Machine Foundation

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 behaviour 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.

There are many types of machines that generate different periodic forces. The most important categories are:

1. Reciprocating machines: The machines that produce periodic unbalanced forces (such as steam engines) belong to this category. The operating speeds of such machines are usually less than 600r/min. Rotary motion of crank is converted into the translatory motion. For analysis of their foundations, the unbalanced forces can be considered to vary sinusoidally.

2. Impact machines: These machines produce impact loads, for instance, forging hammers. Their speeds of operation usually vary from 60 to 150 blows per minute. Their dynamic loads attain a peak in a very short interval and then practically die out.

3. Rotary machines: High-speed machines like turbogenerators or rotary compressors may have speeds of more than 3,000r/min and up to 12,000r/min.

One way to classify machines is based on their speed of operation:

Low to medium frequencies 0-500 rpm (large reciprocating engines, compressors and blowers)

Medium to high frequencies 300-1000 rpm (diesel and gas engines)

Very high frequencies usually greater than 1000 rpm (turbo-generators and high speed internal combustion engines)

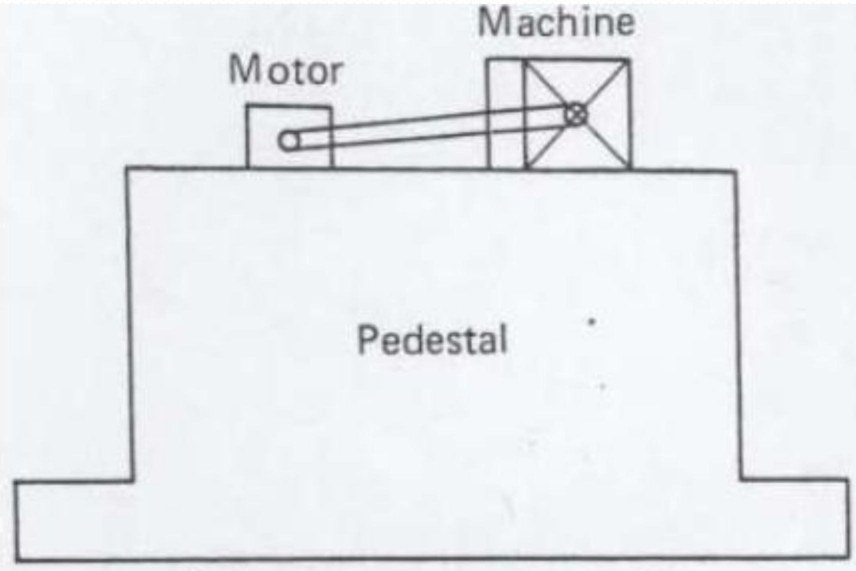
For compressors and reciprocating machines, a block foundation is generally provided.

Block foundation consists of a massive block of concrete resting directly on soil or supported on piles or a pedestal resting on a footing.

If two or more machines of similar type are to be installed in a shop, these can profitably be mounted on one continuous mat.

A block foundation has a large mass and, therefore, a smaller natural frequency.

The block has large bending and torsional stiffness and easy to construct. To modify the block foundation at a later time is extremely difficult.



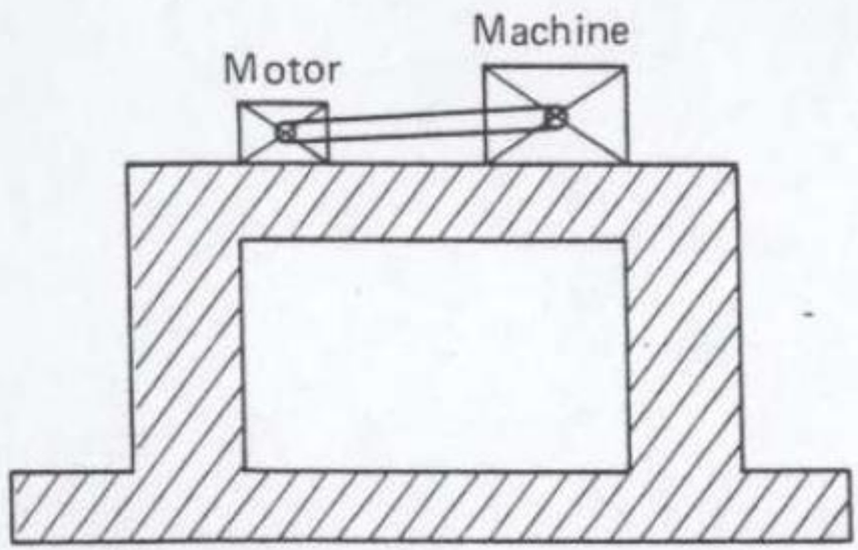
(a) Block type foundation

However, if a relatively lighter foundation is desired, a box or a caisson type foundation may be provided.

The mass of the foundation is reduced and its natural frequency increases.

