Soil Dynamics
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Module - 5
Machine Foundations
Lecture - 25
Types of Machine Foundations, Methods of Analysis, Design of Machine Foundations as per IS:2974 (Part -1)-1969

Let us start our today's lecture on soil dynamics. Now, we will start our module five next module, which is machine foundations. A classification of different types of machine foundations; if we put all different types of machine foundations whatever are used worldwide, it can be categorized in major three categories machine foundations.

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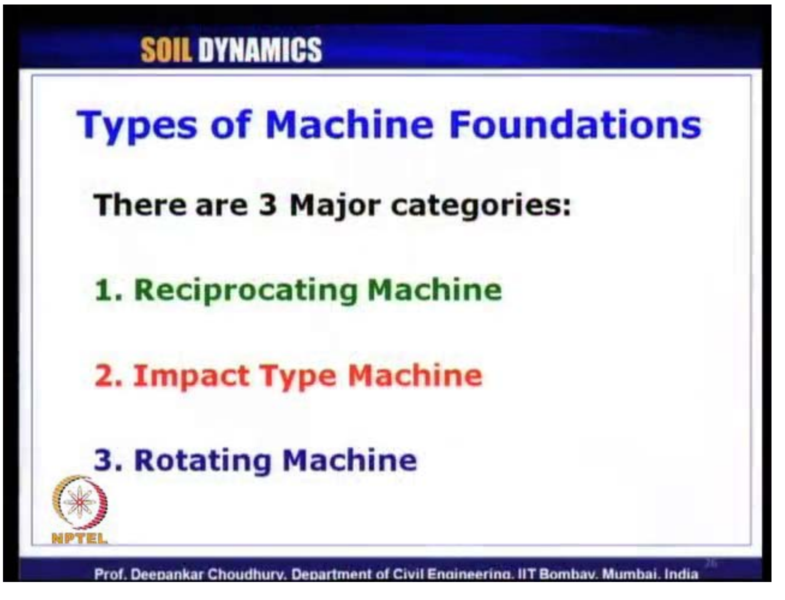

Those are for three different categories of machines, the first category is reciprocating type machine. Second category of machine is impact type of machine and third category of machine is rotating type of machine. So, these are three major categories of machines for which the foundations has to be designed. Now, within each of these let us see what are the different characteristics and examples what we can find.

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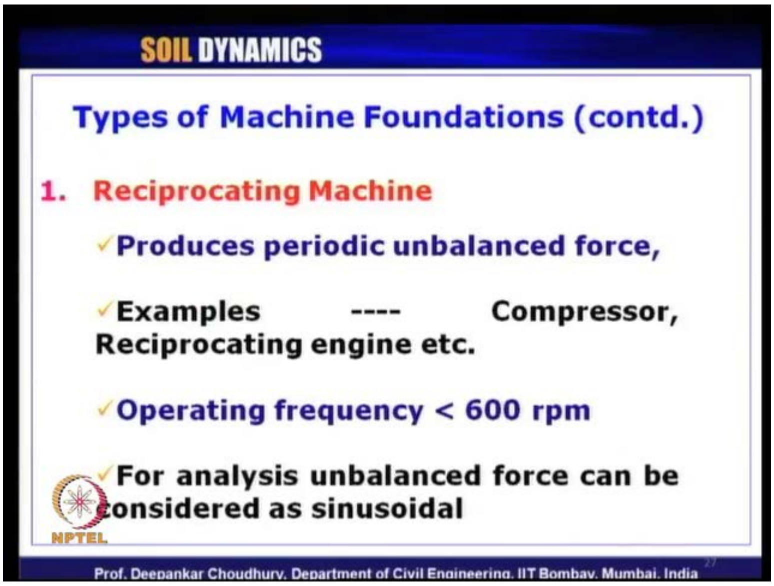

For reciprocating machine, the first category what are the features or characteristics? These machines produce periodic unbalanced force example of such type of machine compressor, reciprocating engine etcetera. What are the typical operating frequencies ranges of operating frequencies for reciprocating machine? They are usually less than 600 rpm. Rpm you know revolutions per minute. So in our SI unit when we are doing calculations we need to convert this rpm to cycles per second. For analysis of such machine foundation generally the unbalanced force can be considered as sinusoidal because the first characteristics what we have mentioned, they generally produce periodic unbalanced force. So, that is why they can be approximated as sinusoidal loading is acting for this kind of machine, it is considered.

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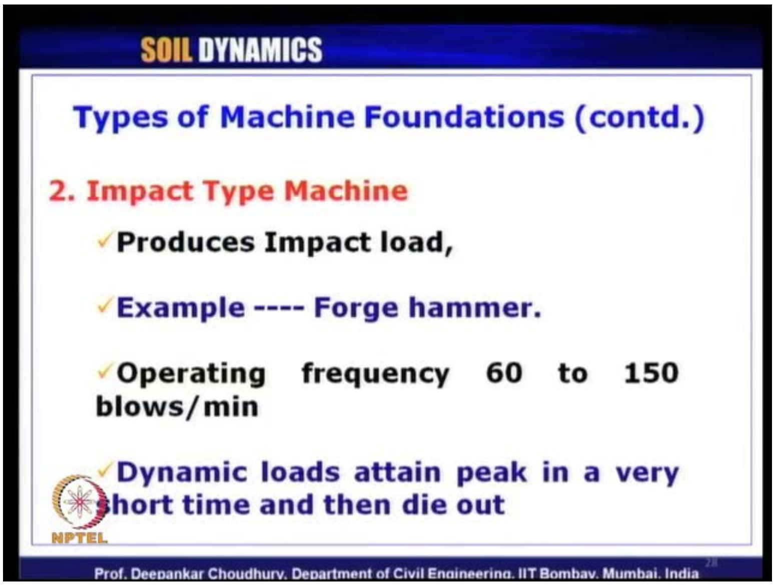

Coming to second category of machine, that is impact type of machine. Of course, they produce impact loads as the name suggest. In this category example of impact type of machine is forge hammer and what is the typical range of operating frequency for these machines typical range is about 60 to 150 blows per minute. That is the typical operating frequency for impact type of machine. As we know about the characteristics of impact load dynamic loads attain peak value in a very short time and then die out. That is the characteristics of impact load that we already know. So, obviously the same thing same type of load impact load will act on these type of machines, impact type of machines as the name suggest.

