

### Mod - III Reciprocating engine/Machines

$\Rightarrow$  Mode of vibration of a rigid foundation block

- 1) Translation along z-axis - vertical vibration
- 2) Translation along y-axis - longitudinal / sliding vibration
- 3) Translation along x-axis - lateral / sliding vibration
- 4) Rotation about z-axis - yawing motion
- 5) Rotation about y-axis - Rocking vibration
- 6) Rotation about x-axis - Pitching or rocking vibration.

$\Rightarrow$  Method of analysis

The following two methods are commonly used for analysing a machine foundation.

- (i) Linear elastic weightless spring method.
- (ii) Elastic half space method.

Linear elastic weightless spring method

- (i) vertical vibration
- (ii) Pure sliding "
- (iii) Pure rocking "
- (iv) Coupled sliding & rocking vibration.
- (v) yawing motion

$\Rightarrow$  Coefficient of elastic uniform compression ( $C_z$ ) =  $\frac{q_z}{S_e z}$

$q_z = \frac{\text{load at the base of foundation}}{\text{Base Contact area}}$

$$K_z = \frac{\text{load}}{\text{elastic deformation}} = \frac{q_z \cdot A}{S_e z} = C_z \cdot A$$

$\Rightarrow$  Coefficient of elastic uniform shear ( $C_x$ )

$$C_x = \frac{q_{nx}}{S_e x}$$

The spring constant

$$K_x = \frac{\text{Shear load}}{\text{S.e.}} = \frac{q_x \cdot A}{S_e x} = C_x \cdot A$$

$\Rightarrow$  Coefficient of elastic non-uniform compression ( $C_\phi$ )

$$C_\phi = \frac{q}{I_\phi}$$

$$K_\phi = \frac{M}{\phi} = C_\phi \cdot I$$

where,  $I$  = Moment of inertia of the base of block  
about the axis of rotation.  
 $M$  = moment caused due to soil reaction.

$\Rightarrow$  Coefficient of elastic nonuniform shear ( $C_\psi$ )

$$M_z = K_\psi \cdot C_\psi$$

$$K_\psi = C_\psi \cdot J_z$$

$J_z$  = polar moment of the inertia of  
contact base area of foundation

Barker derived the equation for determining  
the value of  $C_\psi$ .

$$C_\psi = \frac{1.13 E}{1 - 0.12 \frac{1}{\sqrt{A}}}$$

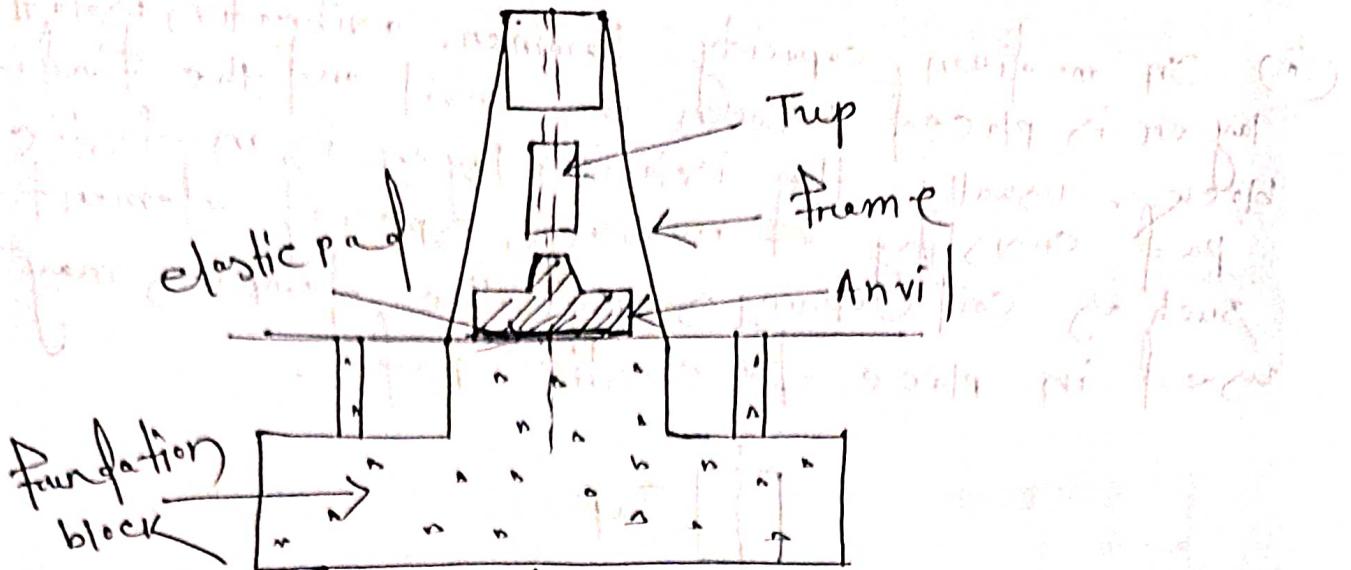
Foundations of impact type Machines

$\rightarrow$  Impact type machines produce transient dynamic  
loads of short duration.

