors upon which the constants depend upon for different modes of vibration.

Table 4: Factors influencing constants for various modes of vibration

MODE OF VIBRATION	VERTICAL MODE	SLIDING MODE	ROCKING MODE
PILE	Damping factor (Constants S_{x1} and S_{x2}), Type of pile, Slenderness Ratio, E/G ratio &Variation of G	Type of pile, Slenderness Ratio, E/G ratio & Poisson's ratio	Distance of each pile from c.g., &Height of c.g. of pile cap above its base
PILE CAP	Depth of embedment, Equivalent radius of pile cap, G & Mass density	Depth of embedment, Equivalent radius of pile cap, G & Mass density	Depth of embedment & Equivalent radius of pile cap
INTERACTION FACTOR(PILE GROUP)	Type of pile i.e. End bearing or frictional pile, Slenderness Ratio, E/G ratio & Variation of G	Type of pile i.e. End bearing or frictional pile, Slenderness Ratio, Spacing of piles, Departure angle, S_{x1} and S_{x2}, Constants S_{x1} and S_{x2} depend on the poison's ratio and its valid for the range of 0 to 2 a_0.	Poisson's ratio, Slenderness ratio & Spacing of piles

5.5 SUMMARY

The design charts available for the dynamic behavior of piles and pile group depend upon several factors and hence the design becomes more complicated. The curves are further digitized to make the design procedure simple. The developed equations are checked for accuracy and then used in the design of reciprocating machines resting on piles.

6.1 SELECTION OF PARAMETERS

6.1.1 Soil Parameters

The soil parameter is represented by the Shear modulus of the soil. For the multiple soil layer the shear modulus of the soil increases with depth. This is represented by the parabolically varying soil profile as depicted in the charts. The parabolically varying soil profile is selected in the problem.

6.1.2 Pile Group Parameters

6.1.2.1 Spacing between piles

The spacing between the piles are varied from 2d to 4d and the variation of natural frequency and the amplitude of the system are studied.

6.1.2.2 Interaction factors

The calculation of interaction factor plays a major role in the dynamic analysis of a pile group. The interaction factor for a pile group depends upon the arrangement and spacing between piles in the pile group. Selection of reference pile plays a major role here.

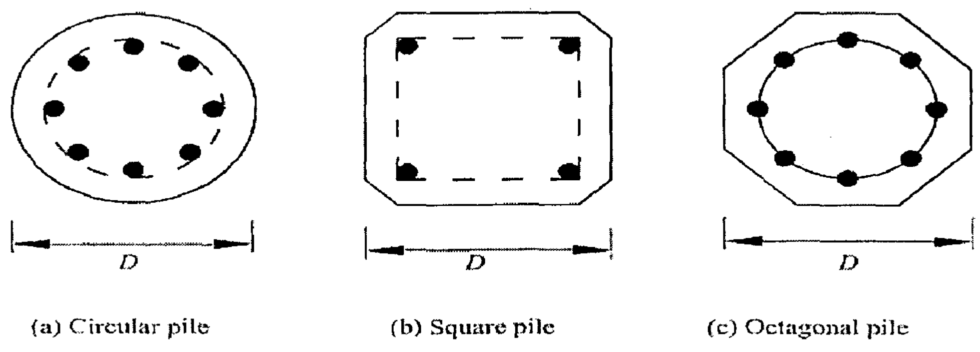


Fig. 14 Geometry of piles [34]

6.1.2.3 Pile group arrangement

The piles in a pile group may be arranged in any of the following pattern. For the Machine foundation the pile group is selected according to the plan area of the Machine. Usually the plan area of the machine is not symmetrical. But in our problem the pile group arrangement is assumed to be symmetrical to simplify the analysis.

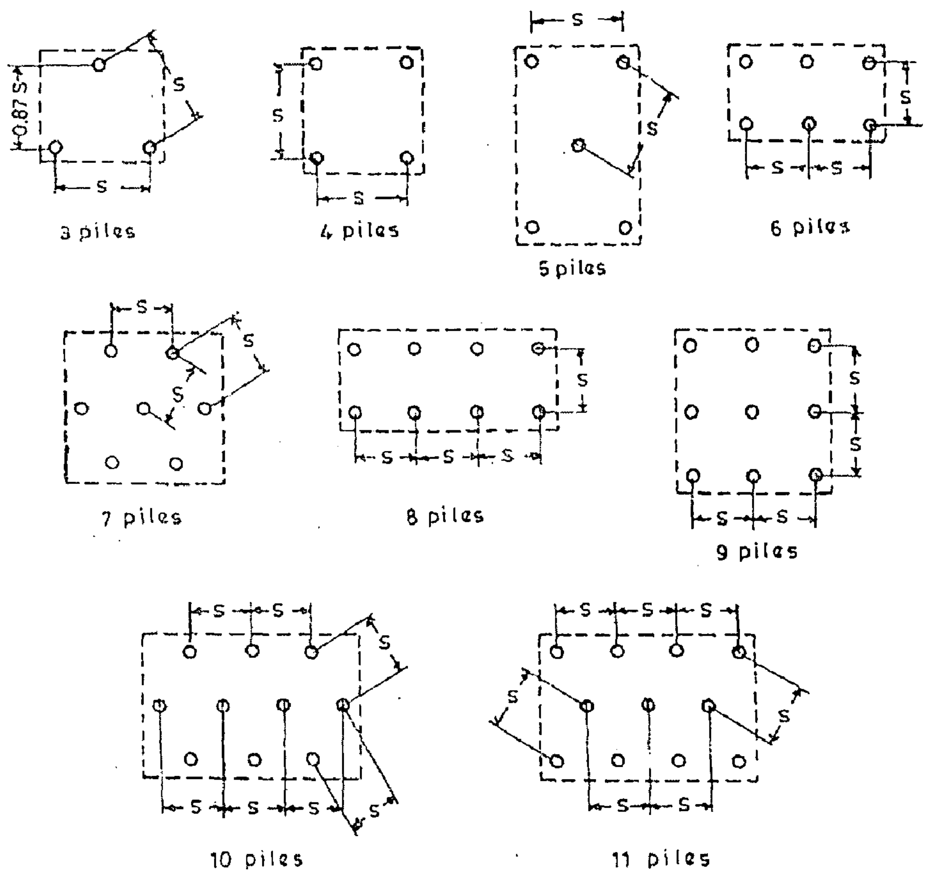


Fig.15 Different types of arrangement of piles in pile group [33]

6.1.3 MACHINE PARAMETERS

The operating frequency and the weight of the reciprocating machine are selected such that the parameters suite the values of the machines that are used in the industries. The operating frequency of the reciprocating machines used in the industries varies between 300 to 1000 rpm usually. The weight of the reciprocating machine varies from 300kN to 1700 kN.

6.1.4 BLOCK FOUNDATION PARAMETERS

For comparing the pile group foundation supporting a reciprocating machine to an equivalent block foundation system the parameters are selected such that the pile group and block plan area are one and the same. The depth of embedment is selected such that the thickness for the working platform is same in both the cases. Thus, considering an equivalent block foundation system to that of a pile group system the variation in the parameters are studied.

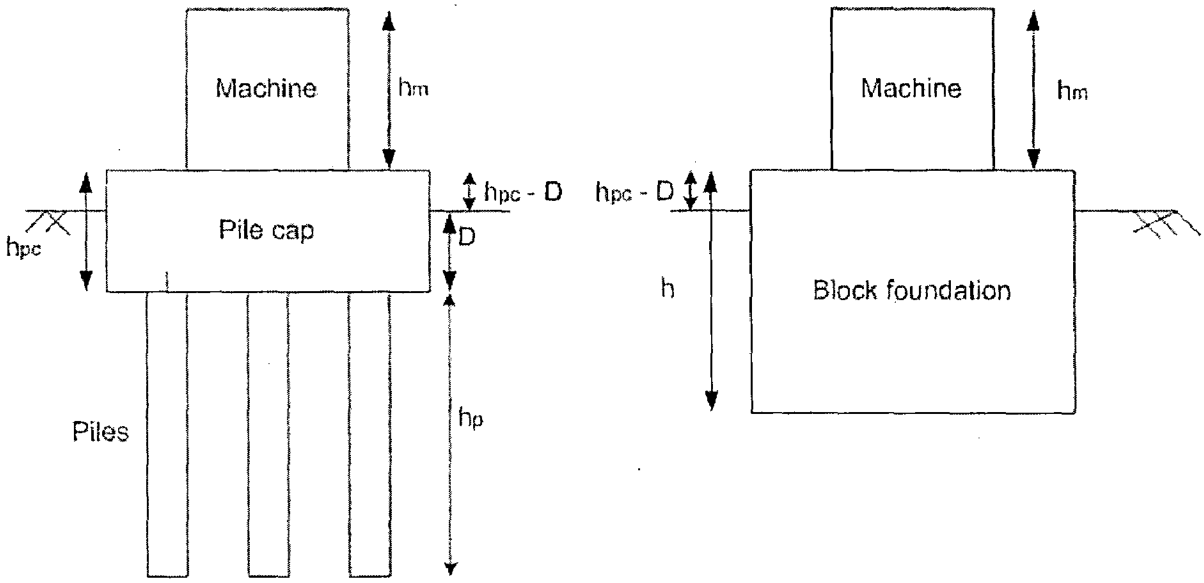


Fig.16 Equivalent block foundation for pile group

6.2 ANALYSIS PROCEDURE

The various parameters that are required to analyze the reciprocating machine resting on the piles is represented in the following figure.

For the above said three cases the procedure used for analysis is represented in the following flow chart. In the flow chart the parameters are kept constant and the analysis procedure remains in the same sequence for all the three cases. MATLAB [26], [27] is used to develop a program to solve the problem in the following sequence.

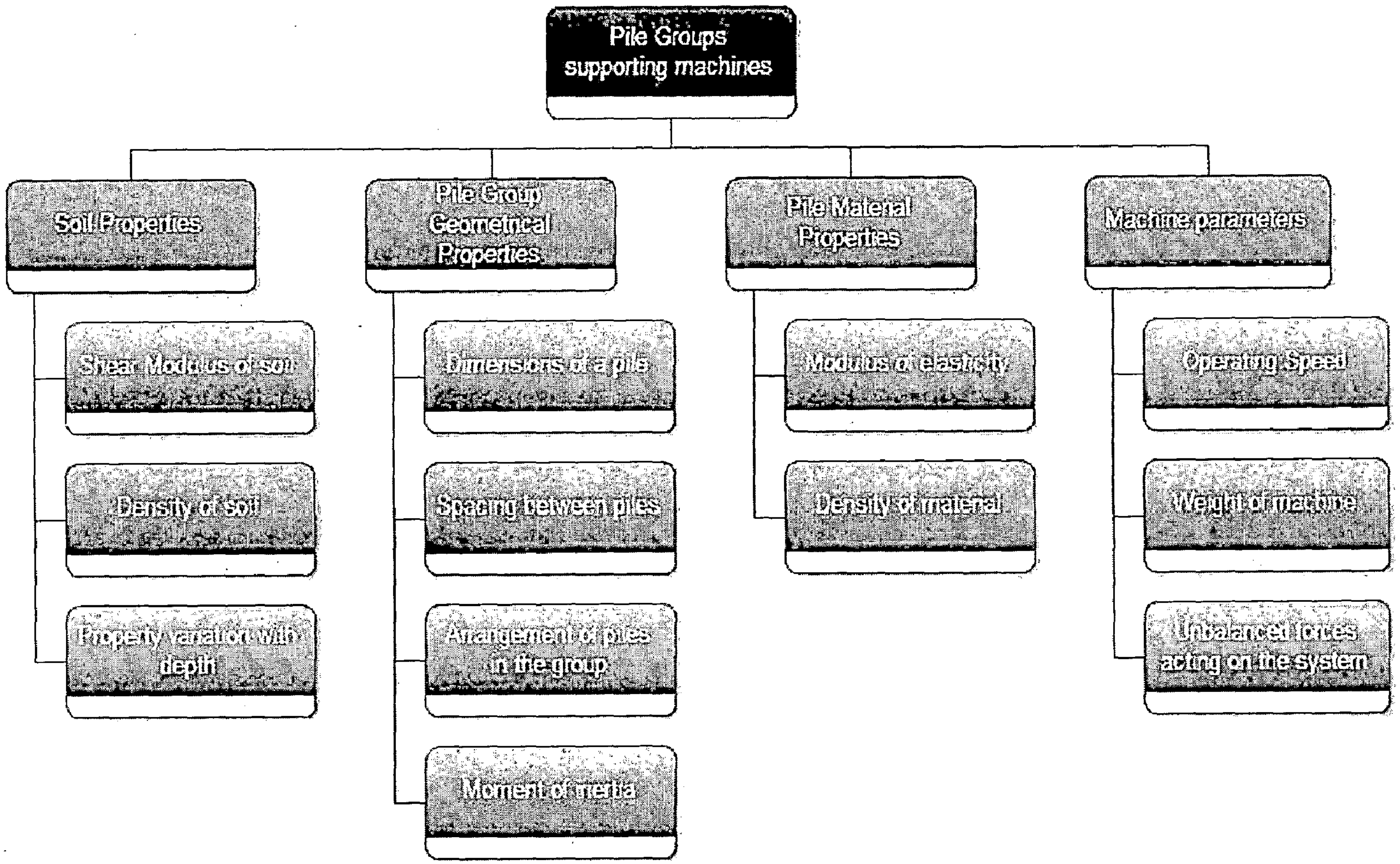


Fig.17 Parameters required for design of pile group

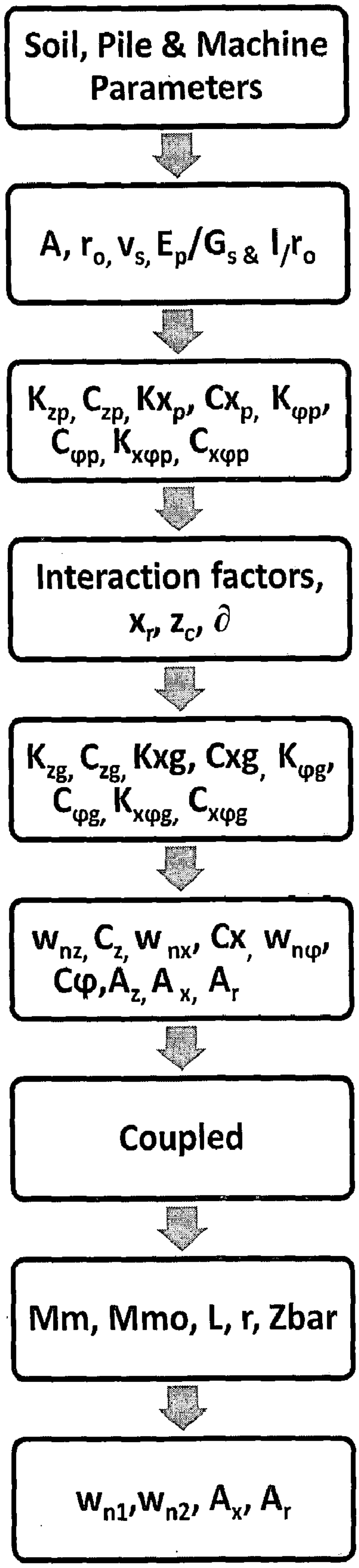


Fig.18 Flowchart representing analysis procedure for pile group

For the selected problem the variation in the frequency and amplitude for different modes of vibration is studied varying the parameters.

Case (i) The machine parameters i.e. the machine weight and the operating frequency are kept constant and the spacing between the piles are varied.