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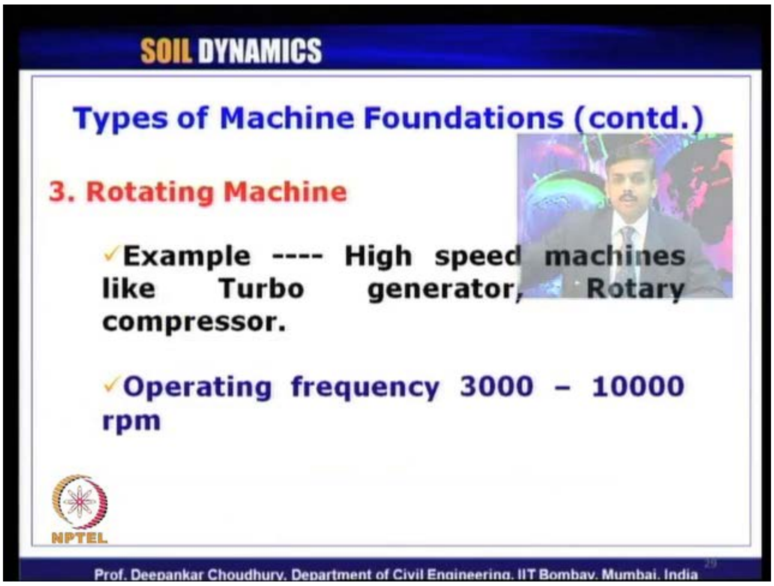

Coming to next that is third category of machine, which is rotating type of machine; example for them high speed machines like turbo generator like in power plants we use turbo generator, rotary compressors, these are coming under rotating type of machine, very high speed machine. What are the typical ranges of their operating frequency generally in the range of 3000 to 10,000 of rpm, very high speed, operating frequency that is why so high. So, if you compared this third category rotating type machine with the first category of reciprocating type machine, you can easily see they are the operating frequency was much lower below 600 rpm in that range whereas, here the order is 3000 to 10,000 of rpm. Why these informations are necessary because it will guide us later on we will see what are the different types of design, we can go for.

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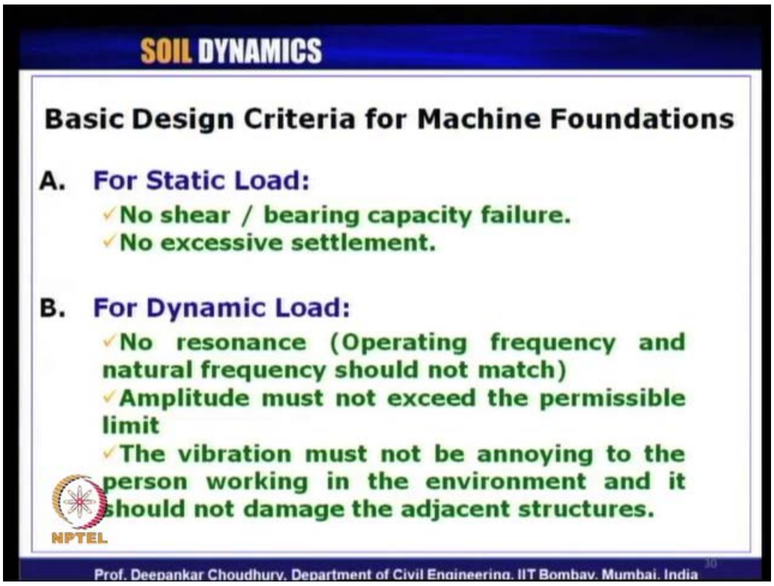

What are the basic design criteria for machine foundations? First one of course, these foundations has to be designed for the static load. These foundations should be well design to take care of the static loads coming on the foundation. So, what are the checks we do for static loading? We have to do the same thing here that is no shear or bearing capacity failure should occur. That means we have to check the bearing capacity of the foundation and have to satisfy, the factor of safety with respect to bearing capacity etc. Whatever we provide in static design of any kind of footing shallow footing of course, here we are taking about mostly shallow footing, we have to check that criteria.

The second criteria we check about no excessive settlement, that is amount of settlement also we need to calculate under static load and that has to be compared with different codal guidelines. As we know for isolated footing as per IS code about 50 millimeter. That is what is the vertical settlement. So, like that raft it is 75 millimeter like that different ranges are already given as per different design code, that has to be checked whether that criteria is satisfy or not. When you are going to design any foundation irrespective of whether it is machine foundation or not. Now, what additional checks we need to do for the design?

That is for dynamic loads of course, these are additional loads coming for these foundations, which are supporting the machines. So, in that check for dynamic load, we have to check for three criteria. These are the three major points. What are those? The first one is no resonance condition of course, the under the dynamic load your foundation should not resonate. Otherwise what will happen, it will have excessive settlement or excessive deflection because we have seen at resonance. the DMF dynamic magnification factor compared to that is dynamic displacement compared to the static displacement is tremendously high. So, that condition has to be avoided so, no resonance condition.

To do that, what is the basic criteria we should follow that operating frequency of the machine must not match with the natural frequency of the machine plus foundation system. So, when we are talking about the system when we are designing the foundation we are not only talking about the foundation itself we are talking about foundation plus machine together because the entire assembly is going to vibrate together So, remember when you are calculating the natural frequency. The natural frequency has to be calculated for the entire system, not for the foundation only. So, remember this this is an important point because consideration of your mass of the, which mass you should take the foundation mass or the foundation mass plus the machine mass, that is what you should take.

The second one to calculate the natural frequency to avoid the resonance. So, they should be far away from each other. Second important criteria for design is that dynamic displacement amplitude, the amplitude of displacement under dynamic condition what we are obtaining that amplitude must not exceed the permissible limit. That permissible limit again will be given by different codal provisions, that we will discuss for our IS code, what is the codal provision? So, we must not exceed the dynamic amplitude should not exceed that permissible limit given to us, it is in addition to this static settlement. Remember this here we are talking about only the dynamic component of the amplitude.

What is the third criteria? Third criteria is based on the vibration of the machine and foundation system together, it must not be annoying to the person working in the environment and it should not damage the adjacent structures. So, when you are designing any machine foundation, what you should not only provide a strong foundation which can take care of the dynamic load by assuring that it is safe against bearing capacity failure, excessive settlement under static load condition as well as it is safe against no resonance criteria and this amplitude dynamic amplitude is less than permissible limit.

Even then there can be a chance that, the vibration created by your machine and foundation assembly be dangerous for adjacent structures or it can be annoying to the persons, who are staying in surrounding area. So, that should not be there. So, this is a kind of qualitative assessment. All other four criteria, first two for static and first two of the dynamic. These four are quantitative criteria, when you are going to design the foundation you can check quantitatively these parameters providing factor of safety and things like that you can design a safe foundation for the machines. However, this last criteria is based on a qualitative issue. So, how to measure that? This qualitative assessment has been provided by Richart.

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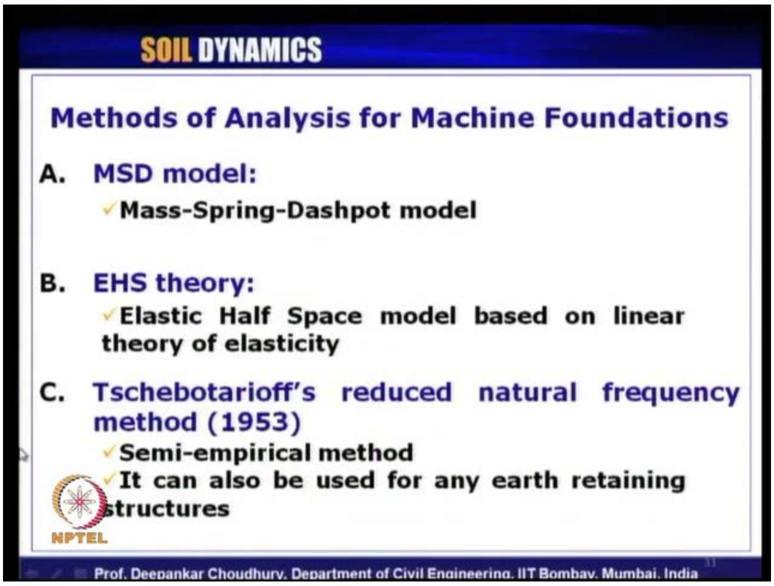

That I will show you soon. In some of the slide later on let us discuss now, different methods of analysis for machine foundations. There are basically three methods of analysis for design of machine foundation. The first method is called MSD model that is nothing but mass-spring-dashpot model. The second method is called EHS theory, EHS theory means it comes from this elastic half space, EHS elastic half space model it is based on linear theory of elasticity, that is another method of analysis for designing machine foundation. And the third method is called Tschebotarioff's reduced natural frequency method.

