Soil Dynamics
Prof. Deepankar Choudhury
Department of Civil Engineering
Indian Institute of Technology, Bombay

Module - 05
Machine Foundations
Lecture - 26
Tschebotarioff's "reduced natural frequency" method, Design Chart and problems based on it

Let us start our today's lecture on soil dynamics.

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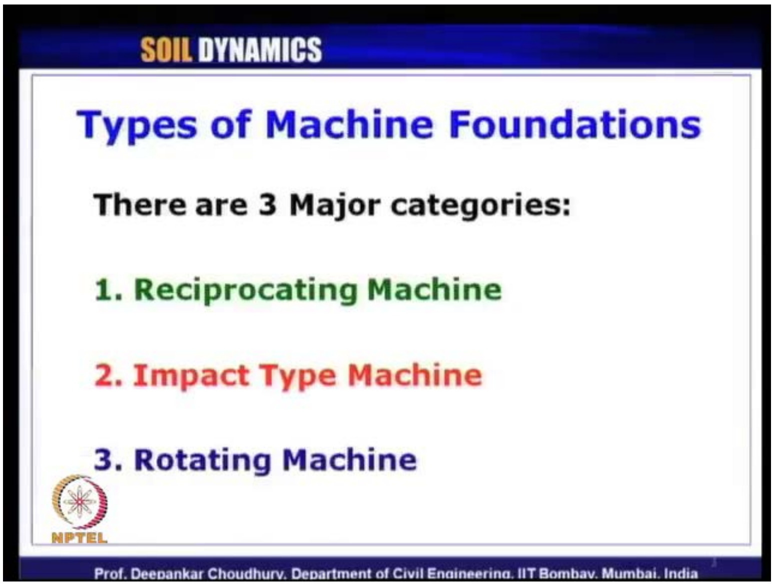

In machine foundations in the previous lecture a quick recap of what we had learnt, there are three major categories of machines, reciprocating machine, impact type machine and rotating machine.

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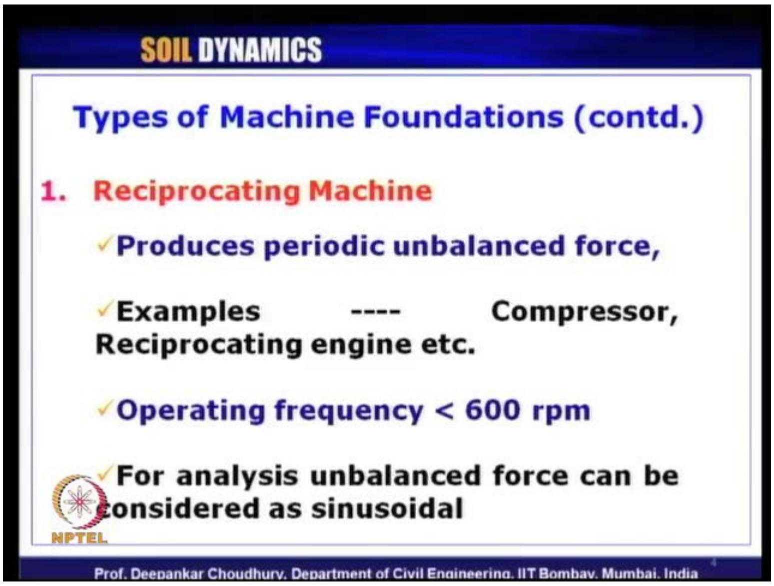

What are their special characteristics that also we have seen, like reciprocating machine produces mostly periodic unbalanced force. Examples of reciprocating type of machines are compressor, reciprocating engine, etcetera, their operating frequency ranges are generally less than 600 r p m. For their analysis we consider the unbalanced force as equivalent to a sinusoidal, because it is a periodic unbalanced force.

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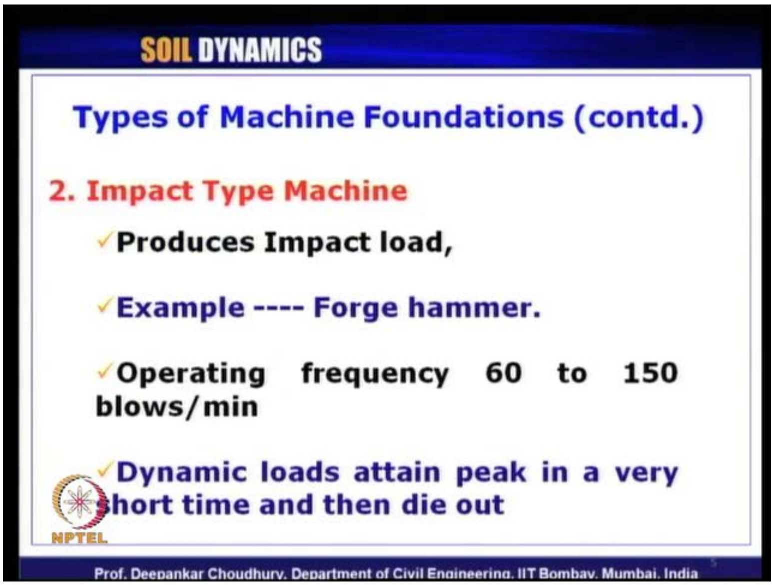

For impact type of machine it produces impact load as the name suggest. Example of such machine is forge hammer and operating frequency is generally between 60 to 150 blows per minute. The characteristics of impact load, that is dynamic loads attain peak in a very short time and then die out.

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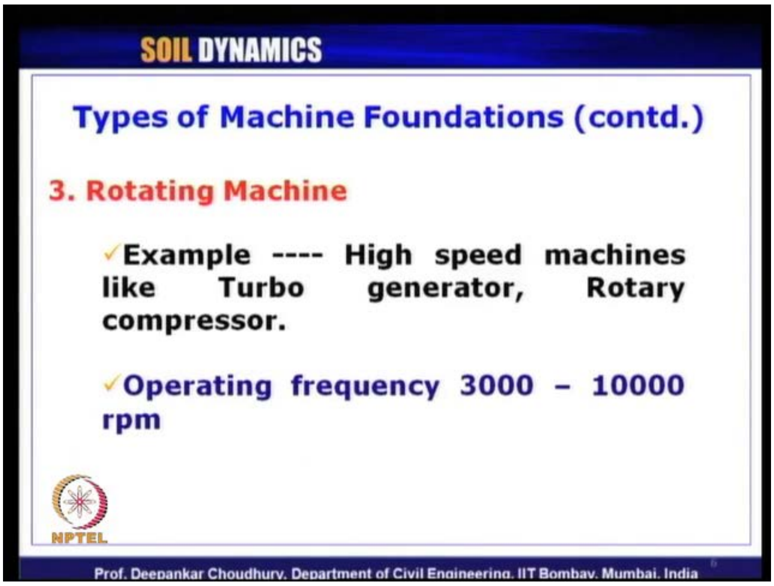

In case of rotating type of machine examples are high speed machines like turbo generators, rotary compressors, etcetera. And operating frequency ranges between about 3000 to 10000 of r p m.

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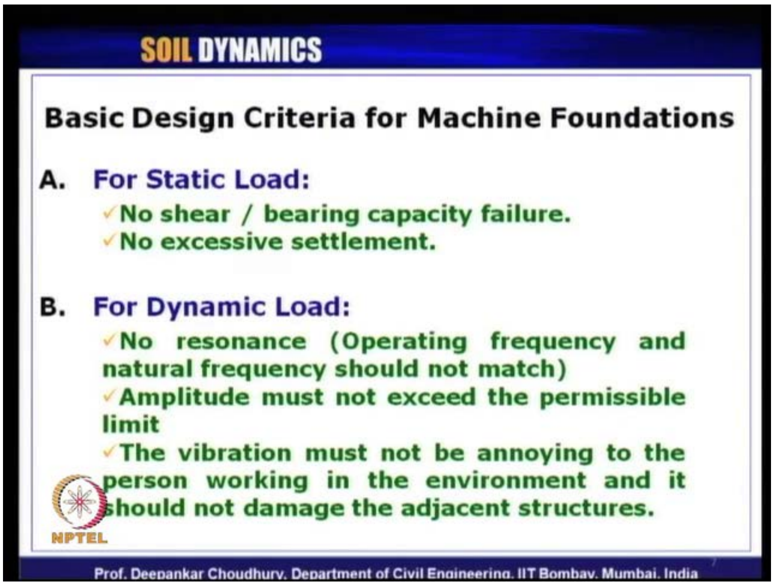

Basic design criteria for machine foundations we have seen, first of all that foundation must be safe against the static load. So, we need to check against that no shear or bearing capacity failure occurs and also no excessive settlement. Then coming for the dynamic load we need to do three checks, actually against three criteria. We have to design for first one is no resonance condition, that is operating frequency and natural frequency of the machine plus foundation system should not match, they should be far away from each other. Dynamic amplitude must not exceed the permissible limit and the third criteria is mostly qualitative in nature, which says that the vibration it must not be annoying to the person working in the close vicinity or it should not be damaging to the adjacent structures.