$\rightarrow$  Hammers are most typical of impact type machines.

$\rightarrow$  Hammer foundation soil system consists of frame  
a falling weight known as tup, the anvil and  
the foundation block.

$\rightarrow$  Figure shows a typical foundation force hammer  
with its frame mounted on the anvil.  
In the below figure, a foundation force  
hammer with its frame mounted on the  
foundation is shown.



(Typical arrangement  
of a hammer foundation with  
A-frame mounted on  
foundation)

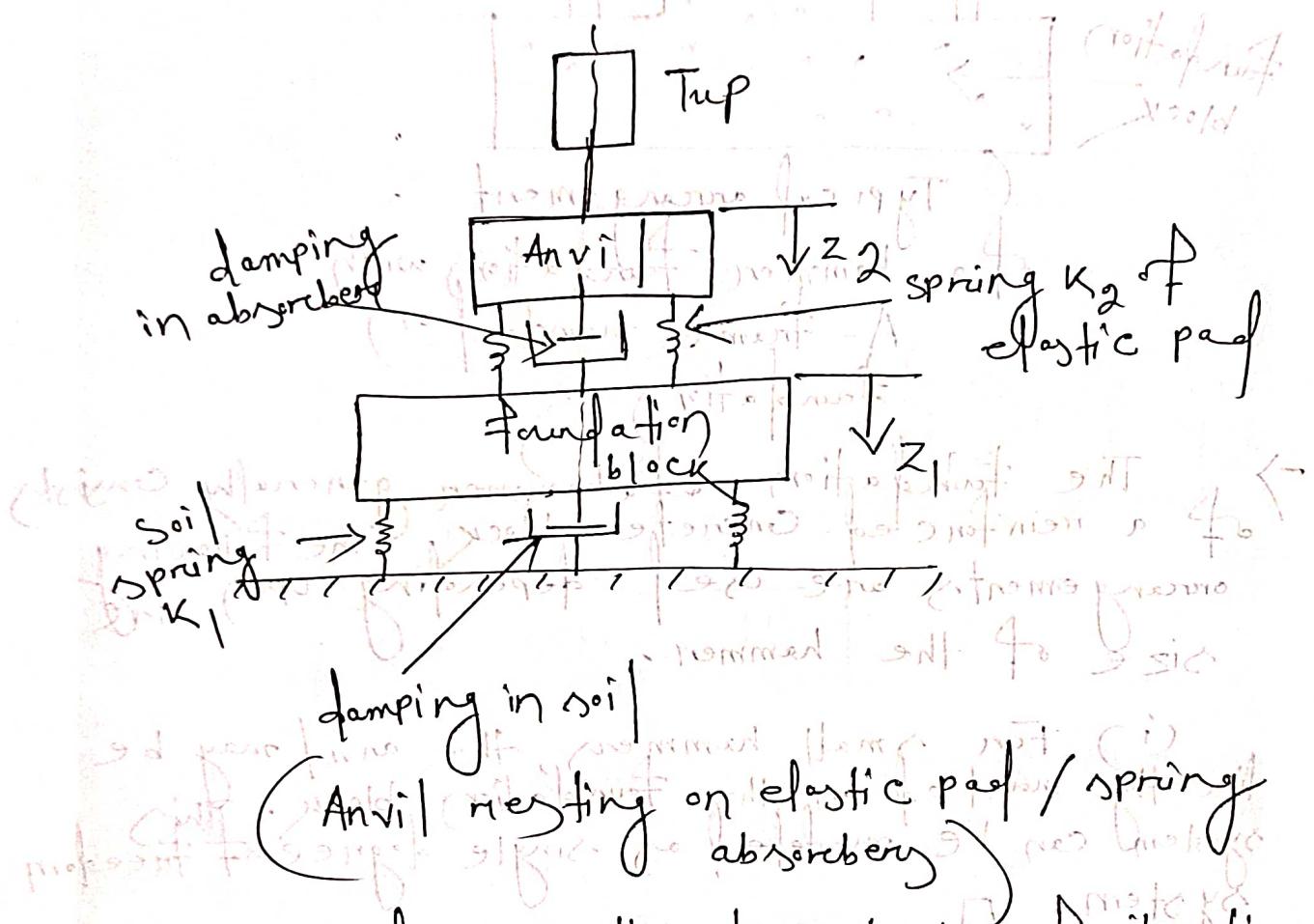
→ The foundation of a hammer generally consists of a reinforced concrete block. The following arrangements are used depending upon the size of the hammer.

