Analysis and Design of Bituminous Pavements

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Lecture – 21

Modulus for Design - Resilient modulus (Granular material)

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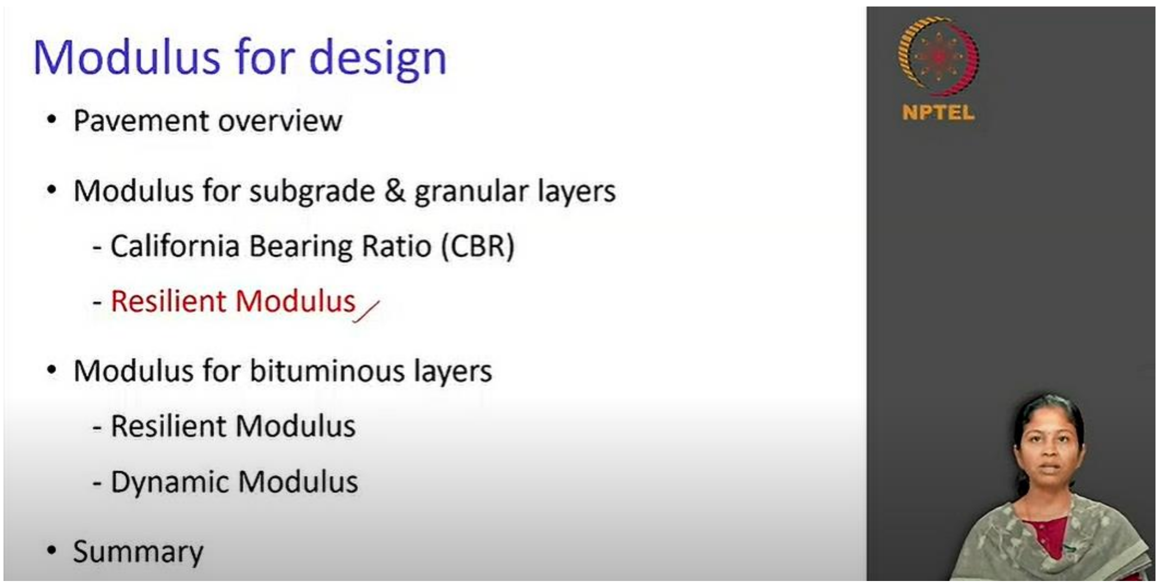

Welcome back. In this lecture, we are going to talk about the measurement of resilient modulus for granular layers. So, for all the granular layers which is nothing but your subgrade, subbase and base materials, the resilient modulus is the input parameter that we are going to use for design purposes. Let us see what this resilient modulus is. It is the parameter which is used to characterize all unbound pavement materials. So, the materials which you are using in your subgrade, which we are using in the base course and the subbase course are typically unbound granular pavement materials or kind of unbound granular materials in most cases. So, for those materials, we are defining something as resilient modulus. So, what is this resilient modulus? The pavement materials typically experience some kind of permanent deformation. So, once I apply the load, there is going to be some amount of permanent deformation. Irrespective of the type of layer, most of these layers might experience the permanent deformation part, except that the degree of permanent deformation will vary from layer to layer. Now, this permanent deformation may continue with n number of cycles or might be experienced for the initial portion of loading and it might reach a resilient state. What do we call as a resilient state? A state wherein there is no more permanent deformation and the material is able to recover most of its strain. So, that we define as a resilient state. So, this resilient modulus is an elastic modulus which is calculated once the material reaches this resilient state. So, it is calculated based on the recoverable strain values, when the material is subjected to repeated load after it reaches a resilient state. So, what this resilient state is, how is it calculated? I will show you with pictures a few slides down.

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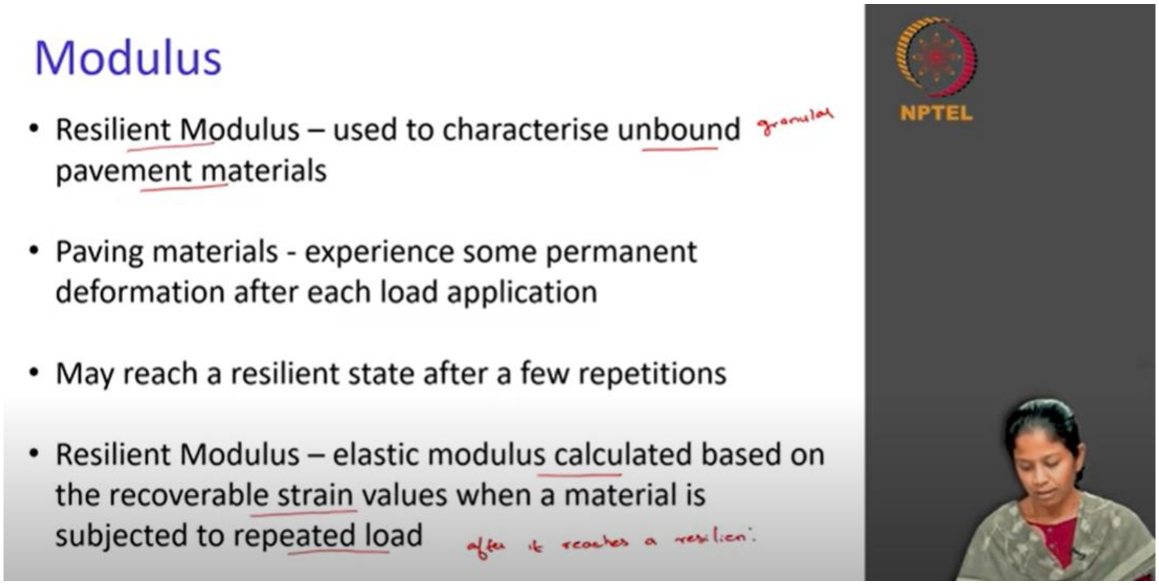

So, now what happens when I apply a load? Let us say that we apply a load like this. So, what this load is, how is it defined? Again, I will show that in a few slides down. So, let us as of now, assume that I apply a load like this. So, now, this is the starting point wherein the stress is 0 and as the stress increases, the strain also increases. Let us say the stress reaches a maximum, the strain will reach maximum at the same time or slightly later depending upon the nature of the material. So, let us say, this is this loading portion here. Once the maximum is reached, then the stress begins to reduce. So, this is nothing but my stress profile. So, now the stress begins to reduce and the strain is also reducing. So, it keeps reducing, you can see this recovery profile, then it comes back to 0. But you can see here that it did not come back to its original position. So, there is some amount of permanent strain that is experienced by this material and the amount of strain that is able to recover, this much amount of strain it is able to recover during the unloading portion. So, this is called as the resilient strain. So, this is for one cycle of loading.

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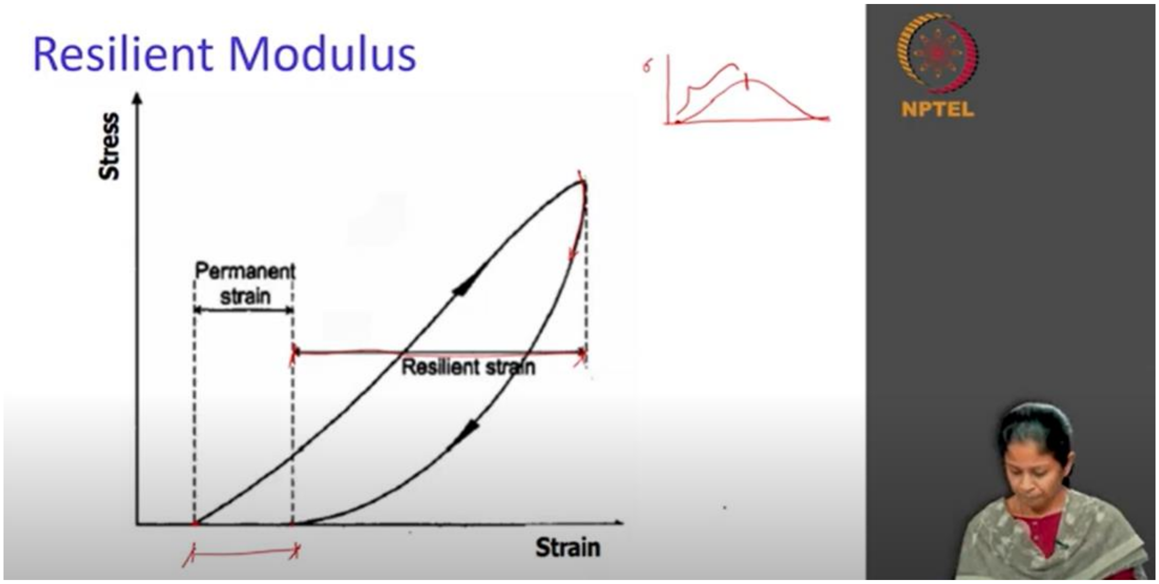

Now, the load is very small in magnitude compared to the strength of the material and is repeated for n number of times. Typically, that is what happens in a pavement application compared to the strength of the pavement, the load that is applied is relatively smaller and it is repeatedly applied for n number of times. So, what happens is after certain repetitions that number might vary depending upon the case, but typically after 100 or 200 repetitions, the deformation under each load is nearly like completely recoverable. So, it kind of reaches an elastic state as that we had discussed before. And this deformation when it reaches that resilient state, the deformation is also seen to be proportional to the load that is applied. So, in that particular scenario, the response can be considered elastic. So, there is an initial stage where there is permanent deformation and after certain number of repetitions, the permanent deformation is almost insignificant and it is considered that all the strains are completely recoverable. Then the material is considered to reach an elastic state and there the deformation is proportional to the load applied. So, in that case, the materials response can be considered to be elastic.