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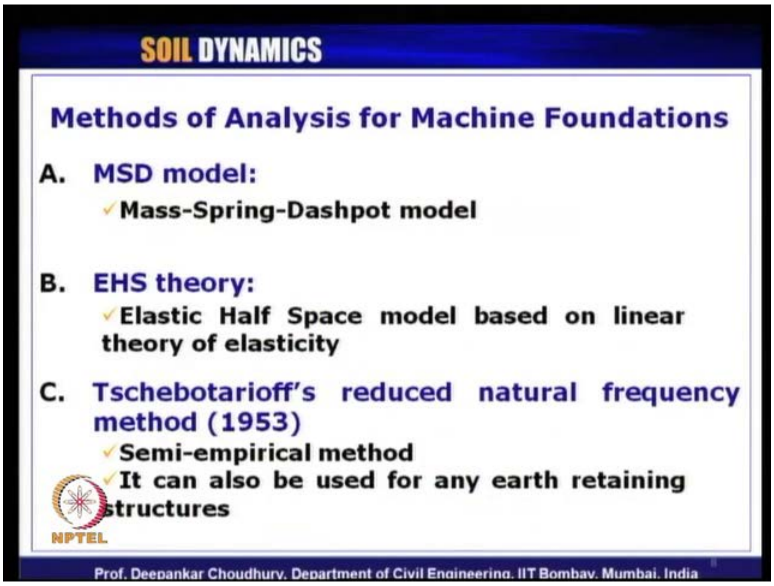

Various methods of analysis are there for machine foundation design, first one is m s d model that is mass spring dashpot model. Second one is e h s theory that is elastic half space theory, based on linear theory of elasticity. Third one is Semi empirical method which is known as Tschebotarioff's reduced natural frequency method.

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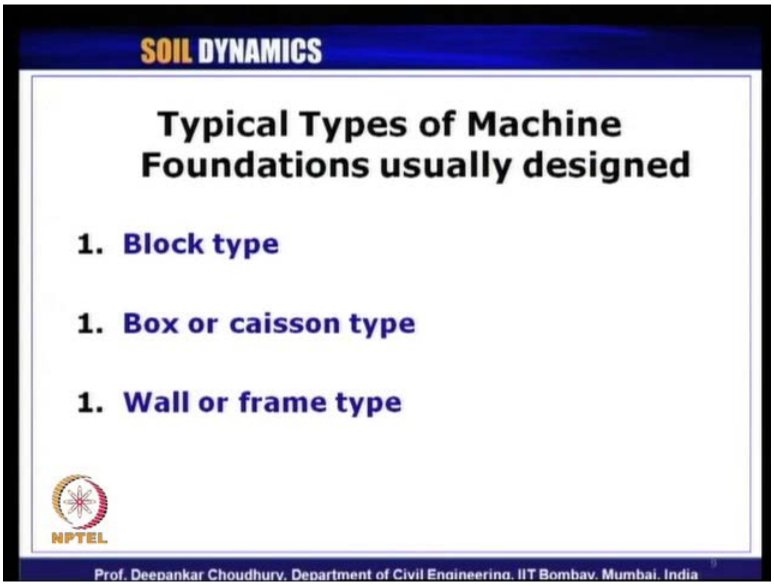

Typical types of machine foundations usually designed are block type, box or caisson type and wall or frame type.

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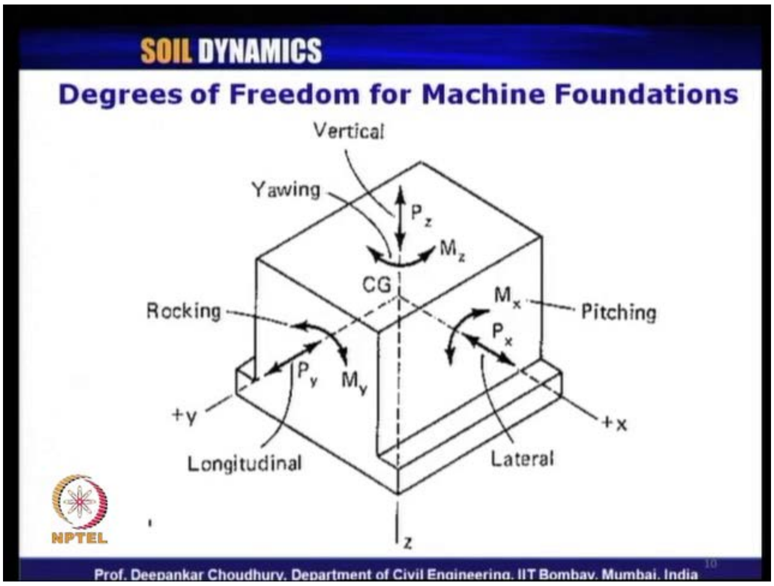

Also we have seen that what are the various degrees of freedom for machine foundations, that is possible deduction of movements like three linear and three rotational deductions of movements or vibration. We name them as this one have vertical vibrations, this one as lateral vibration and this one longitudinal vibrations. These two were also called as sliding mode of vibration or horizontal mode of vibration in x and y direction respectively. Then about the rotational vibration we have this one is called pitching vibration, this is called rocking vibration and this one is called yawing vibration.

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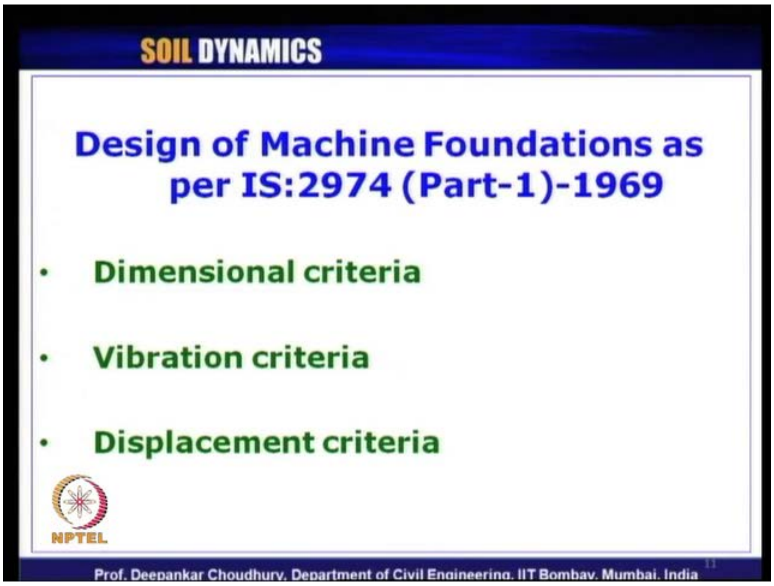

As per Indian design standard code of i s 2974 part 1, the three basic criteria has to be satisfied for the design of machine foundations, dimensional criteria, then vibration criteria and the displacement criteria.

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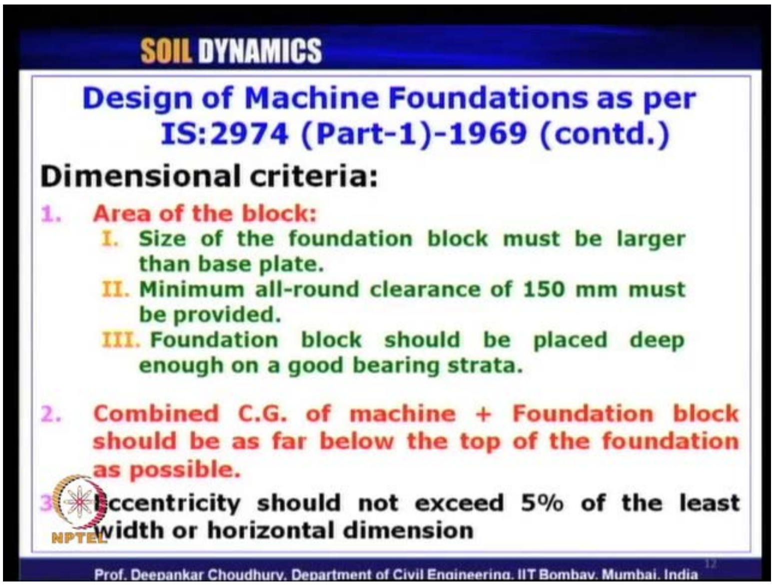

In case of dimensional criteria, we have seen how to select first the area of the block foundation. It says that the size of the block must be bigger than the base plate size on which the machine is placed and a guide line is provided that minimum all around clearance of 150 millimeter has to be provided. The foundation block should be placed deep enough on good bearing strata.