Wm = 400 kN (ω = 41.88 rad/sec) & OS = 400 rpm

Table 5: Frequency variation with varying space between piles

Spacing between piles in m	s=2d	s=2.5d	s=3d	s=3.5d	s=4d
wnz (rad/s)	33.79	29.81	26.60	23.98	21.80
wn1 (rad/s)	42.42	38.63	35.95	34.02	32.63
wn2 (rad/s)	10.25	9.92	9.58	9.20	8.82

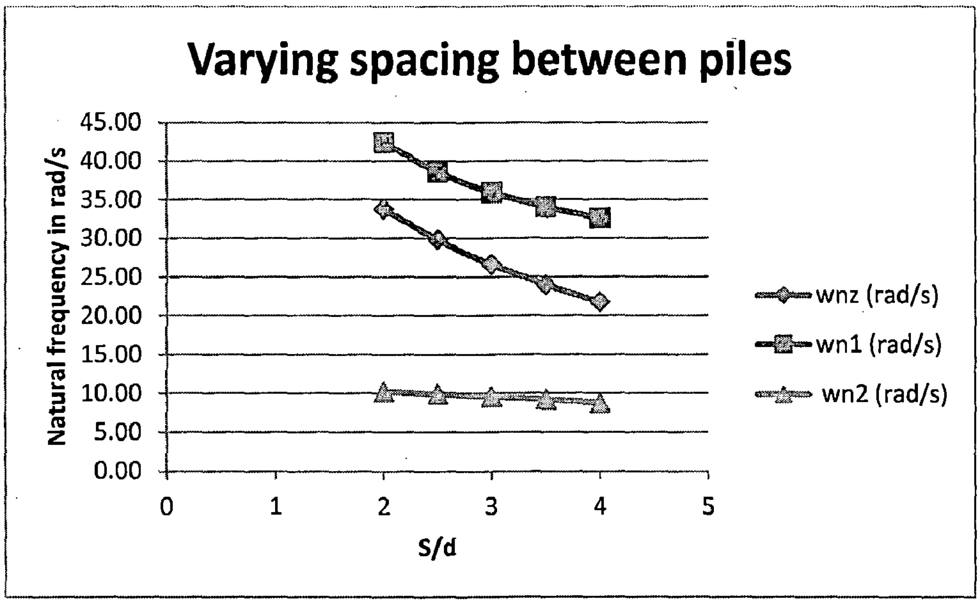


Fig.19 Natural frequency variation with S/d

Table 6: Amplitude variation with varying space between piles

Spacing between piles in m	s=2d	s=2.5d	s=3d	s=3.5d	s=4d
Az (m)	0.000878	0.000627	0.000457	0.000346	0.00027
AX (m)	6.09E-05	4.76E-05	3.78E-05	3.04E-05	2.49E-05
AR (rad)	1.69E-05	1.45E-05	1.24E-05	1.07E-05	9.19E-06

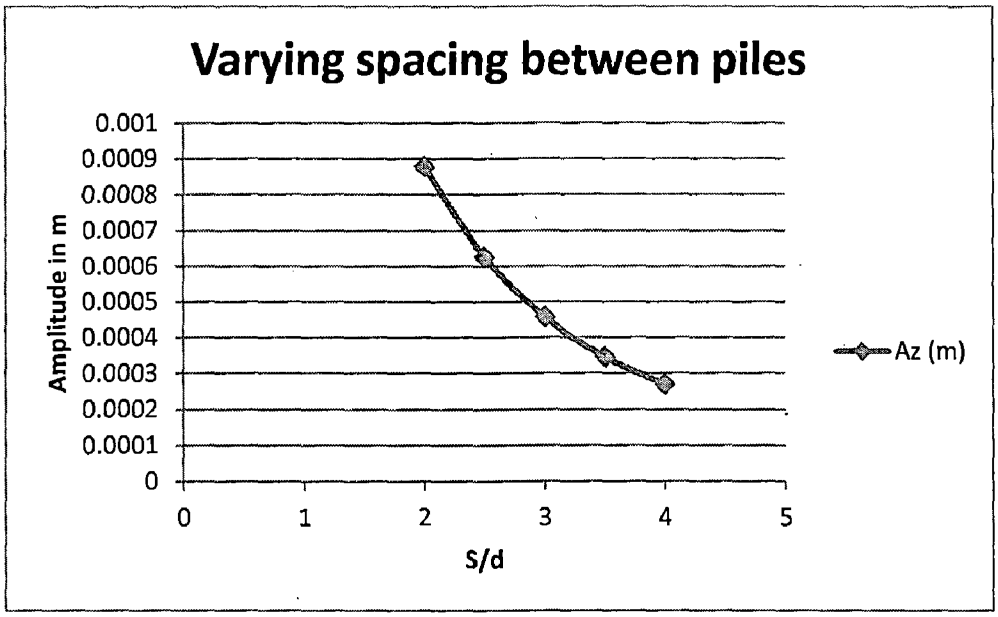


Fig.20 Vertical Amplitude variation with S/d

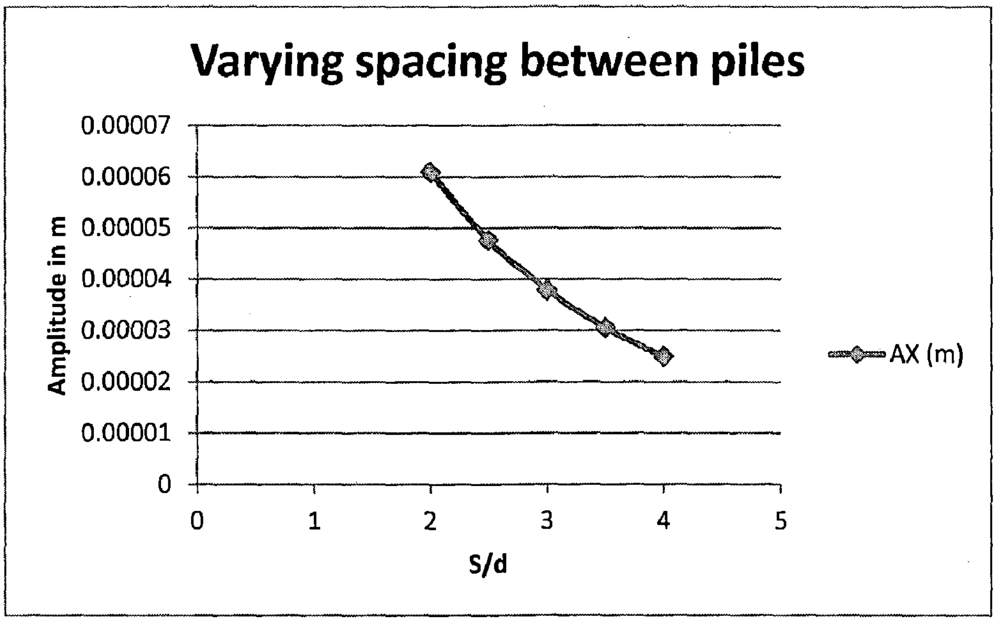


Fig.21 Horizontal amplitude variation with S/d

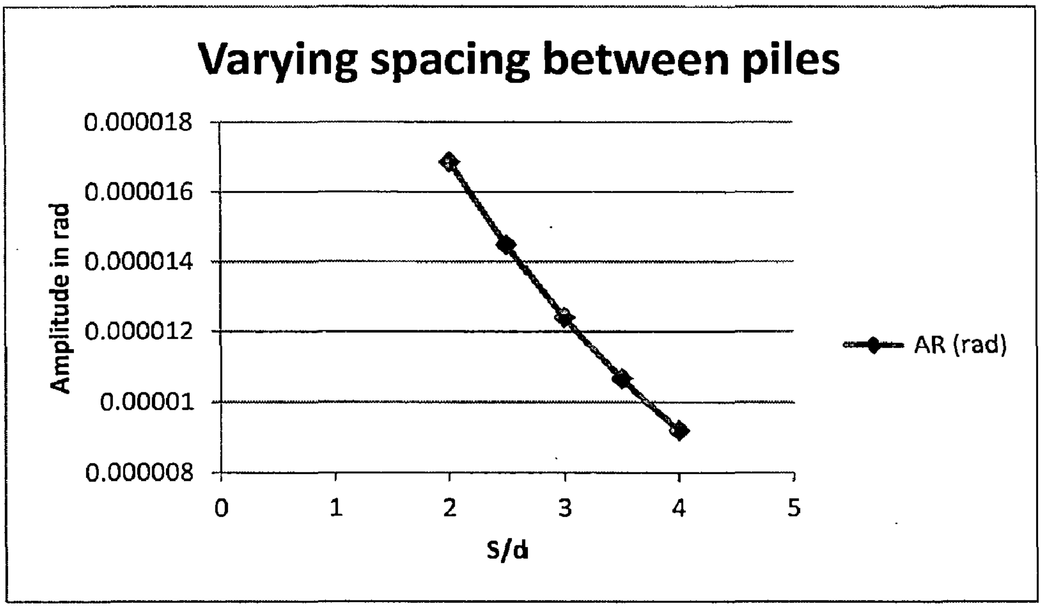


Fig.22 Rotational amplitude variation with S/d

When the weight of the machine & the operating frequency are kept constant and the spacing between the piles are increased

i. The weight of the pile cap increases
ii. The distance from the c.g of the pile system increases

When the spacing is increased from 2d to 4d the total mass increases from 253kg to 608kg whereas the stiffness in vertical direction increases from $2.7x10^5$ to $3.35x10^5$. Thus the increase in stiffness is less when compared to the increase in total mass. Hence, the natural frequency decreases.

Case (ii) The machine weight and the spacing between the piles are kept constant and the operating frequency are varied.

Wm = 400kN (ω = 41.88 rad/sec) and S = 3d

Table 7: Amplitude variation with varying operating speed

Operating speed in rpm	OS = 400	OS = 600	OS = 800	OS = 1000
Az (m)	0.000457	0.000162	8.44E-05	5.23E-05
AX (m)	3.78E-05	1.52E-05	8.03E-06	4.94E-06
AR (rad)	1.24E-05	5.44E-06	2.92E-06	1.8E-06

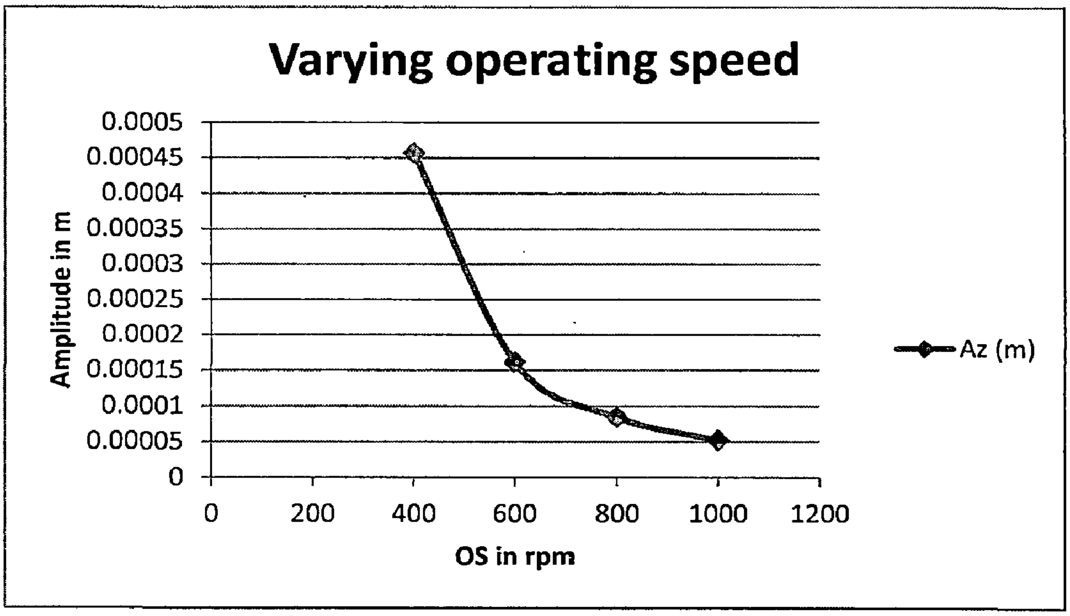


Fig.23 Vertical Amplitude variation with operating speed

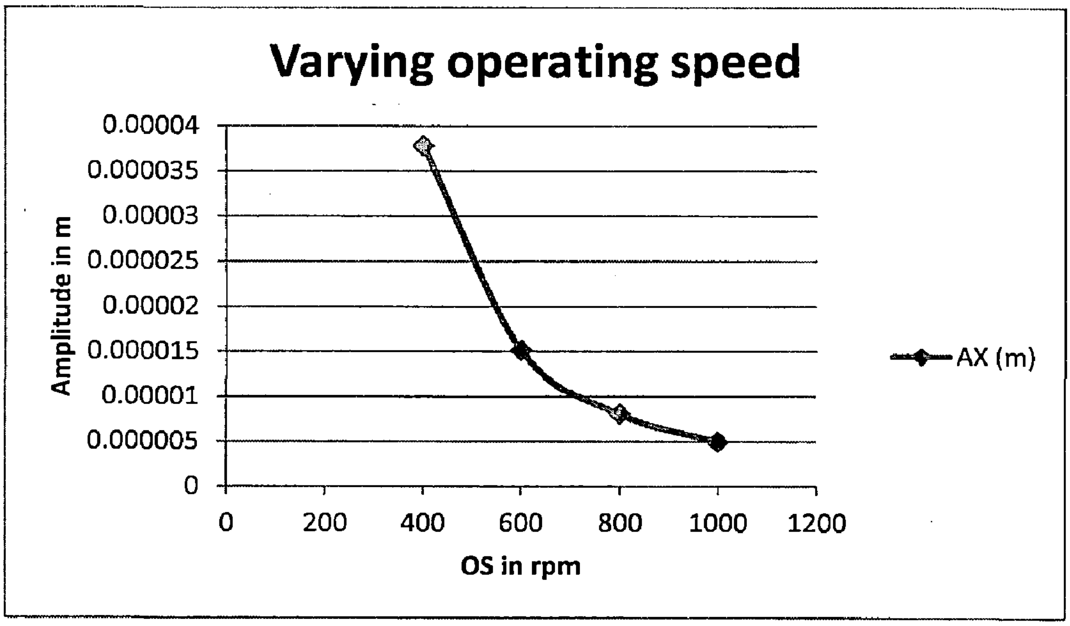


Fig.24 Horizontal Amplitude variation with operating speed

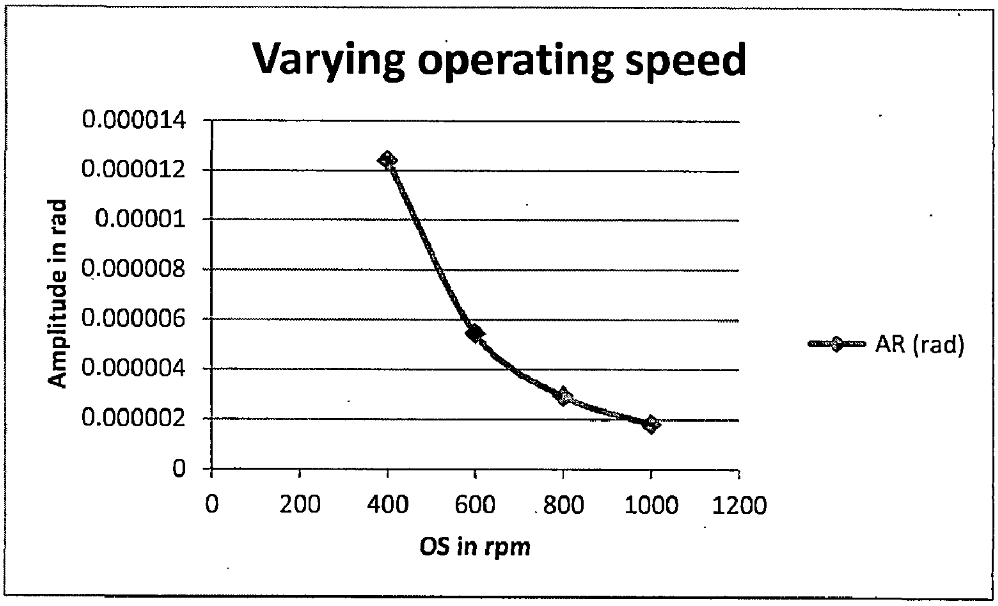


Fig.25 Rotational Amplitude variation with operating speed

When the machine weight & spacing between the piles are kept constant and the operating frequency is increased the amplitude decreases as the natural frequency moves away from the operating frequency.