The method proposed finally, in 1953 by this scientist Tschebotarioff. What about this method? This is a kind of semi-empirical method that is Tschebotarioff had proposed for different types of soil based on different frequency, exciting frequency, what at the reduced natural frequency of the machine plus foundation system. So, it is a semi-empirical method proposed through design charts by this Tschebotarioff's Originally this method was developed also for earth retaining structures. So, it can also be used for any type earth retaining structure analysis or design. Now, we will go through each of this theory and we will see that how one machine foundation can be designed using all these three different theories. Now, typical types of machine foundations which are generally designed, those are block type, box or caisson type and wall or frame type.

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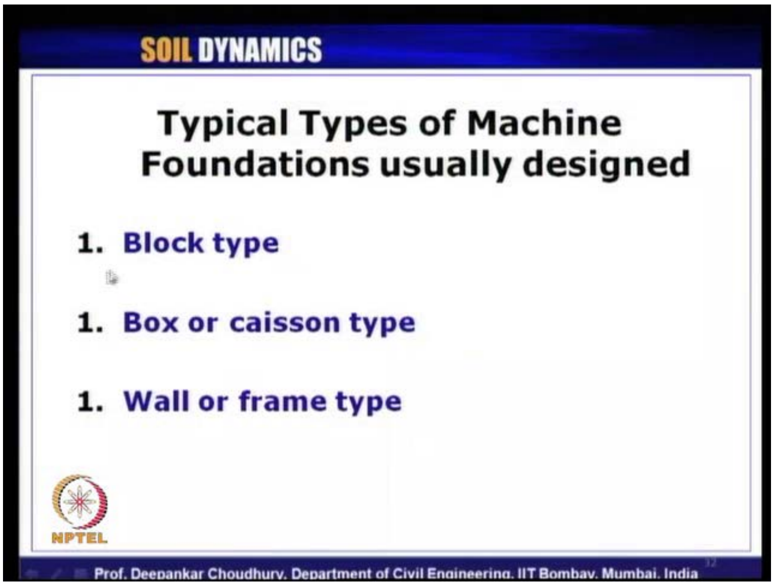

So, these are three typical major types of machine foundations, which are generally designed. Block type machine foundation, box or caisson type machine foundation, wall or frame type machine foundation.

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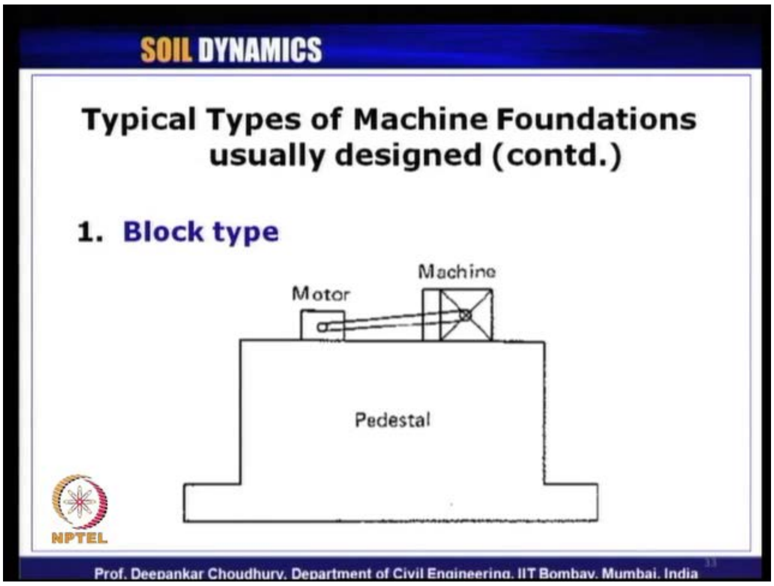

Block type machine foundation will look like this, as the name suggest it is a solid block made of concrete mostly. So, this pedestal machine motor like that, it will be positioned on the top of the block. So, this is the most common type of machine foundation used worldwide. Block type of machine foundations, just a concrete block huge mass of area and depth.

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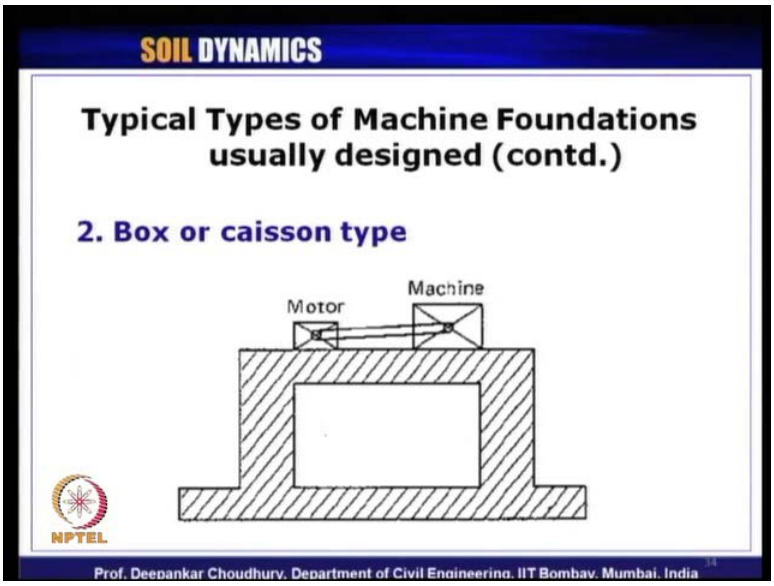

Second type of machine foundation is box or caisson type. It depends when you will go for box or caisson type to save some material of your concrete because in the block type of foundation sometimes in the design procedure you may find that if you provide a block type of foundation, it requires a huge size means area as well as height of the foundation. In that case sometimes it may lead to an uneconomic design, in that case we can check if we can provide a box or caisson type of foundation where this will be a hollow portion and these are concrete area and on top of it, this machines will be positioned.

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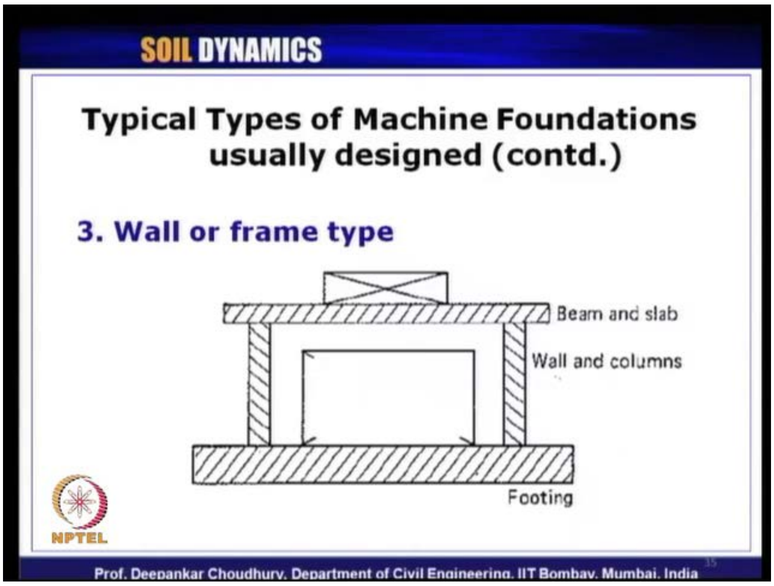

And the third category of machine foundation is wall or frame type of machine foundation. So, it is like as we go for the structural frames, in the same fashion we have a footing then walls and columns and then a beam and slab on top of which we position the machine. So, that is nothing but called wall or frame type of machine foundation. Generally for the third category of machines, where they are subjected to very high operating frequency like turbo generator etc many a times we have to go for probably this wall or frame type of foundations. Whereas, for reciprocating machines etc where operating frequency is pretty small, block type of foundation will be more commonly used or economically valid.