(i) For small hammers, the anvil may be directly mounted on the foundation block. This system can be modeled as a single degree of freedom system.

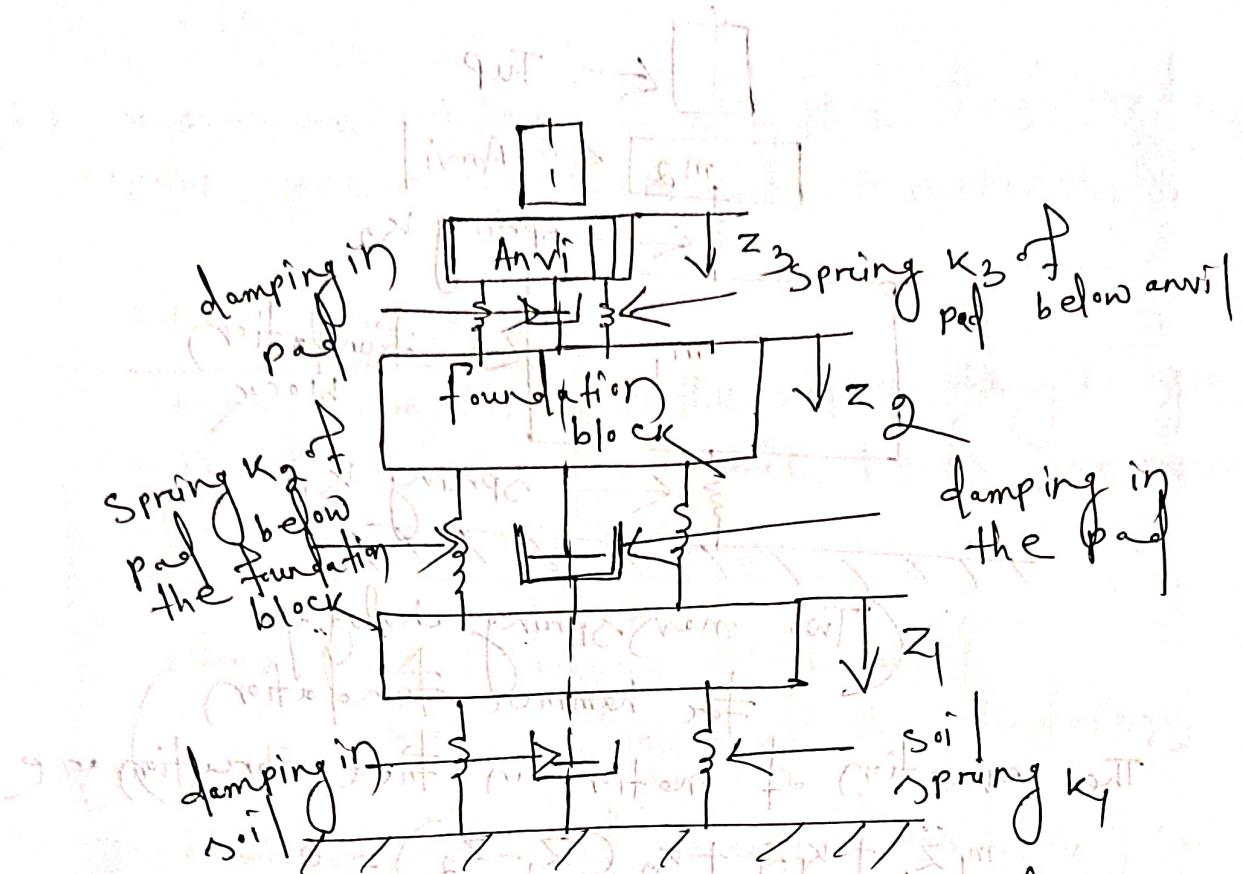


(Anvil resting directly  
on the foundation block)

(ii) In medium capacity hammers, a vibration isolator layer is placed between the anvil and the foundation block. Usually the isolation layer is an elastic pad consisting of rubber, special elements such as coil spring & the damping may be used in place of elastic pads.



(iii) For reducing the transmission of vibration to the adjoining machinery or structures, the foundation block may also be supported on elastic pads or on spring absorbers. In such a case the foundation is placed in a reinforced concrete trough. The space between the foundation block and side of trough is filled up with some soft material (or air gap) is left.