Case (iii) The operating frequency of the machine and the spacing are kept constant and the weight of the machine is varied.

OS = 400rpm (ω = 41.88 rad/sec) & S = 3d

Table 8: Frequency variation with varying machine weight

Weight of the machine in kN	Wm = 400	Wm = 600	Wm = 800	Wm = 1000
wnz (rad/s)	26.60	25.96	25.36	24.81
wn1 (rad/s)	35.95	35.11	34.45	33.93
wn2 (rad/s)	9.58	9.16	8.79	8.46

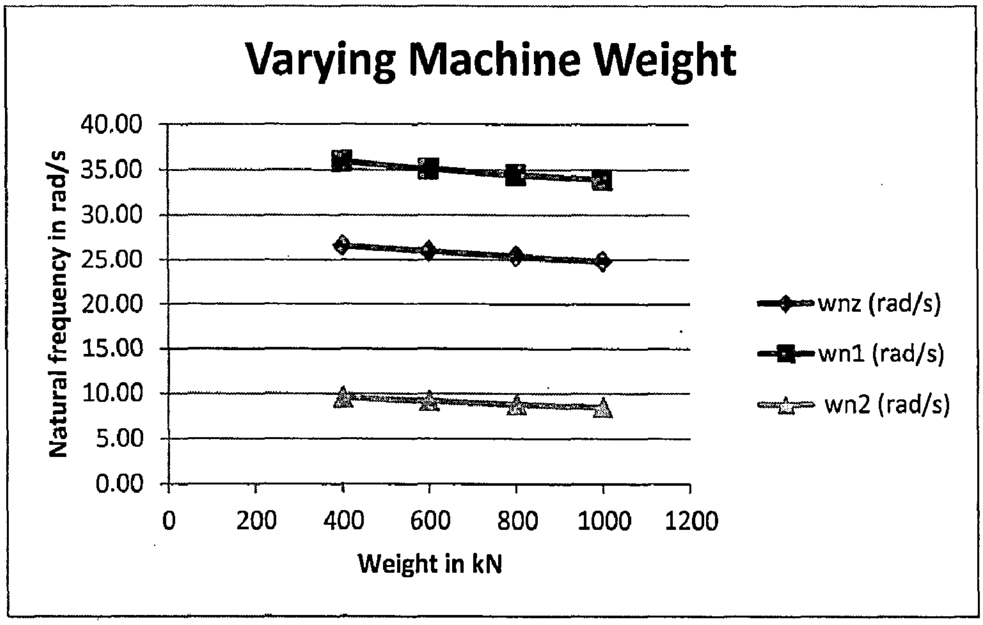


Fig.26 Natural frequency variation with Machine weight

Table 9: Amplitude variation with varying machine weight

Weight of the machine in kN	Wm = 400	Wm = 600	Wm = 800	Wm = 1000
Az (m)	0.000457	0.000429	0.000403	0.000381
AX (m)	3.78E-05	3.48E-05	3.23E-05	3.02E-05
AR (rad)	1.24E-05	1.12E-05	1.02E-05	9.36E-06

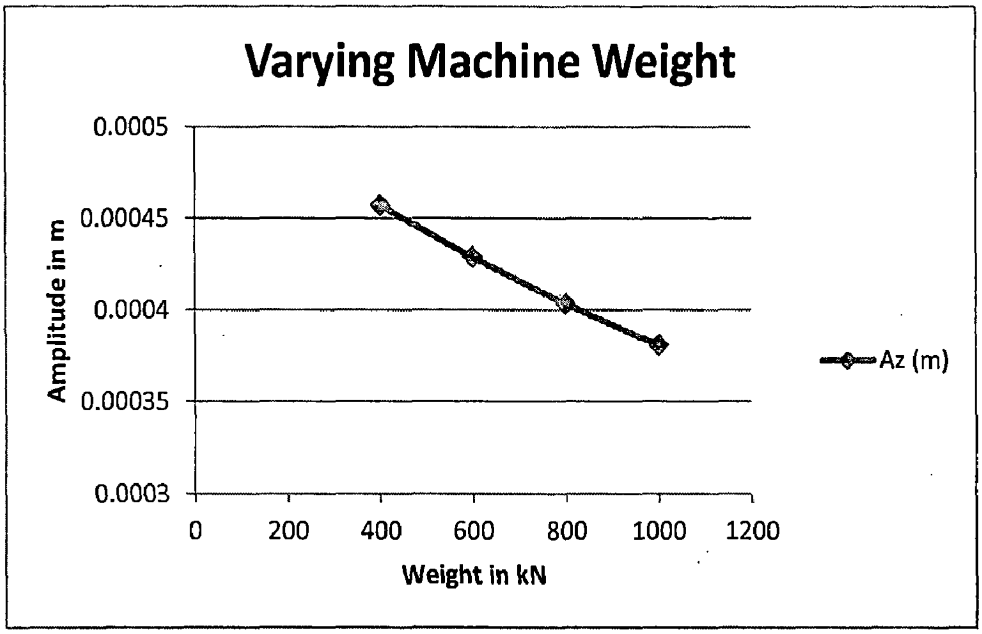


Fig.27 Vertical Amplitude variation with Machine weight

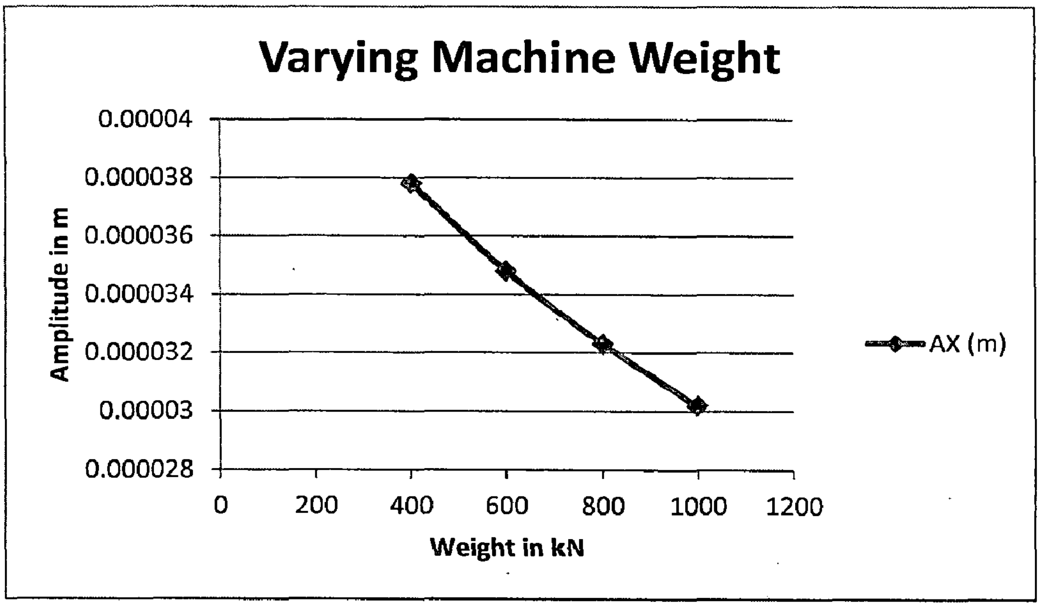


Fig.28 Horizontal Amplitude variation with Machine weight

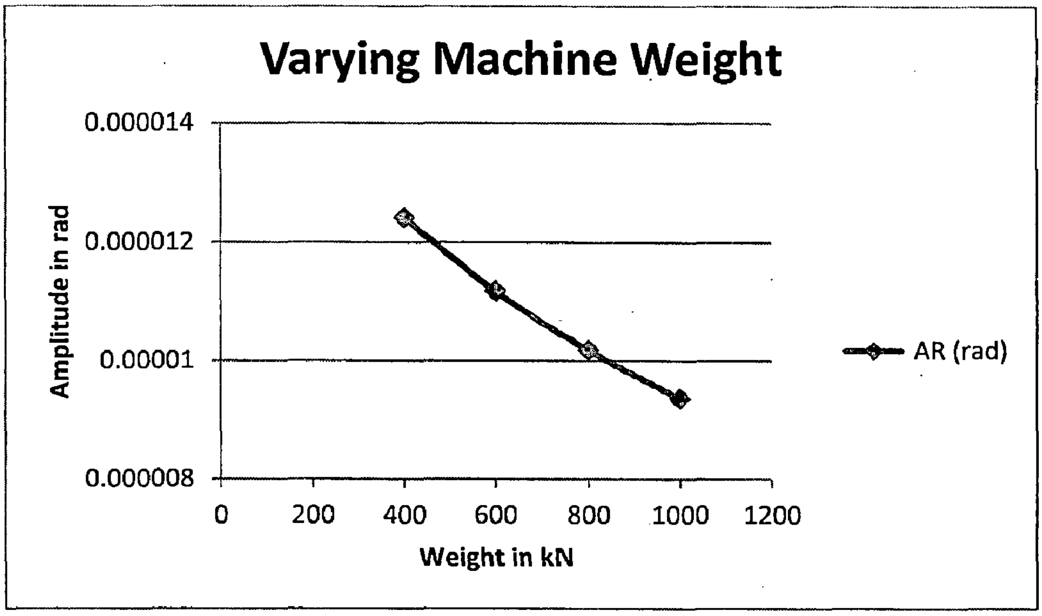


Fig.29 Rotational Amplitude variation with Machine weight

When the operating frequency and the spacing between the piles are kept constant and the weight of the machine is increased the natural frequency of the system decreases with nominal change since the mass of the system increases. The amplitude also decreases as the natural frequency moves away from the operating frequency of the system.

Case (iv) The operating frequency of the machine, the weight of the machine and the spacing are kept constant and the pile parameters i.e. the length and the diameter of the pile are varied.

OS = 400rpm (ω = 41.88 rad/sec), Wm = 400kN & S = 3d

Table 10: Natural frequency variation with varying L/d

L/d	16.66	18.75	20.82	25	25	31.25	37.5	50
L	10	7.5	12.5	5	10	12.5	7.5	10
D	0.6	0.4	0.6	0.2	0.4	0.4	0.2	0.2
wnz(rad/s)	21.49691	30.58817	22.35467	46.35449	32.35487	32.34181	49.3111	48.87364
wn1(rad/s)	33.665	44.88399	29.55362	77.13176	39.26401	35.01349	67.52674	60.41878
wn2(rad/s)	9.135726	11.4001	7.962294	11.14266	9.609312	8.14779	8.770149	7.03742

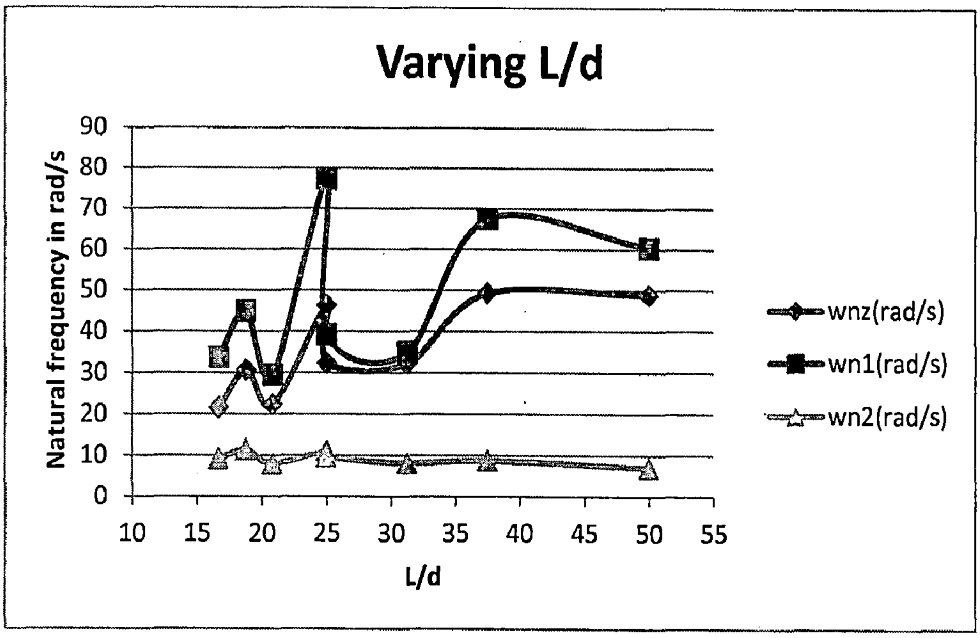


Fig.30 Natural frequency variation with L/d

Table 11: Amplitude variation with varying L/d

L/d	16.66	18.75	20.82	25	25	31.25	37.5	50
L	10	7.5	12.5	5	10	12.5	7.5	10
D	0.6	0.4	0.6	0.2	0.4	0.4	0.2	0.2
Az(m)	0.00028	0.000891	0.000243	0.003106	0.000847	0.000758	0.002506	0.002458
Av(m)	2.66E-05	6.77E-05	2.2E-05	0.00017	5.54E-05	4.72E-05	0.000146	0.000129
Ah(rad)	9.38E-06	2.12E-05	7.07E-06	4.43E-05	1.62E-05	1.28E-05	3.21E-05	2.56E-05