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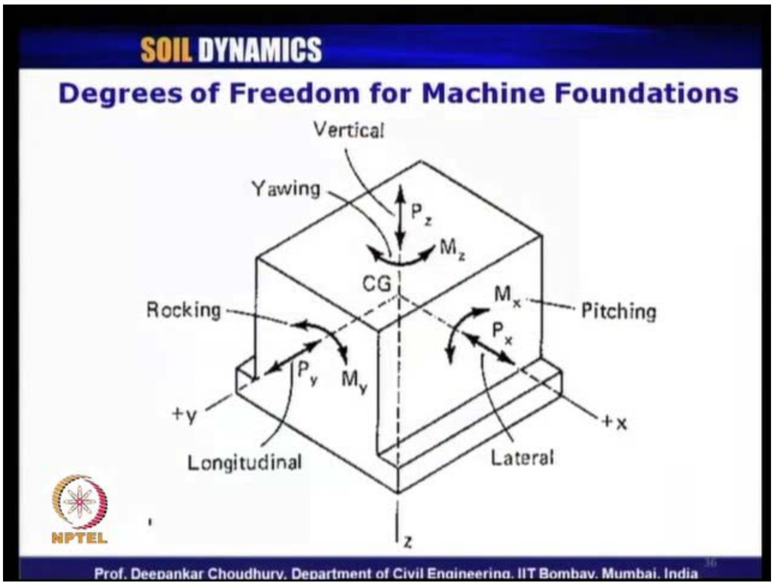

Now, let us discuss what are the different types of motion that machine foundations can be subjected to. In other words how many degrees of freedom one machine foundation can be subjected to. Of course, it is a three dimensional body so, it can have 6 degrees of freedom, that is three translational and three rotational, total six degrees of freedom. Now, what are those named? What are those vibrations called for machine foundation? So, this is a block type of machine foundation is shown in this picture, we have three orthogonal axis system, this is x-axis, this is y-axis and this one is z-axis.

If the foundation is vibrating in this direction. that is called vertical vibration for machine foundation. In that case the dynamic load is this P z, that is vertically applied dynamic load. That is causing the vertical vibration to the machine. Next one is look at this, when it is vibrating about this direction that is in x direction it is vibrating, under the action of this dynamic load P x, then it is called lateral or it is also called sliding mode of vibration lateral or sliding mode of vibration.

Now, when the machine foundation vibrates in this direction, that is when it is subjected to the dynamic load of P y like this, then the name of the vibration is longitudinal vibration or again it can be called as sliding vibration. Remember here sliding occurs in x direction, here sliding occurs in y direction. That is the only difference, otherwise both of them can be called as horizontal vibration or sliding vibration or lateral or longitudinal vibration. So, these are the common terminologies, you should remember they are called horizontal vibration or sliding vibration or lateral or longitudinal vibration and this is one is vertical vibration.

Now, these three are the translational vibration. Now, let us see the three rotational vibrations. When your machine foundation is subjected to a dynamic load like this that is subjected to a moment M x dynamically applied it can rotate about x-axis that mode of vibration is called pitching mode of vibration, it is called pitching mode of vibration. When the block foundation is subjected to a dynamic load, M y like this, then the rotational vibration of the block about y-axis is called rocking mode of vibration and when the block is subjected to a dynamic load like this M z in that case it is called yawing mode of vibration. So, three rotational modes of vibration for any machine foundations are pitching rocking and yawing so, total six modes of degrees of freedom or six modes of vibrations for any machine foundation are vertical vibration two horizontal vibrations pitching vibration rocking vibration and yawing vibrations.

Now, depending on your applied load either any one of them can occur for your machine foundation system or a combination of them can occur for a machine foundation system. So, we have to check that when we are going to design a machine foundation? What are types of dynamic loads acting on the system and what are the possible modes of vibration based on that your analysis will lead you to whether it is individual rocking pitching or vertical or horizontal mode of vibration or a combined effect of sliding and rocking something like that. So, that we have to decide based on the given load conditions.

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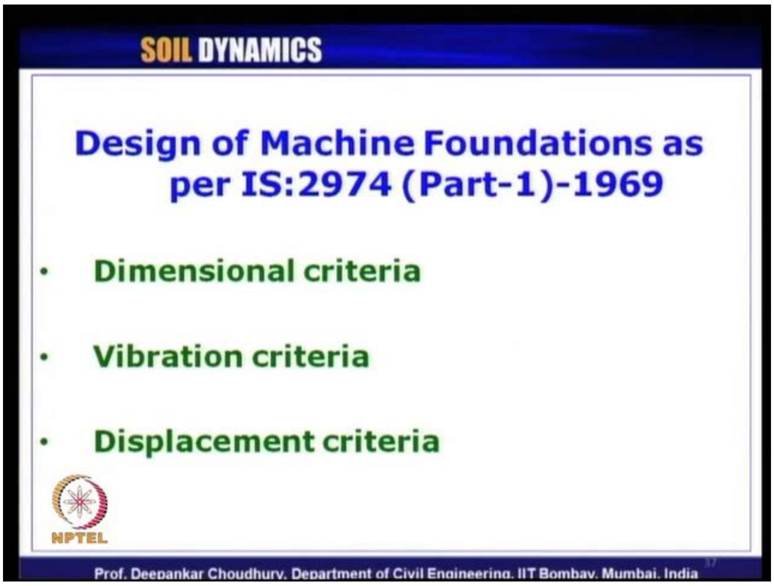

Now, coming to the Indian standard design code provisions. What it says design of machine foundation as per our Indian standard code IS 2974 part one of 1969. It says that machine foundation has to be designed by checking three criteria's. One is called dimensional criteria, another one is called vibration criteria and the third one is called displacement criteria. So, these are the three major criteria, which needs to be checked when we are going to design a machine foundation as per our Indian standard design code 2974. What are these criteria? Let us discuss them in detail now.