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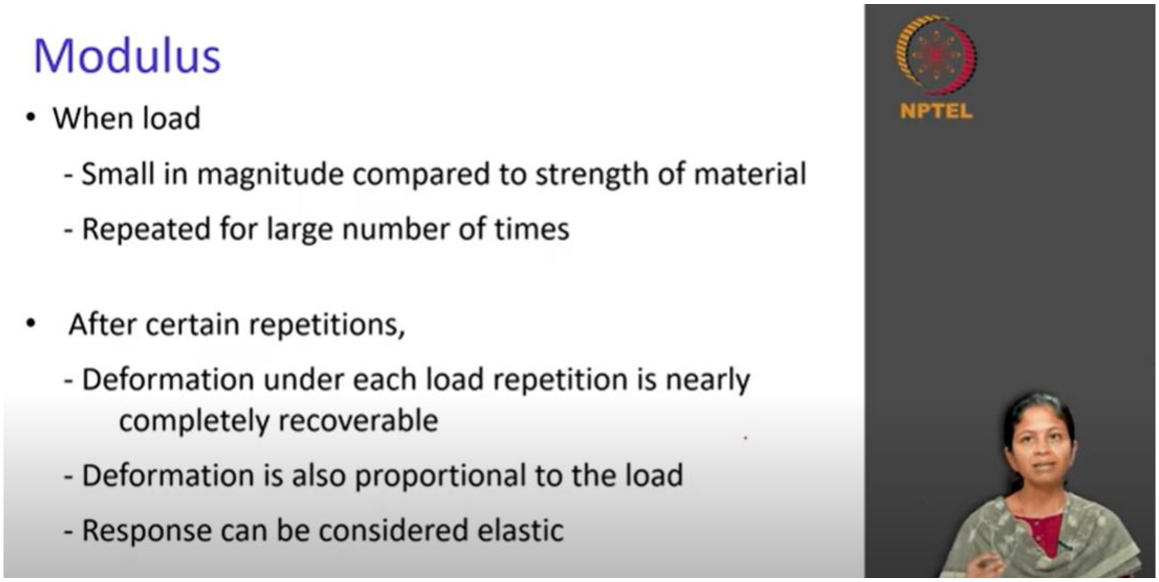

Let me now show this to you pictorially. Now, if you see, let us say that we apply a load, let us say that the load is like this, but we apply it repeatedly for n number of times. We apply, allow it to recover, then we apply, allow it to recover. So, the load is repeatedly applied. So, for the first cycle you can see here, this is the loading portion, this is the recovery portion, and then subsequently loading and then subsequently recovery and so on. So, we have n number of cycles. So, you can see here, initially there is some amount of permanent strain, you can see this is the strain that is not recovered, the y axis is the strain. So, you can see the strain keeps increasing and after some point of time, you can see beyond this point, the permanent strain is almost negligible. The accumulated strain remains constant after this n number of cycles. So, if this is the total strain, this much amount, how much it can recover is called as the elastic strain. And here in this portion, where it is able to recover most of its strains, that is called as the resilient strain. So, if I consider this as the total strain, this is the accumulated plastic strain basically to kind of indicate the irrecoverable portion of strain and this is the recoverable strain that we see here. So, initially there is considerable permanent deformation that is observed in most of the granular materials, that is what I was talking to you about in this portion. So, typically about 100 or 200 repetitions, this permanent deformation will kind of reduce. So, after 100 or 200 repetitions, the permanent strain will become insignificant. Then after these 200 repetitions, we can now consider the material to be in elastic state and compute the resilient modulus. So, as I said before, it is elastic modulus based on the recoverable strain value that we see under repeated load.

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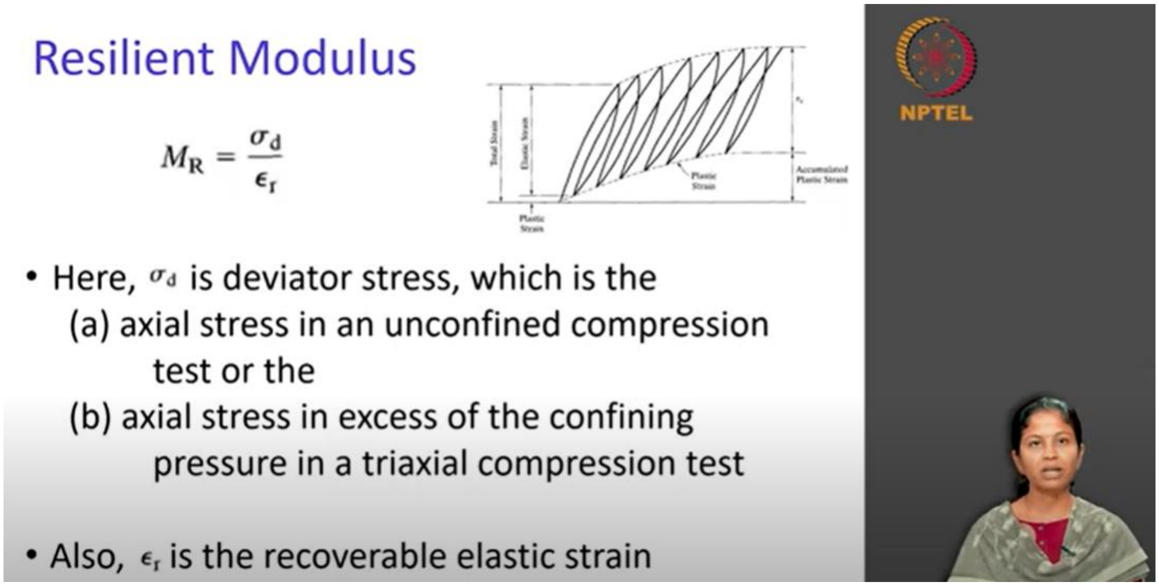

Now, let us define this resilient modulus. What is this resilient modulus? It is a ratio of two parameters. One is your deviatoric stress and second one is the recoverable strain. So, what is the deviatoric stress? It is defined as the axial stress in an unconfined compression test. So, if I do a UCC test, wherein I do not apply any confinement pressure, I simply apply an axial force. So, this axial force that is applied is called as the σ_d parameter or deviatoric stress or let us say, in case I am applying a confining pressure also to my sample, let us say this is σ_3 and this is σ_1. This σ_1 that I am applying, this axial stress in excess of the confining pressure, this difference between σ_1 and σ_3 is my deviatoric stress. So, over and above the confining pressure, what is the extra stress that I apply in this particular direction, in the axial direction that is called as the deviatoric stress. So, these are the two cases through which we can define the deviatoric stress. So, if I do without confinement, it is simply the axial stress and if it is with the confinement, it is the stress which is in excess of the confining pressure. So, that is called as the axial stress and ε_r is the recoverable elastic strain. So, it is nothing but the ratio of deviatoric stress to recoverable elastic strain.

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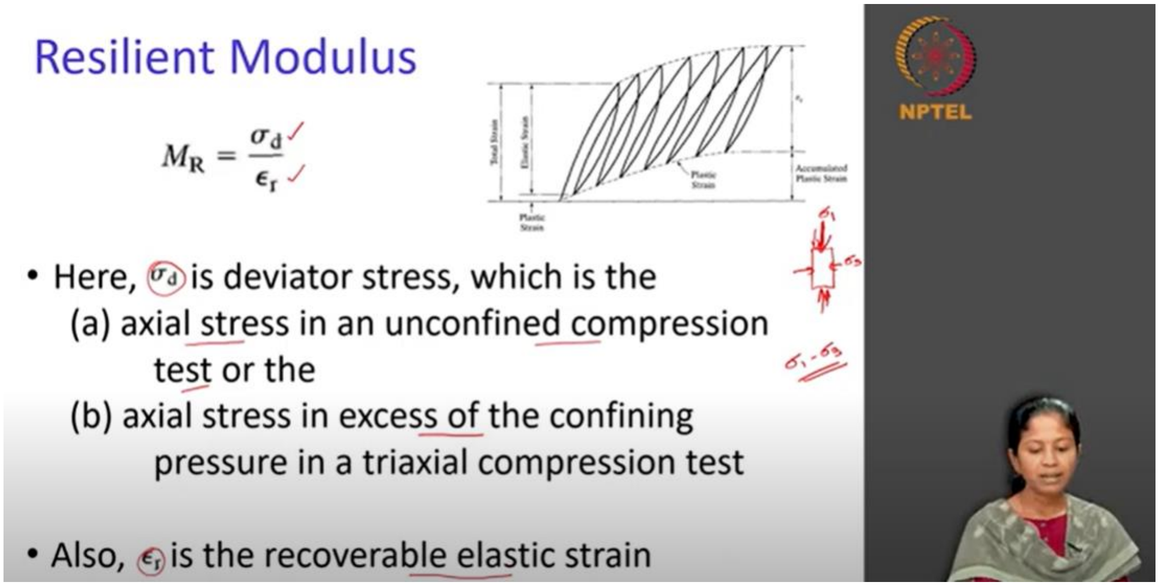

Now, what is the loading waveform that we have to use for this test? Few slides back I was telling you that we apply a load like this. Why should we apply a load like this? There are many ways in which I can apply a loading waveform. I can do something like this or I can do something like this, I can do like this. There are many different load forms that I can apply and find out the corresponding strain value. So, what is the significance of this kind of loading or what is the actual appropriate type of loading that we should apply?

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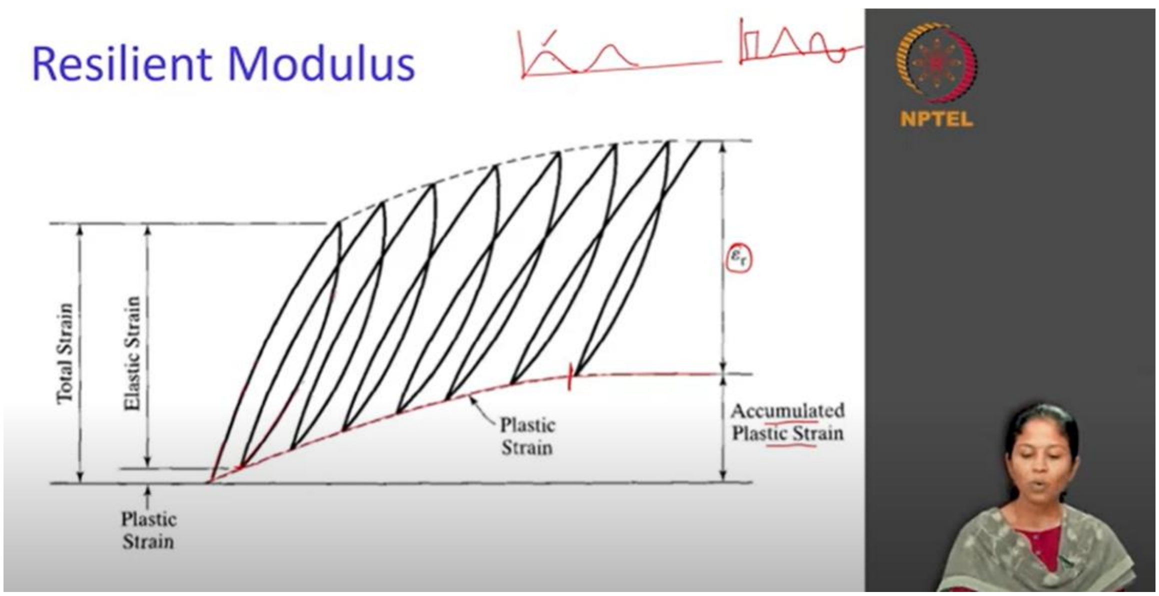

The type and duration of load should be chosen such that it simulates closely to the field condition. Let us take a particular scenario. Let me draw a pavement. This is the point at which I am interested in quantifying the stress. So, there is a vehicle here. So, so this is my stress. So, there is a vehicle here. So, the vehicle is slowly moving, it is traveling on the pavement. So, let us say that when the vehicle is at this point, I am starting to experience a stress or a quantifiable amount of stress at this particular point. So, now when the vehicle is here at this point, there is some amount of stress. So, this is my stress value. So, as the vehicle keeps approaching this particular point, the stress is obviously going to increase. It will reach a maximum when the load is at this point and as it moves away from this, again it will tend to reduce and maybe reach a point beyond which the influence of the vehicle, this particular vehicle is no longer felt at this particular point. This is considering the movement of one vehicle alone and there are no other vehicles on the pavement as of now. So, this is typically the stress profile for a given vehicle. So, it is kind of a haversine, I have drawn it very wide. Let us say, that this vehicle was traveling at a speed of 30 kmph. So, it is going to take more amount of time to cross from this point to reach this point. Let us take another vehicle which was traveling at 70 kmph. So, this vehicle is traveling at a higher speed. So, obviously, the stress profile will be same, but it is going to be felt for a shorter duration of time. So, the influence of the vehicle speed also we will see subsequently. So, now a haversine or a triangular load pulse is assumed and the duration depends upon the vehicle speed.