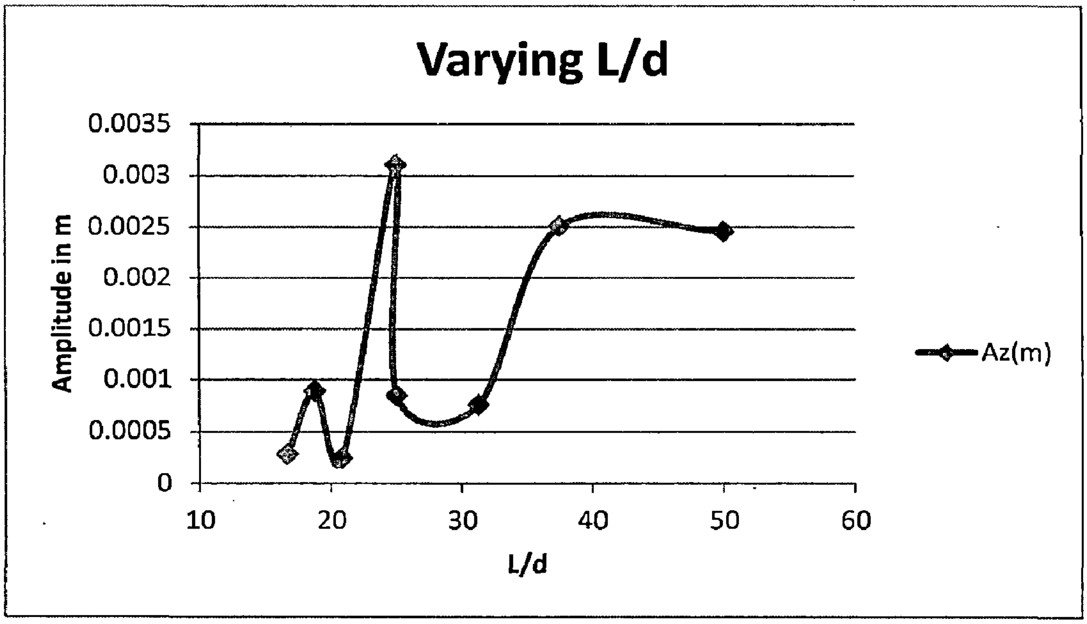


Fig.31 Vertical Amplitude variation with L/d

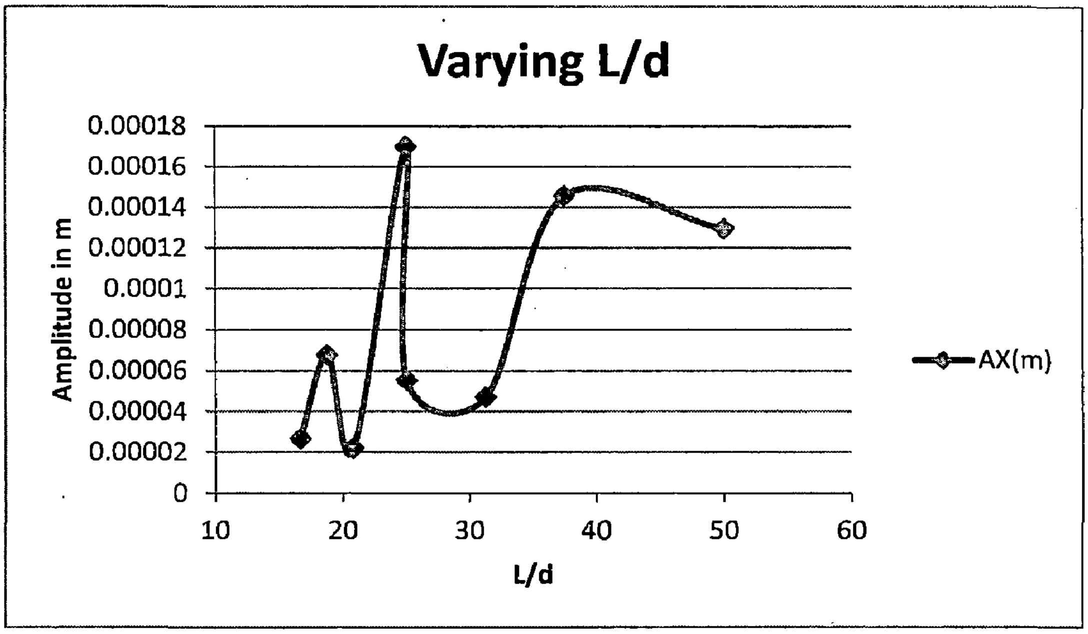


Fig.32 Horizontal Amplitude variation with L/d

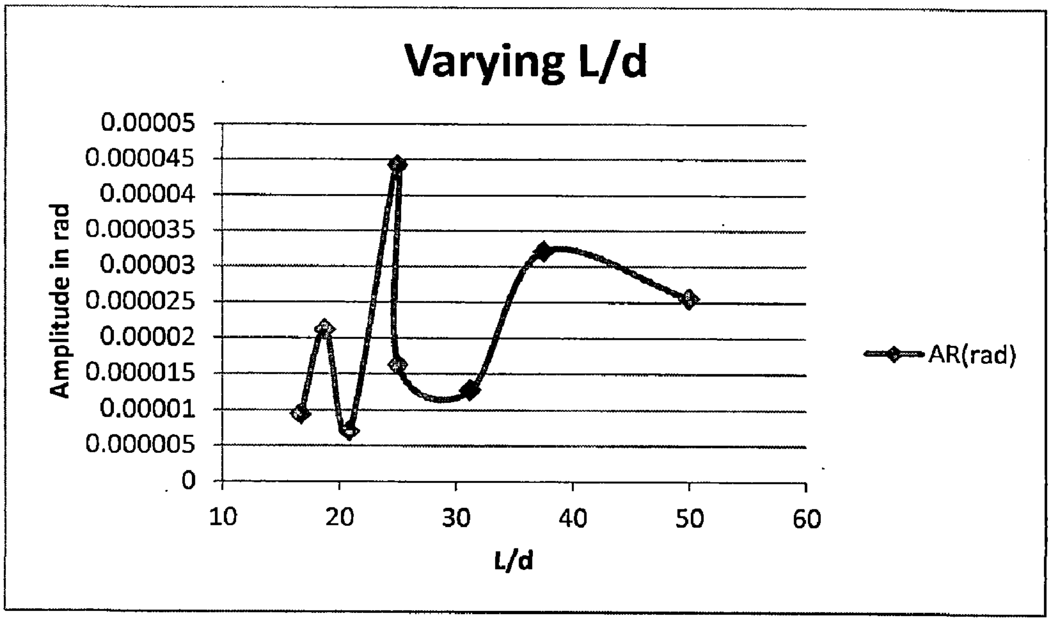


Fig. 33 Rotational Amplitude variation with L/d

Thus, when the operating frequency of the machine, the weight of the machine and the spacing are kept constant and the L/d ratio of the pile is varied the amplitude attains a maximum value when the natural frequency is far away from the operating frequency.

Case (v) The operating frequency of the machine is kept constant and the weight of the machine is varied along with the spacing.

OS = 400rpm (ω = 41.88 rad/sec)

Table 12: Frequency variation with varying machine weight and spacing

Spacing between piles in m	s=2d	s=2.5d	s=3d	s=3.5d	s=4d
Weight of machine in kN	300	450	600	750	900
wnz (rad/s)	34.49333	29.57942	25.96075	23.16836	20.93999
wn1 (rad/s)	43.07917	38.37296	35.11149	32.78374	31.09219
wn2 (rad/s)	10.66188	9.777501	9.159474	8.666559	8.238241

Table 13: Amplitude variation with varying machine weight and spacing

Spacing between piles in m	s=2d	s=2.5d	s=3d	s=3.5d	s=4d
Weight of machine in kN	300	450	600	750	900
Az (m)	0.000916	0.000615	0.000429	0.000317	0.000245
AX (m)	6.54E-05	4.64E-05	3.48E-05	2.71E-05	2.17E-05
AR (rad)	1.82E-05	1.4E-05	1.12E-05	9.11E-06	7.58E-06

As the spacing between the piles increases the weight of the pile cap increases which possibly may intend the increase in the machine weight. In this case the operating frequency is kept constant and as the natural frequency of the system moves away from it the amplitude gets reduced.

Case (vi) Block Foundation for Reciprocating Machines

An equivalent block foundation for a 3x3 pile group with OS = 350rpm, L=10m, d=0.5m, S=2.5*d, G=1e4 & d = (h_{pc}-0.25) is selected and the parametric study is done keeping the plan area in both the case to be constant and varying the depth of the block

a. Elastic Half-Space Method

Table 14: Frequency variation with varying depth of the block

h (m)	1.5	3	4.5	6	7.5	9
wnz(rad/s)	38.76538	31.2935	26.94972	24.02448	21.88291	20.22785
wn1(rad/s)	30.55745	19.94889	13.71098	9.959071	7.581779	5.991527
wn2(rad/s)	63.89109	52.68216	45.96759	41.27562	37.7526	34.98572

Table 15: Amplitude variation with varying depth of block

h (m)	1.5	3	4.5	6	7.5	9
Az(m)	0.000203	0.000187	0.000144	0.000109	8.6E-05	7.03E-05
Av(m)	0.000739	0.000462	0.000351	0.000282	0.00023	0.000186
Ah(m)	0.000885	0.000469	0.000425	0.000431	0.00043	0.000405

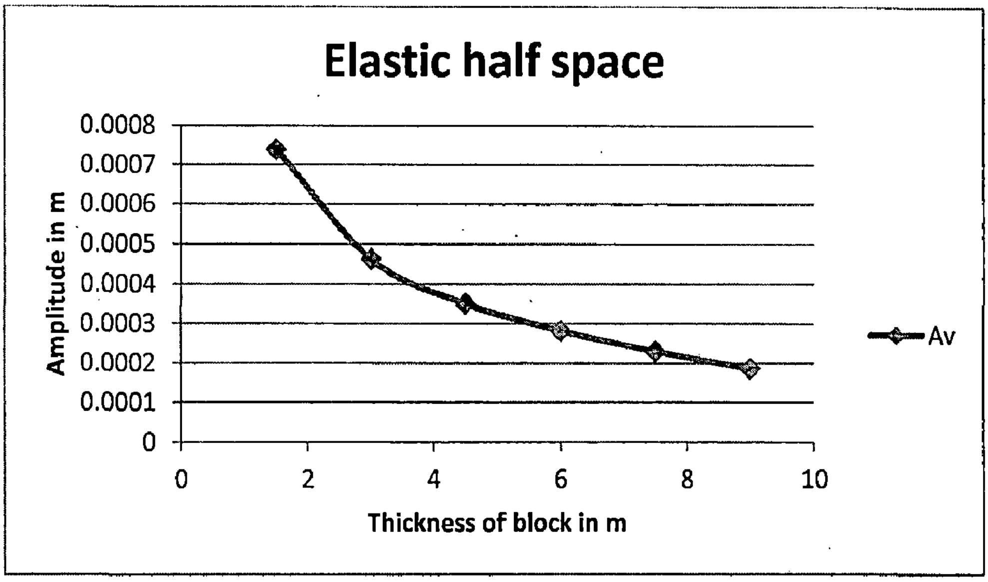


Fig.34 Vertical Amplitude variation with depth of the block

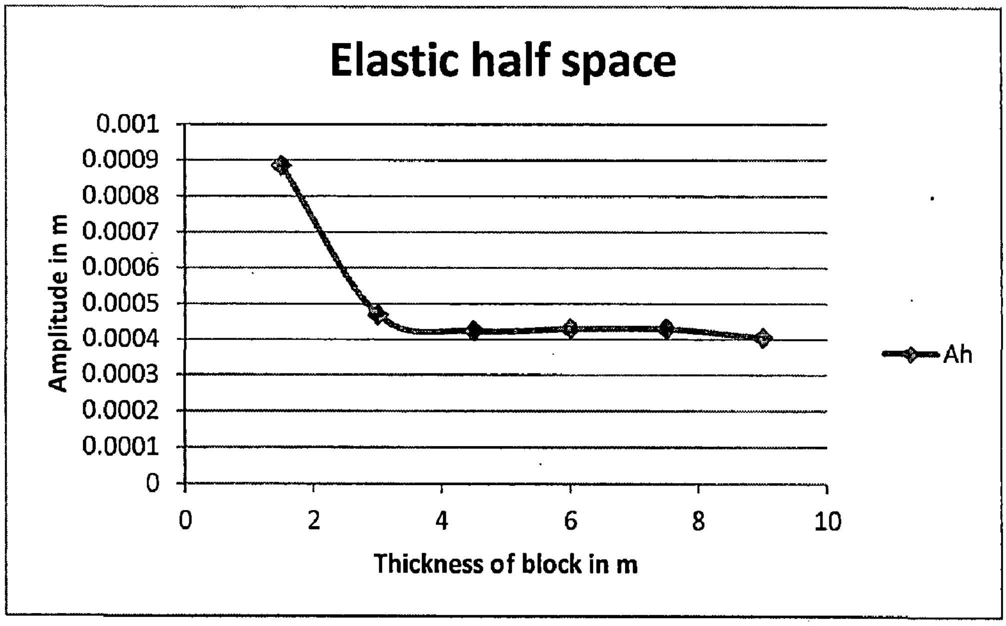


Fig.35 Horizontal Amplitude variation with depth of the block

The vertical and horizontal amplitudes for the considered pile group are 9.63×10^{-4}m and 1.59×10^{-4}m respectively whereas for block foundation it is found out to be 0.000739m and 0.000885m. Thus, the block foundation is subjected to very high amplitude i.e. almost eight times in horizontal mode of vibration.

b. Embedded Block Foundation

Table 16: Frequency variation with varying depth of block considering embedment

h (m)	1.5	3	4.5	6	7.5	9
wnze (rad/s)	53.33497	59.23704	63.13971	65.92788	68.02478	69.66138
wnxe(rad/s)	50.47651	61.8522	68.87836	73.73148	77.3081	80.06198
wnfie(rad/s)	76.97139	86.56133	102.1932	116.0837	127.6463	137.2806

Table 17: Amplitude variation with varying depth of block considering embedment

h (m)	1.5	3	4.5	6	7.5	9
Aze(m)	6.26E-05	3.63E-05	2.56E-05	1.97E-05	1.61E-05	1.35E-05
Axe(m)	9.7E-05	4.32E-05	2.92E-05	2.24E-05	1.82E-05	1.53E-05
Afie(rad)	2.57E-05	1.88E-05	1.59E-05	1.38E-05	1.21E-05	1.06E-05
Av(m)	0.000108	6.92E-05	5.34E-05	4.39E-05	3.73E-05	3.21E-05
Ah(m)	0.000116	7.15E-05	6.5E-05	6.39E-05	6.36E-05	6.31E-05

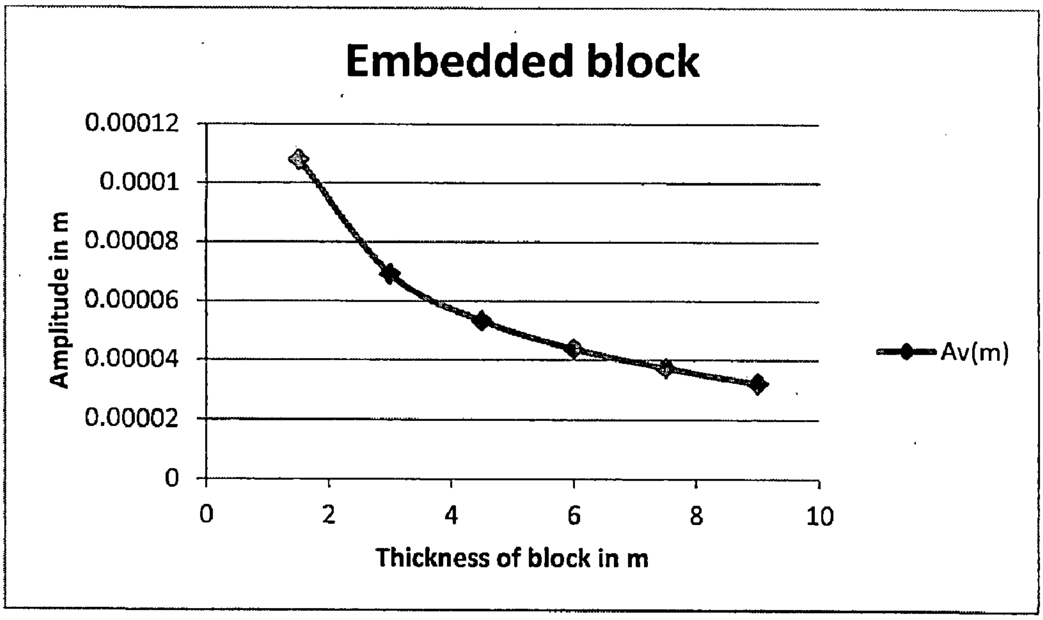


Fig.36 Vertical Amplitude variation with depth of the block considering embedment

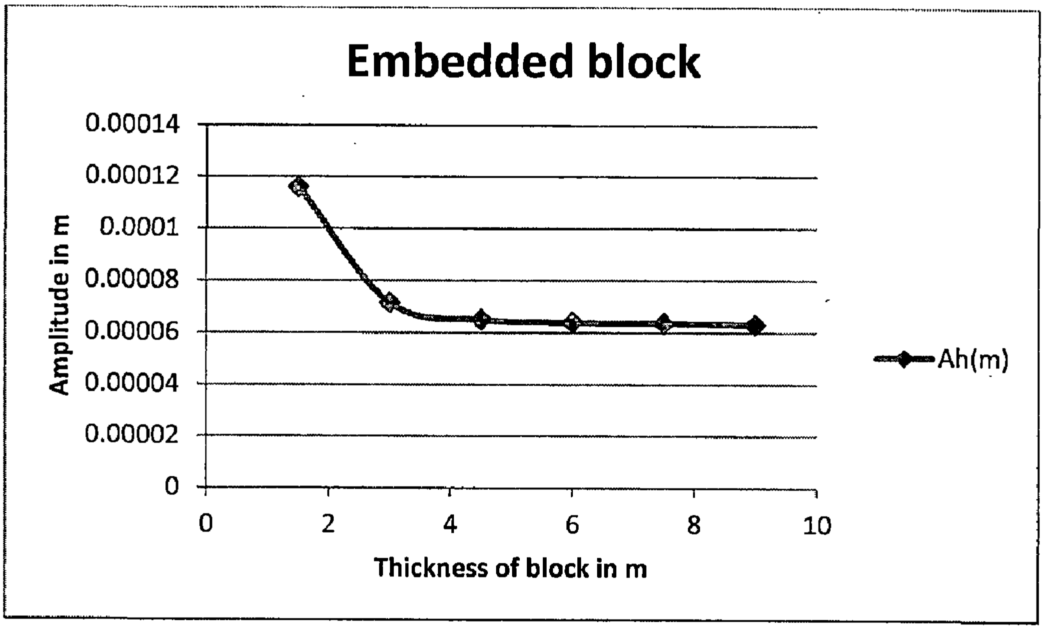


Fig.37 Horizontal Amplitude variation with depth of the block considering embedment

The vertical and horizontal amplitudes for the considered pile group are 9.63×10^{-4}m and 1.59×10^{-4}m respectively. Whereas for block foundation it is found out to be 0.000108 and 0.000116m.