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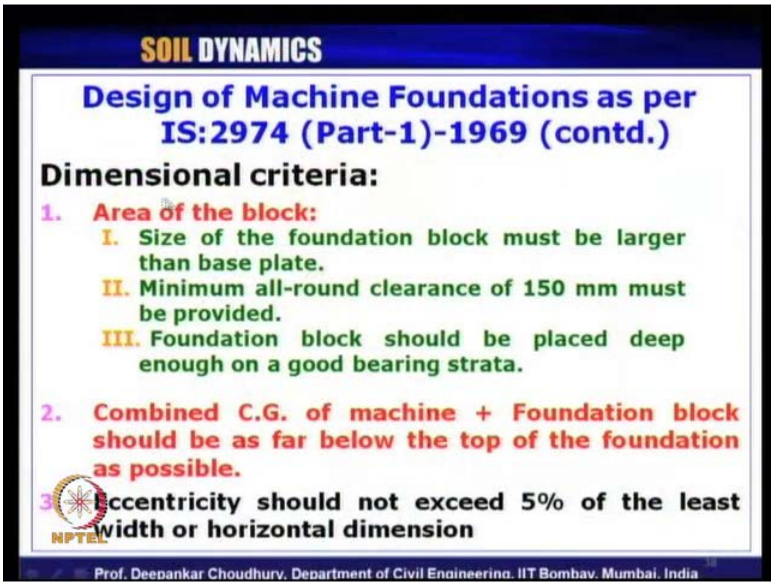

The first one dimensional criteria. What it says in dimensional criteria, we have to find out or check the area of the block. We are going to provide block means block type of foundation assuming that we are providing a block type of foundation. What are the criteria given that size of the foundation block must be larger than the base plate of the machine, which is quite well understood and quite obvious actually. Suppose, we have a machine for which we have a base plate like this. This is the plate provided by the manufacturer to us on top of it the machine will be kept and finally, this plate has to be placed on top of our block type of foundation.

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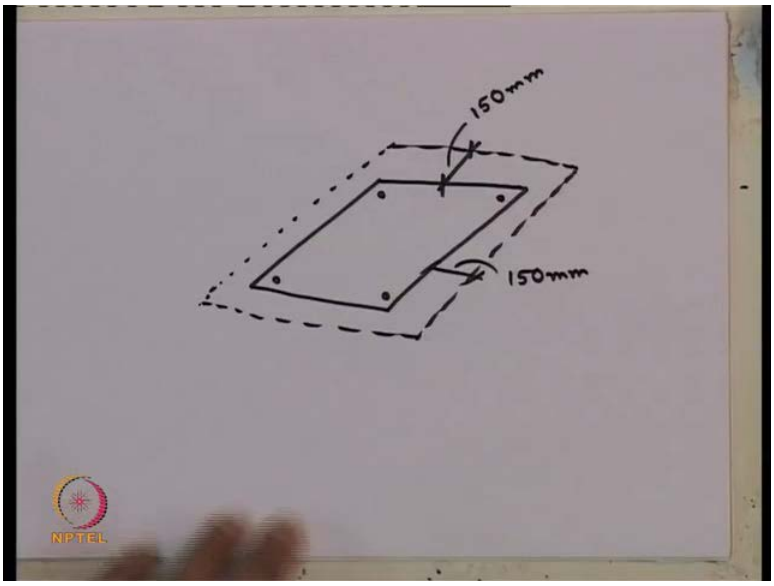

What it says through these points? We will bolt or connect the base plate mostly the steel type of plate to the concrete block type of foundation and for that purpose, what we need? The area of the block, which we are providing should be bigger than that of the base plate otherwise we cannot fix them of course. So, let us look, it look at here again in the slide. The second criteria says minimum all-around clearance of 150 millimeter must be provided. So, this is the second guideline it says as per our IS code, what it says? That this clearance has to be 150 millimeter all around. 150 millimeter minimum. This is the minimum clearance, we have to provide all around the base plate and foundation edges.

Let us look at the slide once again. Third criteria says that foundation block should be placed deep enough on a good bearing strata. Of course, we should place it in a good soil, stiff soil which can take that vibration of the machine plus foundation system. The second criteria says that combined C G combined center of gravity of the machine plus foundation block, that is we can easily calculate by knowing total size and height of the foundation after designing it, we know where the C G of the foundation lies and also for the machine weight we know where the C G etc lies for the machine. Now, you combine them this combined C G of the machine plus foundation block should be as far below the top of the foundation as possible. That is it should be as close as to the base of the machine plus foundation system.

Why because if there is some eccentricity arising out of your operation of the machine in future or if some additional loads are allowed later on on the foundation, it should not create the rotational vibrations in future. So, that is why if you keep the C G of the entire system as low as possible, obviously your generated moments etc load coming on the foundation will be much lesser that is why this criteria is mentioned. And the third criteria for the selection of the area, it says eccentricity should not exceed 5 percent of the least width or horizontal dimension. That is whatever is the least or smallest width or smallest horizontal dimension of the block foundation you are designing, 5 percent of that can be the maximum eccentricity, which can be allowed for your loads etc which is applied on the foundation.

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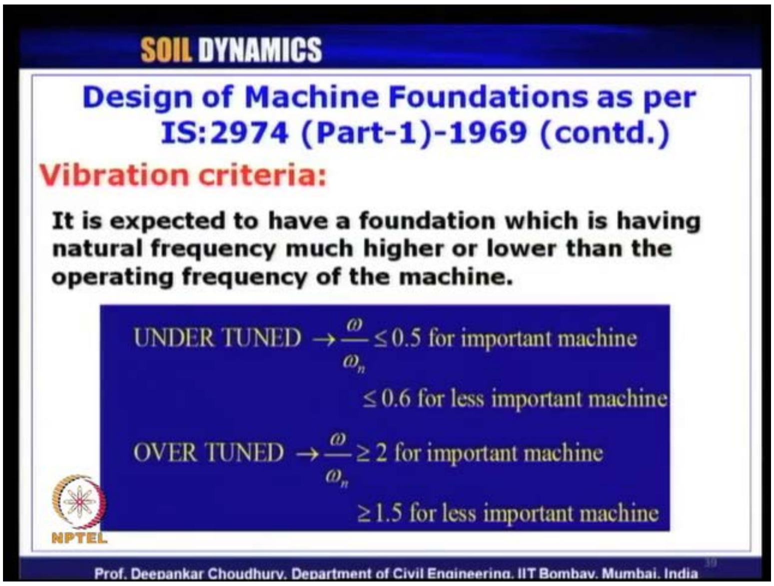

Now, let us go to the next criteria which is vibration criteria. The vibration criteria it says it is expected to have a foundation which is having natural frequency, either much higher or much lower than the operating frequency of the machine. Which is well understood to avoid the resonance criteria, that no resonance condition the first condition of basic criteria for design of machine foundation. So, that is why the natural frequency of the machine plus foundation system should be much higher or much lower than the operating frequency of the machine. Now, there are two cases mentioned. One is called under tuned another is called over tuned. What are these? Let me explain you.