Box or Caisson foundation consists of a hollow concrete block (can be used as operational space) that supports the machine on its top. Hammers may also be mounted on block foundations, but their details would be quite different than those for reciprocating machines.

It has high static stiffness just like a plate foundation and is not easily amenable to alterations at a later date.



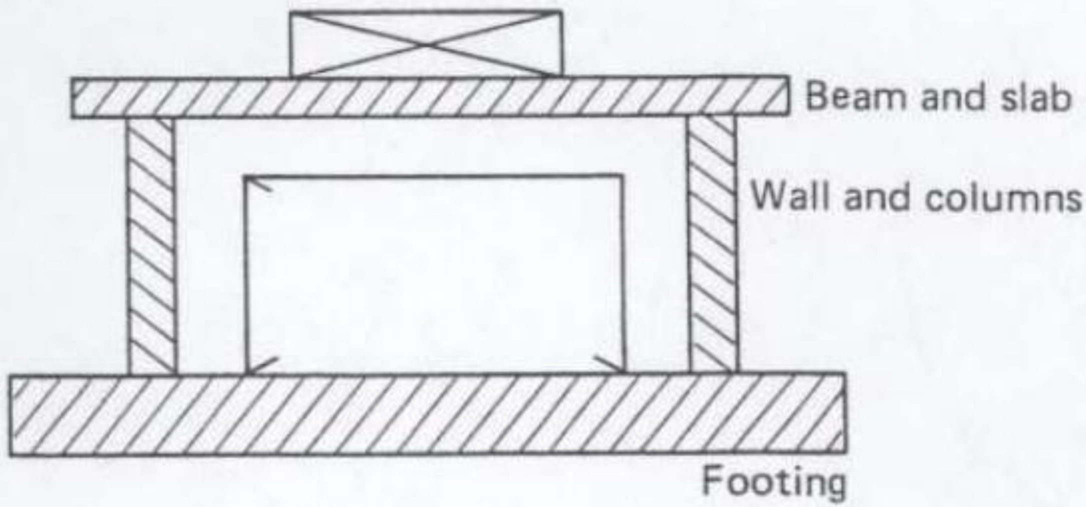
(b) Box or caisson type foundation

Steam turbines have complex foundations that may consist of a system of walls columns, beams and slabs.

This type is usually adopted for very high-speed machines requiring large operational space below for connecting pipes and additional equipment.

It can be made or either RCC or steel frames. Although the frame made of steel is easy to alter at a later date, its behaviour under dynamic loading is not as good as that of an RCC frame.

Each element of such a foundation is relatively flexible as compared to a rigid block and box or a caisson-type foundation.



(c) Wall type foundation

Plate foundation

Plate foundation consists of a continuous plate made of concrete resting directly on soil or supported on piles. The machine is placed on the plate.

The plate has high static stiffness and is easy to construct. Subsequent alterations to this type of foundation are difficult to execute.

Spring foundation

Spring foundation consists of a concrete slab or a steel frame on which the machine rests. The slab/frame is supported on a set of springs.

This type is used, if the subsoil is weak or we need to isolate the subsoil from the transmitted vibrations.

Design Criteria for Machine Foundations

i. It should be safe from a bearing capacity failure under static and dynamic loads,

ii. The settlement must be less than the prescribed ones,

iii. The dynamic amplitudes of the machine-foundation-soil system must be within the prescribed limits under service conditions.

iv. There should be no resonance, i.e. the natural frequency of the machine-foundation-soil system should not coincide with the operating frequency of the machine,

v. Preferably, the centre of gravity of the machine should lie in the same vertical line as the centre of gravity of the foundation system.

When design criteria (iii) to (v) are satisfied then the machine itself is not damaged by the vibrations generated,

the structure in which the machine is housed and adjacent structures do not suffer any vibration induced damage,

performance of machines located in its vicinity is not impaired, and

employees working around the machine are not bothered by the vibrations.

One of the design criteria for machine foundations is that there should be no resonance.

To achieve this it is necessary to *tune* the machine foundation. Tuning is done by adjusting the natural frequency of the machine-foundation-soil system so that it is far away from the operating frequency of the machine.

Shifting the natural frequency of the machine-foundation-soil system well above the operating frequency is called *high tuning*, or in the jargon of Mechanical Engineers *sub-critical run*.

On the other hand shifting the natural frequency below the operating frequency is called *low tuning* or *supercritical run*.

There are thus two choices at your disposal to avoid resonance.

High tuning has the advantage that the machine does not have to go through resonance either during start up or shut down of the machine.

It is also fine if the machine has to run below rated capacity.

Whether choose high tuning or not, depends on the operating frequency of the machine.

Implementing high tuning for a very high-speed machine is difficult to achieve and can be a costly proposition.

Under such situation have to opt for a low tuned system and yet are within the prescribed level.