Then combined c g of the machine and the foundation block should be as far below as possible from the top of the foundations, to avoid the any kind of unbalanced force or rotational force coming on the foundation. Eccentricity of the load should not exceed 5 percent of the least horizontal dimension of the foundation. So, that no tensile pressure generates at the base of the footing, that we know from the static analysis also.

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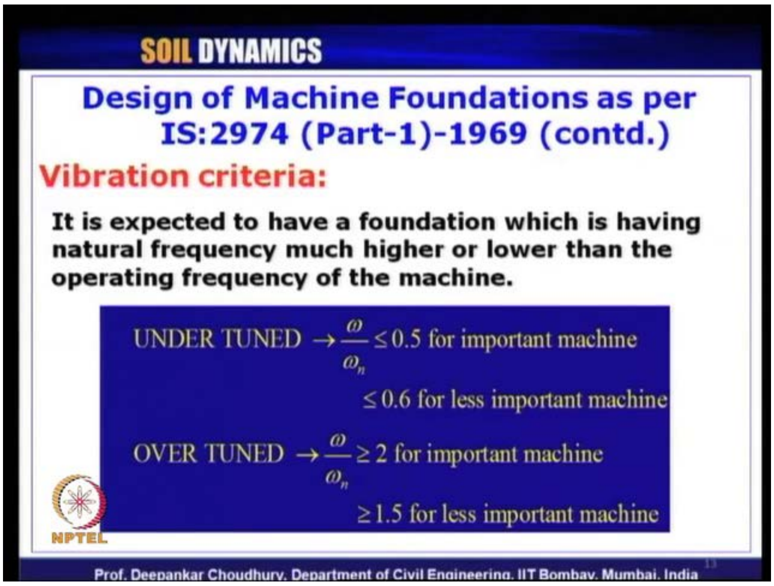

In case of second criteria that is vibration criteria, it says that any machines foundations can be designed either as over tuned or under tuned. In case of under tuned to satisfy the no resonance criteria, the operating frequency and the natural frequency of machine plus foundation system their ratio has to be maintained far away from 1, because they should not be close to each other.

So, in case of under tuned it is proposed that this ratio should be less then equals to 0.5 for important structures or we can go up to say 0.6, it should be less then equals to 0.6 for less important structure. For the case of over tuned machine foundation this ratio should be greater than equals to 2 for important machines and grater then equals to 1.5 for less importance machines.

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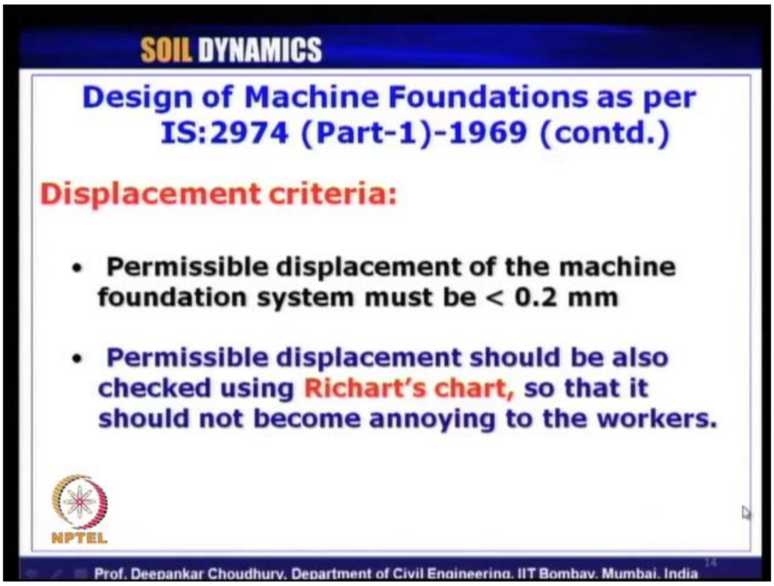

In the third criteria as per our I S code, it is says displacement criteria in that case the permissible displacement amplitude, dynamic amplitude of displacement should be always less than 0.2 millimeter. Another check is that qualitative check what we told you earlier, it has to be checked using the Richart's chart. So, that that displacement is not creating any problem to the people who are staying in the surrounding vicinity or working in the surrounding vicinity.

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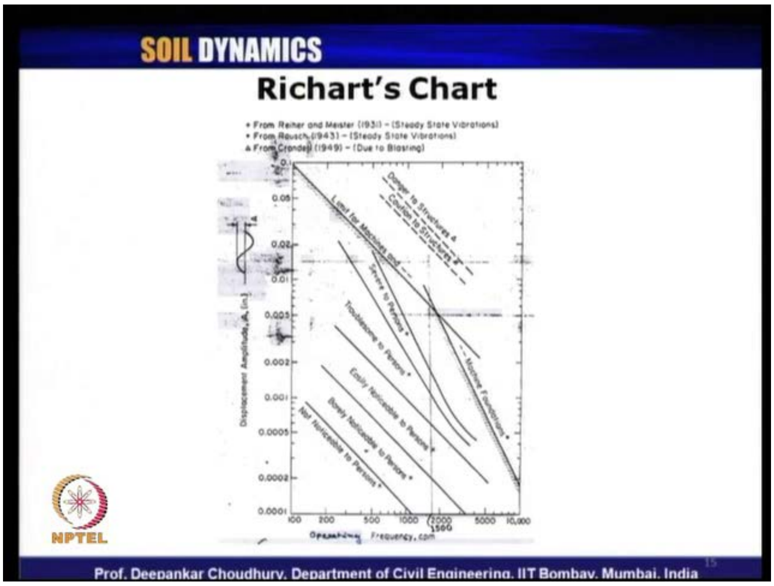

We have seen what is Richart's chart, that is for vertical mode of vibration, how we can find out whether what type of disturbance it is causing. Whether not noticeable to persons to severe to the persons and we should not cross this boundary or limit for design of machine foundation for the design. Similarly, for horizontal mode of vibration also we have seen that type of qualitative chart which we need to satisfy.

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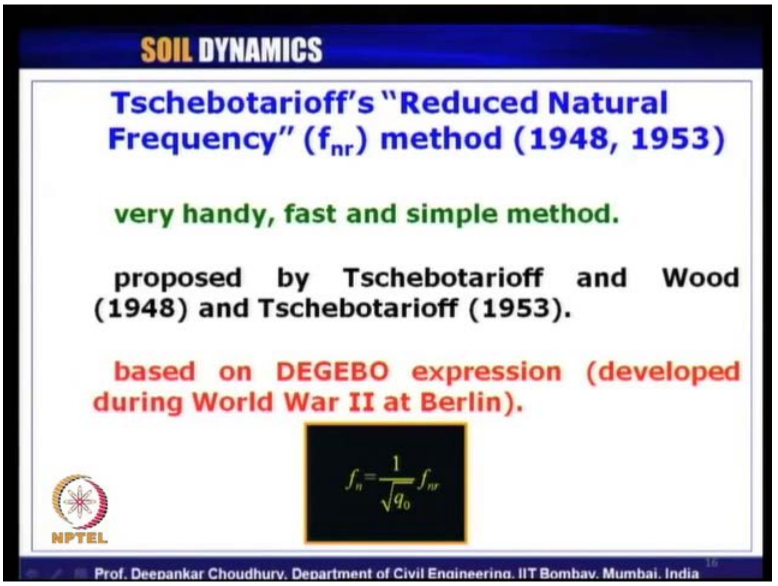

Then coming to the design methodologist, we had started with the third method that is semi empirical method proposed by Tschebotarioff's; that is Tschebotarioff's reduced natural method of 1953.

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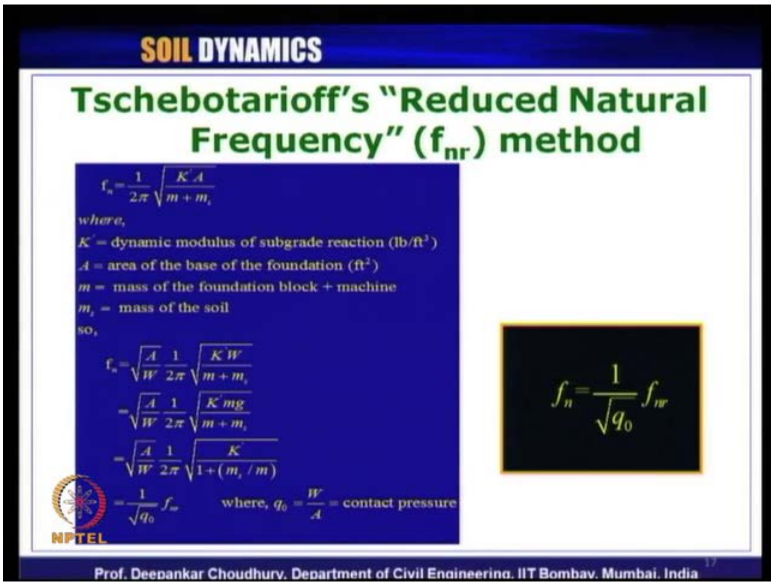

This was the derivations with this equation.