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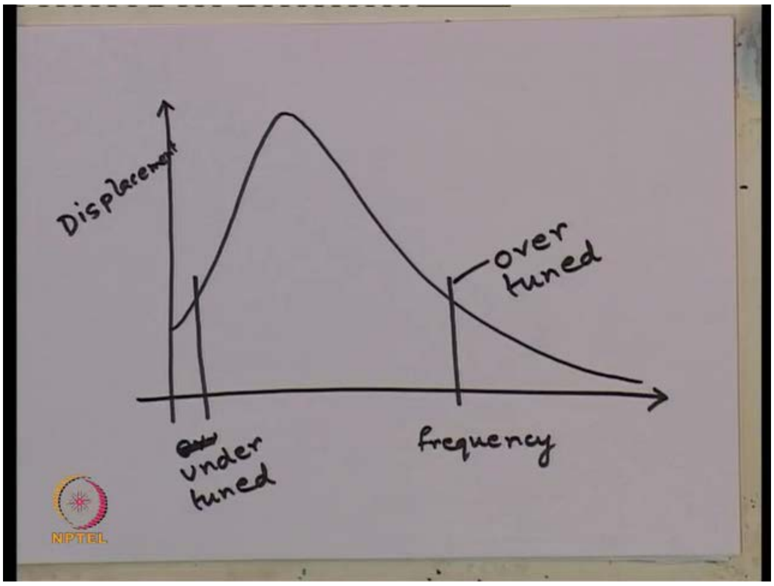

If we plot typically the frequency in x-axis and here the displacement so, typical variation will be something like this. Now, resonance occurs for this frequency. Now, if you keep your operating frequency of the machine far away from this point, either here or here it will be safe. That is, if this is denoting your now, the applied frequency in that case, it has to be far away from this resonance condition to have much lower displacement. So, easily you have seen we can have either of the very high value than natural frequency or very low value than the natural frequency of the machine plus foundation system, to take care of this no resonance criteria.

What are the cases are proposed values typical ranges under tuned means this omega is operating frequency and omega n is natural frequency of the system. If the ratio of operating frequency to the natural frequency, is less than or equals to 0.5 that has to be used for important machines and for less important machine, we can go up to 0.6 also. So, in that case what is happening your natural frequency of the system is much higher than the operating frequency. So, operating frequency is much lower. So, in the picture what I have drawn here let us look here, this case is called under tuned. That is when we are putting our operating frequency, much lower than the natural frequency and the other case it is called over tuned.

So, what is over tuned? In that case operating frequency is much higher than the natural frequency. So, in the slide also it is shown. Let us look at the slide. Over tuned this is operating frequency, this is natural frequency. Ratio of them should be greater than or equals to 2 for important machines and it can be greater than equals to 1.5 for less important machine. Remember this sign as quite obvious from the understanding here it should be less than or equals to whereas here it should be greater than or equals to, to keep them far away from each other. Now, which one has to be chosen? Can you think about it which condition of this under tuned or over tuned you should select as a designer, when you are going to design a machine foundation.

It depends on the operating frequency or the type of machine for which you are going to design the foundation. For example, if we are going to design the turbo generator machine for that if we are going to design the foundation for which operating frequency is very very high, in the order of 3000 to 10,000 rpm. In that case which condition you will prefer under tuned or over tuned? It should be over tuned because if you want to design an under tuned type of foundation for a machine like turbo generators you will end up with very very high value of omega n because already omega is pretty high omega n will be excessively high.

What does it mean? omega n excessively high means mass of the foundation will come negligible. This k has to be excessively high because omega n is nothing but root over k by M. In that case you will find some absurd result, sometimes your result after doing all calculations you will get negative value of mass is required or no mass of the foundation is required, but it is not the case.

So, your given value or input value of operating frequency decides whether you should go for over tuned case or under tuned case. So, for that you have to go for over tuned design, you do not have any other choice. Whereas let us look at the other type that is the first category of machine, reciprocating type. Where typically the ranges of operating frequency are below 600 rpm pretty low. In that case which type of design you should go for? Of course, under tuned because this omega value is pretty low. So, you can go up to a high value of omega n in that case if you try to do a over tuned design. Let us see what will happen in that case omega is pretty low, omega n to maintain this factor these are nothing but kind of factor of safety right we can say these are factor of safety against resonance condition.

So, to maintain this values your omega n has to be again much much lower. What does it mean? Omega n much lower means, mass of the foundation system will be very very high. Means unnecessarily you are going into an uneconomic design so, in that case you are able to design actually not like the previous case that you will get a absurd result. Here you will get some possible dimensions of your foundations, but it will be an uneconomic design. So, you have to check probably for some of the intermediate operating frequencies.

Suppose, in the range of say 1000 rpm or even in the range of 600 rpm it is always better to check your design for both over tuned and under tuned. Then you will get a, an idea what are the dimensions of your footing required by considering whether under tuned or over tuned. Then you do the cost analysis and provide or suggest accordingly that is both safety and economy is maintained. Now, let us see the third.

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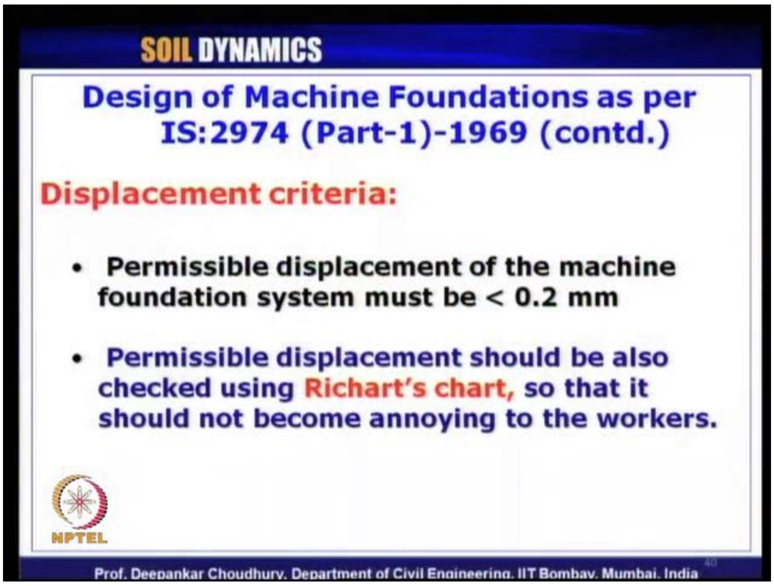

Criteria as per the IS code, that is displacement criteria. What it says? That permissible displacement remember, this displacement means only the dynamic displacement we are talking about amplitude of displacement to be specific we are talking about only the amplitude of dynamic displacement, that permissible value for machine foundation system is, it should be less than or equals to 0.2 millimeter very very low. So, dynamic displacement range it should not exceed 0.2 mm. If it is exceeding, then you have redesign your foundation. The other criteria that is permissible displacement criteria from qualitative assessment.

As I was talking earlier the third criteria for dynamic loading that is it should not be annoying to the surrounding people or it should not be damaging to the adjacent structures to maintain that the permissible displacement should be checked using Richart's chart. So, that it should not become annoying to the workers or adjacent structures like that. So, Richart's chart is worldwide it is used because this chart only provides us that qualitative assessment. That needs to be checked when you are doing any design of machine foundation, IS code also suggests that. Let us look at the Richart's chart now.