This is often accomplished by using a foundation system that allows alteration of the natural frequency of the machine-foundation-soil system when necessary by changing its mass or stiffness.

For example, by increasing the dimensions of the foundation which will change the mass, providing cavities in the block where mass can be added, or using commercially available mechanical springs which will change the stiffness.

Sometimes, avoiding resonance is not possible. In such a case, you will have to make sure that the amplitude of vibration is in the acceptable limits by incorporating dampers in the foundation system. Dampers are instruments that absorb vibrations.

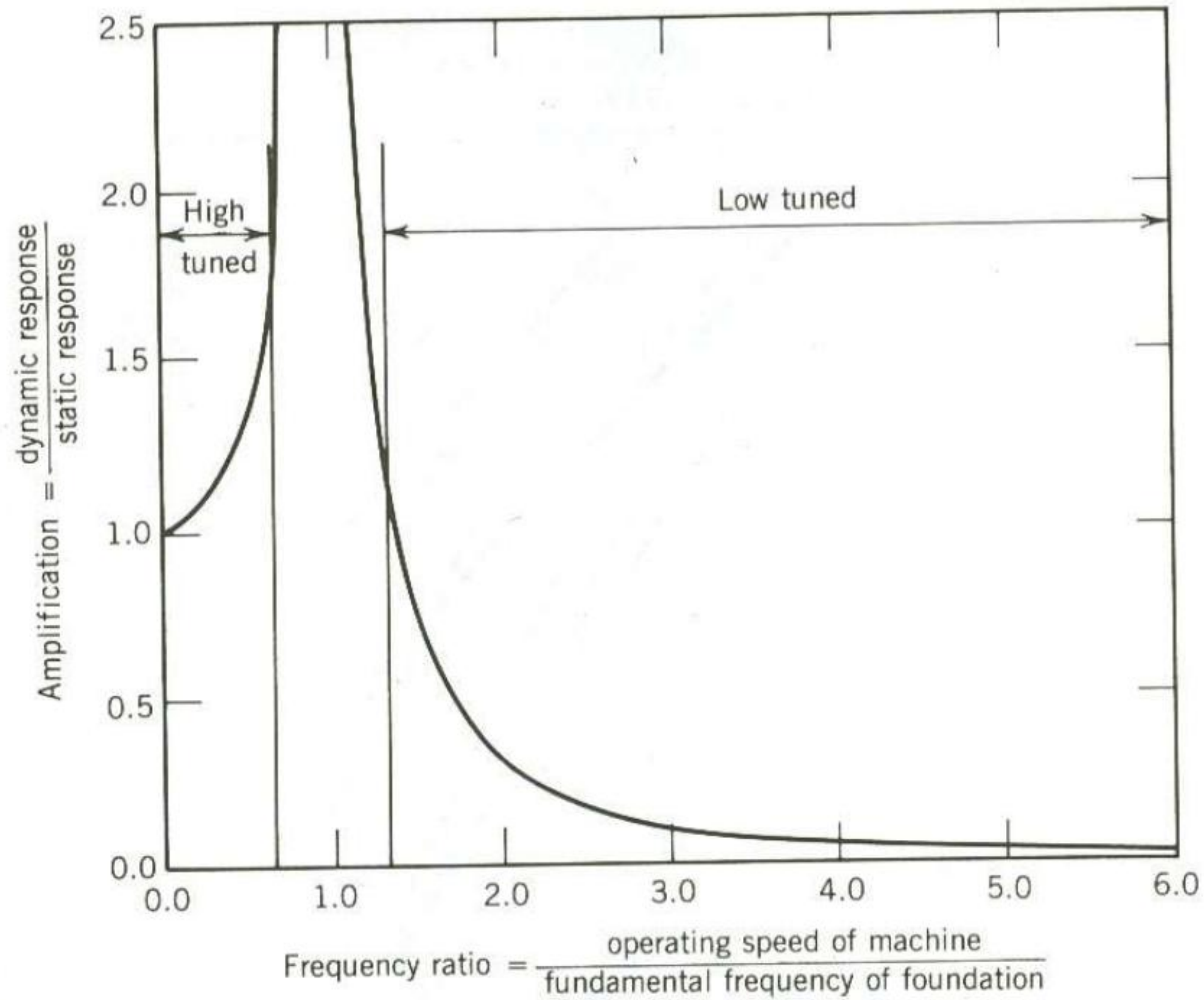


Figure2. *Tuning of a foundation*

The amplitudes of motion at operating frequencies should not exceed the limiting amplitudes, which are generally specified by machine manufacturers. If the computed amplitude is within tolerable limits, but the computed natural frequency is close to the operating frequency, it is important that this situation be avoided.

The natural frequency of the foundation –soil system should not be whole number multiple of the operating frequency of the machine to avoid resonance with the higher harmonics.