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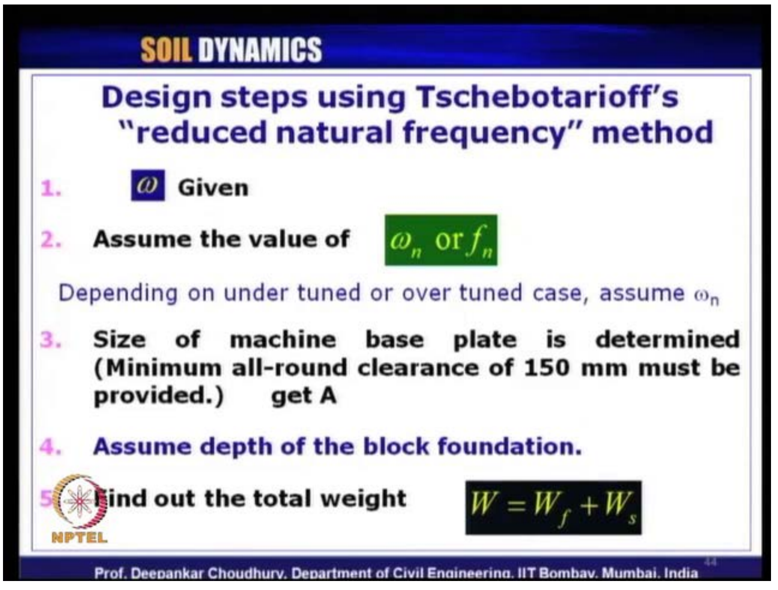

So, let us see what are the design step we should follow when we are going to design any machine foundation using this Tschebotarioff's reduce natural frequency. First step is omega, omega is operating frequency it's given to us, so let us record it operating frequency. Second step, assume the value of omega n, when you are assuming the value of omega n, automatically you are assuming f n, either circular or full natural frequency. How you are assuming this value? Remember the design guide line of either over tuned or under tuned case, using either this ratio of omega by omega n less than equals to 0.5 or greater than equals 2.

So, that is the second step to assume the value of omega n based on the no resonance criteria. The third step is size of the machine base plate, that is base area of the plate we have to assume by considering minimum all around clearance of 150 mm what is given as per the code. So, finally we will get area a, because base plate size will given to us by the machine provider, so base plate size you know, you add all around clearance of 150 millimeter. So, you will get the minimum area required to be provided for your foundation block. Forth step is assuming depth of the block foundation that you have to assume here.

What is the typical assumption typical assumption is generally 150 millimeter or 15 centimeter start with that, that is the minimum depth of the foundation or footing has to be provided remember. In coddle guidelines also the depth footing has to be provided minimum thickness of the depth is 150 mm, so that criteria you use here also, you can assume any value more than or equals to 150 mm.

Then next fifth step is find out the total weight, total weight means? Total weight of the foundation and the machine, machine weight will be given to you and weight of the foundation you can easily now calculate because depth you have assumed, area also you assumed. So, volume your know, if it is r c c block use the unit weight of r c c, you will get the total weight of foundation add it to the machine weight, you will get the total weight of the system.

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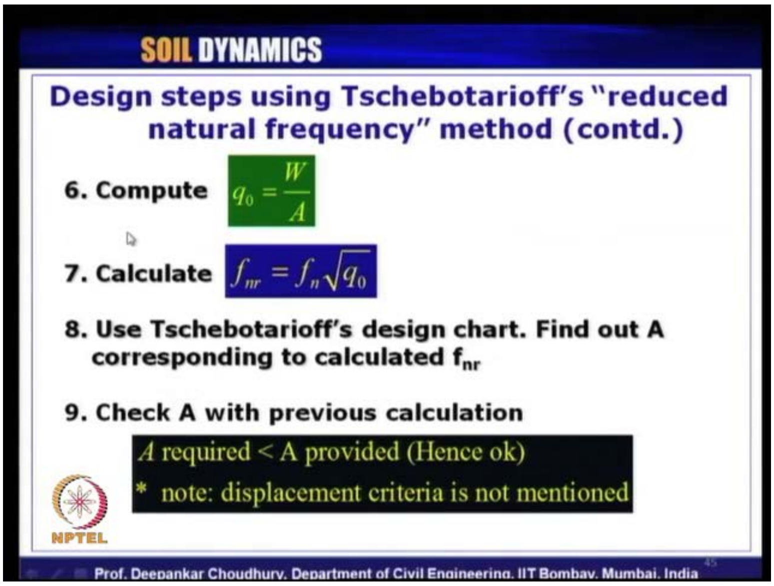

Next, step is compute that q naught, contact pressure from this calculated value of W and assumed value of A what you have selected, so you will get the q naught value. Seventh step is calculate that reduced natural frequency of Tschebotarioff's using this equation, F n already you know because you have assumed using know resonance criteria. Say F n you know, q naught you have calculated just now in the previous step, using this you can get the F n r. Next step says, now you have to use Tschebotarioff's design chart, Tschebotarioff's given design chart of this F n r versus area of the foundation, based on different soil properties.

Ninth step will be, so what you have to do? You have calculated this F n r, go to Tschebotarioff's design chart, corresponding to F n r, find out what is the area required to be provided. In the next step what you are checking, check weather area required is less than of area what you have provided or assumed in the previous step, then it is fine. We will see the Tschebotarioff's chart just in the next slide, before that let me mention one very major drawback or limitation of this Tschebotarioff's reduce natural frequency method is that, displacement criteria is no where mentioned using this method for the design of machine foundation.

You cannot check how much dynamic displacement amplitude your foundation is going to face. The only criteria you were checking here is the no resonance criteria, that is in the second step while selecting your F n value you have used that no resonance criteria, but second and third criteria there is no chance that you can check for. So, that is the major drawback of Tschebotarioff's reduced natural frequency method.

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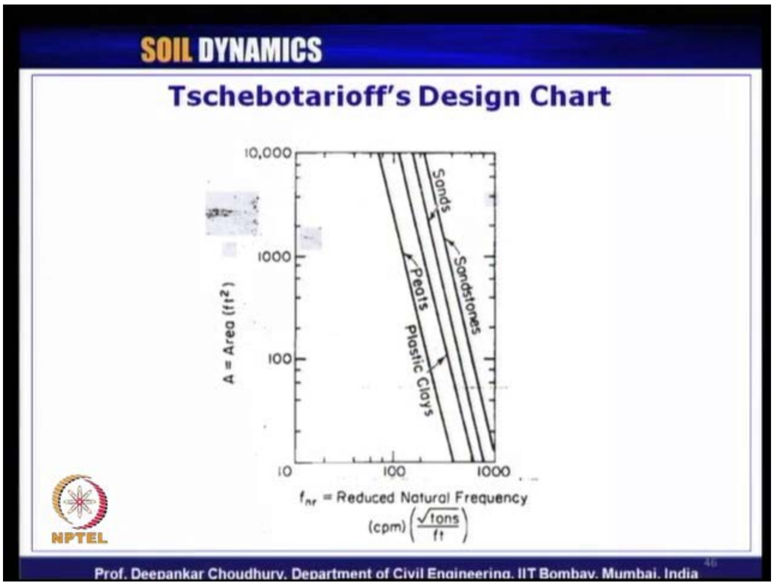

Let us now look at of Tschebotarioff's design chart, so this chart the first one what it shows is f n r in the x axis, which is nothing but reduce natural frequency and y axis is A, that is area in the unit of feet square. As I have said already, these are semi empirical method. So, units you have to be very careful all are in f p s unit. Area when you are providing or you are getting or using from this chart what you will get in feet square, then you have to convert it in your S I unit, what your using. Unit of f n r f n r is also having a particular unit, what is that unit? Tat is c p m that is cycles per minute root over tons divided by feet, right?