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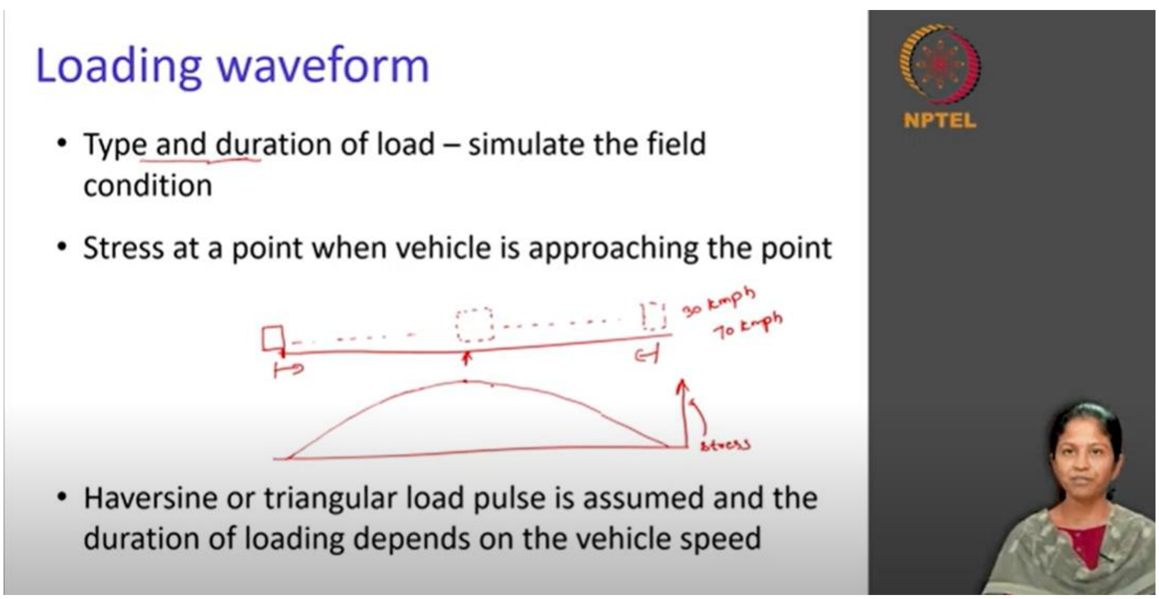

I will show you what that is. You can look at this. This is something similar to that we had drawn. This is based on the vehicle reaching a point and then crossing. So, something like this, we have drawn here. Now, so this could be approximated to an equivalent sinusoidal pulse as shown in the dotted line here. So, the same magnitude, the same stress profile, we are just equating so that we could simulate that in the laboratory and use it for the test protocol. So, we are now approximating it to an equivalent sinusoidal pulse. So, what is the intensity, the maximum value of this is given as σ_{max} and at any given time the magnitude of stress is given as σ_v. So, it can be defined like this, σ_v is a function of the maximum stress, $\sin \pi/2$, the time at any point in which I want to determine the stress and the d value. So, what is this d value? This d value is nothing but the time duration. The time duration in which the stress is experienced in this point.

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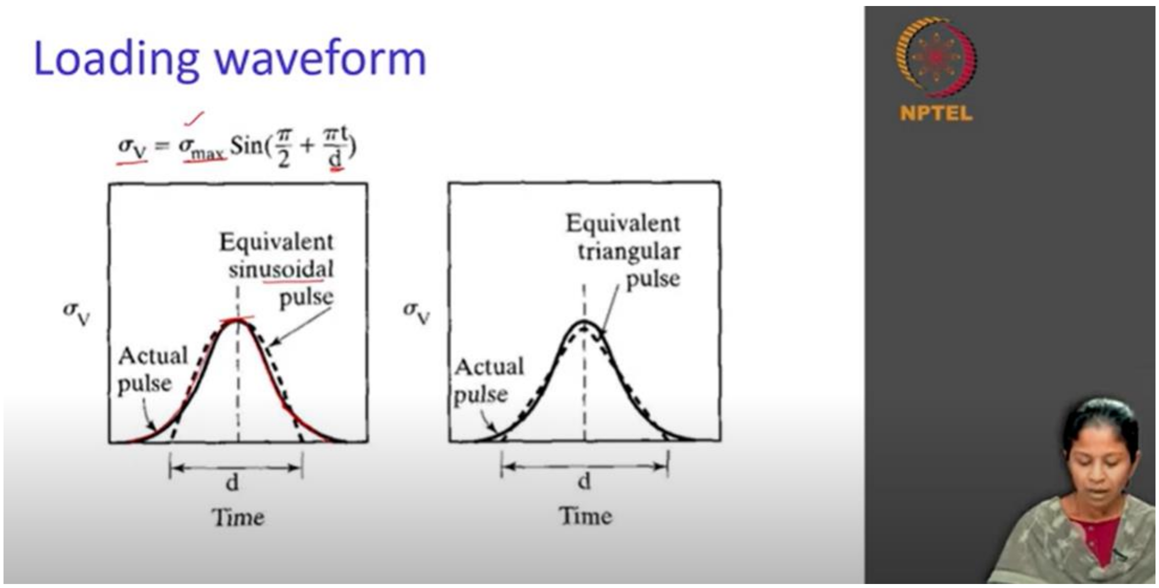

Now if I go back to the same thing, so actually I said I said this is stress. So, if this is my profile for a 30 kmph vehicle, for a 70 kmph vehicle, I will get something like this. The stress magnitude is going to remain the same, but it is going to be applied for a shorter duration of time compared to this case where it is applied over a longer duration of time. So, that is what is given here, that is what is the significance of this parameter d here which is a time during which this particular loading is applied to the pavement. So, if we look at the stress at any given point, it is a function of this maximum value which actually depends on the axle load and it is a function of the duration on which it is applied. So, it actually depends on load, which is nothing but the magnitude of load and the other parameter which is vehicle speed. So, this load will govern the σ_{max} parameter and this is going to govern the d parameter. So, there are many approximations we can do, one is to approximate into a sinusoidal pulse, the other one is to approximate into an equivalent triangular pulse, you can see here something like this. And you can see, compared to a sinusoidal pulse the d value is larger in the case of a triangular pulse. So, the typical loading waveform obtained in field can be approximated into either of these two cases.

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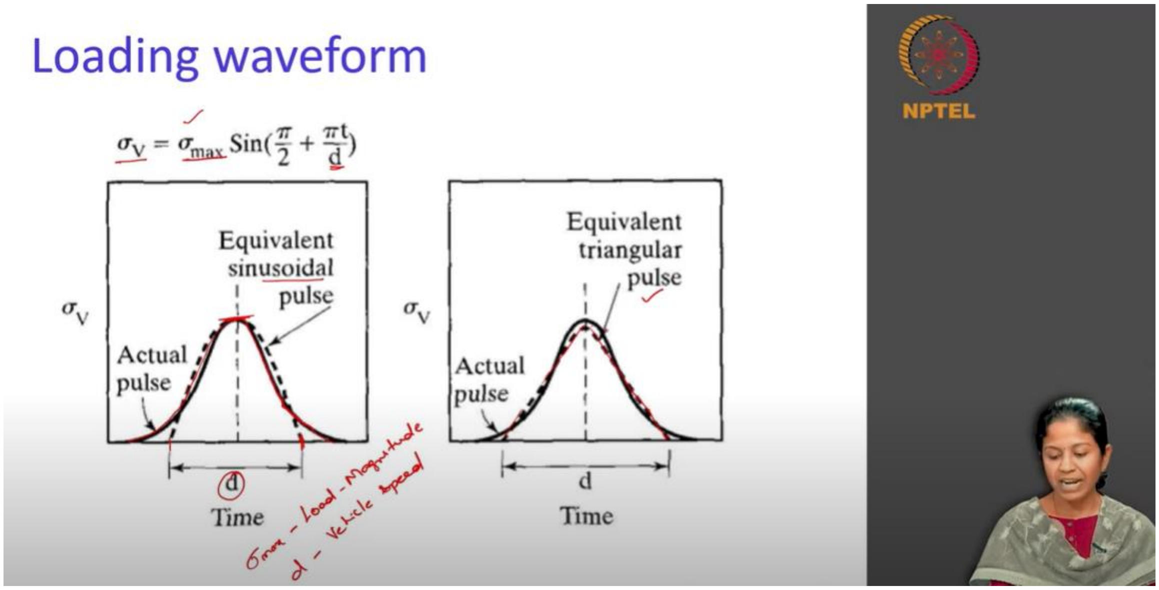

For the resilient modulus computation, we are typically using a haversine loading waveform. Now, how does all these things influence? Let us look at influence of all the parameters one by one. So, now this plot here is a function of the pulse time d and the depth below the pavement surface. So, if this is the surface wherein the load is applied, so at any given depth here how does it vary? Now let us look into the effect of sinusoidal and triangular loading. If I approximate into a sinusoidal, what is going to happen and if I approximate into a triangular loading, what is going to happen? Let us take the case wherein my depth is 8 inches below the pavement and my equivalence pulse time is 0.1. So, let us consider it for a vehicle speed of 45 miles per hour. Now, this black line here, is for a sinusoidal case and this is for a triangular case. So, now if you look at this, you can see here, the equivalent pulse time d is higher for a triangular loading compared to a sinusoidal loading as we had discussed here that is visually seen from this plot also. So, the pulse time d is greater for triangular loading compared to when you approximated for sinusoidal loading that is your first observation.

The second observation is the impact of vehicle speed. So, as the vehicle speed increases, we can see here from 1 mile per hour to 45 mile per hour. So, let us compare between 1 and 45 miles per hour for a sinusoidal loading. So, this is the value of equivalent pulse for 1 mile per hour for a sinusoidal loading and this is the case for 45 mile per hour. So, if I travel at a speed of 45 miles per hour my equivalent loading time is about 0.02 seconds whereas at the same depth, if I travel at a speed of 1 mile per hour, it is about let us say 1.4 or so. So, this is 0.02 and this is approximately 1.2 or so. So, for a given case, there is so much of a difference depending upon the speed of travel that is what we said earlier also. If a vehicle is traveling faster, the equivalent loading pulse time is less compared to a case wherein the vehicle is traveling slow. So, d is less for higher speed.