Table 18: Comparison of Manual and MATLAB results for block

Parameters	Manual Calculation	MATLAB Results
a	3.5000	3.5000
b	3.5000	3.5000
h	4.5000	4.5000
yc	25	25
ys	18	18
os	350	350
w	36.6519	36.6519
x	0.4000	0.4000
X	18	18
F	22.5000	22.5000
A	12.2500	12.2500
Wm	400	400
W	1.7781e+003	1.7781e+003
m	181.2564	181.2564
mu	0.4000	0.4000
G	10000	10000
V	55.1250	55.1250
Cu	28000	28000
Csi	21000	21000
Ctu	14000	14000
Cfi	48440	48440
CuD	33600	33600
CtuD	16800	16800
CfiD	58128	58128
CsiD	25200	25200
Cuav	30800	30800
Ctuav	15400	15400
Cfiav	53284	53284

Csiav	23100	23100
L (m)	2.2500	2.2500
My	47.7000	47.7000
I	12.5052	12.5052
Mm	490.9027	490.9027
Mmo	1.4085e+003	1.4085e+003
r	0.3485	0.3485
D	4.2500	4.2500
rho	1.8349	1.8349
ro	1.98	1.9747
Bz	1.91	1.9244
Kz	131589	1.3164e+005
jhiz	0.30	0.3064
Wnz	26.24	26.9497
Az	0.000142	1.4362e-004
rsi	2	1.9976
Mmz	368.58	370.0651
Bsi	6.13	6.3412
Ksi	424998	4.2511e+005
Xsi	0.035	0.0365
Wnsi	33.32	33.8931
Kx	99698	9.9772e+004
Bx	2.51	2.5392
jhi	0.178	0.1804
Wnx	22.98	23.4617
rfi	2	1.9976
Kfi	354198	3.5426e+005
Bfi	5.03	5.4305
jhifi	0.0097	0.0100
Wnfi	15.24	15.8591
wn1	13.42	13.7110
wn2	45.34	45.9676

dw	1334654	1.3347e+006
Ax (m)	0.0001575	1.5828e-004
Afi	0.0001178	1.1853e-004
Av (m)	0.000347	3.5104e-004
Ah (m)	0.000417	4.2497e-004
Mm	488.6	490.9027
Mmo	1406.97	1.4085e+003
r	0.35	0.3485
D (m)	4.25	4.2500
Kze	1327754	1327900
he (m)	6.25	6.2500
alfa	1	1
S	1.80	1.7857
ro	1	1
ms	150.93	151.8326
Wnze	62.96	63.1397
Aze	0.0000234	2.5555e-005
Kxe	1579974	1580250
Mmxs	45.94	46.0651
Mmos	812.92	814.7174
Wnxe	67.93	68.8784
Io	88.96	89.5599
Kfie	1.3623×10^7	1.3635e+007
Wnfie	100.76	102.1932
Kxx	1578467	1580250
Kxfi	-661198	-6.6120e+005
Iy	59.95	60.7396
Kfifi	6.6618×10^6	6.6628e+006
Kfix	-1608254	-1608425
Ax (m)	0.000028	2.9155e-005
Afi	0.0000154	1.5921e-005
Ah (m)	0.0000639	6.4978e-005

Table 19: Comparison of Manual and MATLAB results for pile group

Parameters	Manual Calculation	MATLAB Results
OS (rpm)	350	350
γ_c (kN/m^3)	25	25
γ_s (kN/m^3)	18	18
l (m)	10	10
d (m)	0.5000	0.5000
N	9	9
h_{pc} (m)	1.5000	1.5000
D (m)	1.2500	1.2500
W_m (kN)	400	400
h_m (m)	0.4000	0.4000
f_z (kN)	2.5000	2.5000
f_x (kN)	2	2
E_p (kN/m^2)	25000000	25000000
G_s (kN/m^2)	10000	10000
Ip	0.0031	0.0031
X	3	3
Ap	0.1963	0.1963
S	1.2500	1.2500
bpc	3.5000	3.5000
bm	3	3
Wpc	459.3750	459.3750
Wp	441.7865	441.7865
Ws	1.8869e+003	1.8869e+003
W	3.1881e+003	3.1881e+003
w	36.6519	36.6519
m	324.9808	324.9808
Apc	12.2500	12.2500

ro	0.2500	0.2500
row	1.8349	1.8349
vs	73.8241	73.8241
Fz	22.5000	22.5000
Fx	18	18
kzp	1.5708e+005	15.708×10^{4}
czp	1.7288e+003	1.7288×10^{3}
kzg	2.5505e+005	25.505×10^{4}
czg	2.8070e+003	2.8070×10^{3}
kzf	33750	3.3750×10^{4}
czf	2.2402e+003	2.24×10^{3}
kzgt	2.8880e+005	28.80×10^{4}
czgt	5.0472e+003	5.0472×10^{3}
ccgt	1.9376e+004	19.376×10^{3}
q	0.2605	0.2605
wnz	29.8103	29.8103
wndz	32.0654	32.0654
n	1.2295	1.2294
c	1.8439	1.8439
y	0.1643	0.1643
Az	9.3226e-004	932.26×10^{-6}
kxp	1.0799e+004	1.0799×10^{4}
cxp	139.6339	139.6339
kxg	2.9452e+004	2.9452×10^{4}
cxg	380.8198	380.8198
kxf	5.1250e+004	5.125×10^{4}
cxf	3.5441e+003	3.5441×10^{3}
kxgt	8.0702e+004	8.0702×10^{4}
cxgt	3.9250e+003	3.9248×10^{3}
wnx	15.7585	15.73

ccxg	1.0242e+004	10.245×10^{3}
dxg	0.3832	0.3829
krp	7.7589e+004	7.76×10^{4}
crp	218.2819	218.27
kxrp	-3.4852e+004	-3.485×10^{4}
cxrp	-215.6845	–215.69
krg	2.6961e+006	2.6959×10^{6}
crg	2.1791e+004	21.78×10^{3}
krf	1.3217e+005	132.2×10^{3}
crf	2.9522e+003	2.95×10^{3}
krgt	2.8283e+006	2.8282×10^{6}
crgt	2.4743e+004	24.728×10^{3}
Zbar	5.2308	5.23
Mm	4.6905e+004	46905
L	6.6692	6.6692
Mmo	1.8870e+005	188698.64
r	0.2486	0.2486
My	94.1550	94.14
ccrg	4.6649e+005	466.52×10^{3}
drg	0.0530	0.0527
wnr	12.1256	12.13
wn1	38.6280	38.58
wn2	9.9219	9.93
dw2	2.3404e+006	2.34×10^{6}
Ax1	3.6159e-005	36.148×10^{-6}
Ar1	8.1206e-006	8.12048×10^{-6}
Ax2	2.8482e-005	28.4817×10^{-6}
Ar2	9.9380e-006	9.9378×10^{-6}
AX	6.4640e-005	64.63×10^{-6}
AR	1.8059e-005	18.058×10^{-6}

Comparing the values of various parameters in the Table 18 and Table 19, it can be proved that the MATLAB program developed gives close results to the manually calculated values. Hence, the program developed is validated.

CONCLUSIONS

The following conclusions are drawn from the above results

i. When the spacing between the piles are increased, the increase in the stiffness is less when compared to the increase in the mass of the system and hence the natural frequency decreases.

ii. As the difference between the natural frequency and operating frequency increases the amplitude decreases.

iii. The increase in machine weight contributes a nominal change in the natural frequency. Hence, in this case the reduction in amplitude is very less.

iv. When the L/d ratio of the pile is increased the natural frequency attains a maximum value when it moves far away from the operating frequency.

v. Varying both the spacing between the piles and the machine weight the natural frequency of the system moves far apart from the operating frequency for coupled mode of vibration. Hence, coupled mode of vibration has the least amplitude when compared to vertical mode of vibration.

vi. Comparing block and pile group foundation for reciprocating machines the pile group is more effective to reduce the horizontal amplitude when compared to the block foundation.

REFERENCES

[1] ACI: 351-3R-2004, "Foundations for Dynamic Equipment", American Concrete Institute.

[2] Barkan D.D (1962), "Dynamics of Bases and Foundation", McGraw hill book company, New York.

[3] Bereduge, Y.O., and Novak, M. (1972), "Coupled Horizontal and Rocking Vibration of Embedded Footings", Can. Geotech. J., 9(4), pp. 477-497.

[4] Bhatia, K.G. (2008), "Foundations for Industrial Machines—A Handbook for Practicing Engineers", D-CAD Publishers, New Delhi.

[5] Chandrasekaran, V. (1974), "Analysis of Pile Foundations Under Static and Dynamic Loads", Ph. Thesis, I.I.T., Roorkee, Roorkee.

[6] CP: 2012-1974, "Code of practice for Foundations for Machinery", BSI, London.

[7] DIN: 4024-1988,"Machine Foundations", German Standards.

[8] Han, Y. C. and Novak, M. (1988),"Dynamic Behaviour of Single Piles under Strong Harmonic Excitation", Canadian Geotechnical Journal, 25, pp. 523-534.

[9] Indrajit Chowdury, Shambu P.Dasgupta (2009), "Dynamics of Structure and Foundation – A Unified Approach",CRC Press, Netherlands.

[10] IS: 2974 (Part I)-1982, "Foundation for Reciprocating Type Machines", I.S.I. New Delhi.

[11] IS: 9211(Part I and IV), "Code of Practice for Design and Construction of Pile Foundations", ISI, New Delhi.

[12] IS0:10816-1995,"Evaluation of Machine Vibration by Measurements on Non-rotating Parts", International Organization for Standardization, Switzerland.

[13] Maheshwari B.K. and Watanabe H. (2005). "Dynamic Analysis of Pile Foundations: Effects of Material Nonlinearity of Soil", Electronic Journal of Geotechnical Engineering, Vol. 10 (E), Paper No. 0585.

[14] Major A. (1962), "Vibration Analysis and Design of foundation for Machines and Turbines", Akademiai kiado, Budapest, Collet's Holdings ltd, London.

[15] Manna, B. and Baidya, D.K. (2010), "Dynamic Response of Pile Foundations under Coupled Vibration", Indian Geotech. Journal, Vol. 40, No. 1, pp. 55-66.

[16] Matlock, H. and Reese, L.C. (1962), "Generalized Solutions for Laterally Loaded Piles", Transactions of the American Society of Civil Engineers, Vol. 127, Part 1, pp. 1220-1247.

[17] Novak, M and Beredugo, Y.O. (1972), "Vertical Vibration of Embedded Footings", J. Soil Mech. Found. Div., ASCE, Vol. 98, No. SM12, pp. 1291-1310.

[18] Novak, M and El-Sharnouby, B. (1983), "Stiffness and Damping Constants of Single Piles", J. Geotech. Engg. Div. ASCE, Vol. 109, No. 7, pp. 961-974.

[19] Novak, M and Grigg, R.F. (1976), "Dynamic Experiments with Small Pile Foundation", Can. Geotech. J. Vol., 13, No. 4, pp. 372-395.

[20] Novak, M. (1974), "Dynamic Stiffness and Damping of piles", Can Geotech. J., Vol.11, No. 4, pp. 574 - 598.

[21] Novak, M. (1985), "Experiments with Shallow and Deep Foundations", Proc. Symp. Vib. Probl. Geotech. Eng., Am. Soc. Civ. Engg., Annu. Conv., pp. 1-26.

[22] Novak, M. and Beredugo, Y. O. (1971), "Effect of Embedment on Footing Vibration", Proc. Can. Conf. Earthquake Eng.,1st, Vancouver, pp. 111-125.

[23] Novak, M. and Sheta, M., "Approximate Approach to Contact Problems of Piles", Proceedings of Geotechnical Engg. Div., ASCE, National Convention, Dynamic Response of Pile Foundations: Analytical Aspects, Florida, October 30, 1980, pp. 53-79.

[24] Novak, M., Nogami, T. and Aboul-Ella, F. (1978), "Dynamic Soil Reactions for Plane Strain Case", Journal of Engineering Mechanics, ASCE, 104 (EMA), pp. 953-959.

[25] Prakash, S. (1962), "Behaviour of Pile Groups Subjected to Lateral Loads", Ph. Thesis, University of Illinois, Urbana, p. 397.

[26] Rudra Pratap,"Getting Started with MATLAB", Oxford University Press, Oxford.

[27] S R Otto, Denier, "An Introduction to Programming and Numerical Methods In MATLAB", Springer.

[28] SAES: Q–007 2003, "Foundations and Supporting Structures for Heavy Machinery", Onshore Structures, Saudi Arabia.

[29] Sheta, M. and Novak, M. (1982), "Vertical Vibrations of Pile Groups", J. Geotech. Engg., ASCE, Vol. 108, No. GT4, pp. 570-590.

[30] Srinivasulu P, Vaidyanathan C.V (1976), "Handbook of Machine Foundation", Tata McGraw Hill Publishing Company Ltd, New Delhi.

[31] Suresh C. Arya, Michael W. O'Neil and George Pincus (1979),"Design of Structures and Foundation for Vibrating Machines", Gulf Publishing Company, London.

[32] Swami Saran (2006), "Soil Dynamics and Machine Foundation", Galgotia Publications Pvt. Ltd, New Delhi.

[33] Swami Saran (2010), "Analysis and Design of Substructures – Limit State Design", Oxford & IBH Publishing Co. Pvt. Ltd, New Delhi.

[34] Tomlinson, M.J. (1986), "Foundation Design Consideration", Longman, Singapore Publishers, Singapore.

LIST OF PUBLICATIONS

1. M. Bharathi, Dr. Swami Saran , Dr. S. Mukerjee, "Modelling of Impact Type Machine Foundations", Advances in geotechnical engineering, Indian Geotechnical Conference, IGC 2012, IIT Delhi, Delhi, India, December 13 – 15, 2012.

