Soil Dynamics
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Lecture 47
Analysis of Machine Foundations (For Rotary Machines- Part I)

Hello everyone, today we will start our new topic in the course soil dynamics, where we will discuss the analysis of rotary machines foundation; that means this foundation will support rotary machines.

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So, typical example of rotary machine is turbogenerator. Generally, for this we use frame foundation; and this frame foundation is consisted of a column or series of columns, longitudinal and transverse beams. A frame foundation can accommodate the auxiliary equipment like you can say condensers, then heat exchanger, then pipelines, air vents et-cetera for turbogenerator. Because, just if we will construct a foundation for the turbogenerator that is not enough, we have to provide space, we have to accommodate these auxiliary components of the turbogenerators.

A frame Foundation provides convenient access to all parts of the machines as well. Generally, cracking due to settlement and temperature changes is a less likely event for frame foundation. This type of foundation that means frame foundation reduces the cost of construction by saving the material cost. Also, it provides freedom to add more members to stiffen if it is required.

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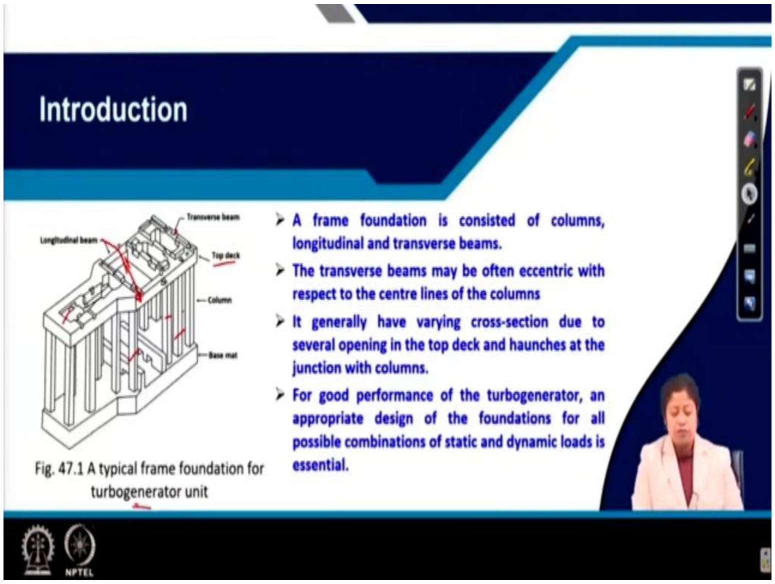

Now, in this figure, you can see a typical frame foundation which can be used for turbogenerator you need. So, what are the different components that we need to see here? You can see base mat which supports these columns, a series of columns you can see here; this is also columns, this is also columns. Now, the columns supports top deck, and it will be better to say columns supports transverse and longitudinal beams on which these top deck is resting.

So, as I said, a frame foundation is consisted of columns that you can say see here, then longitudinal and transverse beam. So, these are longitudinal beams, this one is also longitudinal beams and transverse beam which you can see here, and also this one.

The transverse beams may be often eccentric with respect to the center lines of the columns. It generally have varying cross-section due to several openings in that top deck and hunches at the junction with columns. For good performance of the turbogenerator and appropriate design of the foundations for all possible combinations of load static and dynamic loads is essential. We will see what are the different combinations of loading.

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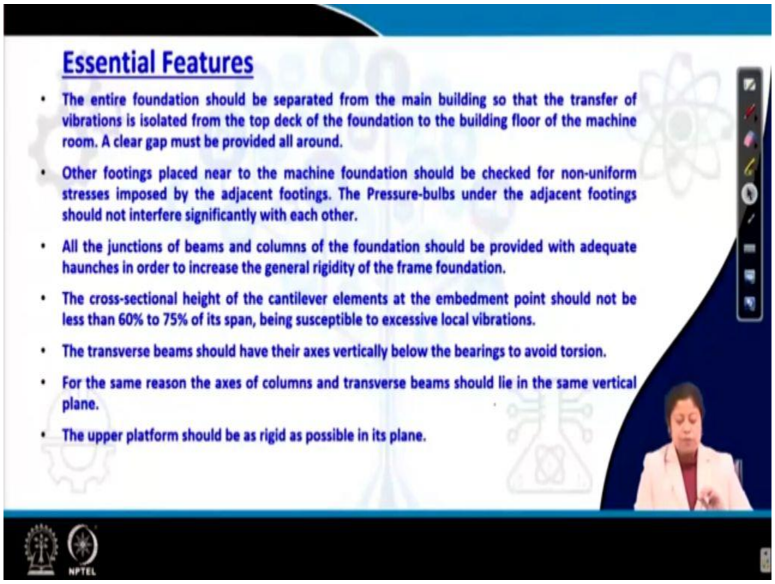

But, before that we will discuss few essential features. So, the first feature is the entire foundation should be separated from the beam building, so that the transfer of the vibrations is isolated from the top deck of the foundation to the building floor of the machine or machine room.

Now, you need to ensure a clear gap also all around the foundation frame. We have already discussed that when we were discussing the machine foundation for reciprocating machine that, if we will provide air gap that will act as vibration isolation. So, in this case also we need to ensure a clear gap.

Now, other footings which are placed near to the machine foundation should be checked for non-uniform stress imposed by the adjusting footings. The pressure-bulbs under the adjacent footings should not interfere significantly with each other. All the junctions of the beams and columns of the foundation should be provided with adequate hunches in order to increase the general rigidity of the frame foundation. Now, the cross-sectional height of the cantilever elements at the embedment point should not be less than 60 to 70 percent of its span, being susceptible to excessive local vibrations.

The transverse beams should have their axes vertically below the bearings to avoid torsion. For the same reason, the axis of columns and transverse beams should lie in the same vertical plane. The upper platform should be as rigid as possible in its plane.

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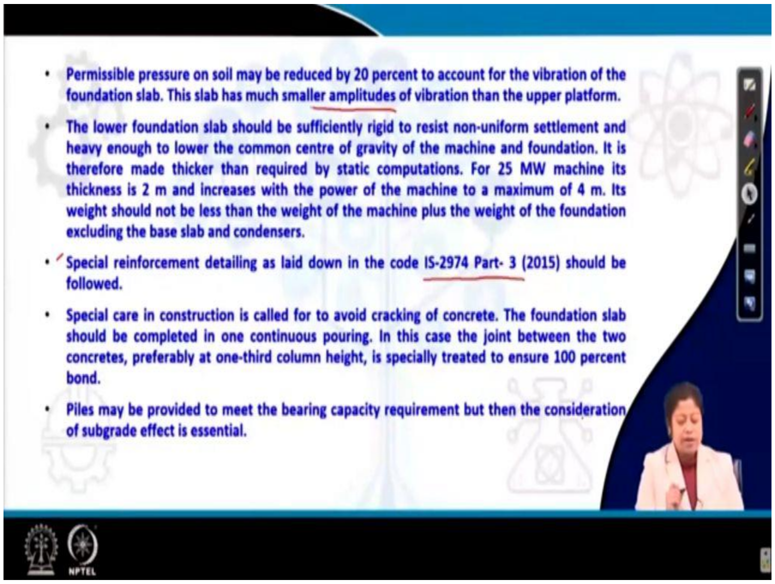

Now, the permissible pressure on soil may be reduced by 20% percent to account for the vibration of the foundation slab. This slab has much smaller amplitude of vibration than the upper platform. The lower foundation slab should be sufficiently rigid to resist non-uniform settlement and heavy enough to the lower, sorry and heavy enough to lower the common center of gravity of the machine and foundation.

It is therefore made thicker than required by static computations. There are some other features among which we need to take care of this one. Special reinforcement detailing as laid down in the code IS-2974 Part-3 published in 2015 should be followed.

Now, special care in construction is called to is called for to avoid cracking of concrete. The foundation slab should be completed in one continuous pouring. In this case the joint between the two concretes preferably at one-third column height, is specifically treated to ensure special care in construction is called for to avoid cracking of concrete. We may need to provide piles to meet the bearing capacity requirement. If we see that the bearing capacity requirement is not fulfilled by the frame foundation alone, then we need to use pile also. And in that case, the consideration of subgrade effect is essential.