Now, let us look at the third parameter which is the influence of depth. Let us take 45 miles per hour and let us take at different depths. So compared to a 4 inch depth from the surface compared to a 16 inch depth from the surface, you can see that the equivalent pulse time increases. So, d increases with increase in depth. So, we would have learnt earlier that the load is distributed somewhere like this. So, the effect of load is felt over a wider area as we go below the pavement compared to a place wherein we are closer to the surface of the pavement. So, that is the reason we see an increase in load pulse time with increase in depth. So, depending upon all these parameters, so what is the speed of vehicle and what is the depth depending upon these two things, we should be ideally choosing the load pulse time and the load magnitude. So, now let us say for a vehicle speed of 40 kmph and depth of 24 inches which is like typically 16 mm at the top of your subgrade, what is the loading duration for haversine loading? So, we can go back to this plot and then find out the number. So, we are talking about 40 kmph or 25 mile per hour and 16 mm. So, 16 mm is 24 inches, so I should be looking at this particular line and I do not have it for 25 miles per hour. Let me just do a simple interpolation. This is 15, 30. So somewhere between here, I will assume the line to pass somewhere like this. So, take here it will be close to 0.1. Let me just simply approximate it as 0.2, it will be 0.14 or kind of a second decimal variation. So, let me approximate it as 0.1 seconds. So, this is how we determine the equivalent pulse time d that we will be using for the resilient modulus test.

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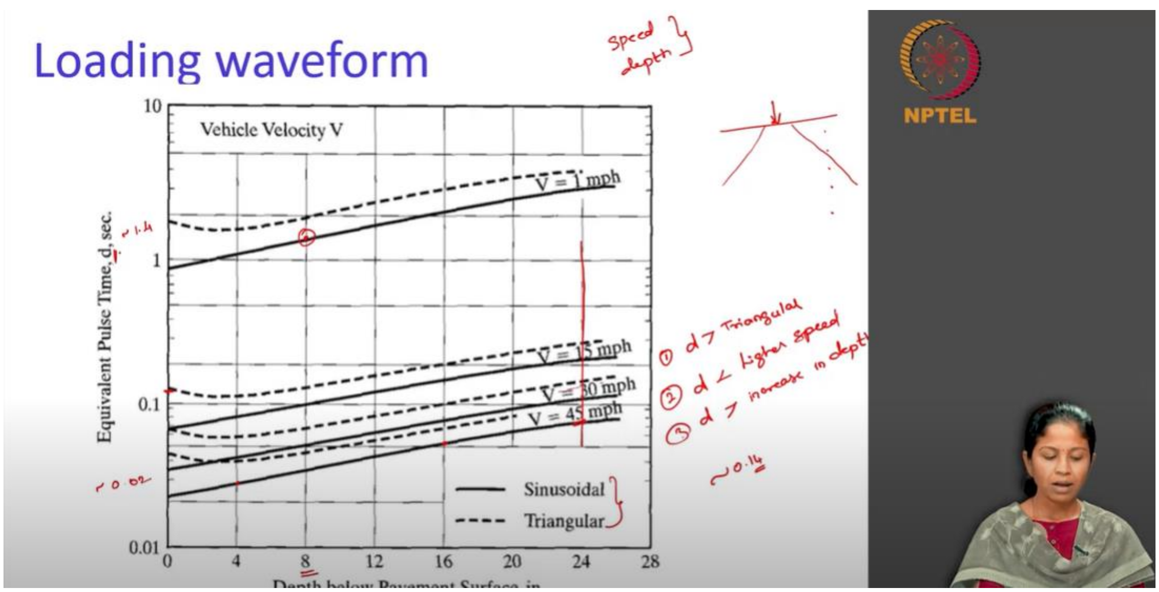

If information on loading which is nothing but the vehicle speed and depth of measurement is not known, the recommended loading condition is simply a haversine loading which has 0.1 second loading and 0.9 second rest period. So how is this done? I apply a haversine loading. So, this loading is applied over 0.1 seconds, may not be exactly to scale, I just wanted to draw one more in this plot. So, it is 0.1 second loading, 0.9 second recovery, another thing over 0.1 seconds and then we allow it to recover and so on. So, this is a typical loading waveform because we have to apply repeated load to measure the resilient modulus. So, we apply a loading waveform something like this. And for most test procedures, these standard conditions are used and rarely people kind of measure all these parameters and use it in the test protocols. So, for now and for the remaining part of this lecture, let us assume that we are going to apply 0.1 second of haversine loading and give a rest period of 0.9 seconds for these strains to recover.

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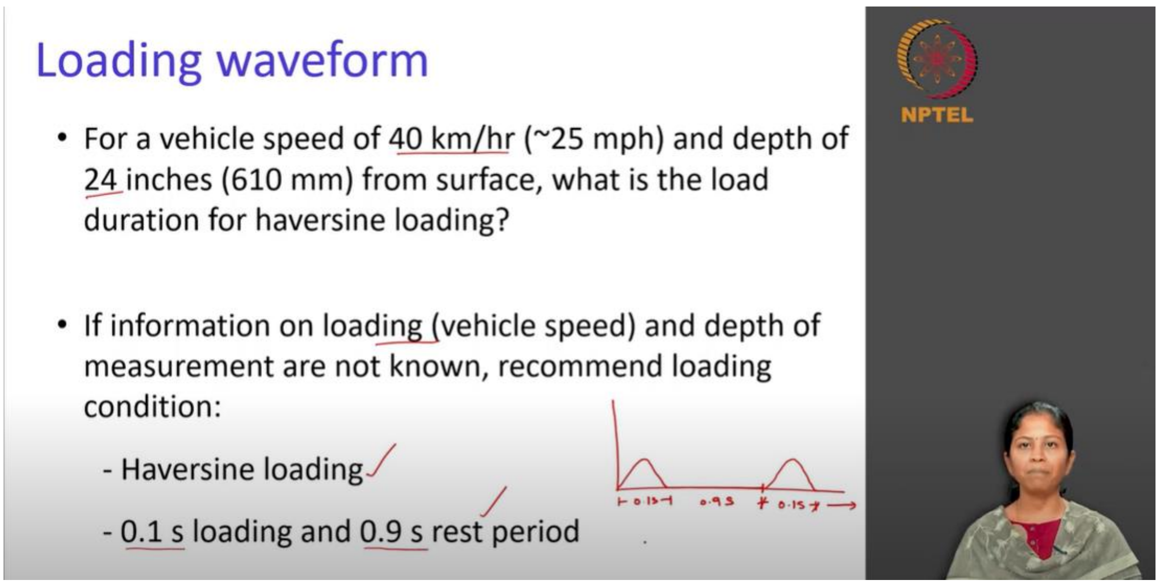

Now, if you look at IRC 37, how to measure this resilient modulus, what does IRC 37 say about the measurement of resilient modulus? The resilient modulus of soils can be determined in the laboratory by conducting the repeated triaxial test as per the procedure detailed in AASHTO T307-99. So, this is the procedure which IRC recommends for measurement of resilient modulus for granular materials. They also have a note since this equipment are usually expensive, they suggest some relationships which we have seen already. But in this part of the lecture, we will see if there is a provision to measure the resilient modulus, how to do it in the laboratory condition.

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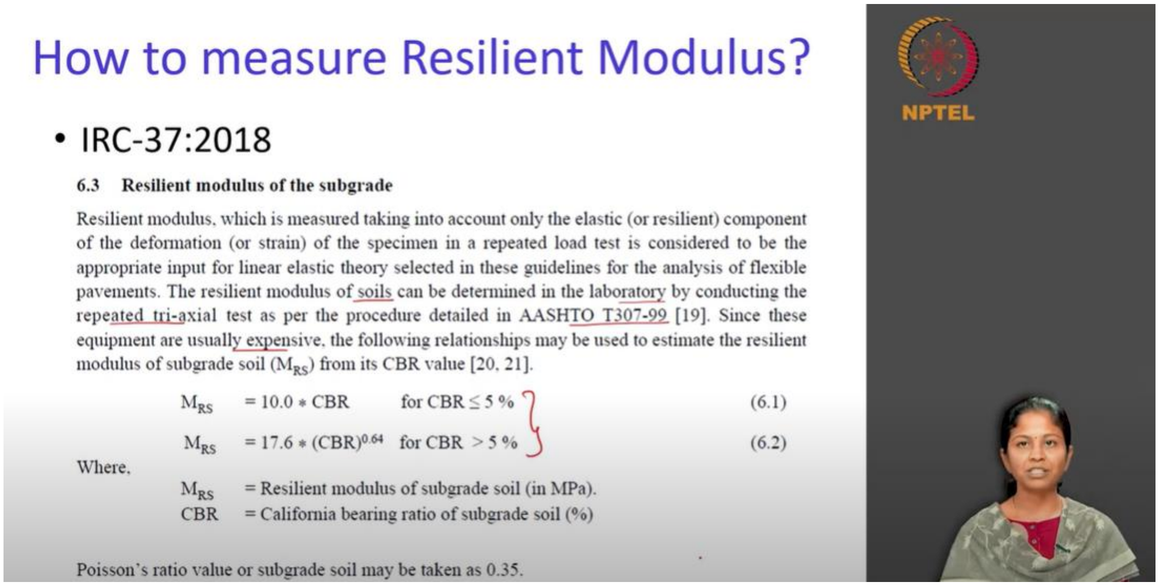

So, this is the procedure from AASHTO T307. There is a triaxial pressure chamber which is used for measurement. This is how the experimental setup looks like. So, we have a specimen that is kept here inside a chamber. So, this, the whole thing is actually a chamber here and they say that we need to have an acrylic thing to just see through to then see when the specimen is failing if something like that happens. And there are base plates here. There are two porous membranes between which the sample is sandwiched. There is a sample cap and it is all sealed nicely. There is also LVDTs to measure the deformation and this is the piston rod through which the load is applied onto the sample. So, it is applied onto the sample cap which is passed uniformly onto the sample and there is a load cell here and all the other components that are associated with that.