2. M. Bharathi, Dr. Swami Saran , Dr. S. Mukerjee, "Dynamic Behaviour of Piles supporting Machines", National Conference on Recent Advancements in Engineering (NCRAE-12), Sanjeevan Engineering and Technology Institute, Maharashtra, India, June 22-23, 2012. [Accepted]

MANUAL CALCULATION

Operating Frequency of machine ω = 350 rpm = $350 \times \frac{2\pi}{60}$ = 36.65 rad/sec

Length of pile = 10.0 m

Diameter of pile = 0.5 m

$G_s = 1.0 \times 10^4$ kN/m^2, $\gamma_s = 18.0$ kN/m^3, $\varphi = 35^o$

E_p =2.5 x 10^7 kN/m^2, $A_p = 0.19625$ m^2, $I_p = 3.1 \times 10^{-3}$ m^4

Dynamic forces acting on the pile group:

$F_x = 2.5 \times 9 \sin \omega t = 22.5 \sin \omega t$ kN

$F_z = 2.0 \times 9 \sin \omega t = 18 \sin \omega t$ kN

Vertical vibration

Estimation of stiffness and damping values:

Single Pile

$r_o = 0.25$ m; $E_p/G_s = 2.5 \times 10^7/(1 \times 10^4) = 2500$;
$L/r_o = 10/0.25 = 40$

Considering the pile as friction pile and parabolic variation of G_s, Fig.7.19b gives

$f_{w1} = 0.0080, f_{w2} = 0.026$

$$v_s = \sqrt{\frac{G_s}{\rho}} = \sqrt{\frac{1 \times 10^4 \times 9.81}{18.0}} = 73.8241 \text{ m/s}$$

$$K_{zp} = \frac{E_p A_p}{r_o} f_{w1} = \frac{2.5 \times 10^7 \times 0.19625}{0.25} \times 0.008 = 15.708 \times 10^4 \text{ kN/m}$$

$$C_{zp} = \frac{E_p A_p}{v_s} f_{w2} = \frac{2.5 \times 10^7 \times 0.19625}{73.8241} \times 0.026 = 1.7288 \times 10^3 \text{ kN/m}$$

3 x 3 Pile Group

Cap thickness = 1.5 m
Selecting one of a pile (No.5) as reference pile
Computation of α_A

$L/2r_o = 10/0.5 = 20$, $\mu = 0.4$ (assumed)

For adjacent piles 2 and 4

$S/2r_o = 1.25/0.5 = 2.5$

For diagonal pile 3

$S/2r_o = (1.25\sqrt{2})/0.5 = 3.54$

α_A for reference pile (No. 5) = 1.00
α_A for adjacent pile (No. 2, 4, 6 and 8) = 0.6153
α_A for diagonal pile (No. 1, 3, 7 and 9) = 0.5204
$\sum \alpha_A$ = 1.00 + 4 x 0.6153 + 4x 0.5204 = 5.5429

$$K_{zg} = \frac{\sum_1^n K_{zp}}{\sum \alpha_A} = \frac{9\times 15.708\times 10^4}{5.5430} = 25.505\times 10^4 \text{ kN/m}$$

$$C_{zg} = \frac{\sum_1^n C_{zp}}{\sum \alpha_A} = \frac{9\times 1.7288\times 10^3}{5.5430} = 2.8070\times 10^3 \text{ kN/m}$$

$$K_{zf} = G_s D\bar{S}_{z1} = 1\times 10^4 \times 1.25\times 2.7 = 3.3750\times 10^4 \text{ kN/m}$$

$$r_{oc} = \sqrt{\frac{3.5\times 3.5}{\pi}} = 1.98$$

$$C_{zf} = Dr_{oc}\bar{S}_{z2}\sqrt{G_s\rho} = 1.25\times 1.98\times 6.7\times \sqrt{1\times 10^4 \times 18.0/9.81} = 2.24\times 10^3 \text{ kN/m}$$

Therefore,

$(K_z)_g = K_{zg} + K_{zf} = 28.80 \times 10^4$ kN/m

$(C_z)_g = C_{zg} + C_{zf} = 5.0472 \times 10^3$ kN-s/m

Weight of pile cap	= 3.5 × 3.5 × 1.5 × 25 = 459.3750 kN
Weight of piles	= 9 × (π/4) × 0.5^2 × 10 × 24 = 441.7865 kN
Weight of soil	= (3.5 × 3.5 × 10 - (π/4) × 0.5^2 × 10 × 9) × 18.0 kN = 1886.91 kN
Weight of machine	= 400 kN
Total weight	= 459.3750 + 441.7865 + 1886.91 + 400 = 3188.07 kN

m = 324.9808 kg

$$(C_c)_g = 2\sqrt{(K_z)_g m} = 2\sqrt{28.88\times 10^4 \times 324.9808} = 19.376\times 10^3 \text{ kN-s/m}$$

$$(\xi)_g = \frac{5.0472\times 10^3}{19.376\times 10^3} = 0.2605$$

$$(\omega_{nz})_g = \sqrt{\frac{28.88\times 10^4}{324.9808}} = 29.8103 \text{ rad/s}$$

$$(\omega_{ndz})_g = \frac{(\omega_{nz})_g}{\sqrt{1-2\xi^2}} = \frac{29.8103}{\sqrt{1-2\times0.2605^2}} = 32.0654 \text{ rad/s}$$

$$\frac{\omega}{\omega_{ndz}} = \frac{36.65}{32.0654} = 1.143 \text{ (hence, safe)}$$

2 $m_e e\omega^2$ = 22.5× 9.81

$$2m_e e = \frac{220.725}{36.65^2} = 0.1643 \text{ kN-m}$$

$$\eta = \frac{\omega}{\omega_{nz}} = \frac{36.65}{29.8103} = 1.2294$$

$$\frac{A_z}{\frac{2m_e e}{m}} = \frac{\eta^2}{\sqrt{(1-\eta^2)^2 + (2\eta\xi)^2}} = \frac{1.2294^2}{\sqrt{(1-1.2294^2)^2 + (2\times1.2294\times0.2605)^2}} = 1.8439$$

$$A_z = (1.8439\times0.1643)/(324.9808) = 932.26\times10^{-6} \text{ mm}$$

Combined sliding and rocking

For parabolic soil profile, $(L/r_0) > 30$,
$\mu = 0.40$ and $(E_p/G_s) = 2500$, we get
$f_{x1} = 0.0022$, $f_{\varphi1} = 0.2529$, $f_{x\varphi1} = -0.0284$
$f_{x2} = 0.0084$, $f_{\varphi2} = 0.2101$, $f_{x\varphi2} = -0.0519$
Values of coefficient for $\mu = 0.5$ are almost same as for $\mu = 0.4$. the difference between the two values may be neglected.

$$K_{xp} = \frac{E_p I_p}{r_0^3} f_{x1} = 1.0799\times10^4 \text{ kN/m}$$

$$C_{xp} = \frac{E_p I_p}{r_0^2 v_s} f_{x2} = 139.6339 \text{ kN-s/m}$$

$$K_{\varphi p} = \frac{E_p I_p}{r_o} f_{\varphi1} = 7.76\times10^4 \text{ kN/m}$$

$$C_{\varphi p} = \frac{E_p I_p}{v_s} f_{\varphi2} = 218.27 \text{ kN-s/m}$$

$$K_{x\varphi p} = \frac{E_p I_p}{r_0^2} f_{x\varphi1} = -3.485\times10^4 \text{ kN/rad}$$

$$C_{x\varphi p} = \frac{E_p I_p}{r_o v_s} f_{x\varphi1} = -215.69 \text{ kN-s}$$

$$K_R = \frac{E_p I_p}{2G(1+\mu)L^4} = \frac{7.75\times10^4}{2\times1\times10^4\times(1+0.4)\times10^4} = 27.68\times10^{-5}$$

Therefore, pile behaves as a flexible pile.

Considering pile No. 1 as reference pile.

$\sum\alpha_L = 3.27$

$$K_{xg} = \frac{\sum_1^n K_{xp}}{\sum \alpha_L} = \frac{9\times 1.0799\times 10^4}{3.3} = 2.9452\times 10^4 \text{ kN/m}$$

$$C_{xg} = \frac{\sum_1^n C_{xp}}{\sum \alpha_L} = \frac{9\times 139.6339}{3.3} = 380.8198 \text{ kN/m}$$

$$a_o = \omega\, r_o\sqrt{\frac{\rho}{G}} = 36.65\times 1.98\sqrt{\frac{18.0/9.81}{1\times 10^4}} = 0.983$$

For $a_o = 0.983$ and $\mu = 0.4$, $S_{x1} = 4.1$ and $S_{x2} = 10.6$ Therefore,

$$K_{xf} = G_s D\bar{S}_{x1} = 1\times 10^4\times 1.25\times 4.1 = 5.125\times 10^4 \text{ kN/m}$$

$$C_{xf} = Dr_{oc}\bar{S}_{x2}\sqrt{G_s\rho} = 1.25\times 1.98\times 10.6\times\sqrt{1\times 10^4\times 18.0/9.81} = 3.5441\times 10^3 \text{ kN/m}$$

$$(K_x)_g = 8.0702\times 10^4 \text{ kN/m}$$

$$(C_x)_g = 3.9248\times 10^3 \text{ kN/m}$$

$$K_{\phi g} = \sum_1^n\left(K_{\phi p} + K_{zp}x_r^2 + K_{xp}Z_c^2 - 2Z_c K_{x\phi p}\right)$$

$x_r = 1.25$ for piles 1,3,4,6,7 and 9

$x_r = 0$ for piles 2,5,8

$Z_c = 1.5/2 = 0.75$

$$K_{\varphi g} = 2.6959\times 10^6 \text{ kN-m}$$

$$C_{\phi g} = \sum_1^n\left(C_{\phi p} + C_{zp}x_r^2 + C_{xp}Z_c^2 - 2Z_c C_{x\phi p}\right)$$

$$C_{\varphi g} = 21.78\times 10^3 \text{ kN-m}$$

For rocking vibration $r_{oc} = \left(\frac{ab^3}{3\pi}\right)^{1/4} = \left(\frac{3.5^4}{3\pi}\right)^{1/4} = 2 \text{ m}$

$$\delta = \frac{D}{r_{oc}} = \frac{1.25}{2} = 0.63$$

$\bar{S}_{x1} = 4.1$, $\bar{S}_{x2} = 10.6$, and $\bar{S}_{\phi 1} = 2.5$ and $\bar{S}_{\phi 2} = 1.8$

$$K_{\phi f} = G_s r_{oc}^2 D\times\bar{S}_{\phi 1} + G_s r_{oc}^2 h\left[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_0}\right)^2 - \delta\left(\frac{Z_c}{r_0}\right)\right]\bar{S}_{x1}$$

$$K_{\varphi f} = 1\times10^4 \times 2^2 \times 1.25 \times 2.5$$

$$+1\times10^4 \times 2^2 \times 1.25\left[\frac{0.63^2}{3} + \left(\frac{0.75}{2}\right)^2 - 0.63\times\frac{0.75}{2}\right]\times 4.1$$

$K_{\varphi f} = 132.2\times10^3$ kN-m

$$C_{\phi f} = \delta r_{oc}^4 \sqrt{\frac{G_s \gamma}{g}}\left\{\bar{S}_{\phi 2} + \left[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_0}\right)^2 - \delta\left(\frac{Z_c}{r_0}\right)\right]\bar{S}_{x2}\right\}$$

$$C_{\varphi f} = 0.63\times 2^4 \sqrt{\frac{1\times10^4 \times 18}{9.81}}\left\{1.8 + \left[\frac{0.63^2}{3} + \left(\frac{0.75}{2}\right)^2 - 0.63\times\frac{0.75}{2}\right]\times 10.6\right\}$$

$C_{\varphi f} = 2.95\times10^3$ kN-s-m

$(K_\varphi)_g = 2.8282\times10^6$ kN-m

$(C_\varphi)_g = 24.728\times10^3$ kN-s-m

$$\bar{Z} = \frac{400\times0.2 + 459.375(0.4+0.75) + (441.7865+1886.9)(0.4+1.5+5.0)}{3188.10} = 5.23 \text{ m}$$

$M_m = 46905$ kN-m^2

$M_{mo} = M_m + mL^2 = 188698.64$ kN-m^2

$$r = \frac{M_m}{M_{mo}} = 0.2486$$

$M_y = 18\times5.23\sin\omega t = 94.14\sin\omega t$ kN-m

$$\omega_{nx} = \sqrt{\frac{K_x}{m}} = 15.73 \text{ rad/s}$$

$$\omega_{n\varphi} = \sqrt{\frac{K_\varphi}{M_{mo}}} = 12.13 \text{ rad/s}$$

Undamped natural frequencies in coupled rocking and sliding are given by:

$$\omega_{n1,2}^2 = \frac{1}{2r}\left[\left(\omega_{nx}^2 + \omega_{n\varphi}^2\right) \pm \sqrt{\left(\omega_{nx}^2 + \omega_{n\varphi}^2\right)^2 - 4r\omega_{nx}^2\omega_{n\varphi}^2}\right]$$

$\omega_{n1} =$ 38.58 rad/s , $\omega_{n2} =$ 9.93 rad/s

$(C_{cx})_g = 2\sqrt{K_x m} = 10.245\times10^3$ kN-s-m

$(C_{c\varphi})_g = 2\sqrt{K_\varphi M_{mo}} = 466.52\times10^3$ kN-s-m

$(\xi_x)_g = 0.3829$

$(\xi_\varphi)_g = 0.0527$

$$\Delta(\omega^2) = \left[\left\{ \omega^4 - \omega^2 \left[\frac{\omega_{nx}^2 + \omega_{n\varphi}^2}{r} - \frac{4\xi_x \xi_\varphi \omega_{nx} \omega_{n\varphi}}{r} \right] + \frac{\omega_{nx}^2 \omega_{n\varphi}^2}{r} \right\}^2 = 2.34 \text{ x } 10^6$$

$$A_{x1} = \frac{F_x \left[\left(-M_m\omega^2 + K_\phi + K_x L^2\right)^2 + \omega^2\left(C_\phi + C_x L^2\right)^2 \right]^{\frac{1}{2}}}{m M_m \Delta\omega^2}$$

$$A_{x1} = 36.148 \times 10^{-6} \text{m}$$

$$A_{\phi 1} = \frac{F_x L \omega_{nx} [\omega_{nx}^2 + 4\xi_x \omega^2]^{\frac{1}{2}}}{M_m \Delta\omega^2}$$

$$A_{\varphi 1} = 8.12048 \times 10^{-6} \text{rad}$$

$$A_{x2} = \frac{M_y L [(\omega_{nx}^2)^2 + (2\xi_x \omega_{nx} \omega)^2]^{1/2}}{M_m \Delta\omega^2}$$

$$A_{x2} = 28.4817 \text{x} 10^{-6} \text{m}$$

$$A_{\phi 2} = \frac{M_y [(\omega_{nx}^2 - \omega^2)^2 + (2\xi_x \omega_{nx} \omega)^2]^{1/2}}{M_m \Delta\omega^2}$$