Let us go back to the equation you will easily understand why the equation or why the unit of f n r is so, what is the unit of F n, c p m, so unit of root over q naught. What is root over q naught? Ton per feet square under roots, so obviously root of tone by feet. Now, for different soil Tschebotarioff's has given this chart, for sands stone this line, for sands this line, for plastic clay this line, for peats this line. So, depending on your nature of soil you can select which line has to be used and also if you check carefully.

If you try to derive the expression you can also derive these charts are not abruptly developed, these are based on g values of the soil. So, the slop of this line the Theta you can calculate easily based on the g value of the soil, that is what Tschebotarioff's have done. If you try to further simplify the expression of f n r you will get that in terms of the g value of the soil by representing the k dash that is dynamic sub grade modules.

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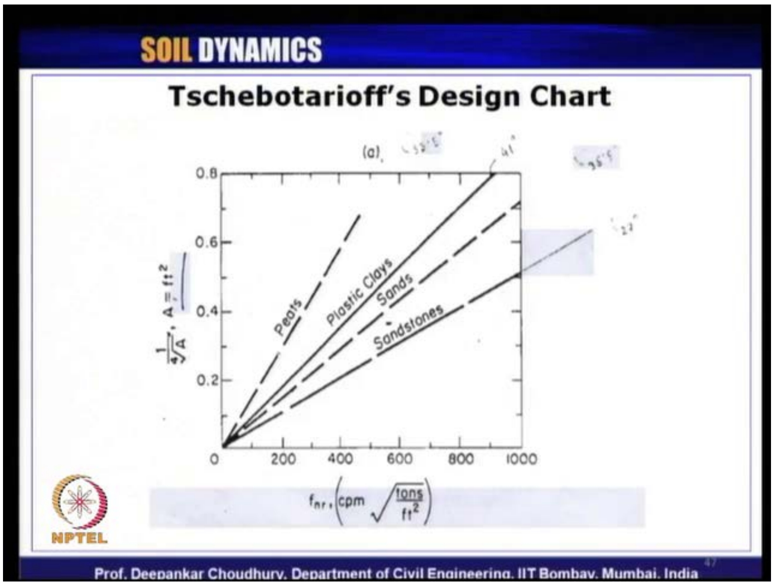

Second Tschebotarioff's design chart is like this, x axis same that is f n r in the unit of c p m root over ton per feet square, where as y axis will give you the value of 1 by 4 root of A, where A is used in feet square unit. So, if you use this chart, second chart for different types of soil again he as proposed here for sand, stone, sand, plastic, clays, peat, you can get different angles that is what it is mentioned here. The slop of the line which will be easily help you to get for different calculated value of your f n r in the design steps whatever I said to this 1 by 4 root of A value very easily and that is you're A required. A provided you have to check with this A required, till they match or if your provided area is more, than it is fine.

Now, both are Tschebotarioff's design chart, as a designer which chart you will prefer to use both are same chart, what are the basic differences between them? If you look very carefully, this first chart is having this and this axis both in log scale, whereas the second chart both x and y axis are in natural scale. So, if you read your design value from this chart to reduce the manual error, it is always better to use the graph with natural scale. Then logarithmic scale because in log scale if you miss a very small point small distance it will be magnified hugely, so that is why among these two charts same charts. The second one is preferred for design propose, though it will give you a complicated value of expression of y axis from which you have to recalculate the area.

Whereas, in the previous chart it was pretty direct you were getting the direct area, but still the second chart will be preferred in the design. We will do some example problem also, how to design a machine foundation using Tschebotarioff's reduced natural frequency method. So, in the next lecture we will do that.

Soil Dynamics
Prof. Deepankar Choudhury
Department of Civil Engineering
Indian Institute of Technology, Bombay

Module - 5
Machine Foundations.
Lecture - 26 (B)

Tschebotarioff's "reduced natural frequency" method, Design Chart and problems based on it. We are continuing with our module five that is machine foundations.

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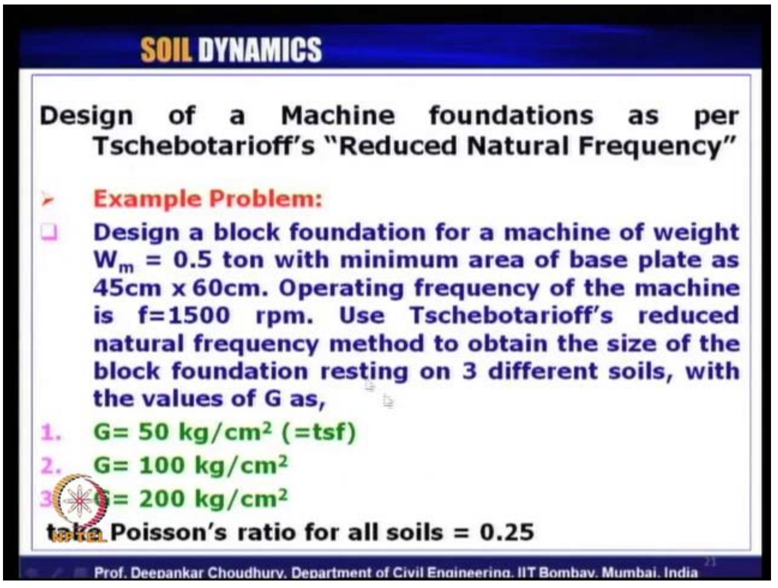

So, today we will design some machine foundation using this Tschebotarioff's reduces natural frequency. Let us first see the problems statement what it says that design a block type machine foundation for a machine of weight of 0.5 ton with minimum area of base plate as 45 centimeter by 60 centimeter that is the area of the base plate and this is the weight of the machine. So, these two input parameters will be provided to us by the machine manufacturer, so for this machine to house this machine we have to design a block type of foundation. Also the machine manufacturer will be given us the operating frequency of the machine, so it given that operating frequency of that machine is 1500 r p m.

Now, using Tschebotarioff's reduce natural frequency method, we need to find out the size of the block foundation for different, three different types of soil that is suppose if we have three different types of soil, what are the different sizes of foundation required to be provided to place this machine which is given to us? So, this is a clearly a complete design problem which we need to consider and the G value for this three different type of soil are given as the first one as 50 kilogram per centimeter square, second 100 kilogram per centimeter square and the third one is 200 kilogram per centimeter square. It is mentioned that assume the Poisson’s ratio for all this three types of soil as 0.25.

Remember this kg per centimeter square unit is nothing but equivalent to or equal to t s f that is ton per square feet, why it is given because while using Tschebotarioff’s design chart we need to convert all the values to f p s unit, because his basic design chart is given in f p s unit. So, with this given problem let us start designing the machine foundation. Let me tell you first I am not covering the static part of design here.

So, remember this one, when you are doing a design in actual case first you must check under static load whether your chosen foundation is safe or not, that is bearing capacity failure and excessive settlement failure has to be checked. Now, beyond that only for the dynamic component I am showing you the design procedure here, so that does not mean that it is the only component for the design, remember this one. I am only covering here under dynamic load whatever the design criteria.

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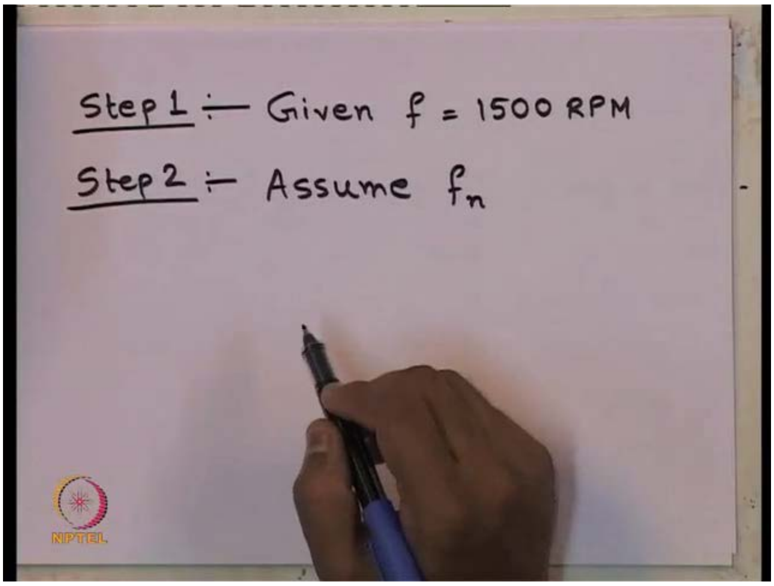

So, let us see step wise, in step one the given value of operating frequency is 1500 r p m, it is given to us. So, the step two says assume f n that is natural frequency of the machine plus foundations system.