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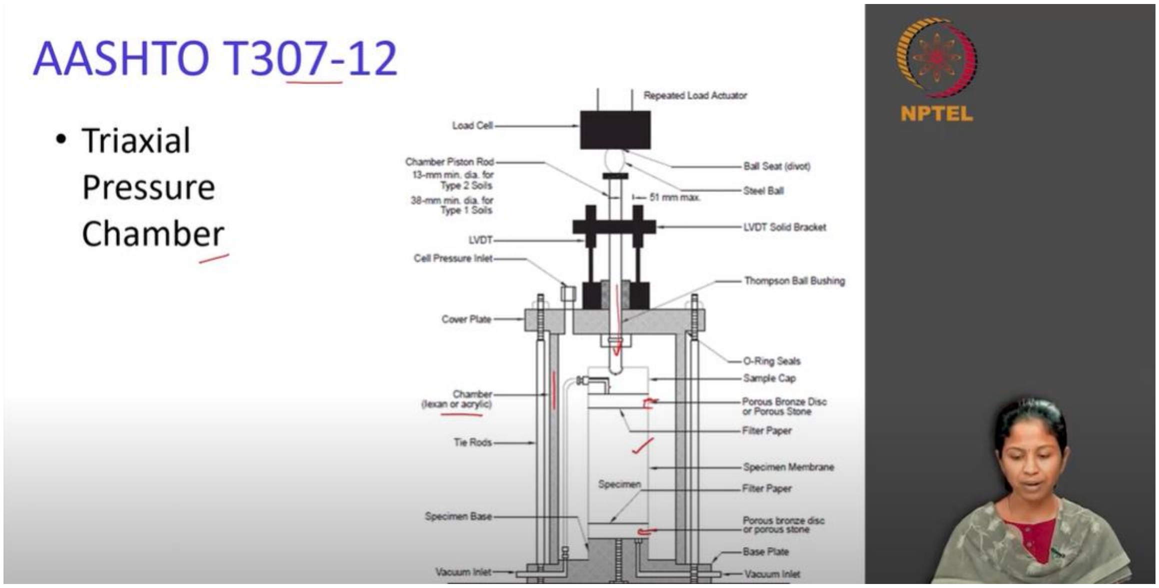

So, this resilient modulus procedure is defined differently for the subgrade material and sub base or base material. Basically, the procedure is same except that the confining pressures are slightly different for these two categories of materials. So, this is one variation. Another variation is the type of material. They specify two types of materials which are type 1 and type 2. What is this type 1 material? These are the exact lines as given in AASHTO T307. Let me read it. Type 1 material is for the purpose of resilient modulus testing, material type 1 includes all untreated granular base and sub base material all untreated. So, it includes all this and all untreated subgrade soil that meet the criteria less than 70% passing the 2 mm sieve and less than 20% passing 75 micron sieve and that has a plasticity index of 10 or less. So, if a soil has all these characteristics, it is classified as type 1 and all type 1 soils will be molded in a 150 mm diameter mold. So, let me repeat type 1 material is all untreated material. It could be a subgrade, sub base, whatever be the layer. So, for all these materials which has less than 70% passing 2 mm and less than 20% passing 75 micron sieve and a plasticity index of 10 or less is classified as type 1. So, for all this, the mold size is 150 mm diameter. What is type 2? All other materials which do not fall under type 1 are classified under type 2. It could be your base again untreated materials, untreated base, subgrade materials which are not meeting the criteria for type 1 are given in type 2. Typically, type 2 materials are prepared using a 70 mm diameter mold. There is a difference. So, it is granular material. So, if you, in brief classify them into type 1 and type 2, most granular materials that are non-cohesive will fall under type 1 and all other cohesive soils will typically fall under type 2.

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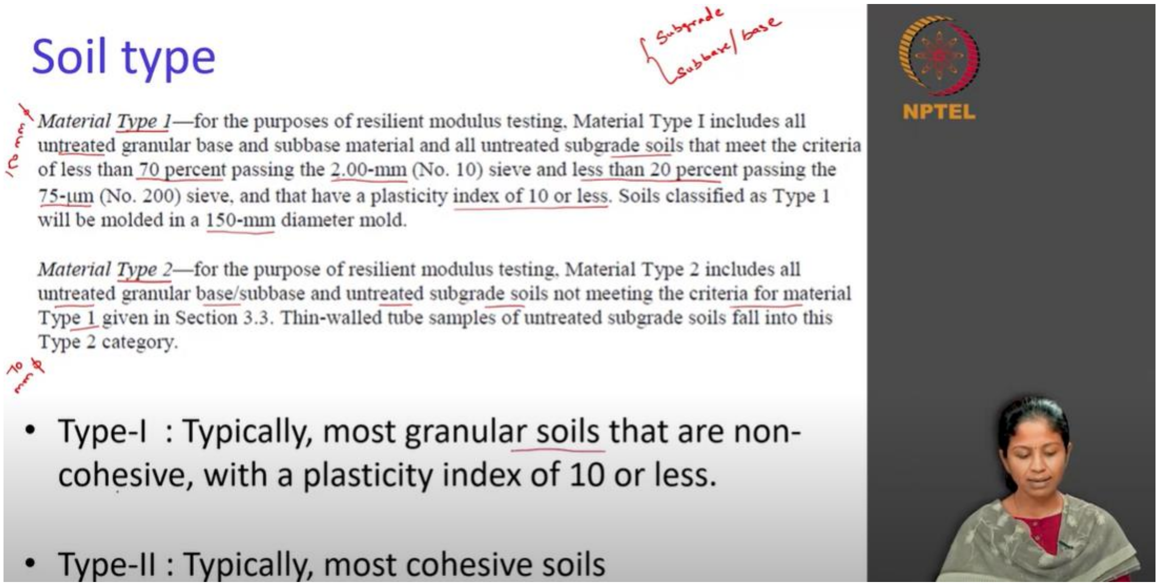

Now, how do we prepare the sample? So, this is a soil classification. Now, how do we prepare the soil for the resilient modulus test? So, this sample preparation procedure is again given differently for type 1 and type 2 materials. If you look at the annexure of this particular standard, annexure A has the procedure to prepare soil for a given water content. Typically, we do all these tests for the optimum water moisture content or any specified moisture content. So, in that case how do we prepare soils for a particular moisture content? That is given in annexure A and in annexure B, the procedure to compact type 1 soil is given. How do you do the compaction for type 1 soil is given in annexure B and annexure C for type 2 soil because type 1 soils are mostly granular and non-cohesive. So, they have to be compacted in a different way, mostly using a vibratory kind of compactor whereas type 2 materials are cohesive materials so they have to be compacted differently. So, that is why the procedure is also given differently for both these particular materials. Now, this soil will be compacted using a split mold. So, what is a split mold? It is a usual mold which you can just split it into two for the ease of placing or removal of sample. And you have to select mold sizes to fabricate a specimen such that the diameter is equal to 5 times the maximum particle size. So, let us say that we have the material whose maximum, whose 100 % is passing a 19 mm or the maximum particle size is 19 mm. So, the diameter of this, let us approximately take it as 20 mm. So, it should be more than 5 times. So, this should be greater than 100 mm. The diameter of the mold should be greater than 100 mm. That is one of the requirements.

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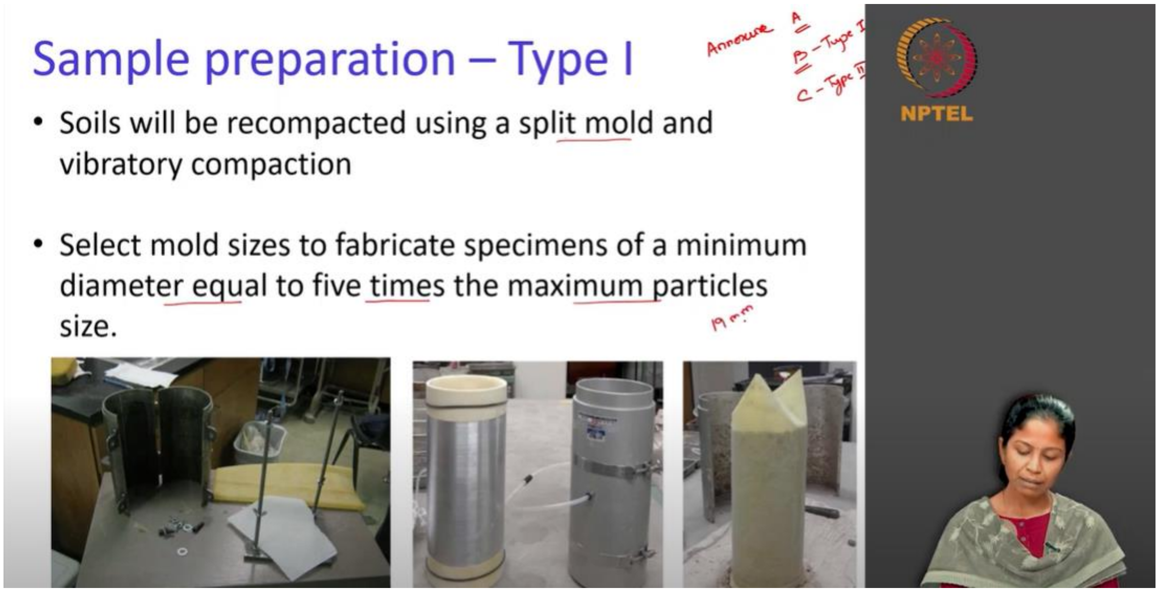

Similarly, the other requirement is, the length of all specimen should be at least 2 times the diameter. So, if you look at the height of specimen, it should be a minimum of twice the diameter. So again, standard molds are specified for all these things and we can use those standard molds but if you do not use standard molds, it should meet these specifications. Now if you look at this, this is your membrane which is used to hold the sample and the sample is typically enclosed in this membrane.

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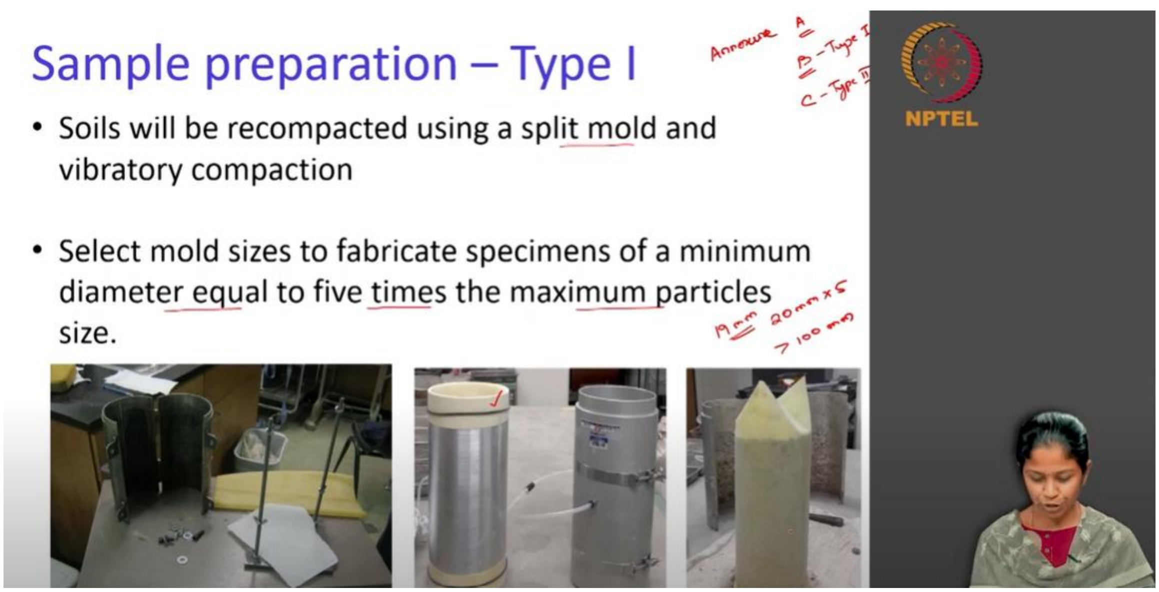

How to do this, I will show you shortly. And this specimen shall be compacted in 6 lifts in a split mold mounted on the base of triaxial cell. So, this is for a granular material. So, here we have to do it in 6 lifts.