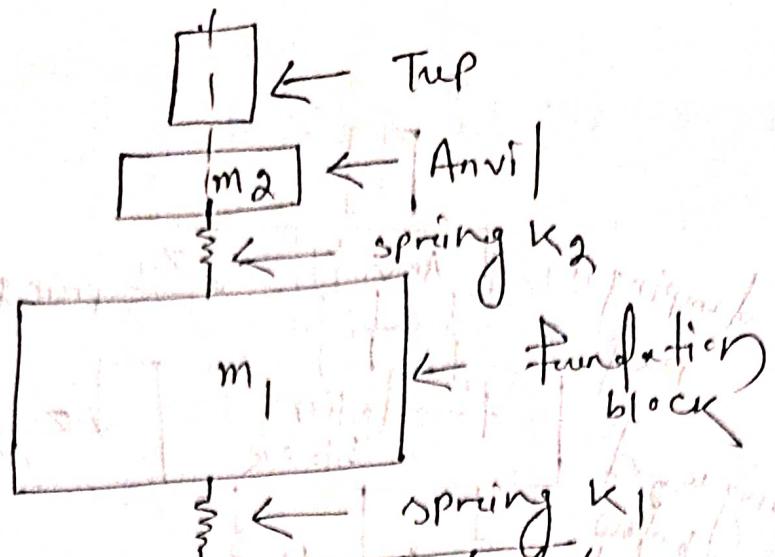
(Foundation block on elastic pad/spring absorbing with R.C trough)

$\Rightarrow$  Dynamic analysis

Two degree freedom system

Assumptions

- 1) The anvil, foundation block, frame and top are rigid bodies.
- 2) The pad and the soil can be simulated by equivalent weightless elastic springs.
- 3) The damping of the elastic pad and soil is neglected.
- 4) embedment effects are neglected.
- 5) The time of impact is short compared to the period of natural vibration of the system.



(Two mass spring system for hammer foundation)

The equation of motion in free vibration are

$$m_1 \ddot{z}_1 + k_1 z_1 + k_2 (z_1 - z_2) = 0$$

$$m_2 \ddot{z}_2 + k_2 (z_2 - z_1) = 0$$

where  $z_1 = A \sin \omega_n t$  — 1

$$z_2 = B \sin \omega_n t$$
 — 2

$$\frac{B}{A} = \frac{k_2 + k_1 - m_2 \omega_n^2}{m_1 \omega_n^2}$$
 — 3

$$\frac{B}{A} = \frac{k_2}{k_2 - m_2 \omega_n^2}$$
 — 4

$\omega_{n1}$  = circular natural frequency of the foundation  
of the anvil on the pad.

$$= \sqrt{\frac{k_2}{m_2}}$$

$\omega_{nl}$  = Limiting natural frequency of the foundation  
and anvil on soil.

$$= \sqrt{\frac{k_1}{m_1 + m_2}}$$

$$\text{Im} = \frac{m_2}{m_1}$$

Q.) Discuss the principle of design of foundation for impact type machine with clear illustrations.

$\Rightarrow$  Stress in the soil

Stress transmitted to the soil through the combined static and dynamic loads are expressed by.

$$\sigma = \frac{W_a + W_f + Z_{am} K_2}{A}$$

where,  $W_a$  = weight of the anvil

$W_f$  = weight of the foundation

$\Rightarrow$  Determination of initial velocity of anvil, ( $V_a$ ) :-

For a single acting drop hammer the initial velocity of the tup  $V_{Ti}$  at the time of impact is given by

$$V_{Ti} = \eta \sqrt{2gh}$$

where,  $h$  = drop of tup in meters

$g$  = Acceleration due to gravity,  $m/s^2$

$\eta$  = efficiency of drop

$$V_{Ti} = \eta \sqrt{\frac{2gh(C_{WT} + P_{AC})}{w_T}}$$

According to Newton's law, the coefficient of restitution,  $e$  is given by

$e = \frac{\text{Relative velocity after impact}}{\text{Relative velocity before impact}}$

$$e = \frac{V_a - V_{Tq}}{V_{Ti}}$$

→ The value of  $\rho$  depends upon the material of the bodies involved in impact.

$$V_a = \frac{1+\rho}{1 + \frac{w_a}{w_T}} V_{Ti}$$

For single degree of freedom system,

$$V_{af} = \frac{1+\rho}{1 + \frac{w_a + w_f}{w_T}} V_{Ti}$$

where,  $w_f$  = weight of the foundation plug

$V_{af}$  = velocity of anvil plug foundation after impact.

⇒ Design procedure for hammer foundation :-

→ The design of a hammer foundation may be carried out in following steps:-

#### Machine data

- (i) Type and weight of striking part of hammer.
- (ii) Dimension of base area of anvil and its weight.
- (iii) Maximum stroke or fall of hammer, mean effective pressure on piston and effective area of piston.
- (iv) Arrangement and size of anchor bolts.
- (v) Permissible amplitudes of the anvil motion and the foundation on block. If this information is not available, the amplitudes of motion given may be considered as limiting values.