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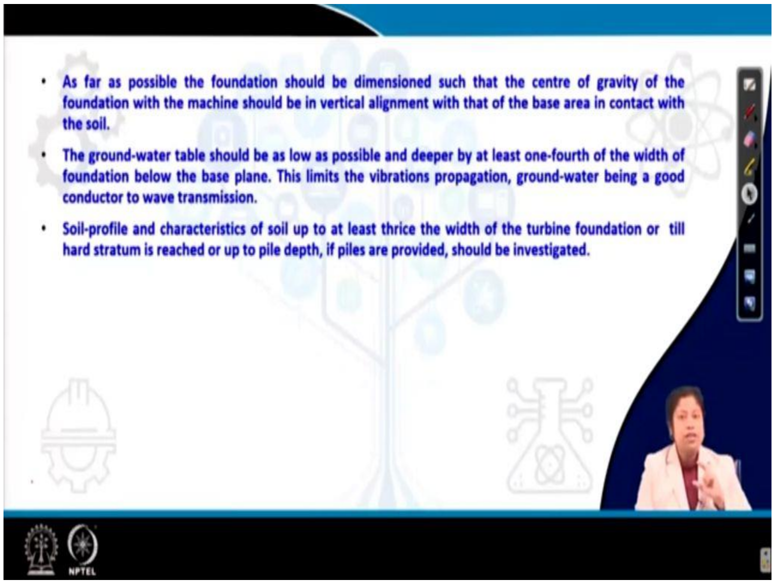

As far as possible, the foundation should be dimensioned such that the center of gravity of the foundation with the machine should be in the vertical alignment with that of the base area in contact to the soil. The groundwater table should be as low as possible and deeper at least one-fourth of the width of the foundation below the base plane.

So, if the width is suppose 4 meter, then we need to ensure that the ground, the distance between the foundation base and the groundwater table should be one-fourth of 4 meter that we need. The groundwater table should be as low as possible and deeper by at least one-fourth of the width of foundation below the base plane.

These limits, the vibrations propagation, groundwater table being a good conductor to wave transmission. That is the reason we need to ensure these minimum gap of one-fourth of the width the width of the foundation. So, what does it mean basically? It means suppose the width of the foundation is 4 meter, then the distance from the distance of the groundwater table from the base of the foundation should be at least 1 meter.

Now, soil-profile and characteristics of soil up to at least thrice the width of the turbine foundation or till hard stratum is reached, or up to pile depth if piles are used, should be investigated. So, soil investigation is another essential feature.

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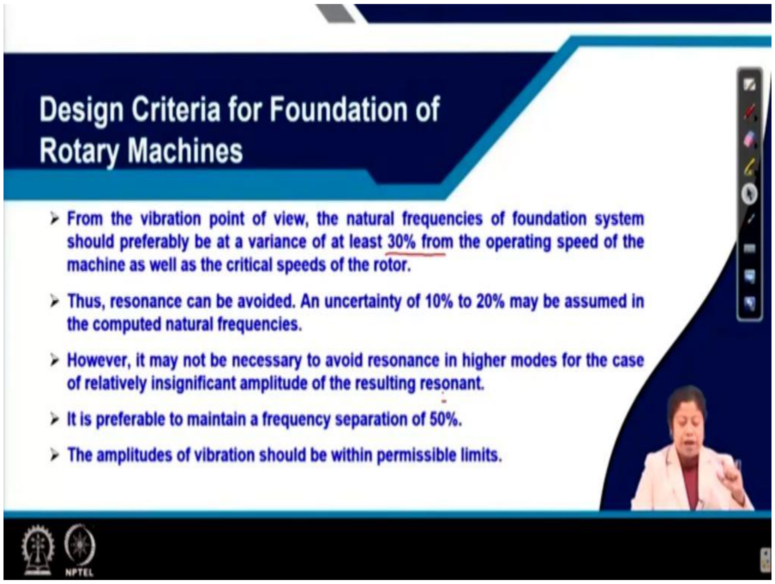

Now, let us see the design criteria for foundation of rotary machines. From the vibration point of view, the natural frequencies of foundation system should preferably be at a variance of at least 30 percent from the operating speed of the machines as well as the critical speeds of the rotor.

So, the resonance can be avoided. And uncertainty of 10 to 20 percent may be assumed in the computed natural frequencies; so, we need to consider also some extent of uncertainties. However, it may not be necessary to avoid resonance in higher modes for the case of relatively insignificant amplitude of resulting resonant. It is preferably, it is preferable to maintain a frequency; it is preferable to maintain a frequency separation of 50 percent.

The amplitudes of vibration should be within permissible limits. So, if you recall in the first class of analysis of machine foundation, we have discussed a few design criteria where the permissible limits of for the vibration was discussed. So, the amplitude of vibration permissible amplitude if I say, for vertical vibration I can write on the board.

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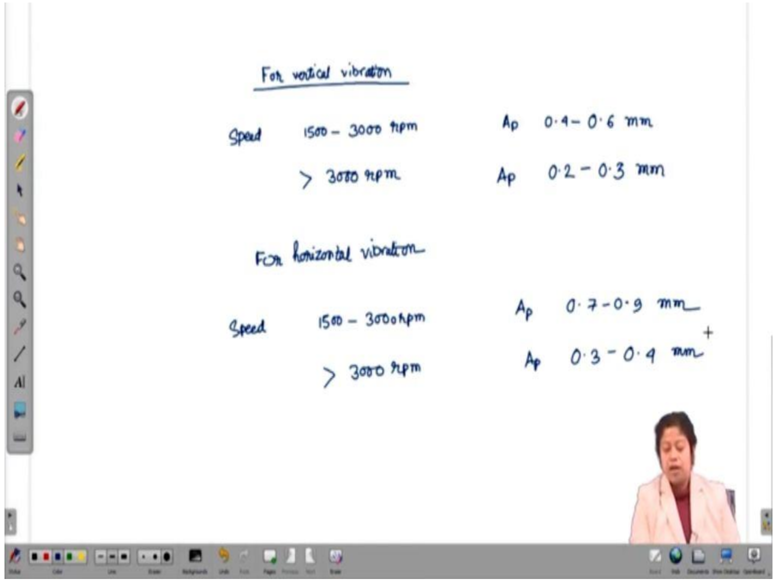

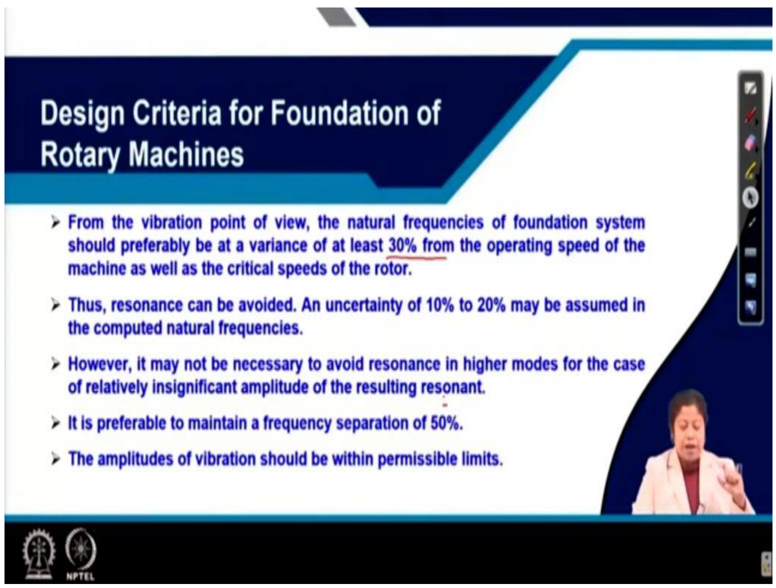

So, for vertical vibration if I will write, for vertical vibration if the motor speed is in between 1500 to 3000; that means one point, sorry that means 1500 to 3000 RPM; then, the permissible amplitude varies from 0.4 to 0.6 in millimeter. Now, if the speed is more than 3000 RPM, that time permissible amplitude which is represented by Ap varies from 0.2 to 0.3 in millimeter. Likewise, we need to check the same for horizontal vibration. So, the permissible values we need to check when the speed is between 1500 to 3000 rpm; this permissible amplitude may vary from 0.7 to 0.9 millimeter.