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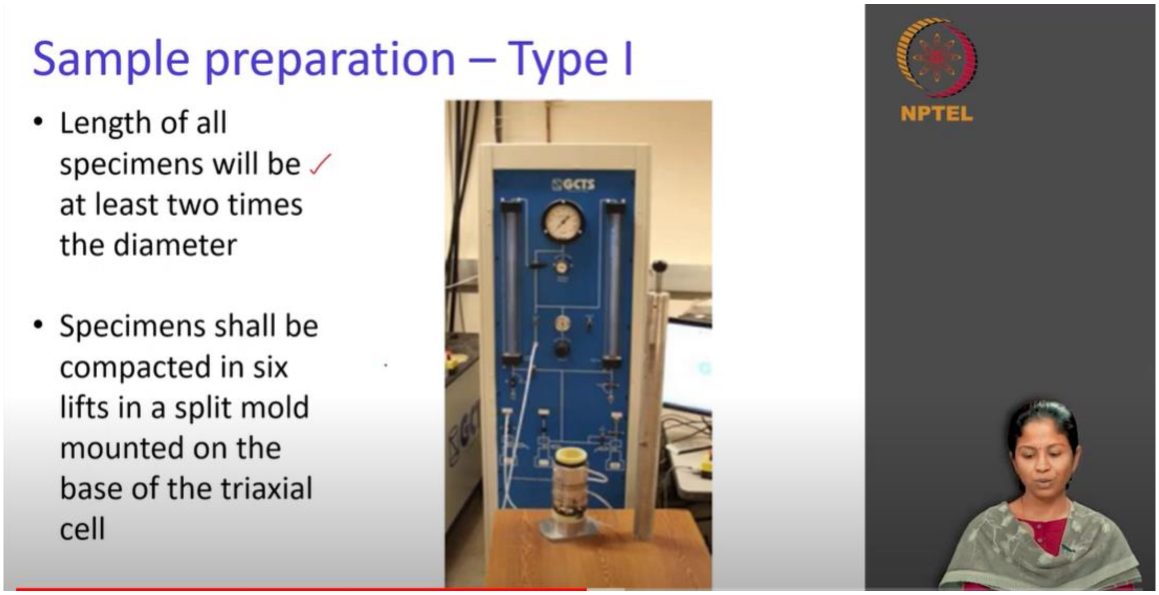

And this is the apparatus which is specified for compaction. So, we have a bottom plate and we put in the soil here. There is a vibrator head here and then we subject this to vibration. The details regarding the vibrator and all those things are given in annexure B as I said earlier. So, we have to use this kind of a setup to compact the type 1 soil.

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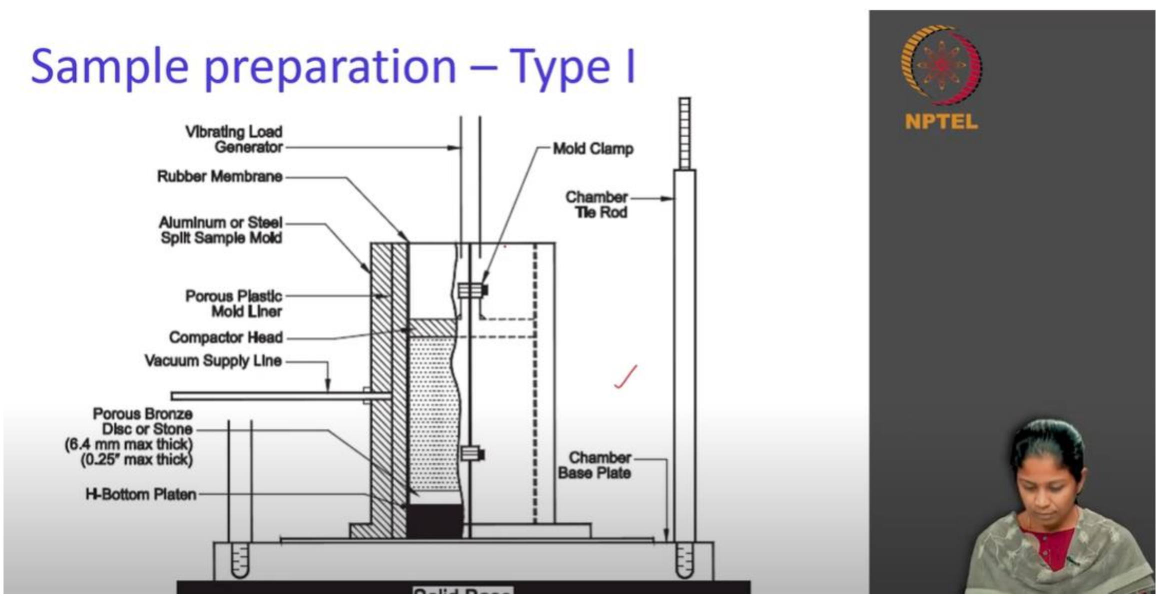

So, what we do here is we have this base plate, we put the bottom of the membrane in this base plate and we put an O-ring to confine the membrane to the base plate. Then, we have a membrane expander which is something like this. This is called as a membrane expander. So, you put in the membrane expander and then you clamp the membrane like this. Then fill in the soil. Then, on the soil we can apply this particular vibration technique. So, once this is over, it has to be removed and then kept ready for testing. Again, there are minor details regarding how to remove the membrane, how to clamp it, how to avoid leakage and all those things. You can refer to the code for all those details.

For type 2 soils, these soils will be recompacted using a static loading. So, we do not apply any dynamic load. We just apply a static load and try to compact the soil. It is a modified version of a double plunger method. I will show you pictures of how this is done. So, we select mold sizes to fabricate specimen so that the minimum diameter is equal to 5 times the maximum particle size, the same criteria as defined earlier. But again, the length of all samples should be at least twice the diameter. And regarding the compaction, it is compacted here in 5 lifts. In the previous case for type 1, it was done in 6 lifts. Here, it is done in 5 lifts. I will show you how it is done.

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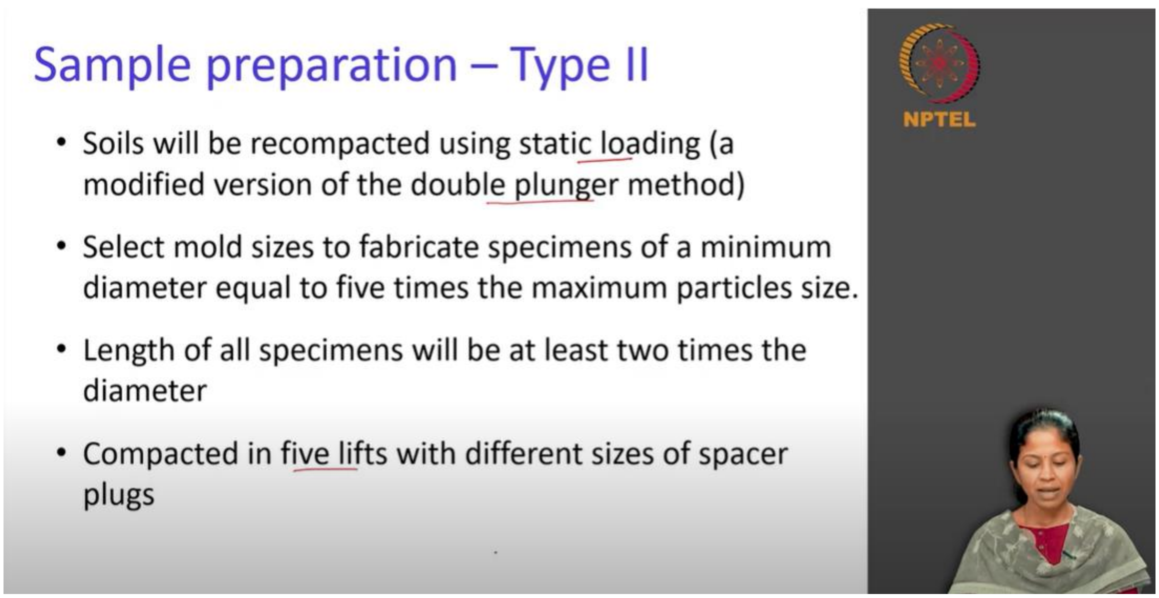

Now, this is the compaction plug or spacer that we will be using for compaction. This is a mold that we have. This one what is given here, these are called as compaction plugs. So, these are nothing but solid cylinders and they are like solid with no space in between. Now for the first case, for the first lift compaction, we said we are going to compact it in 5 lifts. So, for the first lift you put in the soil here. This is my soil. The white color here is the soil. I put in 2 plugs like this and then I try to compact so that both these cylinders are flush with the top and bottom. Initially, before compaction, they would have been something like this. So, once I try to compact it, the sizes are given such that we will achieve the required length of sample at the end of 5 lifts of compaction. So, you compact it, we get the first lift. The procedure is given here step by step.

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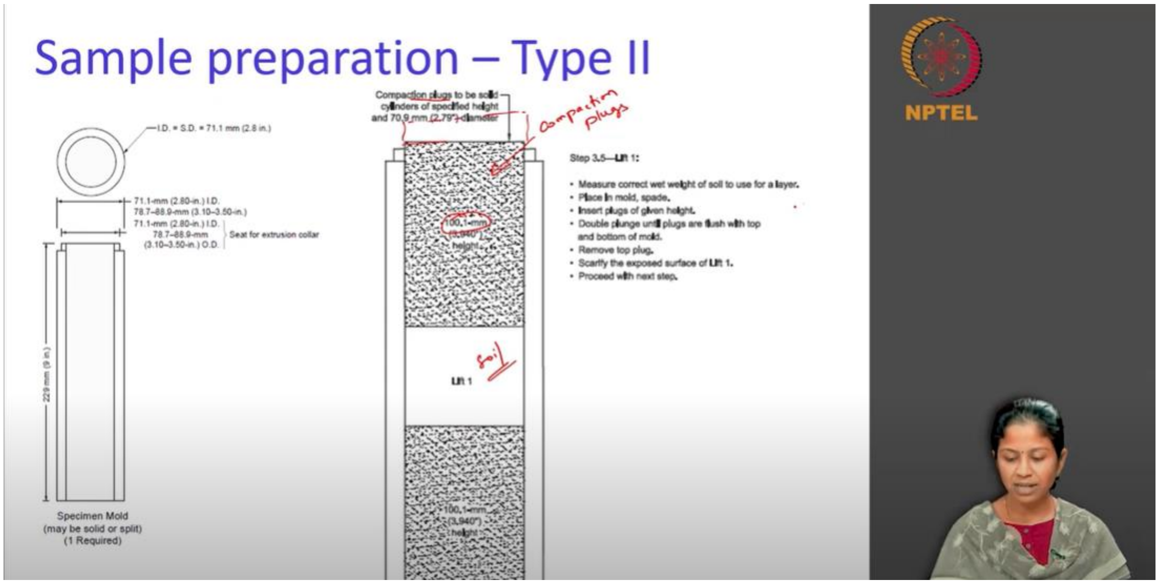

So similarly, in a second lift, except that we use a different kind of spacer because we have to accommodate one more lift thickness of soil. So, we use a different kind of spacer. You can see here, this is 100.1 mm, typically 100 mm and this is 71 mm. So, another, this is again 100 mm only. So, you put in the second lift, again compress it till it is flush with the top and bottom and then you remove this. Each time we put in a new lift, we have to slightly scarify the previous one just to ensure that they are all together acting as one uniform material. So now you put in the third lift. So, this spacer we reduce it from 100 to 72. So, both are now 72. We have accommodated 3 lifts. So, like that we proceed.