$\Rightarrow$  Soil data  
 The following information about the sub-surface soil should be known.

$\rightarrow$  Soil profile. For drop hammer of upto 10kN capacity, soil investigation should generally be done to a depth of 6m. For heavier impact machines it is preferable to investigate soil conditioning to a depth of 12m or to a hard stratum. If piles are used the investigation should be conducted to a suitable depth.

$\rightarrow$  The relative position of the water table below the ground at different time of the year.

$\rightarrow$  Soil investigation to ascertain allowable soil pressure and to determine the dynamic properties of the soil specifically the value of  $C_u$ .

Natural Frequency

$$\omega_{n_a} = \sqrt{\frac{K_2}{m}}$$

$$\omega_{n_d} = \sqrt{\frac{K_1}{m + m_2}}$$

in which  $K_2 = \frac{E}{b} A_2$

where,  $E$  = Young's modulus of soil material

$b$  = thickness of the pad

$A_2$  = Area of the pad

$$K_1 = C_u A = \lambda C_u A$$

- In impact type machinery like forging hammer, punch presser and stamping machinery which produce impact loads. Forge hammers are divided into two groups drop hammer for die stamping and forge-hammer property.
- These machines consists of falling ram, an anvil and a frame.
- The speed of operation usually ranges from 50 to 150 blows per minute. The dynamic loads attain a peak in a very short interval and then practically die out.

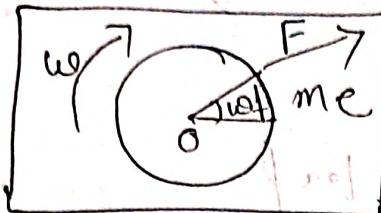
## Rotary type Machinery & Code of provisions

- These machine include high speed machinery such as turbogenerators, turbines and rotary-compressors which operate at frequencies of the order of 3000 rpm to 10000 rpm.
- Associated with these machinery there may be a considerable amount of auxiliary equipment such as condensers, coolers and pumps with connecting pipework and ducting.
- To accommodate these auxiliary equipments a common foundation arrangement by a two-storey frame structure with the turbine located on the upper slab and the auxiliary equipment placed beneath, the upper slab being flush with the floor level of machine hall.
- Rotary machinery is balanced before erection.

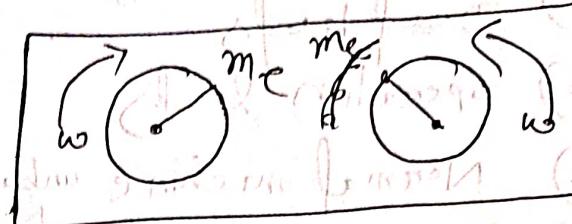
The unbalanced forces produced by such a system in vertical & horizontal directions are.

$$F_V = m_e e \omega^2 \sin \omega t$$

$$F_H = m_e e \omega^2 \cos \omega t$$



(single shaft)



(double shaft)

→ In rotary machinery (IS: 2974 Pt III - 1992)

$$0.8 > \frac{w}{w_{n\min}} > 1.25$$

In impact machinery (IS: 2974 Pt II - 1980)

$$0.4 > \frac{w}{w_{n\min}} > 1.5$$

In reciprocating machine (IS: 2974 Pt I - 1982)

$$\text{For impact machinery } 0.5 > \frac{w}{w_{n\min}} > 2.0$$

$$\text{For ordinary machine } 0.6 > \frac{w}{w_{n\min}} > 1.5$$

→ Frame foundations are commonly used for turbo generators because of following reasons.

- 1) Auxiliary equipment can be arranged more conveniently.
- 2) More economical due to saving in material and freedom to add more members to stiffen if needed.

→ Very liable to cracking due to settlement of  
temp. changes.

→ The inspection of and access to all parts of  
the machine become more convenient.

### Loads on a turbogenerator foundation

- 1) Dead loads
- 2) operation loads
- 3) Normal machine unbalanced load
- 4) Short circuit forces
- 5) Temperature loads in the foundation
- 6) seismic load
- 7) Construction loads.

### Methods of analysis and design

#### 1) Two dimensional analysis

1) Resonance method

2) Amplitude method

3) Combined method

#### 2) Three dimensional method

→ In resonance method, the frame foundation  
is idealized as single degree freedom system  
and consideration is given only to natural  
frequencies of the system to the operating  
speed of the machine. The amplitudes of  
vibration are not considered in this  
method.

## Rotary type Machine

Speed -  $3000 \text{ rpm}$  -  
 $10000 \text{ rpm}$

Hammer  $\rightarrow$  Impact type

Turbogenerator  $\rightarrow$

### Frame Foundation

#### Regions

- 1)
- 2)
- 3)
- 4)

Auxiliary equipment

Freedom to add more member

less cracking due to settlement & temperature changes.