The vibrations must not be annoying to the persons working in the shops or damaging to the other precision machines. The nature of vibrations that are perceptible, annoying, or harmful depends upon the frequency of the vibrations and the amplitude of motion.

METHODS OF ANALYSIS

The analysis of machine foundation is usually performed by idealizing it as a simple System .

Figure shows a schematic sketch of a rigid concrete block resting on the ground surface and supporting a machine.

Let us assume that the operation of the machine produces a vertical unbalanced force which passes through the combined centre of gravity of the machine-foundation system.

Under this condition, the foundation will vibrate only in the vertical direction about its mean position of static equilibrium.

The vibration of the foundation results in transmission of waves through the soil.

These waves carry energy with them. This loss of energy is termed geometrical damping‟. The soil below the footing experiences cyclic deformations and absorbs some energy which is termed ‚material damping‟.

The material damping is generally small compared to the geometrical damping and may be neglected in most cases.

However, material damping may also become important in some cases of machine foundation vibrations.

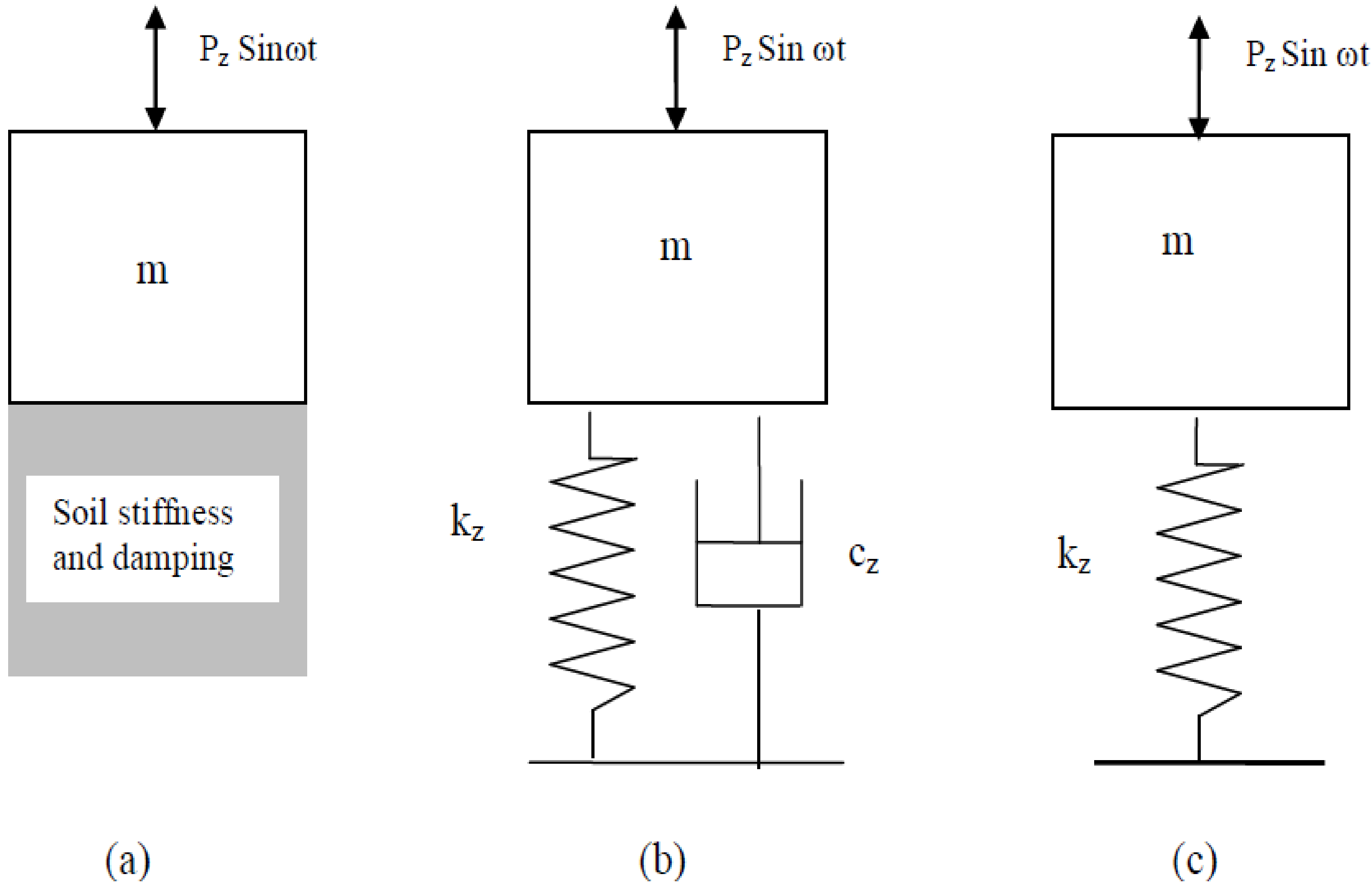
The problem of a rigid block foundation resting on the ground surface, (Fig. a) may therefore be represented in a reasonable manner by a spring-mass-dashpot system shown in Fig. b.