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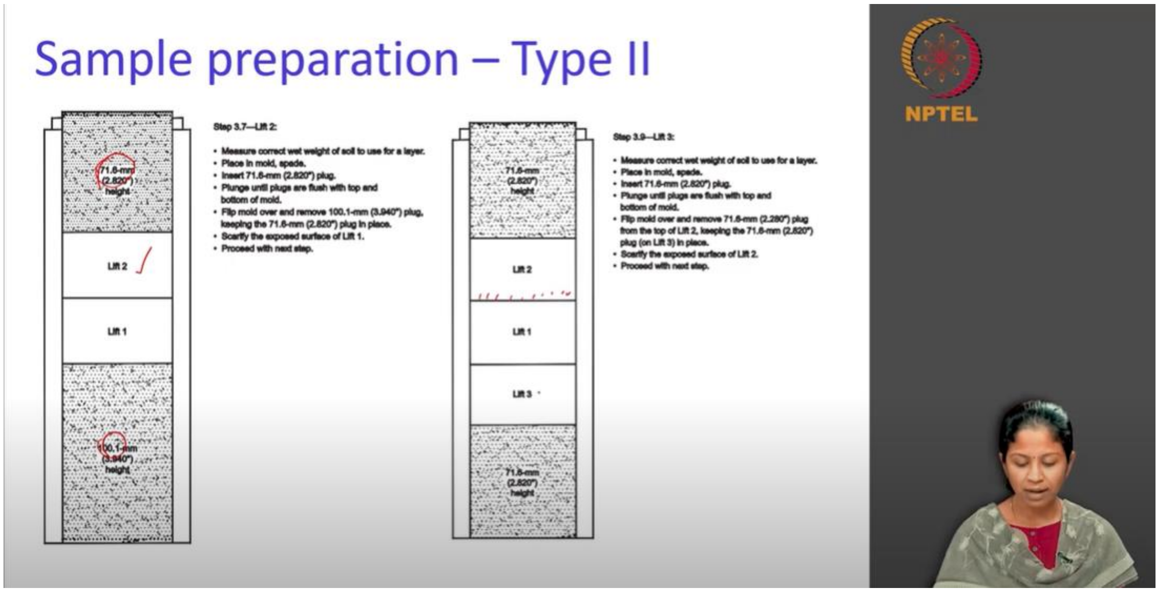

Fourth lift, this 71 becomes 43, this is 71 and then in the fifth lift, we use 43 mm spacer so that we are able to get 5 lifts. So, we do this until we get a compacted specimen. This is the method of compaction which is used for type 2 soils. So, for both these soils, it is suggested that use a membrane to keep the sample in position.

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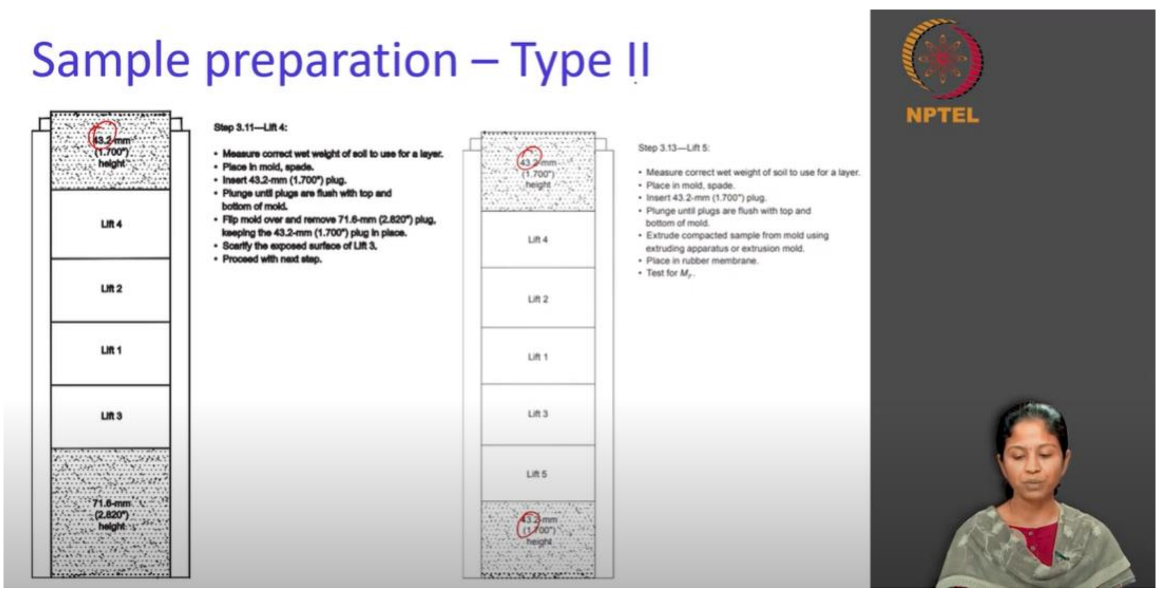

Now, what is the test procedure associated with measurement of resilient modulus? So again, this test could be done on undisturbed specimen or laboratory compacted specimen. So, if it is an undisturbed specimen, we can take it directly from field like I explained in the morning for CBR test and then we can use it for testing. And as I said, type 1 specimens are 150 mm diameter and type 2 specimens are 70 mm diameter. And initially, we place moist porous stone and filter paper on the bottom and we place a membrane to seal the sample. And then, along with the membrane we have sample, I showed you earlier. So, the whole thing you place it, another porous stone filter paper and then porous stone on top of it and then you position it such that it is not aligned in any side, it is exactly vertical. So, we align it and then we start the test.

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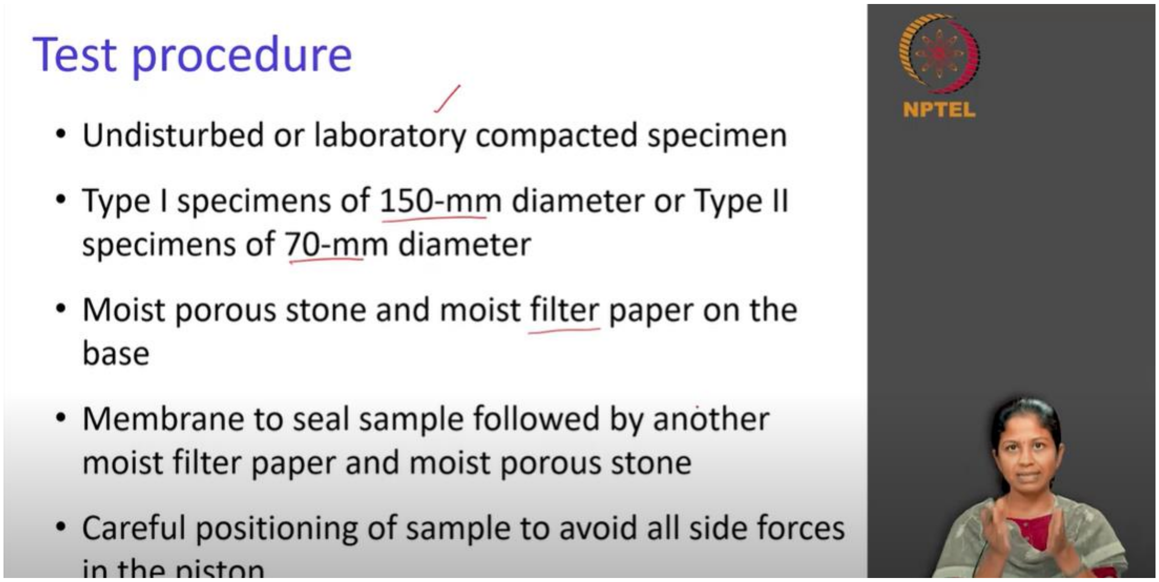

So, in the test procedure air is used as the confining fluid. We do not use any fluid, we use air to give the confining pressure. And loading is typically done like this. We said we are going to apply a haversine loading. These are the loading details. So, I start from 0 here and this is my 360 when the whole load is applied. So, this haversine load pulse is of this form, $(1 - \cos\theta)/2$. You can see here the whole loading duration from here to here until the complete load is applied from here to here is 0.1 second duration and then the rest period starts. So, we have 0.9 seconds rest period, again another load of 0.1 seconds and so on. Now, let us look at the loading values. So, we have what is called as a contact load. So, like we did for the CBR test, here also we have to apply a contact load just to ensure that the loading piston is always in contact with the top surface of the sample. So, this is called as a contact load and then over and above the contact load what we apply is called as cyclic load pulse. So, this is the haversine load pulse that is applied over 0.1 seconds and this is your maximum applied load. So, this includes your cyclic load and the contact load, the sum of cyclic load and contact load is nothing but the maximum applied load. Now, let us define all these things formally.