Foots of machine become more convenient.

#### Design criteria

- 1) The amplitude of vibration should be within the permissible limits.
- 2) The natural frequencies of foundation system should preferably be at a variance of at least 30% from the operating speed.

$\Rightarrow$  Resonance is avoided

$\Rightarrow$  10-20% may be assumed in

Special Computed natural frequency.

$\rightarrow$  Soil profile & characteristics of soil upto at least 3 times the width of the turbine foundation.

## loads

- Dead loads
- operation load
- Normal machine unbalanced load
- Construction loads
- short circuit loads.
- seismic loads.
- Temperature loads in the foundation.
- Loss of blade unbalance (one) bearing failure load

## Dead loads

self wt. of machine +

self wt. of foundation.

## operation loads

→ Supplied by the manufacturer

Frictional forces

Power torque.

Thermal elongation forces

Facuum in Condenser.

Piping forces.

$$P_c = A (P_a - P_c)$$

Condenser

Vacuum

area

Atmospheric

pressure

vacuum

pressure

$T_A, T_B, T_C, T_g$

Depend on magnitude  
of torque.

Unit - kNm

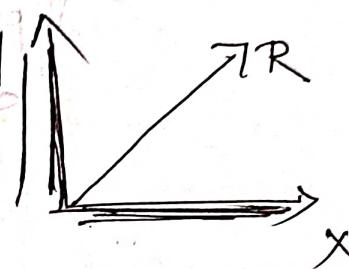
$$M = m_e e \omega^2 l$$

Resultant moment

↓  
operational speed  
of power output

Mass of centre of  
gravity of forces.

The components of the  
moment 'M' in vertical  
and horizontal directions  
are given by



$$\{ M_V = m_e e \omega^2 l \sin \omega t$$

$$\{ M_H = m_e e \omega^2 l \cos \omega t$$

The unbalance force is given by

$$F = g m_e e \omega^2$$

Temp. heady

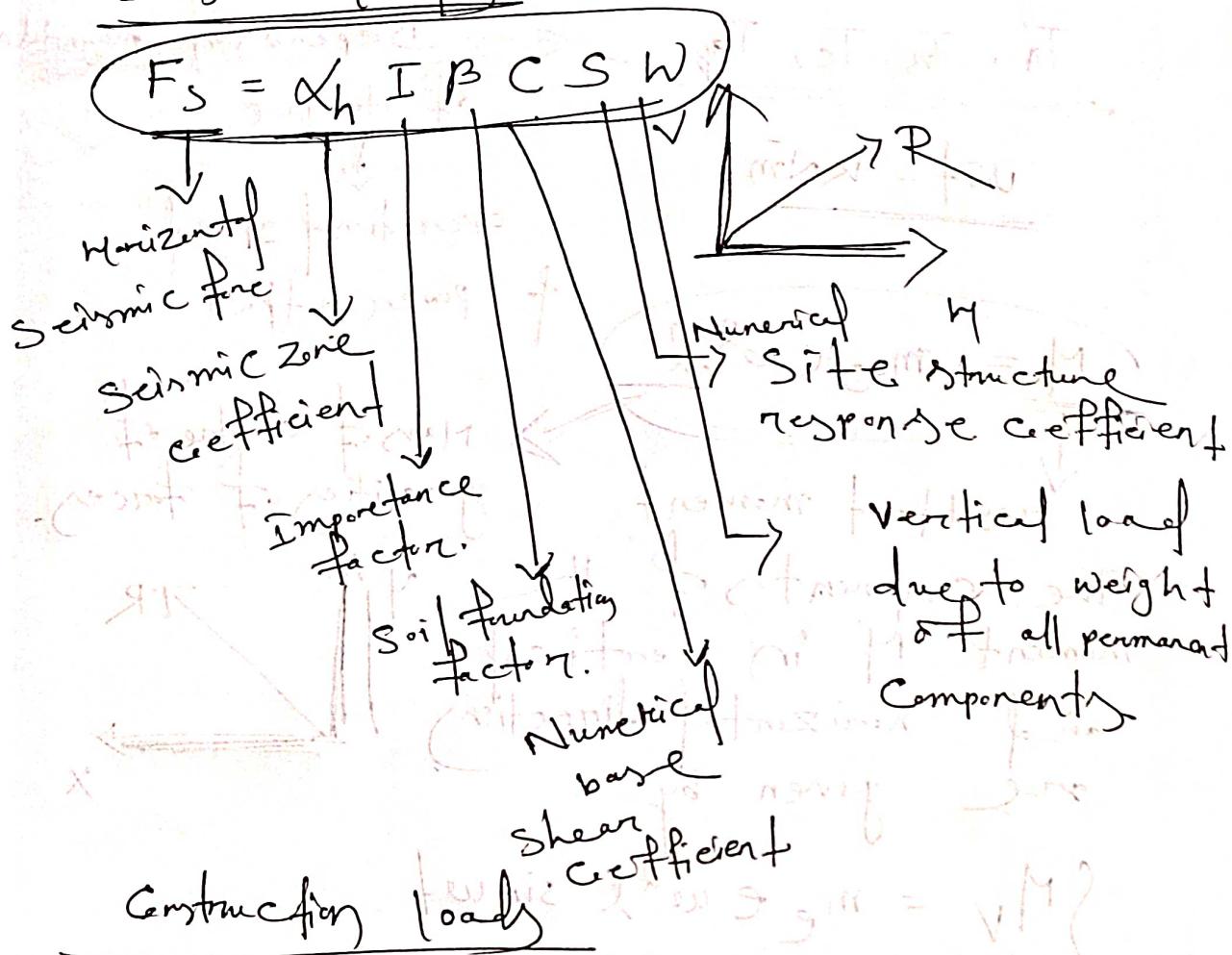
$\rightarrow 10^\circ C \text{ to } 15^\circ C$  may be assumed.