The spring in this figure is the equivalent soil spring which represents the elastic resistance of the soil below the base of the foundation.

The dashpot represents the energy loss or the damping effect. The mass in Fig. b is the mass of the foundation block and the machine.

If damping is neglected, a spring-mass system shown in Fig. c may be used to represent the problem defined in Fig. a.

Single degree of freedom models shown in Fig. b and c may in fact be used to represent the problem of machine foundation vibration in any mode of vibration if appropriate values of equivalent soil spring and damping constants are used. For coupled modes of vibration, as for combined rocking and sliding, two degree-of-freedom model is used.



Vertical Vibrations of a Machine Foundation (a) Actual Case (b) Equivalent model with damping (c) Model without damping

All foundations in practice are placed at a certain depth below the ground surface.

As a result of this embedment, the soil resistance to vibration develops not only below the base of the foundation but also along the embedded portion of the sides of the foundation.

Similarly the energy loss due to radiation damping will occur not only below the foundation base but also along the sides of the foundation.

The type of models shown in Fig. b and c may be used to calculate the response of embedded foundations if the equivalent soil spring and damping values are suitably modified by taking into account the behavior of the soil below the base and on the sides of the foundation.

For designing new foundations or retrofitting existing foundations for machines,

calculate the natural frequency of the machine-foundation-soil system so as to avoid resonance,

evaluate the amplitude of vibrations of the machine-foundation-soil system under operating dynamic loads and frequencies and make sure that they satisfy the acceptability criteria.

with reference to avoiding damage to machinery – it means amplitude of velocity with the limiting value prescribed by the manufacturer and in most cases, it will be governing criterion and will dictate your design.

with reference to avoiding damage to building structures- it can be either amplitude of displacement or velocity as prescribed by local codes for different types of construction, with reference to ensuring comfort of persons-it means amplitude of displacement usually prescribed by the local codes for different frequencies of operation, and

with reference to avoiding excessive settlement due to large number of cycles of load applications- it means amplitude of displacement prescribed by the local codes particularly for soil profiles consisting of loose sands and silts with high water table.

In order to calculate the natural frequency and amplitude of vibrations for a particular machine-foundation-soil-system, you need to know the local soil profile and soil characteristics as also the dynamic loads generated by the machine that are provided by the manufacturer.

1. Empirical
2. Elastic half space method
3. Linear elastic weightless spring method, and

Empirical Method

On such design guideline, rather a rule of thumb was the weight of the foundation should be at least three to five times the weight of machine being supported.

There are some empirical formulae available in literature for estimating the natural frequency, mostly for the vertical mode of vibration.

In these formulae, it is assumed that a certain part of the soil, immediately below the foundation, moves as a rigid body along with the foundation and is called *apparent soil mass* or *in-phase mass*.

For example, D.D.Barken in 1962 suggested that the mass of the vibrating soil should be between 2/3 to 3/2 times the weight of foundation and machine.

These guidelines/formulae do not take into account the nature of subsoil, type of excitation force (harmonic/impact), contact area and mode of vibration.

In using the second and third methods, we use the concept of discrete system or lumped parameter system,

In this system: the mass of the machine and the supporting foundation are lumped together as one discrete rigid mass ‘m’- this is reasonable since the stiffness of reinforced concrete and the machine is several times more than that of soil.

the soil resistance is represented by means of a spring with a constant ‘k’ ,and the energy absorption characteristic of soil is represented by means of a dashpot with a constant ‘c’.

Once we have these three quantities m, k, and c, using the theory of vibrations, the natural frequency as well as the amplitude of vibration for any given type of load can be calculated.

The formulae to calculate amplitude of vibration for either impact or cyclic type of loading can be found in books dealing with structural dynamics.

The soil behaves essentially as a linear elastic material and the resistance to deformation offered by it can be represented by a spring.

This is based on the fact that the magnitude of the dynamic force acting on the foundation is very small compared to the static load, normally no more than 10%.

And, therefore, the amplitude of displacement is extremely small. Since the non-linear behavior of the soil does not come into play, material dumping in the soil can be neglected.

In machine foundations, however, there exists another kind of damping known as *radiation damping* or *geometric damping*.

Every time a dynamically loaded foundation moves against soil, stress waves originate at the contact surface in the form of surface waves and carry away some of the energy transmitted to the soil.

This loss of energy is called radiation damping and in passing that it can be effectively modeled by a dashpot.

Use of the elastic half space method or the linear elastic weightless spring method enables us to calculate the value $\underline{k}$ and c.

number of ways or *modes* in which a machine foundation can deform.

This block foundation can deform in any one or all of six possible modes.

DEGREES OF FREEDOM OF A RIGID BLOCK FOUNDATION

A typical concrete block is regarded as rigid as compared to the soil over which it rests.