If speed is more than 3000 rpm, then permissible amplitude varies from 0.3 to 0.4 millimeter; or we can take it 0.4 to 0.5 also, depending upon some kind of adjustment. So, the amplitudes of vibration should be within the same permissible limits.

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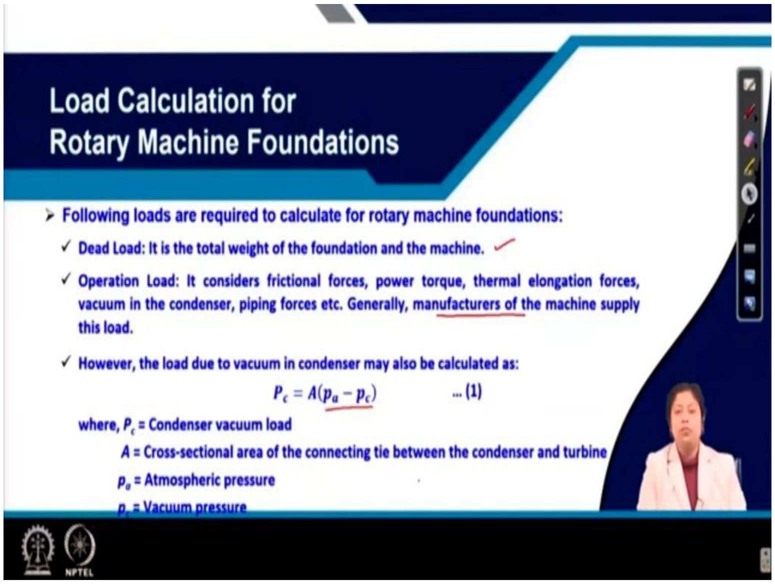

Now, how do we do the load calculation? For load calculation for rotary machine foundations, we need to consider four combinations of loading. So, before knowing all these four combinations of loading, first we need to know what are the different loads. First one dead load; it is the total weight of the foundation and the machine together.

Next is operation load, which considers frictional forces, power torque, thermal elongation forces, vacuum in the condenser, piping forces et-cetera. Generally, manufacturers of the machines supply this load. However, the load due to vacuum in condenser may also be calculated as load Pc is equal to A times pa minus pc, small pa and small pc within the bracket.

So, what is A here? What is pa and pc? So, A is the cross sectional area of the connecting time between the condenser and the turbine; whereas, pa is the condenser vacuum load. Sorry, pc is the condenser vacuum load, small pa is the pressure at atmospheric level, or we can call it as atmospheric pressure; whereas pc is the vacuum pressure. So, if we know the vacuum pressure from that we can calculate the condenser vacuum load using equation-1.

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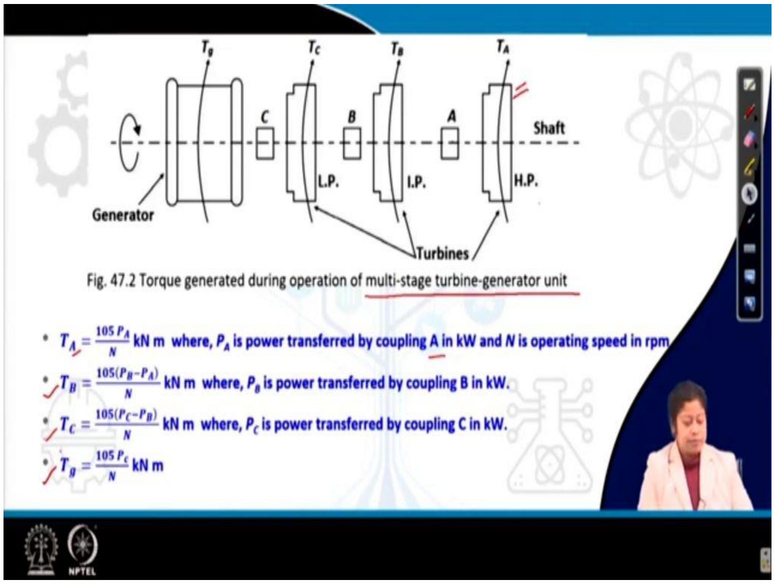

Now, in this figure, you can see the torque generated during operation of a multi-stage turbine generator unit. So, here using the expansion given, we can find out the torque generated at different stages of the turbine generator unit. So, TA can be calculated if we know PA which is the power transferred by the coupling A in kilo watt; and capital N which represents the speed of the operating speed in rpm. Likewise, we can calculate TB, TC and Tg in kilo newton meter, if we know the power transferred by coupling B and C as well.

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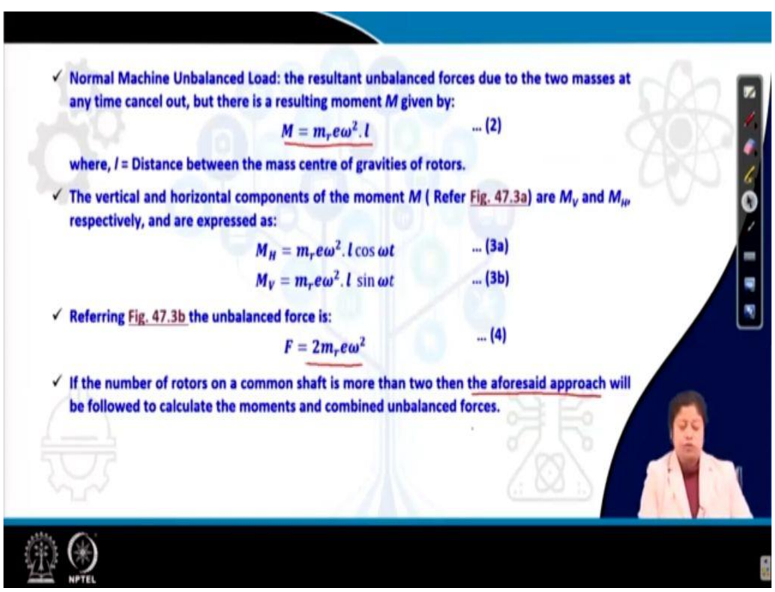

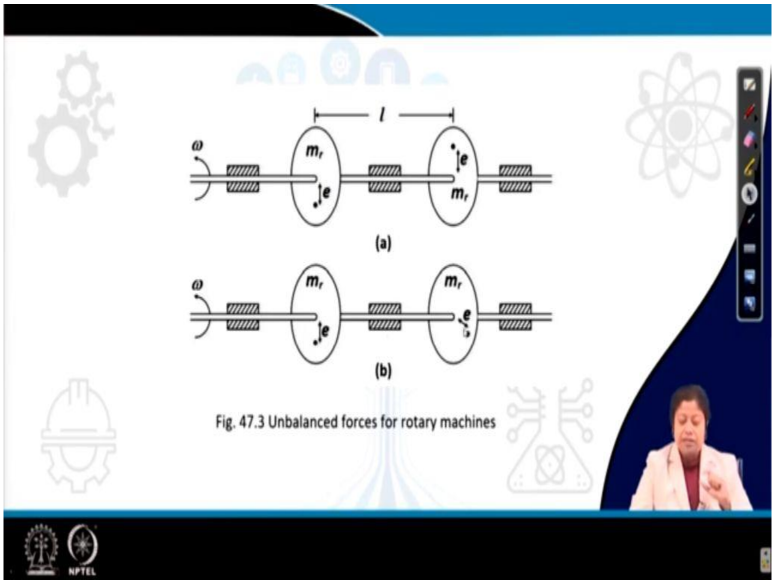

Next load is normal machine unbalanced load. The resultant unbalanced forces due to the two masses at any time can be canceled out. However, the resulting moment should always be there and how do we calculate that? So, we can calculate the resulting moment in using this equation, M is equal to mr times e times omega square times l. So, what is l here? l is the distance between the mass center of gravity's of rotors; the vertical and horizontal components of the movement M, if we consider vertical component as capital MV and horizontal component at capital as capital MH respectively.

Then, we can express MV and MH as, MH means mr times e omega square times m cosine omega t. Likewise, MV means mr times e omega square times l times sine omega t. Here let us see the figure. So, this is mass rotating mass mr; it maintains an eccentricity e from the axis of the shaft; and you can see the operating speed is omega in this case.