$$M_{sc} = 10 \pi \frac{W_r}{R} \text{ kNm}$$

Capacity of T.G

Radius  
of the  
rectangle.

## Seismic load



a) operation Condition :-  $OP + DL + NUL + TLF$

b) Short circuit Condition :-  $DL + OL + NUL + TLF$  SCF

c) Leans of blade Condition / bearing-failure condition :-  $DL + OP + TLF + (LBL/BFL)$

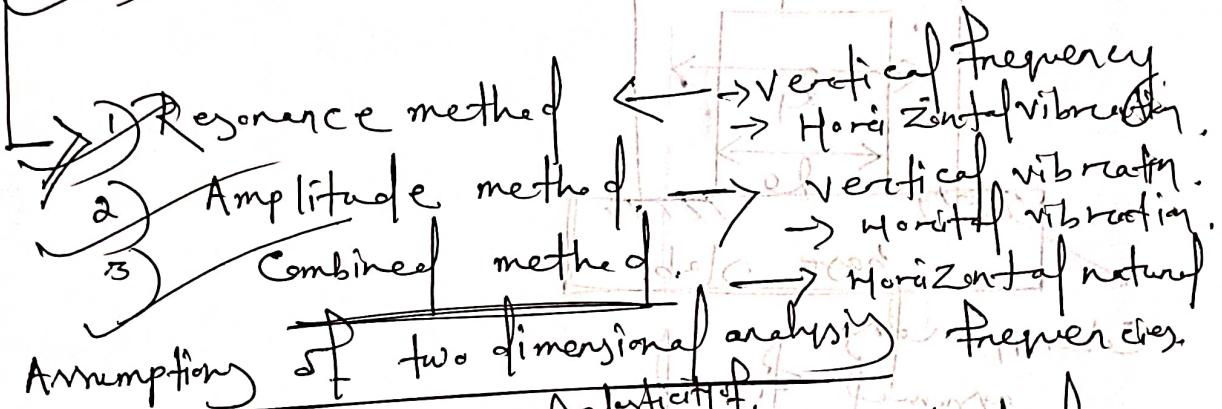
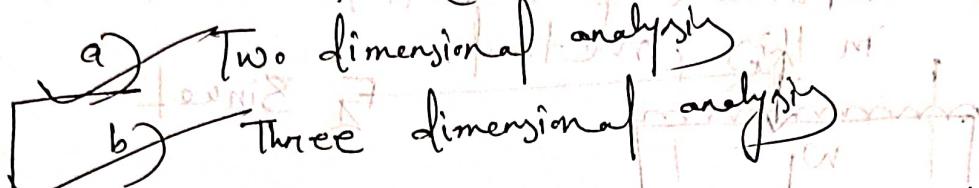
d) seismic condition :-

$DL + OL + NUL + TLF + EQL$

earthquake load / seismic load

## Methods of analysis & design

→ To check the frequencies & amplitudes of vibration for design the members of frame.



Assumption of two dimensional analysis

→ The effect of ~~elasticity of~~ subsoil is neglected.