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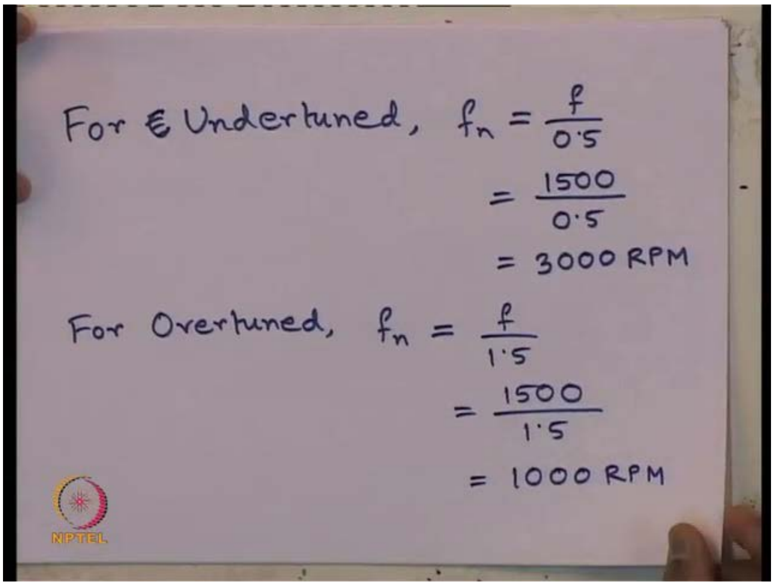

So, in that case, so for under tuned what are getting f n is f by 0.5 that is 1500 by 0.5 will give us 3000 r p m. For over tuned we are getting f n equals to f by 1.5 1000 r p m.

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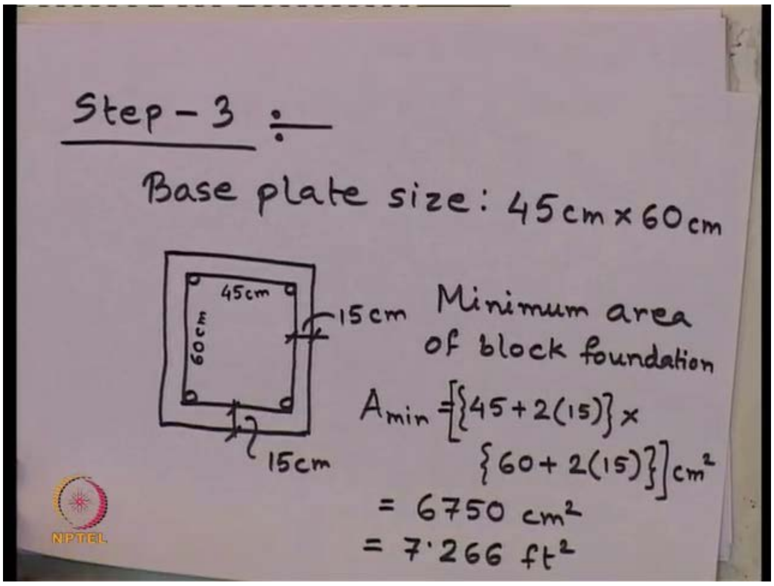

Now, let us move to step three of the design, in step three what was mentioned that based on the given base plate size, what is the base plate size? Let us look at the problem statement, base plate size is given as 45 centimeter by 60 centimeter. What we know from I S code design specification, that minimum all around clearance of 15 centimeter needs to be provided, so this is 15 centimeter and this is also 15 centimeter. Whereas, this dimension is 45 centimeter and this dimensions is 60 centimeter, this is the minimum area required remember, we off course can provide bigger area also.

So, the minimum area of block foundation will be 45 plus 2 times 15 multiplied by 60 plus 2 times 15, so much of centimeter square. It comes out to be 6750 centimeters square, we need to convert this to f p s unit for using Tschebotarioff's design chart. So, let us convert from centimeter square to feet square. If we use conversion factor it will give us 7.266 feet square, so this is step three.

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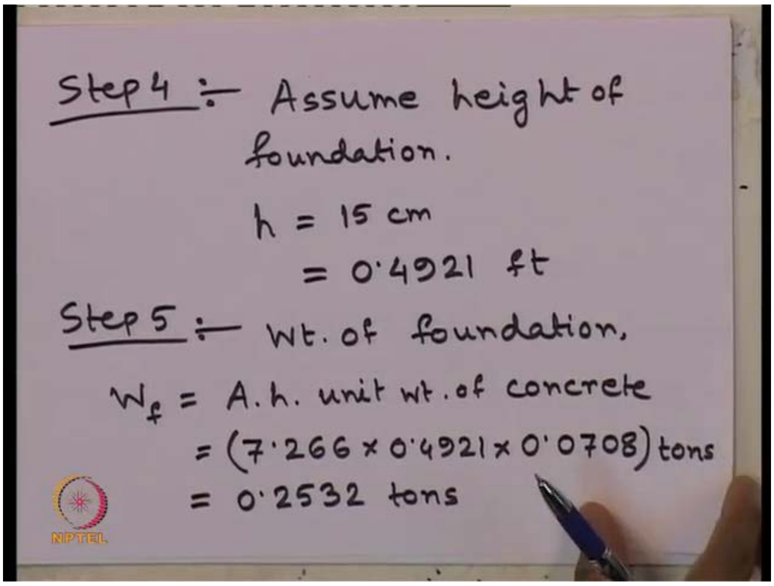

Now, let us move to next step, step four it says assume height of foundation, so let us assume height is minimum thickness of the foundation, what the guide line says 15 centimeter, thickness of the footing or thickness of the foundation 150 m m. Let us convert it to f p s unit of feet 0.4921 feet. So, next is step five, what it says, find out the total weight of machine plus foundation system, so weight of foundation W f that will be area A times height age times unit weight of let us say it is of concrete, so concrete.

Say if we put the standard value of unit weight of concrete and this value of A and h in f p s unit 7.266 feet square is the area, height is 0.4921 and unit weight is concrete is about 0.0708 ton per feet cube unit. So, this will give me unit of tons, this is the unit weight of concrete 0.0708 in a unit of tons per feet cube, so it giving us about 0.2532 tons as the weight of the foundation. So, in this step five only we have to now compute the total weight of machine plus foundation, weight of the machine is given to us which is 0.5 ton.

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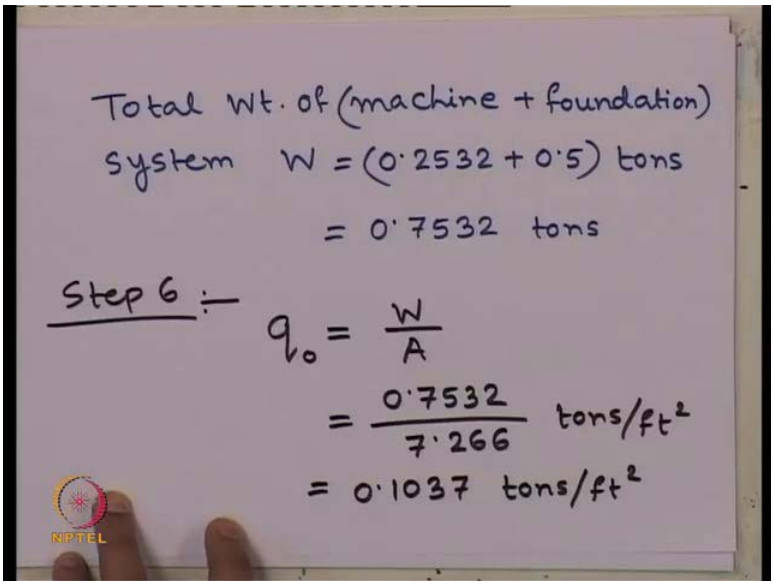

Total weight of machine plus foundation system, that is W equals to 0.2532 plus 0.5, so much of tons, fine? So, it is giving me about 0.7532 of tons. Now, in the next step, step six what it says? Compute the uniform bearing pressure below the footing, that is q naught as for the nomenclature of Tschebotarioff's reduce natural frequency method, that is W by A in ton per feet square unit, so 0.7532 by 7.266 ton per feet square. If we calculate this we will get 0.1037 tons per feet square, this is q naught.