So, now, next is the calculation of the unbalanced force for position b. So, here if we need to calculate the unbalanced force, what will be that unbalanced force is equal to you can see here; it is 2 times mr times e omega square. Already we know what is mr, what is e and what is omega; so I am not repeating that.

If the number of rotors of on a common shaft is more than two, then that aforesaid approach that means, whatever written in equation 2 to 4 will be followed to calculate the moments and combined unbalanced forces.

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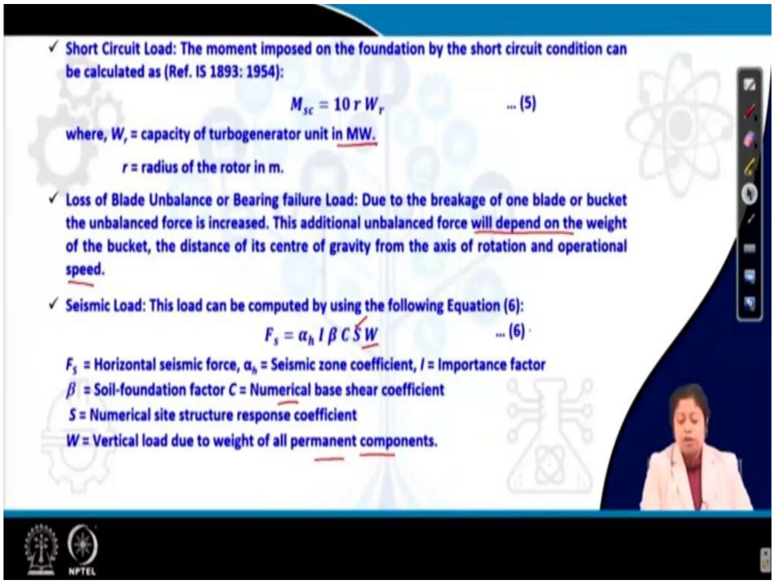

Next load is short circuit load. The moment imposed on the foundation by the short circuit condition can be calculated using IS code 198; sorry using IS code 1893 published in 1954. So, what it is said? Moment due to short circuit condition is equal to 10 times of r, times Wr. So, here Wr is the capacity of the turbogenerator in megawatt, r is the radius of the rotor in meter. So, if we know that capacity of the turbogenerator unit and if we do the radius of the rotor, from that we can calculate the magnitude of the moment that is imposed on the foundation due to short circuit condition.

Next, load is due to loss of blade unbalance or bearing failure load. So, due to the breakage of one blade or bucket the unbalanced force is increased. This additional unbalanced force depends upon the weight of the bucket; the distance of its CG from the axis of rotation and operational speed. So, these additional unbalanced force as I said, it depends upon it is just a repetition of the previous line.

Next, so, next is seismic load; this load can be computed by using the equation shown here. So, you can see seismic force Fs is equal to alpha times h, times I, times beta, times C, times S, times W. So, we need to know what are the meaning of these symbols which I read just now.

So, next load is seismic load. So, seismic load can be computed by using the equation-6, this one. So, what it is saying? Fs which is representing the seismic load is equal to alpha h times I, times beta, times C, times S, times capital W. So, we need to note here what are the meanings of these different symbols? Fs already we know; this is the seismic load. Now, alpha h is seismic zone coefficient; so, it depends upon the seismic zone. I is an importance factor, so it may also vary; beta is soil-foundation factor, whereas, C is numerical base shear coefficient.

Capital S is numerical site structure response coefficient, and W is vertical load due to the weight of all the permanent components. So, depending upon the total vertical load because of the permanent components, and also considering the site soil-foundation factor and other factors; we can calculate the seismic load using equation-6.

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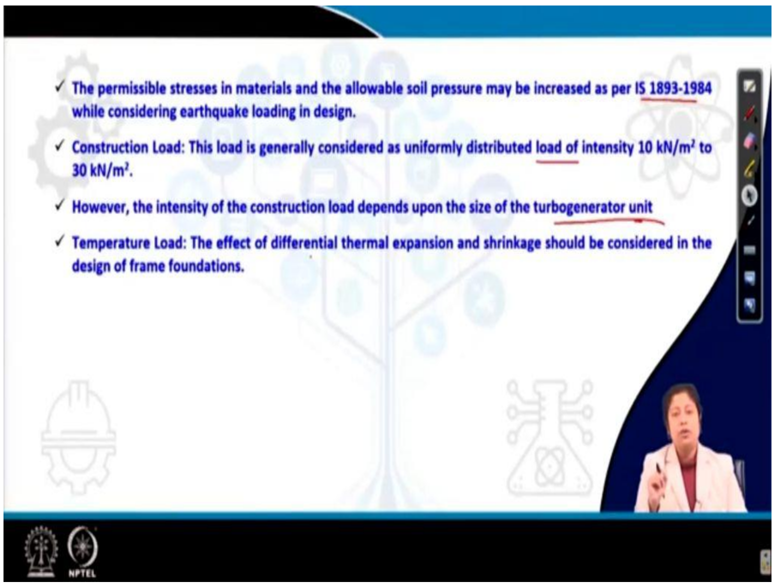

Now, the in presence of seismic load what is happening? The permissible stresses in materials and the allowable soil pressure may be increased as recommended in IS 1893, while considering earthquake loading in design; so, we need to take care of this point as well.

Now, construction load: this load is generally considered as uniformly distributed load of intensity 10 kilo Newton per square meters to 30 kilo Newton per square meter. However, the intensity of the construction load depends upon the size of the turbogenerator unit. So, the effect of differential thermal expansion and shrinkage should be considered while designing the frame foundations. So, we need to consider temperature load as well.

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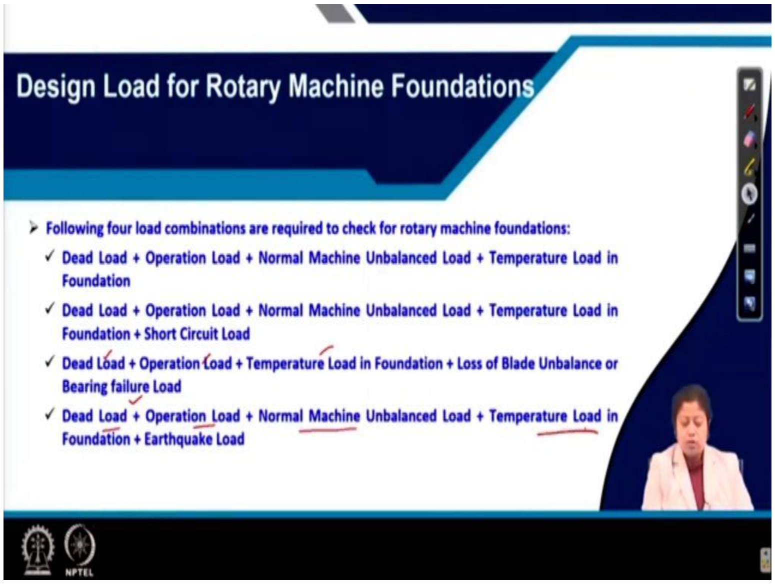

Now, how to calculate the design load for rotary machine foundations? So, we need to consider four load combinations which are state, which I will now show you. So, the first one is the combination of dead load, operation load, normal machine unbalanced load, and temperature load together. So, how many loads we are considering here? 4 different loads are considered in first case; let us see the second case. Here we are considering five cases, five loads. What are those five loads? Dead load, operation load, normal machine unbalanced load, temperature load and short circuit load as well.

In third case, we also consider the four different loads; these loads are dead load, operation load, temperature load in foundation, loss of blade unbalance or bearing failure load. So, third case considers four different loads. Now, the fourth case which considers five different which consider five different loads, dead load, then operation load, normal machine unbalanced load, then temperature load, and earthquake load.