Therefore, it may be assumed that it undergoes only rigid-body displacements and rotations.

Under the action of unbalanced forces, the rigid block may thus undergo displacements and oscillations as follows

1. translation along *Z axis*
2. translation along *X axis*
3. translation along *Y axis*
4. rotation about *Z axis*
5. rotation about *X axis*
6. rotation about *Y axis*

Any rigid-body displacement of the block can be resolved into these six independent displacements. Hence, the rigid block has six degrees of freedom and six natural frequencies.

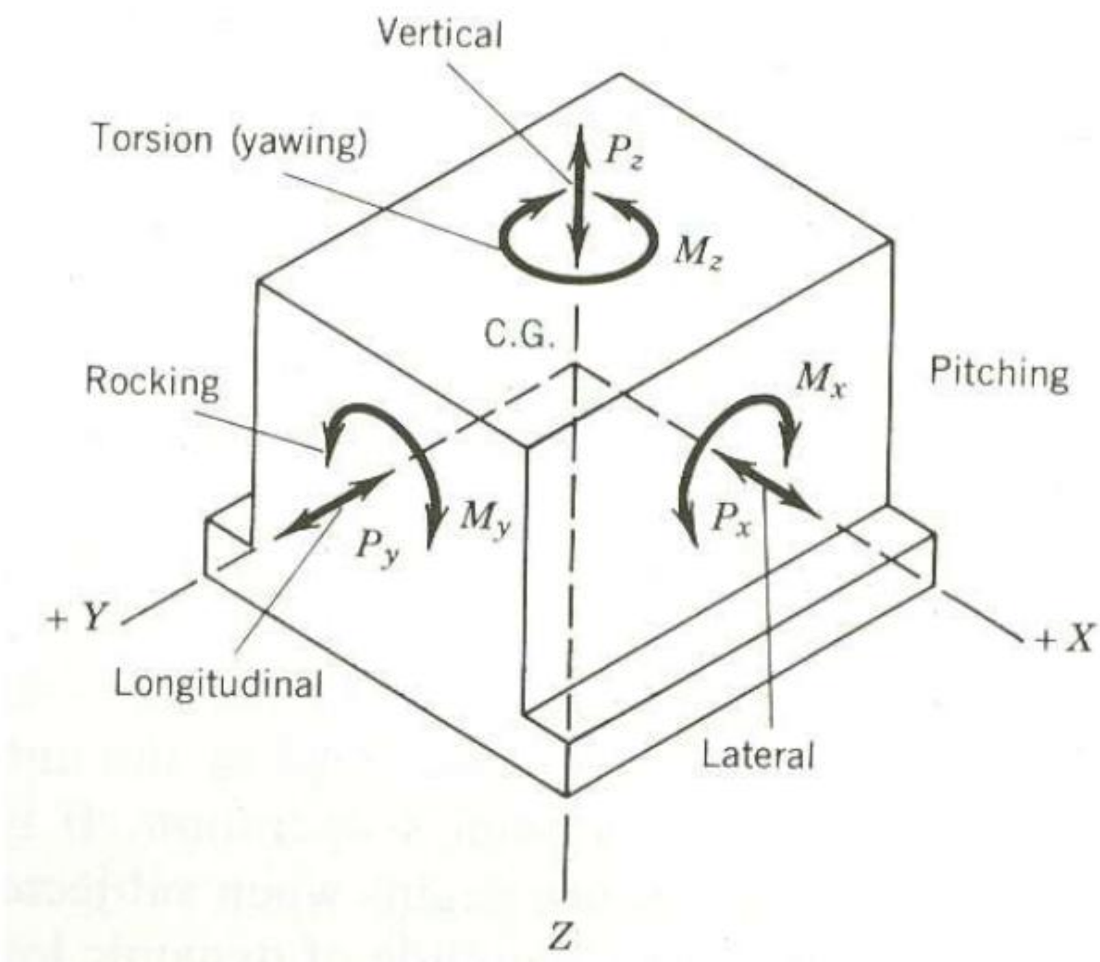
Of six types of motion, translation along the Z axis and rotation about the Z axis can occur independently of any other motion. However, translation about the X axis (or Y axis) and rotation about the Y axis (or X axis) are coupled motions..

Therefore, in the analysis of a block, we have to concern ourselves with four types of motions.

Two motions are independent and two are coupled. For determination of the natural frequencies, in coupled modes, the natural frequencies of the system in pure translation and pure rocking need to be determined.

Also, the states of stress below the block in all four modes of vibrations are quite different.

Therefore, the corresponding soil-spring constants need to be defined before any analysis of the foundations can be undertaken



Modes of Vibration of a rigid block foundation

Elastic Half Space Method

This method is called the elastic half space method because the ground is assumed to be an elastic, homogeneous, isotropic, semi-infinite body which in the Theory of Elasticity is referred to as elastic half space.