$$A_{\phi 2} = 9.9378 \times 10^{-6} \text{rad}$$

$$A_x = A_{x1} + A_{x2} = 64.63 \text{x } 10^{-6} \text{m}$$

$$A_\varphi = A_{\varphi 1} + A_{\varphi 2} = 18.058 \times 10^{-6} \text{rad}$$

MATLAB RESULTS

os = 350

yc = 25

ys = 18

l = 10

d = 0.5000

N = 9

hpc = 1.5000

D = 1.2500

Wm = 400

hm = 0.4000

fz = 2.5000

fx = 2

Ep = 25000000

Gs = 10000

Ip = 0.0031

X = 3

Ap = 0.1963

S = 1.2500

bpc = 3.5000

bm = 3

Wpc = 459.3750

Wp = 441.7865

Ws = 1.8869e+003

W = 3.1881e+003

w = 36.6519

m = 324.9808

Apc = 12.2500

ro = 0.2500

row = 1.8349

vs = 73.8241

Fz = 22.5000

Fx = 18

VERTICAL VIBRATION IN SINGLE PILE

kzp = 1.5708e+005

czp = 1.7288e+003

al = 5.5429

kzg = 2.5505e+005

czg = 2.8071e+003

roc = 1.9747

kzf = 33750

czf = 2.2402e+003

VERTICAL VIBRATION IN PILE GROUPS

kzgt = 2.8880e+005

czgt = 5.0472e+003

ccgt = 1.9376e+004

q = 0.2605

wnz = 29.8105

wndz = 32.0657

n = 1.2295

c = 1.8439

y = 0.1643

Az = 9.3226e-004

SLIDING VIBRATION IN SINGLE PILE

sx1 = 4.1000

sx2 = 10.6000

als = 3.3000

kxp = 1.0799e+004

cxp = 139.6339

kxg = 2.9452e+004

cxg = 380.8198

kxf = 5.1250e+004

cxf = 3.5441e+003

SLIDING VIBRATION IN PILE GROUPS

kxgt = 8.0702e+004

cxgt = 3.9250e+003

wnx = 15.7585

ccxg = 1.0242e+004

dxg = 0.3832

Ax = 3.1507e-004

ROCKING VIBRATION IN SINGLE PILE

sr1 = 2.5000

sr2 = 1.8000

krp = 7.7589e+004

crp = 218.2819

kxrp = -3.4852e+004

cxrp = -215.6845

roc2 = 1.9976

xr = 1.2500

zc = 0.7500

krg = 2.6961e+006

crg = 2.1791e+004

dl = 0.6258

krf = 1.3217e+005

crf = 2.9522e+003

ROCKING VIBRATION IN PILE GROUPS

krgt = 2.8283e+006

crgt = 2.4743e+004

Zbar = 5.2308

Mm = 4.6905e+004

L = 6.6692

Mmo = 1.8870e+005

r = 0.2486

My = 94.1550

ccrg = 4.6649e+005

drg = 0.0530

wnr = 12.1256

COUPLED SLIDING AND ROCKING VIBRATION

wn1 = 38.6280

wn2 = 9.9219

dwp1 = 1.0249e+010

dwp2 = 5.4672e+012

dw2 = 2.3404e+006

Ax1 = 3.6159e-005

Ax2 = 2.8482e-005

Ar1 = 8.1206e-006

Ar2 = 9.9380e-006

AX = 6.4640e-005

AR = 1.8059e-005

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ncrae 12 <ncrae12@seti.edu.in> Wed, May 30, 2012 at 1:03 PM
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SANJEEVAN ENGINEERING & TECHNOLOGY INSTITUTE,PANHALA
Sanjeevan Knowledge City, Panhala,
Tal. Panhala, Dist. Kolhapur-416201,Maharashtra State, India**Email:** duradundi.badkar@seti.edu.in, ncrae12@seti.edu.in
Mobile: +91-9545913434, +91-9620397797

With best regards

Yours Sincerely

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2 attachments

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Dear Sir,

I have attached my paper according to the format suggested by the committee.
Thankingy you

Regards
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DYNAMIC BEHAVIOUR OF PILES SUPPORTING MACHINES

Ms. M. Bharathi[1], Dr. Swami Saran[2], Dr. S. Mukerjee[3]
Earthquake Engineering Department, IIT Roorkee
Roorkee, India 247 667.
[1]bharathi.iitr@gmail.com
[2]saranswami@yahoo.co.in
[3]shyamfeq@iitr.ernet.in

Abstract- **Machine foundations are generally classified as special foundations. They require a detailed analysis of the foundation response to the dynamic load coming from the anticipated operation of the machines. Reciprocating type machines produce periodic loads and works on a crank piston mechanism. The reciprocating machines are usually supported on block type of foundations. This paper describes the dynamic behavior of piles and pile groups supporting reciprocating machines. The Indian Standards specifications suit block type machine foundation and not pile type machine foundation. There is no such suggested procedure to design the machines supported on piles. Hence, suitable assumptions are made such that they suit the field condition and the pile group is analyzed with the help of MATLAB program. Here, an attempt has been made to study the variation of amplitude for different modes of vibration of the machine foundation system.**

Keywords- Dynamic Behavior, Pile groups, Translational, Rotational, Coupled.

I INTRODUCTION

A. General

Machine foundations require a special consideration because they transmit dynamic loads to soil in addition to static loads due to weight of foundation, machine and accessories.

The dynamic load due to operation of the machine is generally small compared to the static weight of machine and the supporting foundation. In a machine foundation the dynamic load is applied repetitively over a very long period of time but its magnitude is small and therefore the soil behavior is essentially elastic, or else deformation will increase with each cycle of loading and may become unacceptable. The amplitude of vibration of a machine at its operating frequency is the most important parameter to be determined in designing a machine foundation, in addition to the natural frequency of a machine foundation soil system. [3]

B. Reciprocating Machines

The machines that produce periodic unbalanced forces (such as steam engines) belong to this category. These machines include steam, diesel and gas engines, compressors and pumps. The operating speeds of such machines are usually less than 1000 rpm. [5]

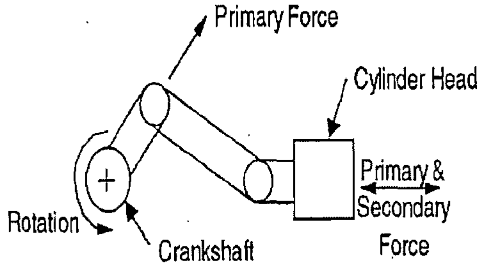

Fig. 1 Parts of a reciprocating machine

The dynamic forces developed by the reciprocating machines are much higher compared to those generated by the rotary machines. These dynamic forces are predominant along the piston axis and are generated at operating speed as well as at its first harmonic. Allowable limits of amplitude are higher for reciprocating machines compared to those for rotary machines. The system vibrates in all six degrees of freedom and thus requires computation of frequencies and amplitudes corresponding to all six degrees of freedom.[1]

C. Types of foundations [5]

Reciprocating machines are very frequently encountered in practice. Usually the following two types of foundation are used for such machines:

i. Block type foundation
   The machine rests on a concrete block which rests on the soil. The depth of embedment of the block in the soil also plays a very significant role in calculating the stiffness and damping of the system.
ii. Box type foundation
   A hollow concrete block is used to support the machine. The mass of the block is less in this case and hence the natural frequency will be higher than the previous case.

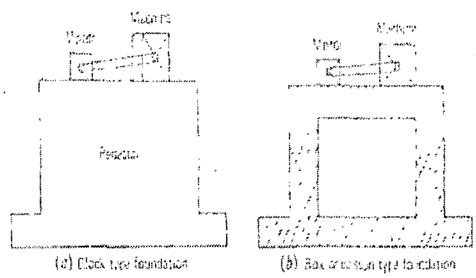

Fig.2 Types of foundations

D. Supports for foundations [2]

The reciprocating machines mounted on the foundation may rest either on soil or on piles. For foundations resting on piles, the blocks supporting the machinery rests on piles. The block plays the role of the pile cap for the pile group. The thickness of the pile cap i.e. the block should not be less than 600mm.

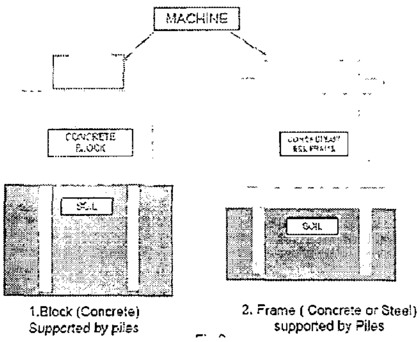

Fig.3 Foundations resting on piles

The introduction of pile in a soil stratum makes the system stiff. Due to this the natural frequency and the amplitudes of motion are affected. In all vibration problems, resonance needs to be avoided. Therefore, the natural frequency of the structure poil system is required for analysis and design. For machine foundation application, piles are provided in the following cases:

i. When soil is weak in bearing capacity to withstand pressures due to both static and dynamic loads.
ii. When significant loss of soil strength is postulated under dynamic loads on account of critical soil and water table conditions.
iii. When it is required to increase natural frequency of the machine foundation system.
iv. When dynamic amplitudes are required to be reduced.
v. When it is required to stiffen the support system on account of seismic consideration.

The selection of pile type, pile size, pile depth, number of piles etc is an involved task and is accomplished using standard pile design procedures based on soil data and the load data. In certain cases, selection of pile type, pile size, pile depth, number of piles etc becomes a tricky issue and for all practical purposes may turn out to be a difficult task. In either case, evaluation of dynamic characteristics of piles is a complex task and suffers with many associated uncertainties. [6]

A machine foundation block itself serves as rigid pile cap that connects piles at the top. Evaluation of dynamic characteristics of a single pile, in itself, is a difficult task and evaluation of dynamic characteristics of a group of piles connected by a rigid pile cap becomes complex and calls for many assumption resulting in added levels of uncertainties. [4]

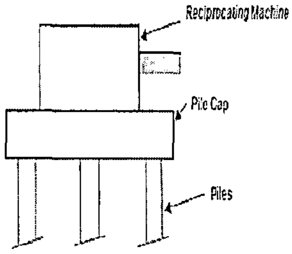

Fig.4 Reciprocating machine resting on piles

E. Types of analysis

The stiffness and damping of piles under various modes of vibration were computed by two different analytical approaches

i. Novak's frequency independent solutions with static interaction factor for parabolic soil profile
ii. Novak's complex frequency dependent analytical solutions with dynamic interaction factor approach for layered media.

The vibratory modes may be 'decoupled' or 'coupled'. Of the six modes, translation along vertical axis and rotation around vertical axis can occur independently of any other motion and are called decoupled modes. But the translation along the longitudinal or lateral and the corresponding rotations always occur together and are called coupled modes. [5]

Hence the dynamic analysis of the machine foundations subjected to coupled sliding and rocking motion passing through the common centre of gravity of machine and foundation becomes must.

II DESIGN OF FOUNDATIONS ON PILES

Designing foundations with piles for vibrating machinery is a difficult task for the simple reason that practical design methods are not readily available or published in codes of practice. When designing a foundation with piles, the method of design is not explicitly given by the code. Therefore, a simple method to determine the stiffness and damping of pile group subjected to different modes of vibration is to be used to design the foundation on piles. The procedure to calculate the stiffness and damping of the pile group subjected to different modes of vibration is discussed in detail in the next chapter.

Dynamic behaviour of piles and pile group [5]

The dynamic behavior of piles and pile groups were studied and the following theories were formulated from Novak's work.

1) Single Pile Subjected To Vertical Vibration

$K_{zp} = (E_pA/r_o)*f_{w1}$ (2.1)

$C_{zp} = (E_pA/v_s)*f_{w2}$ (2.2)

f_{w1} and f_{w2} are parameters which depend on (i) type of pie whether end bearing or friction (ii) pile slenderness (iii) E_p/G_s

(iv) Variation of G_s with depth and they are obtained from Fig.5.

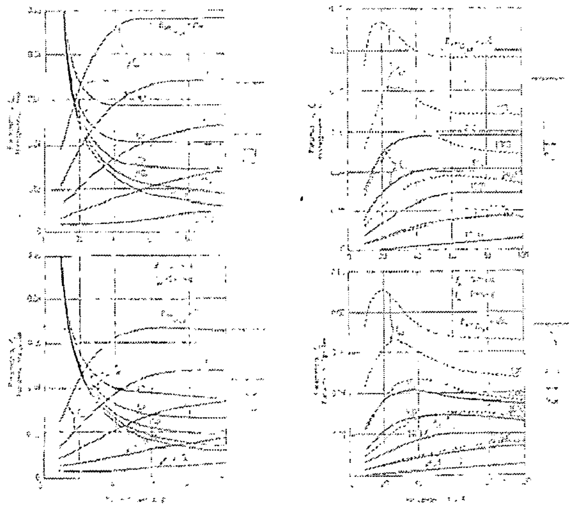

Fig.5 Constants for vertical vibration [5]

2) Single Pile Subjected To Translation Motion

$K_{xp} = (E_p I_p / r_o^3) * f_{x1}$ (2.3)

$C_{xp} = (E_p I_p / r_o^2 v_s) * f_{x2}$ (2.4)

f_{x1} and f_{x2} are parameters which depend on (i) Poisson's ratio (ii) pile slenderness (iii) E_p/G_s (iv) variation of G_s with depth (v) type of support of pile head and they are taken from Table I.

3) Single Pile Subjected To Rotational Motion

$K_{\phi p} = (E_p I_p / r_o) * f_{\phi 1}$ (2.5)

$C_{\phi p} = (E_p I_p / v_s) * f_{\phi 2}$ (2.6)

$f_{\phi 1}$ and $f_{\phi 2}$ are parameters which depend on (i) Poisson's ratio (ii) pile slenderness (iii) E_p/G_s (iv) Variation of G_s with depth and they are taken from Table I.

4) Single Pile Subjected To Coupled Motion

$K_{x\phi p} = (E_p I_p / r_o^2) * f_{x\phi 1}$ (2.7)

$C_{x\phi p} = (E_p I_p / r_o v_s) * f_{x\phi 2}$ (2.8)

$f_{x\phi 1}$ and $f_{x\phi 2}$ are parameters which depend on (i) Poisson's ratio (ii) pile slenderness (iii) E_p/G_s (iv) Variation of G_s with depth and they are taken from Table I.

5) Pile group subjected to vertical vibration

$$K_{zg} = \frac{\sum_1^n K_{zp}}{\sum_1^n \alpha_A} \quad (2.9)$$

$$C_{zg} = \frac{\sum_1^n C_{zp}}{\sum_1^n \alpha_A} \quad (2.10)$$

$$K_{zf} = G_s D S_{z1} \quad (2.11)$$

$$C_{zf} = D r_{oc} S_{z2} \sqrt{G_s \rho} \quad (2.12)$$

$$K_{zgt} = K_{zg} + K_{zf} \quad (2.13)$$

$$C_{zgt} = C_{zg} + C_{zf} \quad (2.14)$$

The constants are taken from Fig.6.