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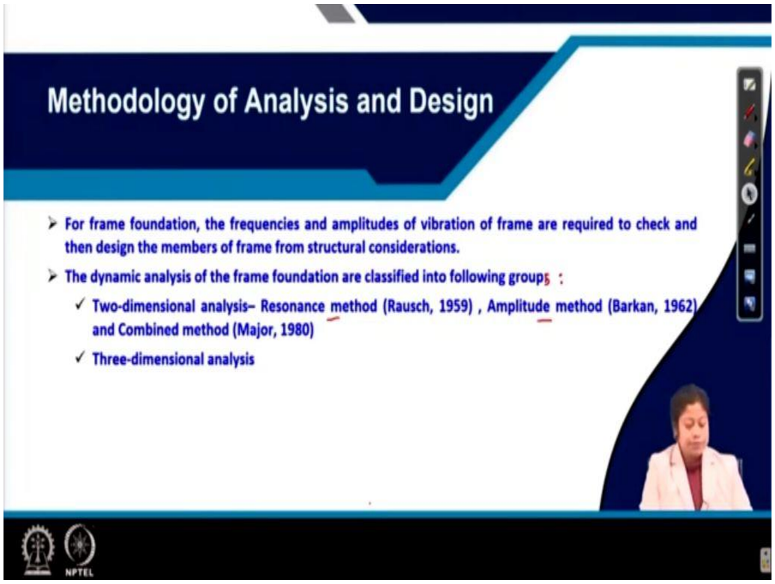

Now, considering all these four load combinations, our next target is to learn the methodology of analysis and design of machine foundation. So, for frame foundation, the frequencies and amplitudes of vibration of frame are required to check, and then the design the members of the frame from structural considerations.

sThe dynamic analysis of the frame or frame foundation can be classified into following groups; it should be groups. What are the different groups? We can do two-dimensional analysis; under two dimensional analysis, there are three different methods. First one you can see resonance method, second one amplitude method, and third one is the combined method. Another one is three-dimensional analysis.

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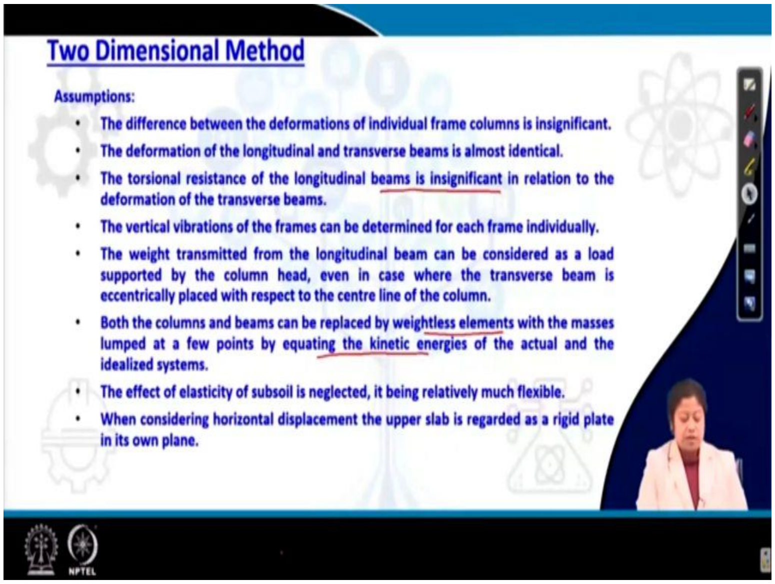

So, we will study two-dimensional analysis or two dimensional method. So, before studying that, we need to know what are the assumptions based on which this analysis will be carried out. So, here you can see the different assumptions, I am reading it for you. The difference between the deformations of individual frame column is in significant; that means we are not considering any kind of differential settlement in this case. The deformation of the longitudinal and transverse beams is almost identical. The torsional resistance of the longitudinal beams is insignificant in relation to the deformation of the transverse beams.

The vertical vibrations of the frames can be determined for each frame individually. The weight time transmitted from the longitudinal beam can be considered as a load supported by the column head, even in case where the transverse beam is eccentrically placed with respect to the centerline of the column.

Both the column and the beams can be replaced by weightless elements with the masses lumped at a few points, by equating the kinetic energies of the actual and idealized system. The effect of elasticity of subsoil is neglected; it being relatively much flexible. Another assumption is that when considering horizontal displacement, the upper slab is regarded as a rigid plate in its own plane.

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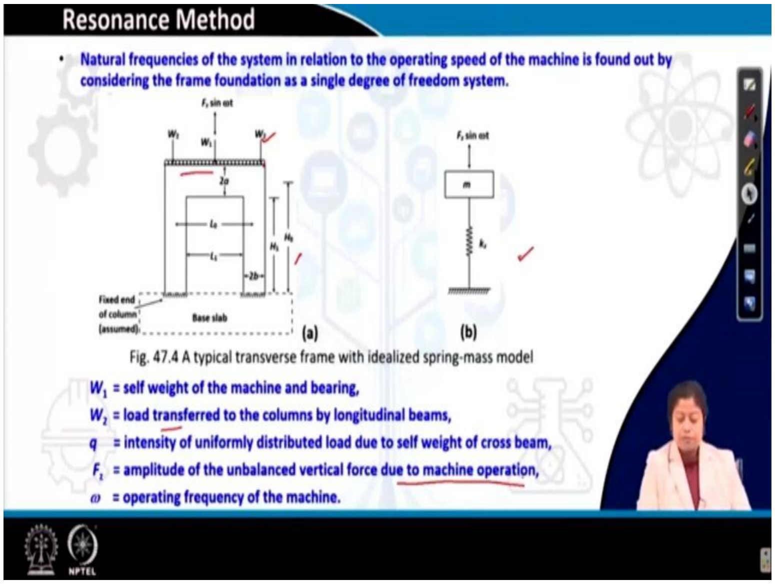

So, now we will study how to do the two-dimensional analysis. Already I told there are three methods; first one resonance method, second one amplitude method, and the third one is the combined method proposed by major.

So, first we will learn resonance method. In this method, natural frequencies of the system in relation to the operating speed of the machine is found out by considering the frame foundation as a single degree of freedom system. I am repeating in this method, natural frequencies of the system in relation to the operating speed of the machine is found out by considering the frame foundation as a single degree of freedom system.

Here you can see a typical transverse frame in Figure a; and that is mathematically represented by mass-spring model in figure b. So, what are the different components we can see in figure a transverse beam? So, on transverse beam you can see different loads are acting; so, we need to know what are these different loads.

So, you can see here W1 is the self weight of the machine and the bearing; whereas, W2 this is the load which transfer to the columns by the longitudinal beam. So, longitudinal beam means beam in this direction. So, I am just erasing what I have drawn just now.

So, W2 as I say is the weight of the transverse beam; sorry weight of the longitudinal beam which is transferred to the column this one and this one. Now, q is the intensity of uniformly distributed load due to self weight of this cross beam. Next is Fz, it is the amplitude; you can see here Fz sin omega t is the unbalanced force. So, Fz is the amplitude of the unbalanced vertical force due to machine operation; and omega is the operating speed of the machine.

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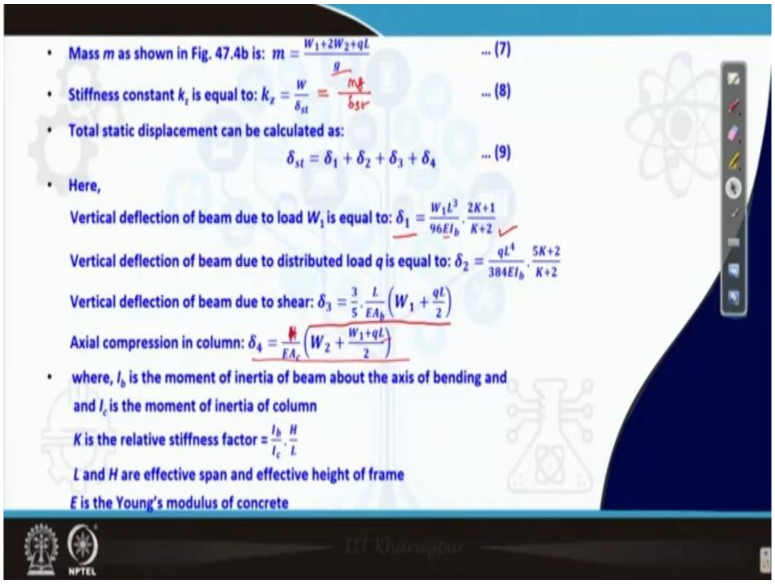