The elastic half space theory 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. These are known as the „the elastic half space analogs‟.

The machine foundation is idealized as a mechanical oscillator with a circular base resting on the surface of ground.

The Boussinesq's solution for finding the stresses induced in soil due to a point load on the ground surface.

In the elastic half space method, the point load is assumed to be dynamic. By integrating the solution for a dynamic point load over a circular area, the stresses due to a circular machine foundation is calculate.

It may be mentioned here that the equivalent soil spring and damping values depend upon the ;

(i) type of soil and its properties,

(ii) geometry and layout of the foundation, and

(iii) nature of the foundation vibrations occasioned by unbalanced dynamic loads.

Using the theory the values *k* and *c are calculated* .

Soil properties that are required to determine *k* and *c* are the shear modulus *G*, mass density ρ and Poisson's μ.

According to the theory with the vertical vibrations of a machine foundation of radius r_0 :

$$K_z = \frac{4\,Gr_0}{1-\mu}$$

$$C_z = \frac{3.4\,r_0^2}{1-\mu}\sqrt{\rho^{G}}$$

Linear Elastic Weightless Spring Method

The linear elastic weightless spring method differs from the elastic half space method in two respects:
the soil below the foundation is considered weightless – this assumption is not valid but it does not appreciably affect the computed response, and

damping in the soil below the foundation is neglected- this assumption is also not valid since radiation damping exists in a machine foundation. The effect of damping is incorporated in this method by independently estimating it using a field test.

These assumptions make it possible to represent the machine-foundation-soil-system with and equivalent mass spring system.

There is no dashpot here since damping has been neglected. In this method, the spring constant k for vertical vibrations is expressed as a function of the area of the foundation A_f and the coefficient of elastic uniform compression C_u is

$$K_z = C_u A_f$$

INFORMATION NEEDED FOR DESIGN

1. Static weight of the machine and accessories.
2. Magnitude and characteristics of dynamic loads imposed by the machine operation and their point of application
3. The soil profile of the site and dynamic soil properties such as dynamic shear modulus and damping
4. Trial dimensions of the foundation. These are generally supplied by the manufacturer. This will give the total static weight.
5. An acceptable method of analysis i.e., a mathematical model to determine the response of the foundation-soil system
6. A criteria for adequate design

SOIL PROFILE AND DYNAMIC SOIL PROPERTIES

Satisfactory design of a machine foundation needs information on soil profile, depth of different layers, physical properties of soil and ground water level.

This information can be obtained by usual sub-surface exploration techniques. In addition, one must determine dynamic shear modulus, material damping, poisons ratio and mass density of soil for dynamic analysis of the machine foundation.

Dynamic shear modulus of a soil is generally determined from laboratory or field tests.

Material damping can be determined from vibration tests on soil columns in the laboratory.

The values of dynamic shear modulii and damping may be estimated from empirical estimations for preliminary design purposes. Geometrical damping is estimated from elastic half-space theory and appropriate analogs.

Design Procedure for a Block Foundation (Reciprocating Machine-Cyclic Loading)

Obtain machine data: Operating speed of the machine; layout of the machine and a detailed loading diagram; unbalanced forces from the machine; and permissible amplitude of vibrations.
Obtain soil data: Soil properties to compute the allowable bearing capacity and spring and damping constants of the soil.

Assume a trial size of the foundation: Usually the size of the machine dictates the minimum plan size of the block. The minimum thickness of the block is dictated by the depth of embedment required from bearing capacity considerations plus any ground clearance required for operational purpose.

Evaluate the natural frequency and amplitude of vibration: First determine the natural frequency of the block of size assumed in above placed on top of soil. Then determine the amplitude of vibrations at this natural frequency subjected to unbalanced loads.

Check for resonance and whether amplitude is within acceptable limits:

If resonance is not likely to occur and the amplitude of vibrations is within the permissible limits then the trial size of the block assumed at step (ii) is acceptable. If not, change the dimensions assumed in (ii) and repeat steps (iii) and (iv) until the design requirements are satisfied. Design is almost invariably an iterative process. Trial dimensions are assumed based on experience.

Design Criteria for Foundation of Reciprocating Machine

The machine foundation should be isolated at all levels from the adjoining foundations

The natural frequency of the foundation –soil system should be higher then the highest disturbing frequency and the frequency ratio should not be less then 0.4.

The amplitude of vibration should be within the permissible limits or any specified permissible limits

For most soils, the another criterion, amplitude for low speed machines is usually taken as 200 micron (=0.2 mm)

According to another criterion, the amplitude in mm is limited to 4/f frequencies less then 30 hertz and $125/f^{2}$. For higher frequencies, where f is frequencies in hertz (cycles/sec).

Concrete block foundations should be used. However, when the soil is not suitable to support block foundation, cellular foundation may be used.