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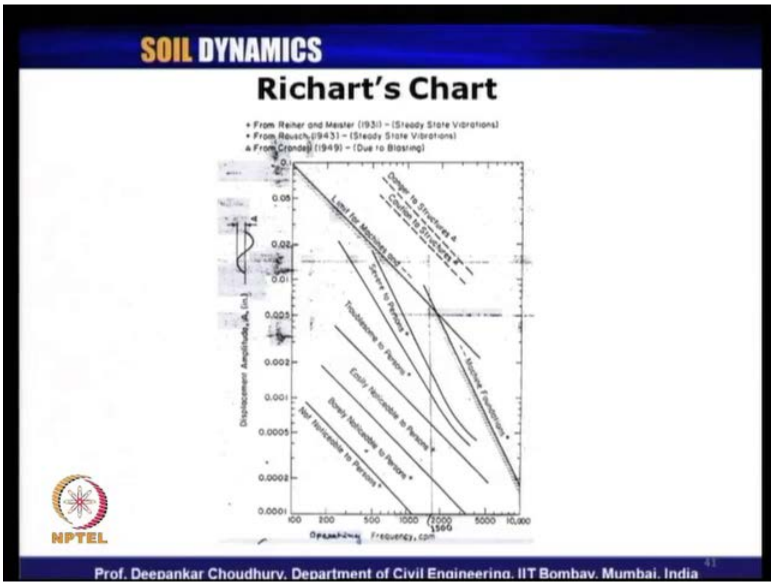

This is Richart's chart. You can note down this Richart was proposed by the scientist Richart in 1962 and this chart is valid for only vertical mode of vibration please note it down. This chart how was developed? It was developed from several experimental results, that is what if you look at the top of the chart it is given that from Reiher and Meister in 1931 steady state vibration, from Rousch 1943 steady state vibrations, from

Crondel 1949 due to blasting. So, after assembling all these affects Richart, what he did? He divided the chart into different zone. What is y-axis of the chart that is displacement amplitude and of course, this is dynamic displacement.

It is what the to mention it is amplitude only. So, that is why they have shown here this is the maximum value. This a and unit also you should record it is in inch unit, Richart chart is in FPS unit So, whenever you are doing your design in SI unit you need to convert it, that is after getting calculated the dynamic displacement amplitude, you need to convert it to inch unit, to read your Richart chart. What is x-axis? x-axis gives frequency, it means operating frequency of the machine. In the unit CPM. CPM means cycles per minute that is same as revolutions per minute nothing but and remember this x-axis is in logarithmic scale also y-axis is in logarithmic scale. So, that is why this is 100, this is 1000, this is 10,000.

As I said, turbo generators etcetera will be in this range of operating frequency whereas, your reciprocating machines will be in this range of operating frequency. Now, based on your machine for which you are designing the foundation and from your calculated displacement amplitude from the analysis using any of the model, you go to this chart then your point will come to any of this zone. So, that will guide you whether it is good or not? So, what Richart said this line this boundary gives not noticeable to person. So, suppose if your point after calculations it comes somewhere say operating frequency was 500 rpm and maximum displacement amplitude in inch is 0.0002 inch so the point will come here that means your designed foundation will not create any problem, to any people or any adjacent structure because the vibrations are not noticeable to persons. That is the most safest zone.

Next zone is this one barely noticeable to persons. If your point design point comes here it will be hardly noticeable to the person. Next zone is easily noticeable to person, this zone is troublesome to person, this zone is severe to persons, this is the final limit for machines and machine foundation. So, beyond this we should never go because then danger to the structures or caution to the structures come into play that is adjust structure will be affected. So, it is always preferred to be up to this maximum of easily noticeable to person zone but preferably if it is within these two zone. Then you have designed your machine foundation in the best possible way so, this is the qualitative assessment one must do for machine foundation design.

But you can see for very high value of rpm it is very very difficult to come to this zone. So, that is why I said you can go up to this zone also for turbo generator, that is why of course, we know that power plants etc or not in the close vicinity of any residential area or things like that or hospital or schools and more so far their turbo generators etc because of this result. Now, this chart what I have shown you. This is valid only for vertical mode of vibration. what about other modes of vibration? One more chart is available.

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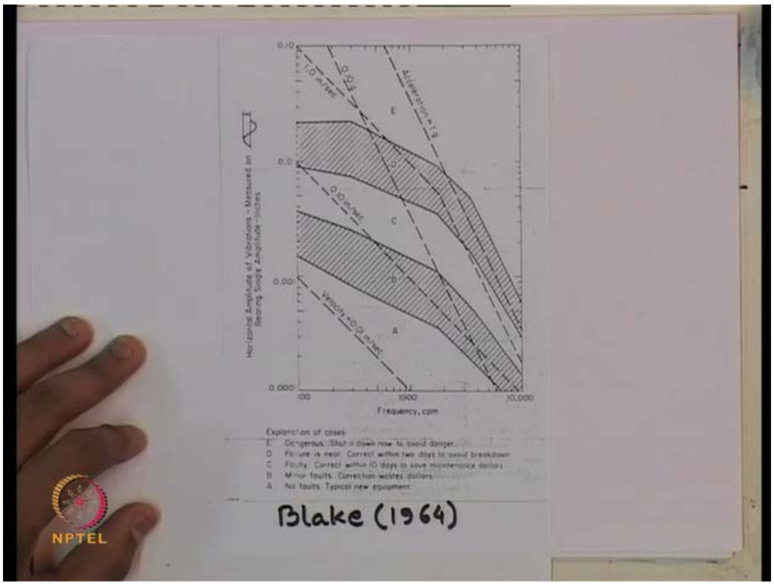

Let us look here. Yes this chart this chart was given by let me write it here Blake. B l a k e in 1964. This chart is valid for horizontal mode of vibration. See you can note down this chart is useful for same purpose, same purpose what for the Richart's chart is used for vertical mode of vibration here also it is used for horizontal mode of vibration. In this case x-axis again frequency in CPM cycles per minute and y-axis gives us horizontal amplitude of vibration measured on bearing single amplitude in inch unit once again. Ranges of different velocities and accelerations are given, depending on that zones have been marked as a, b, c, d or e as you can see obviously in this region a means no false typical new equipment.

So, no danger whereas, e will be dangerous that is the machine immediately it should be stopped to avoid danger to surrounding structures and foundations. So, this is another chart which has to be used for horizontal vibration. So, now let us discuss those three major methods for design and analysis of machine foundation. Let us start with the third method. First that is Tschebotarioff's reduced natural frequency method.

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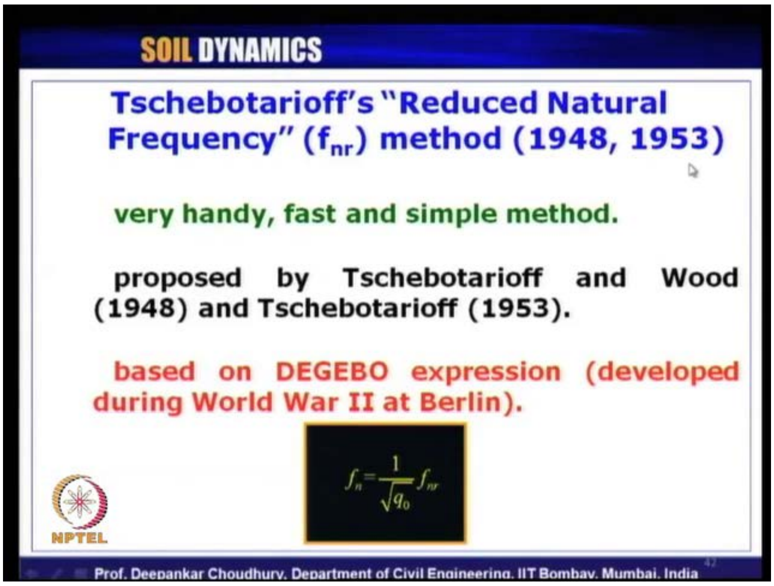

It was initially developed in 1948 and finally, it has been modified and proposed in 1953. What are the major characteristics of this method? This method is very handy, very fast and very simple to use. It is semi-empirical method, they are very handy, fast and simple method. It was originally proposed by Tschebotarioff and Wood in 1948 and later on further modified by Tschebotarioff in 1953. So, that is why finally, it is called Tschebotarioff's reduced natural frequency 1953. What was the basis for deriving or formulating the semi-empirical method? The basis was based on DEGEBO expression. DEGEBO is the short form of an agency, it was operational during second world war at Berlin.