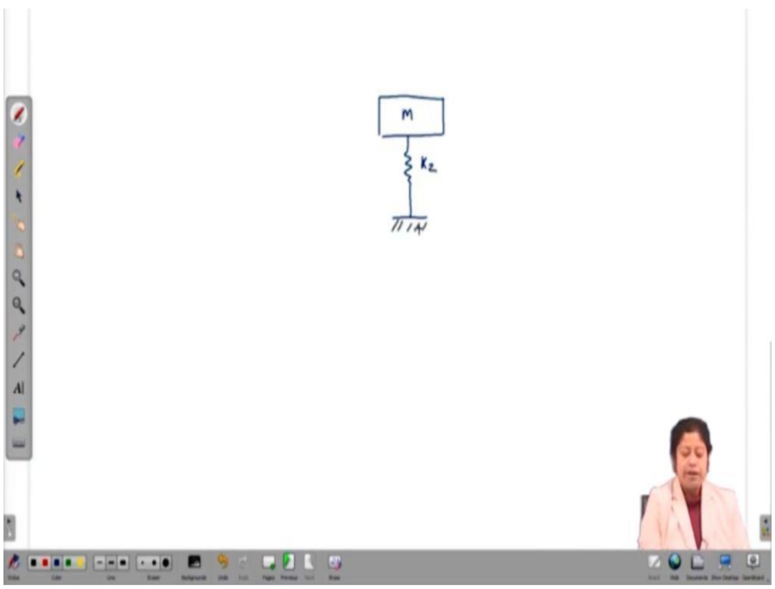

Now, what is mass here? Mass means I am just we have seen that the system can be represented by a mass-spring system. So, mass-spring system means we have a mass here which is M and that is connected to a spring Kz in this case.

Now, what is in the M then? M is W1 plus 2 times of W2 plus q L divided by g. From this we can calculate stiffness constant Kz. So, Kz is equal to capital W divided by delta st; what is capital W here? Capital W means m times g. So, I can also write here as m times g divided by delta is st. Now, what is delta is st here? Total static displacement is delta is st; and that can be calculated by some of delta1, delta2, delta3 and delta4.

Now, the question what are delta1, delta2, delta3 and delta4? So, let us see here. Vertical deflection of beam due to load W1 is equal to delta1; and that can be calculated by this equation. Next is delta2, which is the vertical deflection of the beam due to the distributed load of intensity small q; and delta2 can be calculated using this equation. Delta3 is the vertical deflection of the beam due to shear. So, here you can see the expression that we can use to calculate delta3. Next is to find out the axial compression in column which is written here as delta4.

So, delta4 is equal to h divided by E times Ac, whole thing is multiplied with the W2 plus W1 plus q l divided by 2; where you can see the meaning of different parameters. So, here we have used Ib which is Ib, that is written the moment of inertia of beam about the axis of bending. In this equation, what new term we have seen? We have used H; let us write it capital H, it is not small h. So, capital H is the effective height of the frame whereas, capital L here this is the effective span of the frame.

And you can see we have used E, what is E? E is the Young's modulus of the concrete, which is used for the construction of the frame. And Ac is the cross sectional area of the column. So, let us give the number of these three equations.

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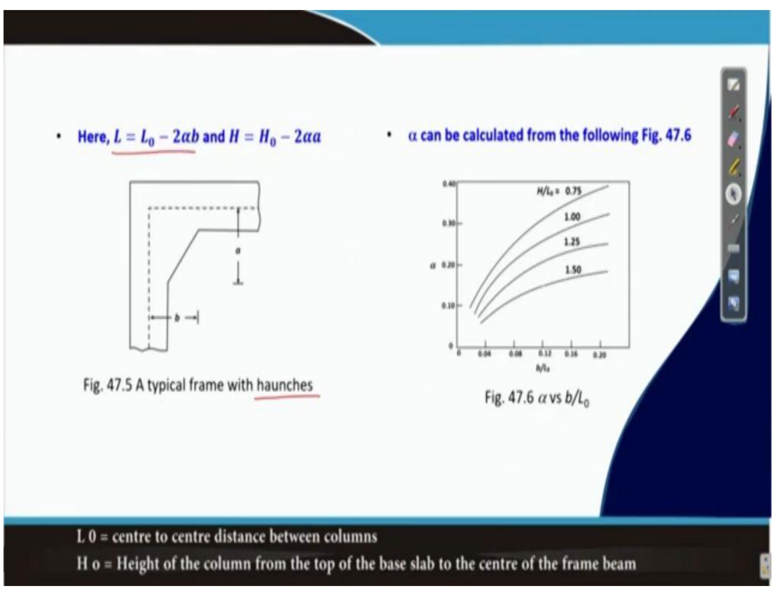

In figure 47.5, what you can see? Here you can see typical frame with hunches. Now, if there is no hunch, then we can just take L and H, which represents which represent the effective length and effective height of the frame. However, if haunches are present, that time how do we calculate L that is shown here. L is equal to L0 minus 2 times of alpha b.

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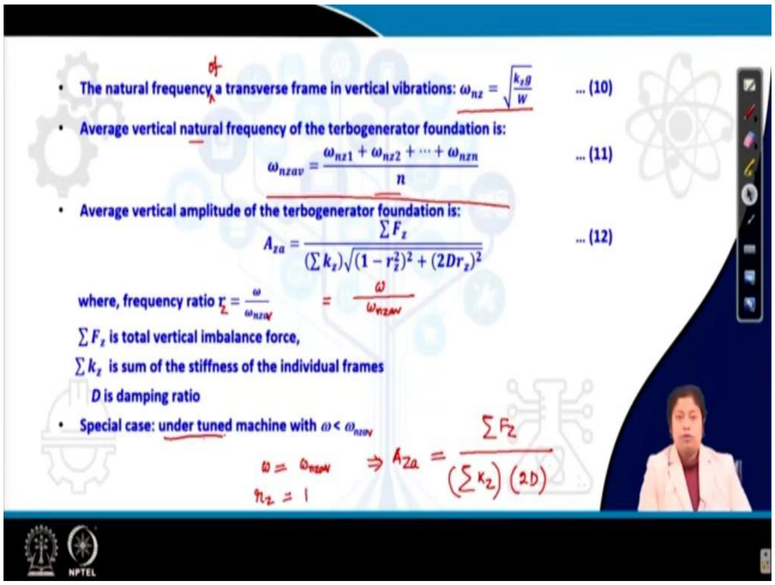

So, if we are able to calculate the mass or total weight W, either total mass m or total weight W; from that we can calculate the natural frequency of a transverse frame subjected to vertical vibration using this equation. Already, we know how to calculate W.

So, for each frame if we calculate omega nz, then the average value of all the natural frequencies can be considered as the average vertical natural frequency for the turbogenerator foundation. So, you see here omega nz average can be calculated by averaging all the natural frequency for all the frames. Likewise, we can calculate also the average vertical amplitude of the foundation using equation-12.

So, what is rz here? rz is the frequency ratio; so, you can see here this is rz not just r, rz is equal to omega divided by omega nz average; I can write it as average. So, I am just rewriting omega divided by omega nz average. What is summation of Fz? It represents the total vertical imbalance force; whereas, Kz it summation of Kz represents the sum of the stiffness of individual frame here; and D is the damping ratio.

So, if we know the damping ratio, if we are able to calculate the average vertical natural frequency, then we can also find out average vertical amplitude for this foundation system. Now, the special case is under tuned machine when you can see omega is less than omega nz average.

So, that time what we can do? We can consider omega is equal to omega nz average, because this is the maximum value possible and for under tuned machine. So, what will be A za at that time? So, basically rz in that case will be equal to 1. So, the first term here 1 minus rz square whole square, this will be 0; only the second term will be left. So, we will get summation of Fz divided by summation of Kz times 2D, rz it is already 1. So, this is the value of average vertical amplitude of the machine foundation when the machine is under tuned.