The size of the block in plan should be larger then the bed plate of the machine. There should be a minimum all round clearance of 15 mm.

The total width of the foundation measured at right angles to the shaft should be at least equal to the distance between the center of the shaft and bottom of the foundation.

The eccentricity of the foundation system along X-X and Y-Y axes should not exceed not 5% of the length of the corresponding side of the contact area.

The combined center of gravity of machine and foundation should be as much below the top of foundation.

The depth of foundation should be sufficient to provide the required bearing capacity and to ensure stability against rotation in the vertical plane.

The stresses in the soil below the foundation should not excess 80% of the allowable stresses under static loads. The base pressure is limited to half the normal allowable pressure q_{na} in extreme case.

Where it is not practicable to design a foundation to give satisfactory dynamic response, the transmitted vibrations may be reduced by providing anti – vibration mounting either between the machine and foundation or between the foundation and the supporting system.

The machine should be anchored to the foundation block using a base plate and anchor blots. Blot holes should be backfilled with concrete and the space below the plate should be filled with 1: 2 cement mortars.

A number of similar machines can be erected on individual pedestals on a common raft.

The analysis for such machines can be made assuming that each foundation acts independently up the raft into sections corresponding to separate machines.

Design Procedure for a Block Foundation (Hammer- Impact Loading)

The hammer system usually consists of a frame that guides a falling, weight, known as the *tup*, that strikes down on the *anvil* that is supported on the foundation block.

Typical tup weights range between 2.5kN and 100kN and the drop height is in the range of 0.3 m to 2 m or more.

The anvil gets repeated blows from the tup so that the piece of metal held by the anvil gests forged to a desired shape or is broken.

High impact energy is transmitted to the anvil form the falling tup. A part of the energy is used in forging and the rest gets transmitted to the soil below.

To avoid breakage of the concrete foundation due to impact stresses, an elastic pad made of felt, cork or rubber is placed between anvil and foundation block.

We have to ensure that the compressive stresses induced in the pad do not exceed the specified value. This is an additional design criteria for block foundations for a hammer.

You should note that unlike, the one degree freedom system with two springs and two masses. One mass, M_1, represents the mass of the anvil and spring. K_1, represents the stiffness of the elastic pad and the other mass, M_2 and spring k_2 represents the mass of the concrete foundation and the stiffness of soil.

In the design of these foundations, the damping in the soil is neglected since the period of impact is very small compared to the period of natural frequency of vibration of machine-foundation-soil system.

The rest of the design procedure is the same as that discussed for the block foundation for reciprocating machines.

The equations to estimate the natural frequency of the machine-foundation-soil system, vibration amplitudes of foundation and anvil and dynamic stresses in the pad are different.

Reinforcement and Construction Details

The reinforcement in the concrete block should not be less than 25kg/m^3.

For machines requiring special design considering of foundations, such as machine pumping explosive gases, the minimum reinforcement is 40 kg/m^3.

Steel reinforcement around all pits and opening shall be at least equal to 0.5 to 0.75 % of the cross sectional area of the pit or opening.

The reinforcement shall usually consist of 12 mm bars at 200 to 250 mm spacing extending both vertical and horizontally near all face of the foundation block. The ends of all bars should always be hooked.

If the height of the foundation block exceeds one metre, shrinkage reinforcement shall be placed at suitable spacing in all the three directions.

The cover should be a minimum of 75 mm at the bottom and 50 mm on sides and the top. The concrete shall be at least M-15 with a characteristic strength of 15 N/mm^2.

The foundation block should be preferably cast in a single, continuous operation. In case of very thick blocks (exceeding 5m), construction joints can be provided.

Transmission of vibration can be controlled and the detrimental effects considerably reduced by isolated either the source (active isolation) or by protecting the receiver (passive isolation)

The following measures are generally adopted.

The machine foundation should be located away from the adjoined structures. This is known as geometric isolation.

The amplitude if surface waves (R-waves) reduce with an increase in distance. A considerable reduction in the amplitude is achieved by locating the foundation at a great depth, as the R-waves also reduce considerably with an increase in depth.

Additional masses known as dampers are attached to the foundations of high frequency machines to make it a multiple degree freedom system and to change the natural frequency.

In reciprocating machines vibrations are considerably reduce by counter balancing the exciting forces by attaching counterweight to the side of the crank.

Vibration are considerably reduce by placing absorbers such as rubber mounting, felts and crock between the machine and the base .

If an auxiliary mass with a spring is attached to the machine foundation, the system becomes a two degree freedom system. The method is especially effective when the system is in resonance.

If the strength of the soil is increased by chemical or cement stabilization, it increases the nature frequency of the system. The method is useful for machines of low operating frequency.

The natural frequency of the system is modified by making structure changes in foundation, such as connecting the adjoined foundation, changing the base area or mass of foundation or use of attached slabs.

The propagation if wave can be reduced by providing sheet piles, screens or trenches.