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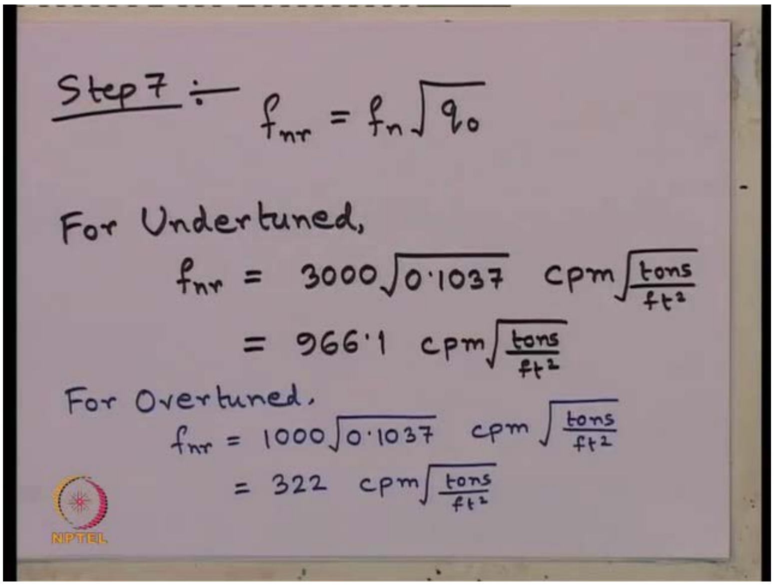

Let us move to next step that is step seven, it says let us calculate f n r which is f n times root of q naught. So, this is the formula given by Tschebotarioff's reduce natural frequency method which we are using here. Now, we have two cases here, for under tuned f n r is coming out to be f n is how much we got? 3000 r p m times q naught we got 0.1037. So, r p m is nothing but same as c p m, cycles per minute, revaluation per minute it is nothing but the same unit that is what the chart of Tschebotarioff's method use the unit.

So, we can right down in the same form c p m root over tons per feet square that is the unit, it is always better to write the units side by side so that we are following the whatever is given in Tschebotarioff's chart, it is not dimension less. So, that is why have to be careful while using this semi empirical method. So, let us calculate this how much it is coming?

It is coming about 966.1, so much c p m root of tones per feet square. Whereas, if we go for the over tuned design, in that case f n r is f n is how much? 1000 0.1037, so much it is giving us? About 322 c p m root over tons per feet square, so this is step seven. In the next step, step eight what we need to do we need to use Tschebotarioff's design chart which I have shown earlier.

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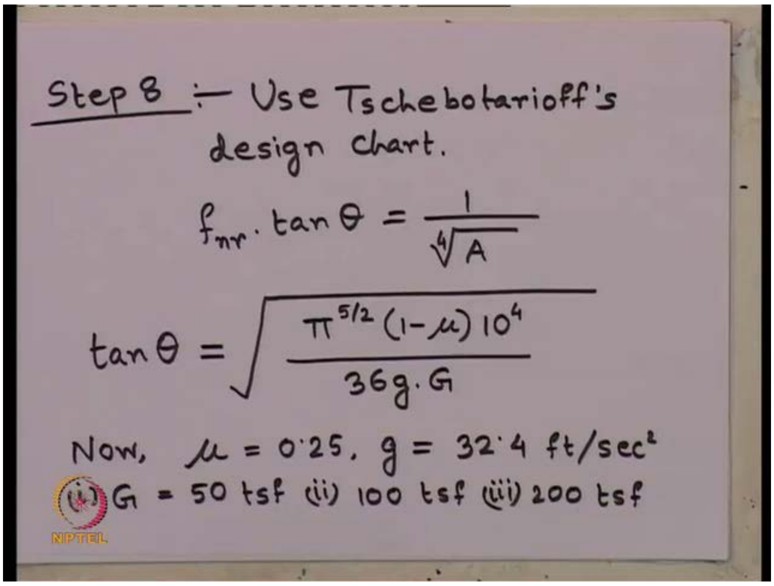

So, step eight use Tschebotarioff's design chart that gives for various g values, that is against the calculated f n r in the previous step using various types of soil based various g values we can get the area required. Now, if you look at the equation, the equation is given for the Tschebotarioff's design chart in normal scale, the second graph or second design chart whatever I have given earlier. The form of equation is f n r times tan Theta equals to 1 by 4 root of A that is the equation, the equation of a straight line.

Let us look at the chart here once again, so in this chart this is y axis, this is x axis, so equation for all different types of soil. Equation is nothing but a straight line equation passing through origin, so it will be y equals to m x equation, that is why I have written it in the form of here y equals to m x. What I had mentioned to you earlier if you try to derive from the basic of the formulation of Tschebotarioff's reduce natural frequency method, you will get the expression for tan Theta in terms of g will be like this, pi to the power of 5 by 2 1 mines mu 10 to the power of 4 divided by 36 small g times capital G.

Small g is acceleration due to gravity, capital G is shear modules of the soil, mu is Poisson's ratio of the soil. So, these expressions can be easily obtained or derived from the basic of Tschebotarioff's method what I had explained earlier, so you try to derive this one. So, what we will do instead of using his design chart, that is one option off course. That is how he has developed that design chart actually based on different mu and g value of the soil, these two are soil properties.

Now, instead using the design chart as we know this expression we will directly use this value for computation of this tan Theta, which we will give us this value of A finally. Now, for the given problem we have mu equals to 0.25 for the all the types of soil, acceleration due to gravity g in terms of f p s unit is 32.4 feet per seconds square. We have three cases of capital G that is shear modules has 50 ton per square feet 100 ton per square feet and 200 ton per square feet, these are the three g values of the soil given to us that is in three different soil conditions we have to design the foundation.

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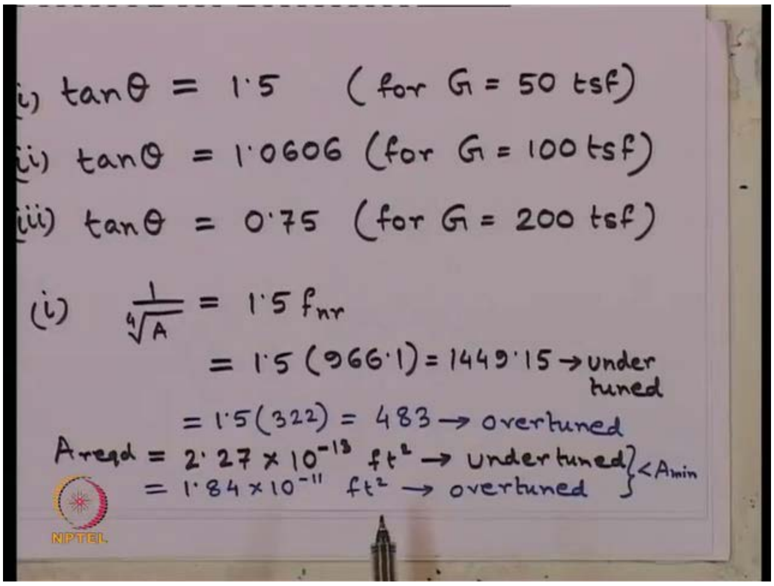

So, let us now calculate this tan Theta using this using this expression, tan Theta for the first case comes out to be 1.5 approximately for G equals to 50 t s f, please put the values of known parameters in the equation and check if it is so. The second type of soil tan Theta coming to be about 1.0606for G equals to 100 t s f, please check if you are getting this value of ten Theta for G equals to 100 t s f. In the third type of soil tan Theta is coming out to be about 0.75 for G equals to 200 t s f. So, after this we have to go to next step that is step eight where we were, we had already calculated this tan Theta values using Tschebotarioff’s chart in this same step actually.

Now, corresponding to this f n r value and tan Theta we have calculated we can calculate the A value in the same step. So, for the first case what we are getting 1 by 4 root of A is equals to 1.5 times f n r, first step of soil which will be how much? 1.5 times f n r is 966.1, so it will give me a value of 1449.15 this is for the case of under tuned. The other case for over tuned it will be 1.5 times f n r, in that case f n r how much we got? 322 483 this is for over tuned, do not write the units here, because here the unit will be 1 by 4 root of feet square. So, from this what we will get A required, because the Tschebotarioff’s chart, Tschebotarioff’s equation will give us A required.

If we use this how much we are getting? 2.27 into 10 to the power mines 13 feet square for under tuned. Whereas, for over tuned case we are getting 1.84 into 10 to the power mines 11 feet square for over tuned. Both of them are much less than A minimum, whatever is required based on the dimensional criteria. So, why this such a low value comes? We will see soon. It is because of, it seems that already the base plate of the machine, whatever it is provided is very very good enough to take care of the vibration, that is why truly speaking no more size or extra size is required.

So, minimum size provided based on the dimensional criteria to keep the free clearance all around, we are getting the much more than what is required from this analysis. But we will see we have to check this once again in terms of another parameter, we will come to that soon, so this for first type of soil. Let us do this for other two types of soil.