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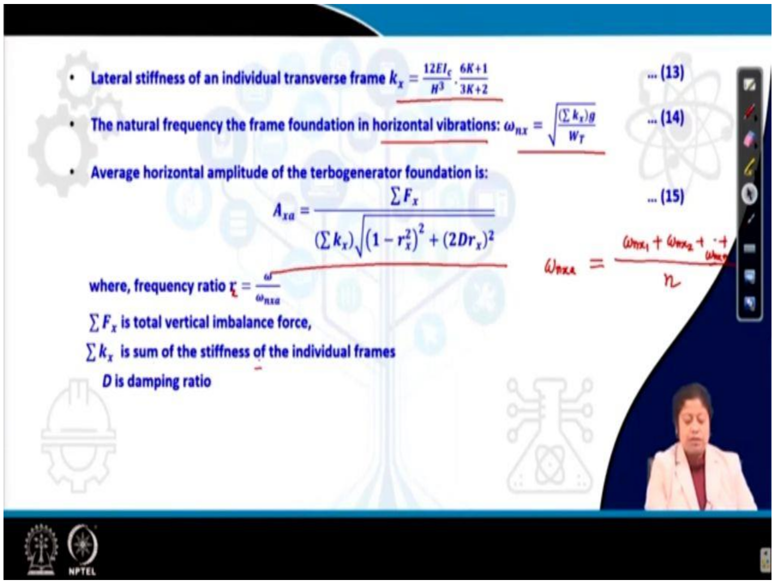

Now, when we are interested to do the horizontal details for the horizontal vibration, what we need to do? First, we need to calculate Kz. Sorry, Kx which is the stiffness or I can say it is as lateral stiffness of an individual transverse frame; so, that can be calculated using this expression 13. Then, from Kx we can calculate the natural frequency of the frame foundation in horizontal vibration.

So, here next step is to know the average horizontal, average horizontal amplitude of the foundation; and that can be calculated using this equation. So, here also not r, this is rx; rx is frequency ratio, which is equal to omega divided by omega nx average.

So, what is omega nxa here? Here omega nxa means some we are averaging omega nx value for all the frames, divided by n; n is total number of frames. And so, from this we can calculate rx, then summation of Fx is total vertical imbalance force; and summation of Kx is the sum of the stiffness for individual frame.

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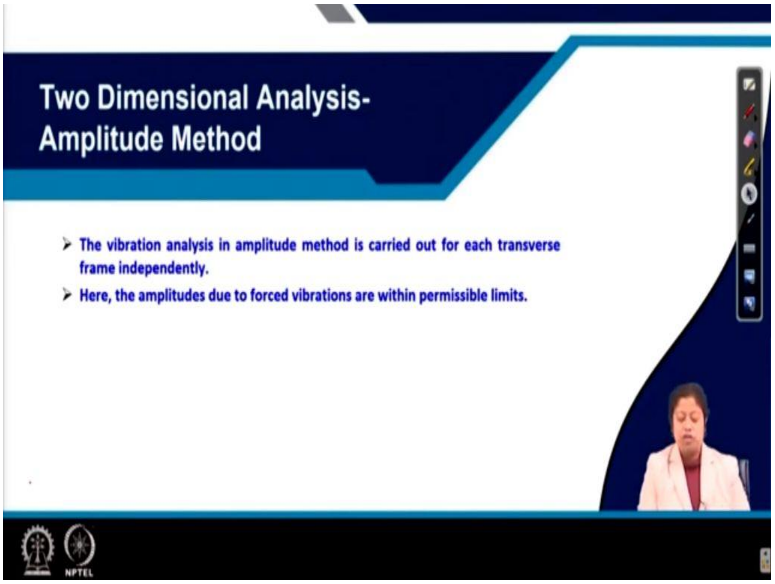

So, next method is amplitude method, which also in two dimensional analysis. As I already said, there are three methods which we can use. First one is resonance method, second one is amplitude method, and third one is the combined method. So, already we have studied resonance method, the second one is amplitude method. So, the vibration analysis in amplitude method is carried out for each transverse plane independently. Here the amplitudes due to the forced vibrations are within permissible limit.

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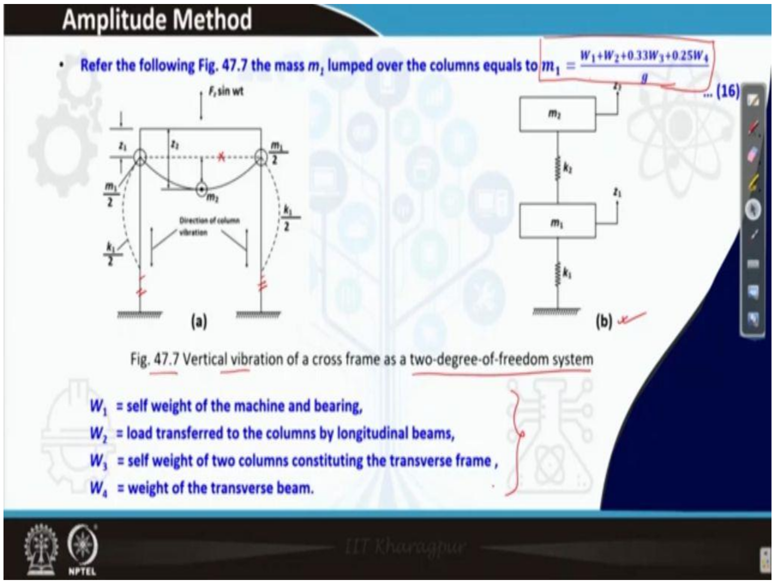

In figure 47.7, you can see a cross frame is subjected to vertical vibration; and this cross frame can be represented by a two-degree of freedom system as shown in figure b. So, in Figure a, what we can see? We can see the cross frame has different components; you can see the columns and the cross beam. So, what are the loads acting on this beam that we need to see and how to calculate the lumped mass over the column? So, in this figure, you can see total lumped mass acting over the column is equal to m1; and that is divided into equally divided into two columns column one and column two.

So, m1 is equal to here you can see W1 plus W2 plus 0.33 W3 plus 0.25 times W4, divided by g. And we can write it by equation-16; we can give a number 16. Now, what is W1, what is W2, what is W3 and W4 that is mentioned here. So, W1 is self weight of the machine and the bearing; whereas, W2 represents the load transferred to the column by longitudinal beams. W3 is the self weight of the two columns constituting the transverse frame, and W4 is the weight of the transverse beam.

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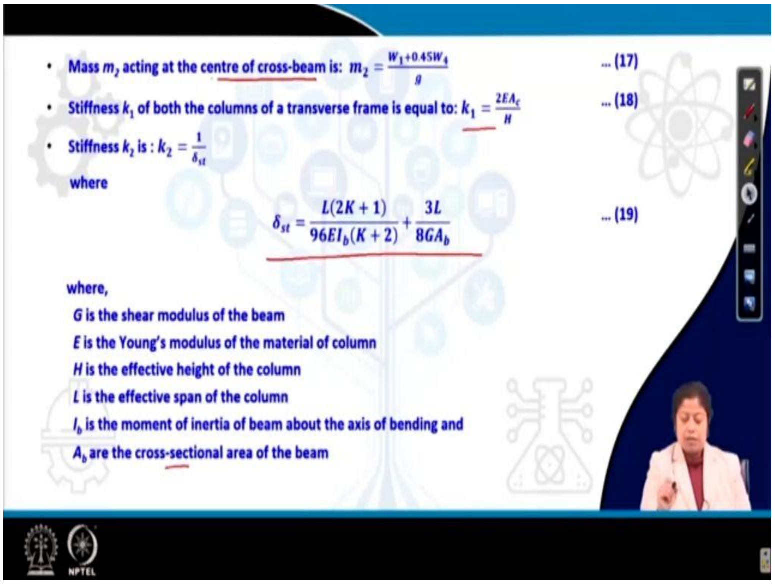

Now, next is to calculate the mass m2. So, mass m2 acting at the center of cross-beam is W1 plus 0.45 times W4 divided by g. Next, we need to calculate stiffness K1. K1 is the stiffness of both the columns of a transverse frame; so, there are two columns. So, for both the columns, this stiffness K1 can be calculated using equation 18. That can be calculated using the expression, 1 divided by delta st, where delta st is this expression shown in equation 19.

So, here what are the other symbols L? Already we know what is L; L is the effective span of the column; then k which is the stiffness already we have discussed. Then, next is E, E is Young's modulus of the material of column; G is shear modulus of the column material. Ab is the cross-sectional area of the beam.