→ The effect of flexible

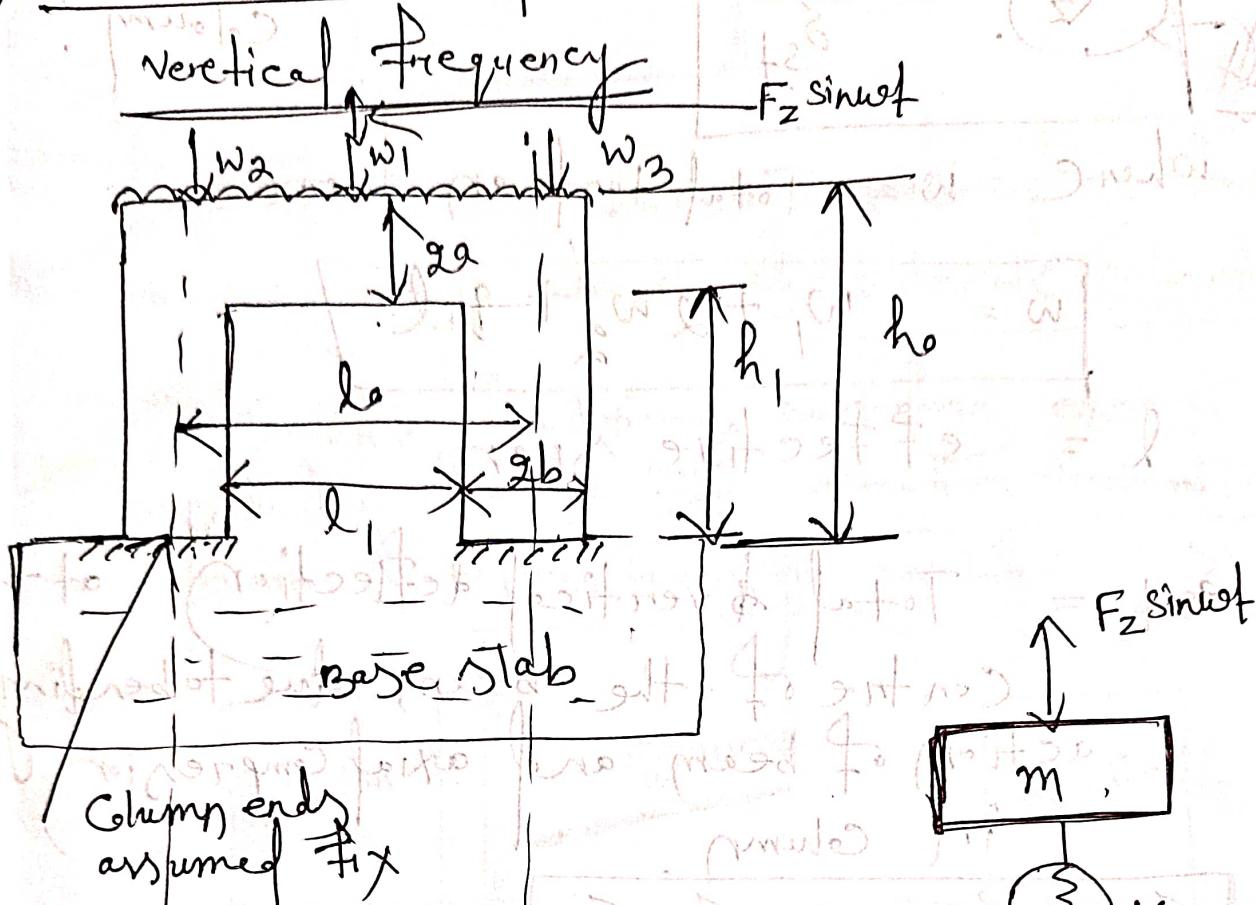
→ when considering the horizontal displacement the upper slab is regarded as a rigid plate.

→ ~~The vertical vibration of the frame~~ can be determined for each frame individually.

→ The deformation of the longitudinal & transverse beam is almost identical.

→ Both the columns and beam can be replaced by weightless elements.

## Resonance method



(Typical transverse frame)

The loads acting on this frame are

i) dead load of the machine & bearing

ii) Load transferred to the column by longitudinal beam

iii) UDL due to self weight of cross beam,  $q$  per unit length.

$$m = ql + w_1 + 2w_2$$

(Idealised model)

(iv) Unbalanced vertical force due to machine operation,  $F_z \sin \omega t$

Mass-spring system

$$\text{equivalent spring constant} \quad K_z = \frac{w}{\delta_{st}}$$

→ Combined stiffness of beam & Column.

where  $w = \text{Total load on frame}$ .

$$w = w_1 + 2w_2 + q \cdot l$$

$l$  = effective span.

$\delta_{st}$  = Total vertical deflection at the centre of the beam due to bending action of beam and axial compression in column.

$$\delta_{st} = \delta_1 + \delta_2 + \delta_3 + \delta_y$$

where,  $\delta_1$  = vertical deflection of beam due to load  $w_1$ .

$\delta_2$  = vertical deflection of beam due to the distributed load  $q$ .

$\delta_3$  = vertical deflection of the beam due to shear.

$\delta_4$  = Axial compression Column.