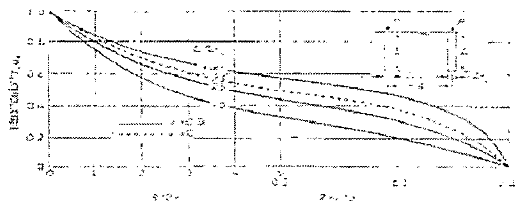

Fig.6 Interaction factor for vertical vibration [5]

TABLE I
STIFFNESS AND DAMPING CONSTANTS

ν	Stiffness Parameters					Damping Parameters			
	E_{pile}/G_{sc}	(f_{x1})	$(f_{x\phi 1})$	$(f^*_{\phi 1})$	(f^{ϕ}_{x1})	(f_{x2})	$(f_{x\phi 2})$	$(f^*_{\phi 2})$	(f^{ϕ}_{x2})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Homogeneous Soil Profile									
0.25	10,000	0.2135	-0.0217	0.0042	0.0021	0.1577	-0.0333	0.0107	0.0054
	2,500	0.2998	-0.0429	0.0119	0.0061	0.2152	-0.0646	0.0297	0.0154
	1000	0.3741	-0.0668	0.0236	0.0123	0.2598	-0.0985	0.0579	0.0306
	500	0.4411	-0.0929	0.0395	0.0210	0.2953	-0.1337	0.0952	0.0514
	250	0.5186	-0.1281	0.0659	0.0358	0.3299	-0.1786	0.1556	0.0864
0.4	10,000	0.2207	-0.0232	0.0047	0.0024	0.1624	-0.0358	0.0119	0.0060
	2,500	0.3097	-0.0459	0.0132	0.0068	0.2224	-0.0692	0.0329	0.0171
	1000	0.3860	-0.0714	0.0261	0.0136	0.2677	-0.1052	0.0641	0.0339
	500	0.4547	-0.0991	0.0436	0.0231	0.3024	-0.1425	0.1054	0.0570
	250	0.5336	-0.1365	0.0726	0.0394	0.3377	-0.1895	0.1717	0.0957
Parabolic Soil Profile									
0.25	10,000	0.1800	-0.0144	0.0019	0.0008	0.1450	-0.0252	0.0066	0.0025
	2,500	0.2452	-0.0267	0.0047	0.0020	0.2025	-0.0484	0.0159	0.0076
	1000	0.3000	-0.0400	0.0086	0.0037	0.2499	-0.0737	0.0302	0.0147
	500	0.3489	-0.0543	*0.0136	0.0059	0.2910	-0.1008	0.0491	0.0241
	250	0.4049	-0.0734	0.0215	0.0094	0.3361	-0.1370	0.0792	0.0398
0.4	10,000	0.1857	-0.0153	0.0020	0.0009	0.1508	-0.0271	0.0067	0.0031
	2,500	0.2529	-0.0284	0.0051	0.0022	0.2101	-0.0519	0.0177	0.0084
	1000	0.3094	-0.0426	0.0094	0.0041	0.2589	-0.0790	0.0326	0.0163
	500	0.3596	-0.0577	0.0149	0.0065	0.3009	-0.1079	0.0544	0.0269
	250	0.4170	-0.0780	0.0236	0.0103	0.3465	-0.1461	0.0886	0.0445

(f^{ϕ}_{x1}) and (f^{ϕ}_{x2}) are parameters for pinned head

* Fixed-translating head

6) Pile group subjected to translation Motion

$$K_{xg} = \frac{\sum_1^n K_{xp}}{\sum_1^n \alpha_A} \quad (2.15)$$

$$C_{xg} = \frac{\sum_1^n C_{xp}}{\sum_1^n \alpha_A} \quad (2.16)$$

$$K_{xf} = G_s D S_{x1} \quad (2.17)$$

$$C_{xf} = D r_{oc} S_{x2} \sqrt{G_s \rho} \quad (2.18)$$

$$K_{xgt} = K_{xg} + K_{xf} \quad (2.19)$$

$$C_{xgt} = C_{xg} + C_{xf} \quad (2.20)$$

The constants are taken from Fig.7 and Table II.

TABLE II
CONSTANTS OF PILE CAP FOR TRANSLATION MOTION [5]

Poisson's Ratio ν	Validity Range	Constant Parameter
0.00	$0 < a_0 < 1.5$	$\bar{S}_{x1} = 3.6$ $\bar{S}_{x2} = 8.2$
0.25	$0 < a_0 < 1.5$	$\bar{S}_{x1} = 4.0$ $\bar{S}_{x2} = 9.1$
0.40	$0 < a_0 < 1.5$	$\bar{S}_{x1} = 4.1$ $\bar{S}_{x2} = 10.6$

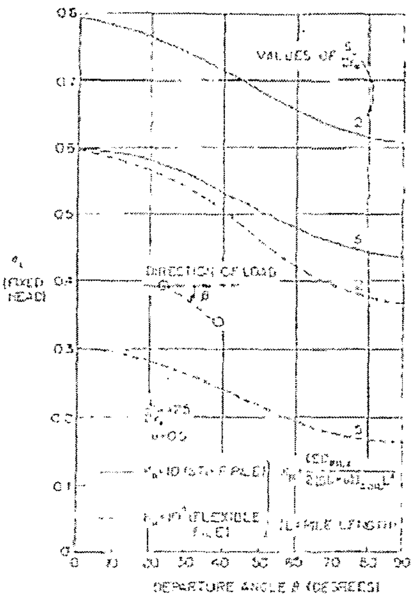

Fig.7 Interaction factor for translation motion [5]

7) Pile group subjected to rotational motion

$$K\phi_g = \sum_1^n \left(K_{\phi p} + K_{zp} x_r^2 + K_{xp} Z_c^2 - 2Z_c K_{x\phi p}\right) \quad (2.21)$$

$$C\phi_g = \sum_1^n \left(C_{\phi p} + C_{zp} x_r^2 + C_{xp} Z_c^2 - 2Z_c C_{x\phi p}\right) \quad (2.22)$$

$$K\phi f = G_s r_{oc}^2 D S_{\phi 1} + G_s r_{oc}^2 D \left[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_o}\right)^2 - \left(\frac{Z_c}{r_o}\right)\right] S_{x1} \quad (2.23)$$

$$C\phi f = \delta r_{oc}^4 \sqrt{\frac{G_s \gamma}{g}} \left\{ S_{\phi 2} + \left[\left(\frac{\delta^2}{3}\right) + \left(\frac{Z_c}{r_o}\right)^2 - \delta\left(\frac{Z_c}{r_o}\right)\right] S_{x2} \right\} \quad (2.24)$$

$$K_{\phi gt} = K_{\phi g} + K_{\phi f} \quad (2.25)$$

$$C_{\phi gt} = C_{\phi g} + C_{\phi f} \quad (2.26)$$

8) Pile group subjected to coupled motion

Undamped natural frequencies in coupled rocking and sliding are given by

$$\omega_{n1,2}^2 = \frac{1}{2r}\left[\left(\omega_{nx}^2 + \omega_{n\phi}^2\right) \pm \sqrt{\left(\omega_{nx}^2 + \omega_{n\phi}^2\right)^2 - 4r\,\omega_{nx}^2\,\omega_{n\phi}^2}\right] \quad (2.27)$$

$$\Delta\omega^2 = \left[\left\{\omega^4 - \omega^2\left[\frac{\left(\omega_{nx}^2 + \omega_{n\phi}^2\right)}{r} - \frac{4\xi_x \xi_\phi \omega_{nx}\omega_{n\phi}}{r}\right] + \frac{\left(\omega_{nx}^2 \omega_{n\phi}^2\right)}{r}\right\}^2 + 4\left\{\left(\frac{\xi_x \omega_{nx}\omega}{r}\left(\omega_{n\phi}^2 - \omega^2\right)\right) + \left(\frac{\xi_\phi \omega_{n\phi}\omega}{r}\left(\omega_{nx}^2 - \omega^2\right)\right)\right\}^2\right]^{1/2} \quad (2.28)$$

$$\omega_{nx} = \sqrt{\frac{K_{xgt}}{m}} \quad (2.29)$$

$$\omega_{n\phi} = \sqrt{\frac{K_{\phi gt}}{M_{mo}}} \quad (2.30)$$

$$r = \frac{M_m}{M_{mo}} \quad (2.31)$$

$$\xi_x = \frac{C_{xg}}{2\sqrt{K_{xgt} m}} \quad (2.32)$$

$$\xi_\phi = \frac{C_{\phi g}}{2\sqrt{K_{\phi gt} M_{mo}}} \quad (2.33)$$

$$A_{x1} = \frac{F_x\left[\left(-M_m\omega^2 + K_\phi + K_x L^2\right) + \omega^2\left(C_\phi + C_x L^2\right)^2\right]^{1/2}}{m\,M_m\,\Delta\omega^2} \quad (2.34)$$

$$A_{\phi 1} = \frac{F_x L\,\omega_{nx}\left[\omega_{nx}^2 + 4\xi_x \omega^2\right]^{1/2}}{M_m \Delta\omega^2} \quad (2.35)$$

$$A_{x2} = \frac{M_y L\left[\left(\omega_{nx}^2\right)^2 + 2\xi_x \omega_{nx}\omega\right]^{1/2}}{M_m \Delta\omega^2} \quad (2.36)$$

$$A_{\phi 2} = \frac{M_y\left[\left(\omega_{nx}^2 - \omega^2\right)^2 + \left(2\xi_x \omega_{nx}\omega\right)^2\right]^{1/2}}{M_m \Delta\omega^2} \quad (2.37)$$

$$A_x = A_{x1} + A_{x2} \quad (2.38)$$

$$A_\phi = A_{\phi 1} + A_{\phi 2} \quad (2.39)$$

III SELECTION OF PARAMETERS

A. Soil Parameters

The soil parameter is represented by the Shear modulus of the soil. The parabolically varying soil profile is selected in the problem.

B. Spacing between piles

The spacing between the piles is varied from 2d to 4d.

C. Interaction factors

The calculation of interaction factor plays a major role in the dynamic analysis of a pile group. The interaction factor for a pile group depends upon the spacing between two piles in the pile group.

D. Pile group arrangement

The piles in a pile group may be arranged in any of the following pattern. For the Machine foundation the pile group is selected according to the plan area of the Machine.

E. Machine parameters

The operating frequency and the weight of the reciprocating machine are selected such that the parameters suite the values of the machines that are used in the industries. The operating frequency of the reciprocating machines used in the industries varies between 300 to 1000 rpm usually. The weight of the reciprocating machine varies from 300kN to 1700 kN.

IV RESULTS

For the selected problem the variation in the frequency and amplitude for different modes of vibration is studied varying the parameters.

Case (i) The machine parameters are kept constant and the spacing between the piles are varied.

Wm = 400 kN & OS = 400 rpm

TABLE III
AMPLITUDE VARIATION WITH VARYING SPACE PILES

S	2d	2.5d	3d	3.5d	4d
Az (m)	8.8E-4	6.3E-4	4.6E-4	3.5E-4	2.7E-4
Axc (m)	6.09E-5	4.8E-5	3.8E-5	3.0E-5	2.5E-5
Arc (rad)	1.7E-5	1.5E-5	1.24E-5	1.07E-5	9.19E-6

Case (ii) The machine weight and the spacing between the piles are kept constant and the operating frequency are varied. Wm = 400kN and S = 3d

TABLE IV
AMPLITUDE WITH VARYING OPERATING FREQUENCY

OS rpm	400	600	800	1000
Az (m)	4.6E-04	1.6E-04	8.4E-05	5.2E-05
Axc (m)	3.8E-05	1.52E-05	8.03E-06	4.9E-06
Arc (rad)	1.24E-05	5.44E-06	2.92E-06	1.8E-06

Case (iii) The operating frequency of the machine and the spacing are kept constant and the weight of the machine is varied. OS = 400rpm & S = 3d

TABLE V
AMPLITUDE VARIATION WITH VARYING MACHINE WEIGHT

W_m kN	400	600	800	1000
Az (m)	4.6E-04	4.3E-04	4.0E-04	3.8E-04
Axc (m)	3.8E-05	3.5E-05	3.23E-05	3.02E-05
Arc (rad)	1.24E-05	1.12E-05	1.02E-05	9.36E-06

From the above results the following points were observed

i. As the spacing increases the amplitude decreases for all the modes of vibration.
ii. As the operating frequency increases the amplitude decreases.
iii. As the weight of the machine increases the frequency and amplitude decreases with a very nominal change.

V CONCLUSIONS

These common observations lead to the broad conclusions that

i. Definite gaps exist in understanding the dynamic behavior of a single pile as well as group of piles.
ii. Dynamic Interaction of group of piles is a very complicated task.

There is huge amount of work available in the literature that appears to be good for R&D purposes and its translation as a design tool is lacking for practical applications in the industry. In view of the limitations and associated uncertainties, practically every method is to be used with caution till better design methods are available. Hence, more analytical works are required to bridge the gap between the theoretical and practical application.

REFERENCES

[1] Bhatia, K.G. (2008), *"Foundations for industrial machines—A handbook for practicing engineers"*, D-CAD Publishers, New Delhi.

[2] IS: 2974 (Part I)-1982, *"Foundation for Reciprocating Type Machines"*, I.S.I. New Delhi.

[3] Major A. (1962), *"Vibration Analysis and Design of foundation for machines and turbines"*, Akademiai kiado, Budapest, Collet's Holdings ltd, London.

[4] Srinivasulu P, Vaidyanathan C.V (1976), *"Handbook of Machine Foundation"*, Tata McGraw Hill Publishing Company Ltd, New Delhi.

[5] Swami Saran (2006), *"Soil dynamics and machine foundation"*, Galgotia Publications Pvt. Ltd, New Delhi.

[6] Tomlinson, M.J. (1986), *"Foundation Design Consideration"*, Longman, Singapore Publishers, Singapore.

Symbols:

α_A	Interaction factor for pile group
A	Area of cross section of pile in m^2
C_{xf}	Damping of pile cap for translation motion in kN-s/m
C_{xg}	Damping of pile group for translation motion in kN-s/m
C_{xgt}	Total damping of pile group and pile cap for translational vibration in kN-s/m
C_{xp}	Damping of single pile under translation motion in kN-s/m
$C_{x\phi p}$	Damping of single pile under coupled motion in kN-s/m
C_{xf}	Damping of pile cap for rotational motion in kN-s/m
C_{zf}	Damping of pile cap for vertical vibration in kN-s/m
C_{zg}	Damping of pile group for rotational motion in kN-s/m
C_{zg}	Damping of pile group for vertical vibration in kN-s/m
C_{zgt}	Total damping of pile group and pile cap for vertical vibration in kN-s/m
C_{zp}	Damping of single pile under vertical vibration in kN-s/m
$C_{\phi gt}$	Total damping of pile group and pile cap for rotational vibration in kN-s/m
$C_{\phi p}$	Damping of single pile under rotational motion in kN-s/m
D	Depth of embedment of pile cap in m
ω	Operating frequency of the machine in rad/s
ω_{nz}	Operating frequency of the machine in rad/s
ω_{nx}	Operating frequency of the machine in rad/s
$\omega_{n\phi}$	Operating frequency of the machine in rad/s
ω_{n1}	Operating frequency of the machine in rad/s
ω_{n2}	Operating frequency of the machine in rad/s
E_p	Modulus of elasticity of pile material kN/m^2
f_{w1}	Stiffness constant for vertical vibration
f_{w2}	Damping constant for vertical vibration
f_{x1}	Stiffness constant for translational vibration
f_{x2}	Damping constant for translational vibration
$f_{x\phi 1}$	Stiffness constant for coupled vibration
$f_{x\phi 2}$	Damping constant for coupled vibration
$f_{\phi 1}$	Stiffness constant for rotational vibration
$f_{\phi 2}$	Damping constant for rotational vibration
G_s	Shear modulus of soil in kN/m^2
I_p	Moment of inertia of pile cross section in m^4
K_{xf}	Stiffness of pile cap for translation motion in kN/m
K_{xg}	Stiffness of pile group for translation motion in kN/m
K_{xgt}	Total stiffness of pile group and pile cap for translational vibration in kN/m
K_{xp}	Stiffness of single pile under translation motion in kN/m
$K_{x\phi p}$	Stiffness of single pile under coupled motion in kN/m
K_{zf}	Stiffness of pile cap for vertical vibration in kN/m
K_{zg}	Stiffness of pile group for rotational motion in kN/m

K_{zgt}	Total stiffness of pile group and pile cap for vertical vibration in kN/m .
K_{zp}	Stiffness of single pile under vertical vibration in kN/m
$K_{\phi gt}$	Total stiffness of pile group and pile cap for rotational vibration in kN/m
$K_{\phi p}$	Stiffness of single pile under rotational motion in kN/m
A_z	Amplitude for vertical vibration in m
A_x	Linear horizontal amplitude of the combined centre of gravity in m
A_ϕ	Rotational amplitude in radians around the combined centre of gravity in radians
r_o	Equivalent radius of pile in m
r_{oc}	Equivalent radius of pile cap in m
S	Spacing between piles in m
S_{x1}	Stiffness constant of pile cap for translation motion
S_{x2}	Damping constant of pile cap for translation motion
S_{z1}	Stiffness constant of pile cap for vertical vibration
S_{z2}	Damping constant of pile cap for vertical vibration
$S_{\phi 1}$	Stiffness constant of pile cap for rotational motion
$S_{\phi 2}$	Damping constant of pile cap for rotational motion
v_s	Shear wave velocity in m/sec
x_r	Distance of each pile from c.g. in m
Z_c	Height of c.g. of the pile cap above its base in m
ξ_x	Damping ratio for translational vibration
ξ_ϕ	Damping ratio for rotational vibration