Hitler used this to protect the underground or to protect soldiers and arms etc against any type of vibrations or bombing. So, that is how this DEGEBO model was proposed, that was used and further modified and so on and finally, it took a shape of today's Tschebotarioff's that 1953 reduced natural frequency method. How this is done? In this expression, what is given here f n is nothing but natural frequency of the machine plus foundation system. Remember this is f not omega omega is circular natural frequency. So, you need to convert when you are doing this analysis. Q naught is called average vertical contact pressure between base of the foundation and soil and this f n r is called reduced natural frequency. That is what I have mentioned here f n r. f n r is known as reduced natural frequency as was proposed by Tschebotarioff. Now, let us see what is the use of this method.

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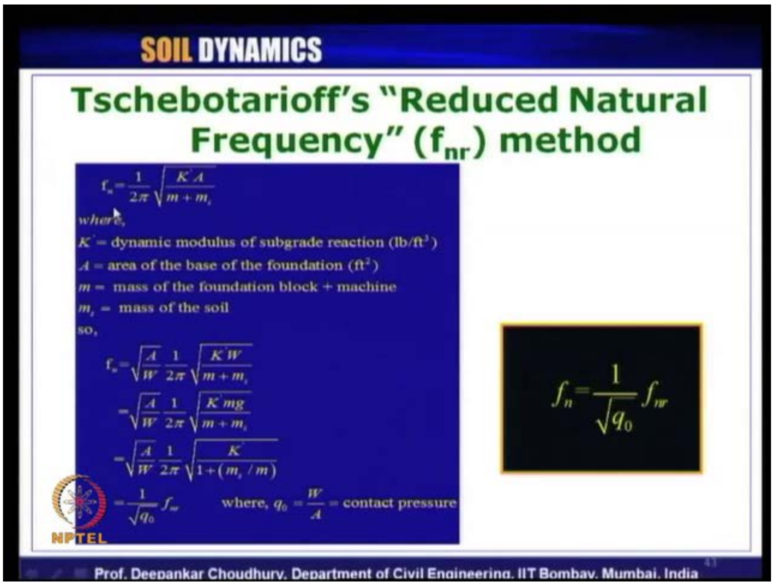

Now, natural frequency how the natural frequency is calculated? We all know omega n is nothing but root over K by m. So, when we are talking about f n it will be omega n by 2 pi. So, omega n is root over K by m. now, it is K can be represented as K dash times a. What is K dash? K dash is dynamic modulus of sub grade reaction. So, unit of it will be in kiloNewton per meter cube. If we are using SI unit but as Tschebotarioff has proposed this semi empirical method in FPS unit. Let us stick to FPS unit only. So, automatically the dynamic modulus of sub grade reaction unit will be pound per feet cube. We have seen how to estimate this K dash.

Earlier we have use the symbol c z, the same thing. In cyclic plate load test we had computed c z so, that is nothing but same as K dash here dynamic modulus of sub grade reaction. What is A? A is cross sectional area of the base of the foundation in the unit of feet square. So, that is why here you are getting the unit of stiffness, that is pound per feet or kiloNewton per meter, if you use SI unit. So, root over K by m. What is m? m comprise of mass of the foundation block plus machine and m s is called mass of the soil, which mass of the soil?

During this vibration when DEGEBO model was proposed, it was proposed that a portion of the soil is also vibrating along with the machine plus foundation. So, that portion of the soil which is vibrating along with machine and foundation is the mass of the soil we should take in this expression. But later on it has been simplified by Tschebotarioff's, that is why it is said that Tschebotarioff's basic model is generated from the concept of DEGEBO's model because in DEGEBO's model if we draw it.

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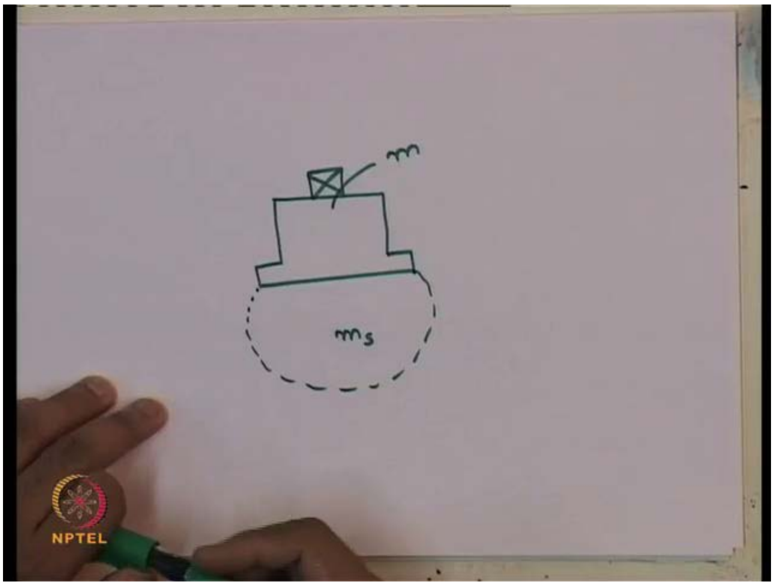

Suppose, if we have a block type of foundation. So, on top of it we have some machine here, we have machine plus foundation together some mass m and when it vibrates some portion of the soil is also getting vibrated along with this. That portion of soil is m s. So, that is what DEGEBO's expression it was developed in Germany and it has been now simplified by Tschebotarioff's in this fashion. f n can be rewritten this equation, root over A by W 1 by 2 pi root over K dash W by m plus m s. This W W gets cancelled so, it remains same root over A by W 1 by 2 pi root over K dash m g by m plus m s. W is the nothing but weight of the machine plus foundation, which is again further simplified as root over A by W into 1 by 2 pi into root over K dash by 1 plus m s by m.

Now, this W by A that is weight of machine plus foundation divided by the base area of the foundation is nothing but our contact pressure, at the base of the foundation. That is denoted by Q naught as I have said just now, in the previous slide. While explaining this notation this Q naught is nothing but contact pressure between the foundation base and the soil weight of the machine plus foundation divided by the area of the foundation. So, this root over A by W is nothing but 1 by root over Q naught and this entire term that is 1 by 2 pi times root over K dash by 1 plus m s by m is denoted by Tschebotarioff by this symbol f n r which is called reduced natural frequency. Why it is called reduced natural frequency?

Because in this case the natural frequency of the machine plus foundation system has been reduced by considering the effect of the soil, which is also vibrating in face with the machine plus foundation system. So, that is the reason why this terminology was proposed by Tschebotarioff that reduced natural frequency and this is the expression f n r given by Tschebotarioff. Finally f n and f n r are correlated by this simple expression. What Tschebotarioff's as given for different type of soil? This K dash value will of course, depend on your type of soil. This dynamic sub grade modulus of sub grade reaction depends on type of soil. What type of soil you are using? So, with this we have come to the end of today's lecture, we will continue further in our next lecture.