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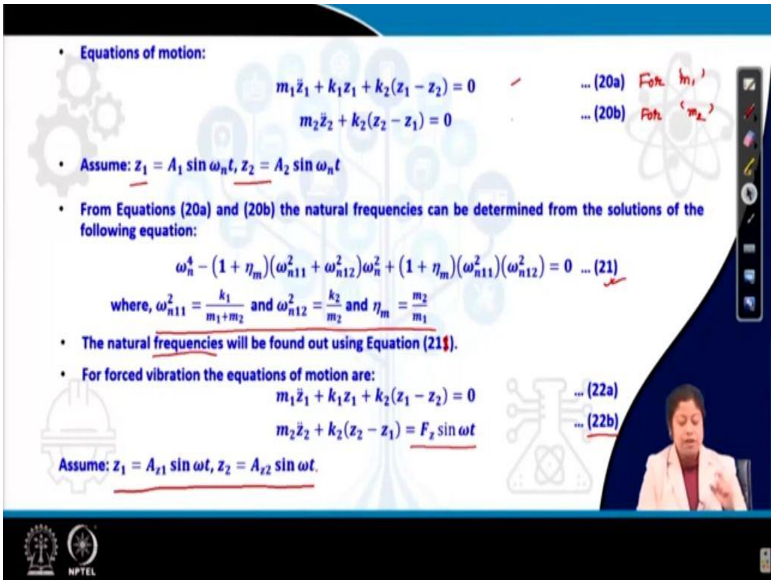

If we have several times solved different two-degrees of freedom system; so, we already know how to get the equations of motions for the two-degrees of freedom system. So, the problem which is already shown to you. For that also first we can draw the free body diagram for the two masses m1 and m2 respectively. And from that, we can get these two equations of motions which are equation 21 and 20, sorry 20a and 20b respectively; so, 20a for mass m1, 20b for mass m2. Now, after getting the equations of motion, we can assume trial solutions z1 for the z1 and z2 as shown here.

So, from these trial solution and the equations 20a and 20b, we can get the equation 21. If we solve equation 21 which is shown here, then from this equation finally we can get the natural frequencies. So, solving equation 21, it is 21 please correct it. So, solving equation 21, we can get the natural frequencies. So, in equation 21 what is omega in 11, then omega in 12, and eta in that is those are explained here you can see. Now, if the, now if we consider the forced vibration which is the actual case in the current problem, then the equations of motion will change from 20a to 22a, and 20b to 22b.

So, in equation 22b, you can see the right hand side is now non-zero. In this case, if we assume the trial solutions as shown here, then solving this equation 22a and 22b, what we get? We get the values for Az1 and Az2. So, what are these Az1 and Az2? These are the amplitudes of vertical vibrations.

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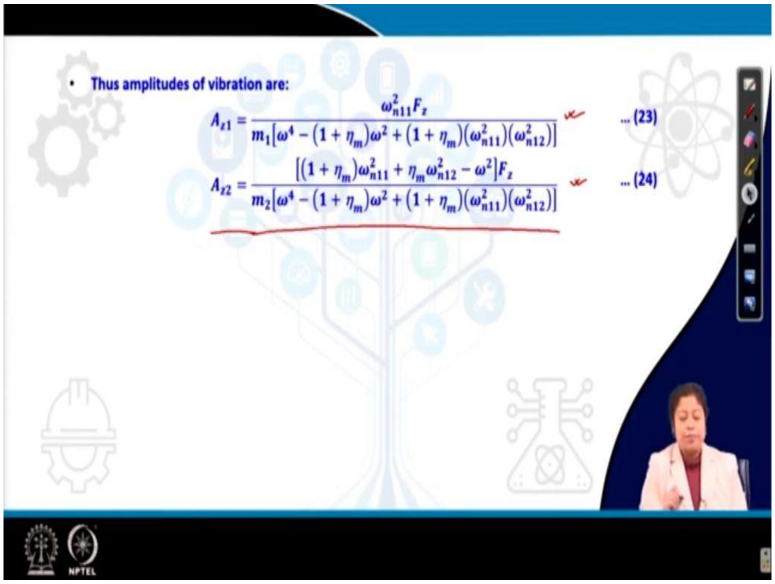

So, amplitudes of vibration Az1 can be expressed by this equation. Likewise, Az2 which is the amplitudes of vibration for the mass m2, that can be determined by using the second equation. So, equation 23 and 24 provide the amplitudes of vibration Az1 and Az2.

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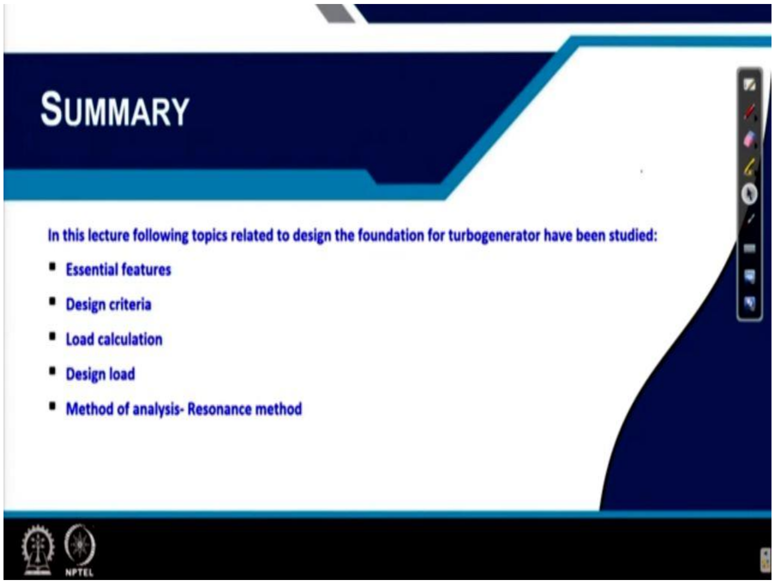

So, come to the summary of today's class. In this lecture, we have discussed the frame foundation which is required for the turbogenerators; and what are the specific things of frame foundations we have discussed. We have discussed about its essential features, then we have discussed the design criteria. Then, we have discussed the load calculation; that means how we will calculate different types of loads. And then how to calculate the design load that also we have seen.

After calculating design load, what we have done? We have studied how to do the analysis by two-dimensional method. In this for two-dimensional analysis, we have studied the resonance method for vertical and horizontal vibrations; whereas, for vertical vibration only, we studied the second method which is amplitude method. In next class we will continue the amplitude method, where we will study how to calculate the horizontal vibrations. That means, considering horizontal vibrations, how we will calculate the natural frequencies and the amplitudes of vibrations.

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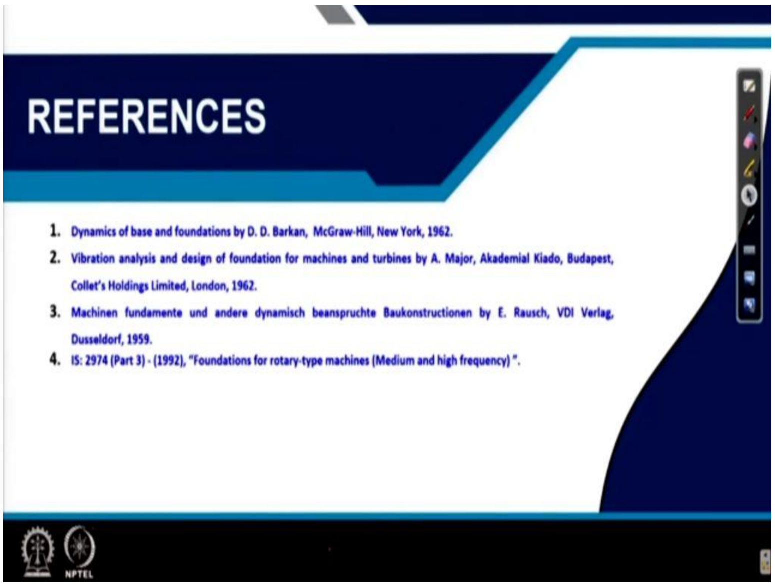

So here you can see the references that I have used for today's class. Thank you.