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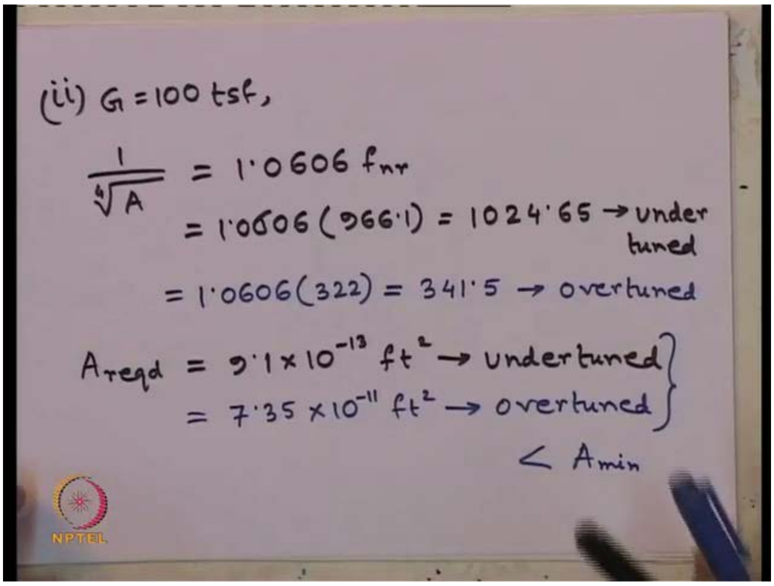

For second type of soil where G is, for G is 100 t s f in that case, how much we are getting? 1 by 4 root of A is tan Theta that is 1.0606 times f n r, which will give us 1.0606 f n r is 966.1 is 1024.65 that is for under tuned. For the other case of over tuned it will be 1.0606 times f n r is 322 341.5 for over tuned. So, finally how much they are coming A required for the first case of under tuned will be 9.1 into 10 to the power of mines 13 feet square for case of under tuned and 7.35 into 10 to the power of mines 11 feet square for the case of over tuned. Again both of them are much less than A minimum.

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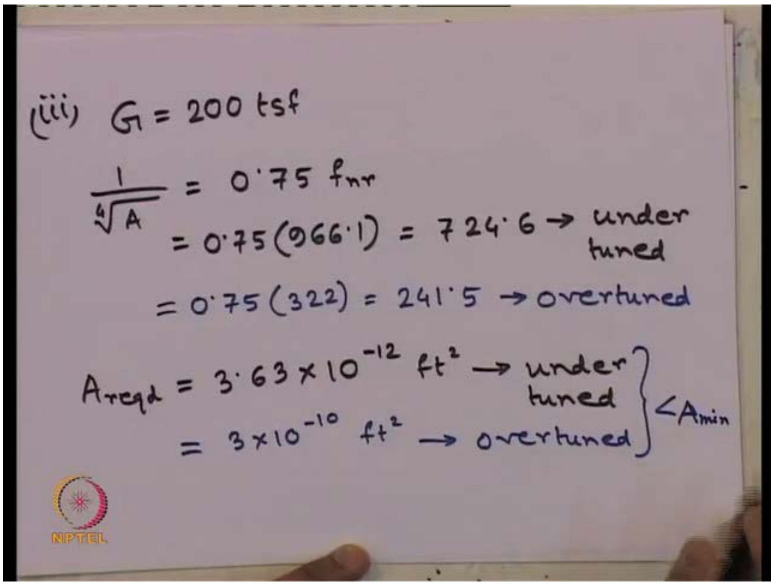

Now, for the third type soil that is for which G equals to 200 t s f what we got? This equals to tan Theta we got as 0.75 times f n r, 724.6 for the case of under tuned 241.5 for case of over tuned. So, which is giving us A required as 3.63 into 10 to the power of mines 12 feet square, for under tuned and 3 into 10 to the power of mines 10 feet square for over tuned. Again both calculate values are much less than A minimum based on the base plate dimension. So, what does it mean from this calculation using Tschebotarioff's method?

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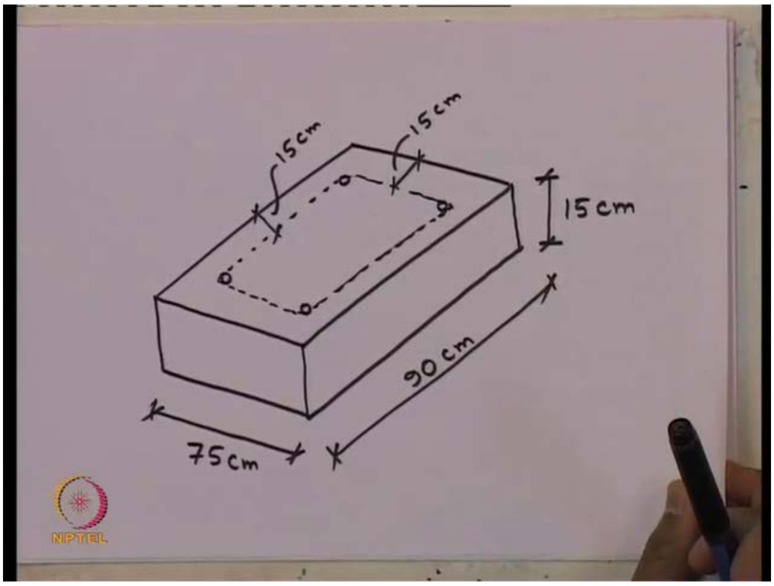

That whatever size we had provided for the block foundation, so we had provided 15 centimeter thickness, this dimension we had given has 75 centimeter and this dimension we had given has 90 centimeter. Whereas, on top of it, the placing of machine base plate should be done like this, so that this clearance of 15 centimeter all around is available, that is the design component. Now, this is provided size is much more good enough than whatever we are getting from Tschebotarioff's chart, does it end the design process here?

No, why here, why it is not ending the design procedure, because we are not yet sure whether no resonance criteria has been satisfied or not, the provided size, based on provided size we have not calculated the value of natural frequency of the entire system. Unless that is far away from the operating frequency we cannot say that this provided dimension is safe. So, it is not the end of the design, but some more checks have to be done, so it is a repetitive process unless both the things are satisfied, let us do that.

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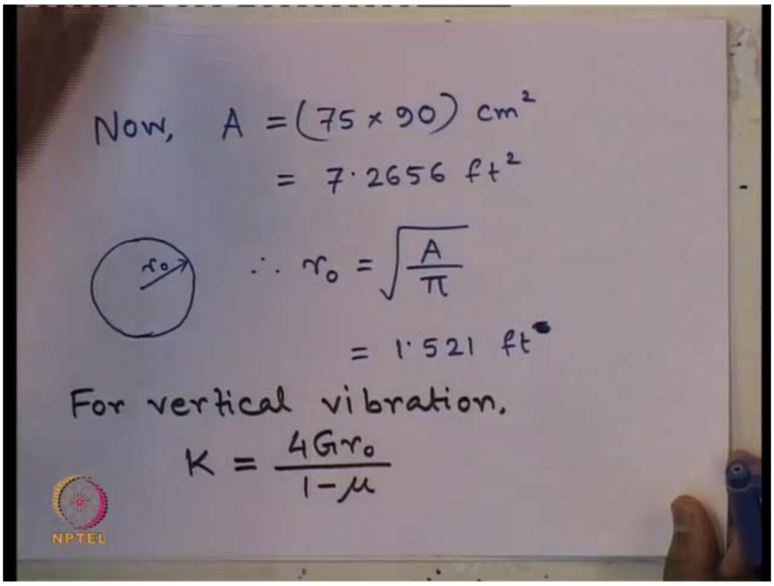

So, with this dimension what we have provided now let us go back and calculate the Area, Area is 75 by 90 centimeters square which is giving us 7.2656 feet square, from which what we can do? We can find out the equivalent radius of a circular footing, this is off course our rectangular footing we have provided. Suppose, if we want to find out equivalent radius of a circular footing keeping the area constant, therefore r naught will come as how much? A by pie 1.521 feet square, sorry r naught is 1.521 feet, that is called radius of equivalent footing base.

Why it is required? For vertical vibration for vertical vibration the stiffness of the system K is computed by this expression 4 G r naught by 1 mines mu, this expression based on the theory of elasticity was developed by (( )) here. So, in the book of (( )) will find the expression for vertical mode of vibration the stiffness of the system is calculate in terms of the size of the foundation and the soil properties. So, 4 G is share modules of the soil, r naught is this equivalent radius of the circular foundation, mu is Poisson's ratio of the soil.

So, with this knowledge of K, which is required off course to calculate the natural frequency, because natural frequency we need to root over K by m, m. Of course, we can calculate from the size provided, we know the m of the footing, but K we need to compute. So, with this we will stop all lecture today here, we will continue further in the next class.