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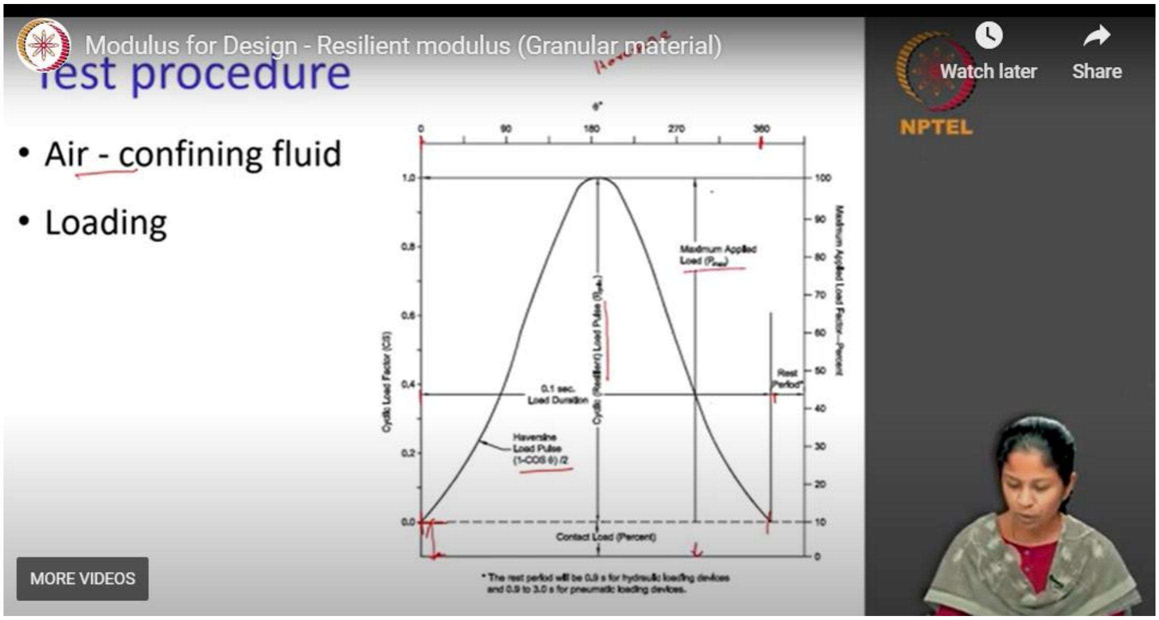

So, maximum applied axial load that is called as P_{max} which is nothing but the sum of contact load and cyclic load. That is what we call as maximum applied axial load. So, contact load is nothing but 0.1 % of the maximum load. Usually, it is taken as 0.1 times the maximum load or 10 % of the maximum load. Then, the cyclic load is nothing but the maximum load minus the contact load. So, that difference we take as the cyclic load. Then we convert all of them into the corresponding stress values. So maximum stress is nothing but the maximum load divided by the area. Area is nothing but the initial cross section area of the specimen. Before the test is started, what is the cross-sectional area? That we take as A. So now, we can compute also the cyclic stress which is nothing but cyclic load divided by the cross-sectional area.

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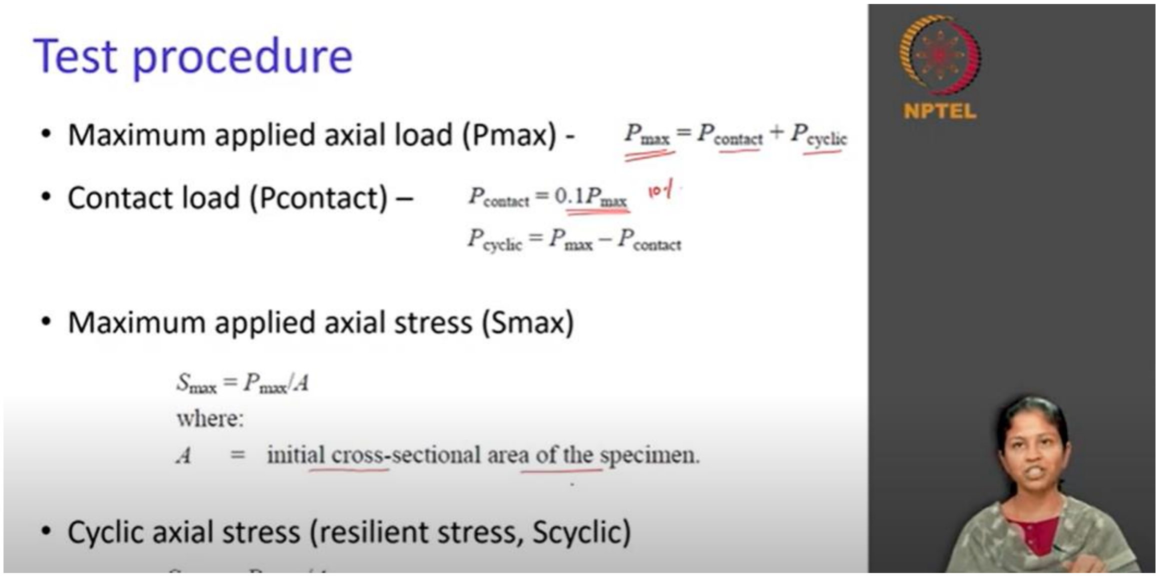

And I can also compute contact stress, which is nothing but contact load divided by the area. So, these are all the things that I will be able to compute. And what is strain? e_r is nothing but the recovered axial deformation. It is the deformation, not the strain. Axial deformation due to cyclic stress. We are converting stress to load to stress and we are using the stress for definition. So, it is nothing but the stress which is over the contact stress. So, e_r is nothing but the recovered or which is nothing but the resilient axial deformation due to cyclic stress. And ϵ_r is the resilient recovered axial strain due to cyclic stress. So how do we get the strain? We take in the deformation., we divide it by the original specimen length and that is how we compute the strain value. So, resilient modulus is defined as S_{cyclic}/ϵ_r. If you remember the previous definition, we wrote it as σ_d/ϵ_r. ϵ_r has the same meaning in both the cases. σ_d, we defined as the deviator stress which is nothing but the cyclic stress that is given here. We said deviator stress is nothing but the axial stress over and above the confining pressure and that is what we are defining as the cyclic stress here.

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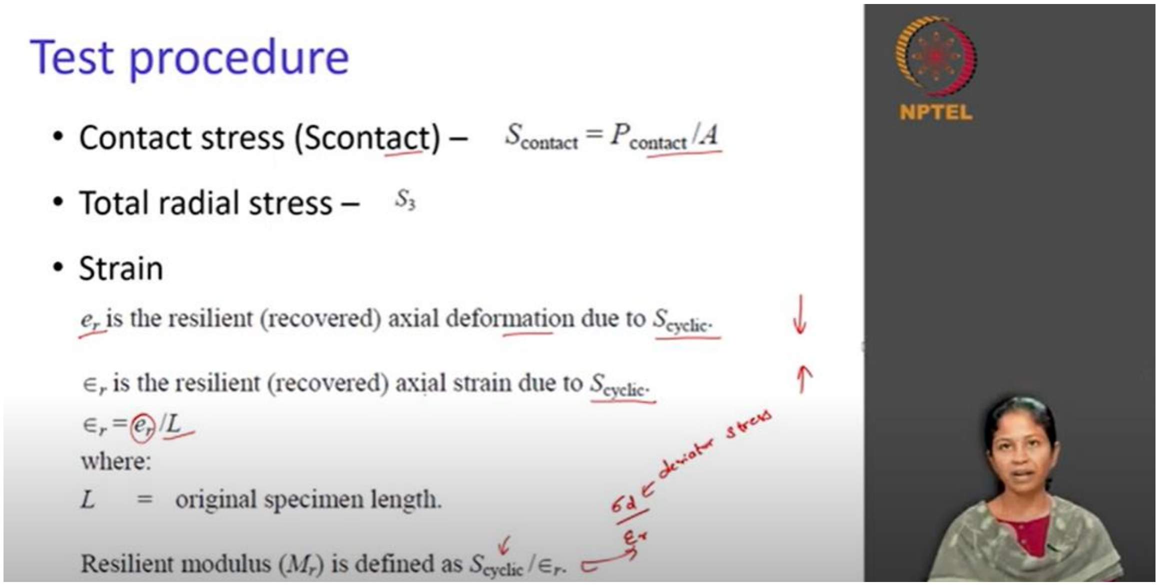

So, these are the terminologies that are used in this particular codal provision and this is again the test procedure. You can see here, we have two LVDTs here. So, these LVDTs are mounted to the top plate and this is mounted to the top of the specimen. So, how much is the deformation in the specimen, we will be able to capture through these LVDTs. We also have a specimen membrane here as I told you, you can see here, filter paper, porous stones and all that placed. Now, this is the generic case.

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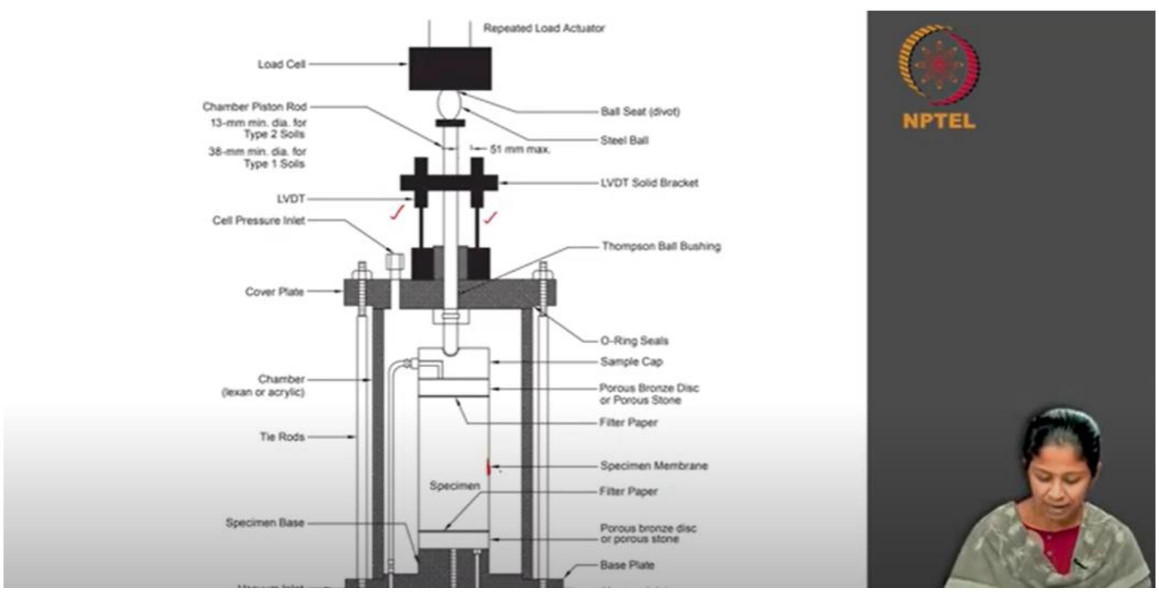

Now, let us see the specific experimental procedure for subgrade and I will also show you the specific experimental procedure for subbase and base materials. For subgrade, air again is used as the confining fluid. Now, there is some preconditioning that we do on the sample. This preconditioning is carried out for a confining pressure of 41.4 kPa. So, a contact stress of 10 % $\pm$ 0.7 kPa. So, we said always the contact stress is 0.1 times maximum stress. So, we have this contact stress, which is 10 % of maximum applied stress during each sequence. So, we have different sequence numbers, I will show you. So, for each sequence number, this is 10 % of the maximum. And, we begin the test by applying minimum of 500 repetitions of a load equivalent to maximum axial stress of 27.6 kPa. So, ultimately, we should have an axial stress of 27.6 kPa. Correspondingly the load is calculated and that is applied for the initial 500 repetitions. So, if you have a total maximum stress of 27.6, we said that the contact stress is 10 % of it. So, if you take 0.9 × 27.6, we will be getting 24.8 kPa, right. This is nothing but the cyclic stress that is used and the corresponding strain will be measured.

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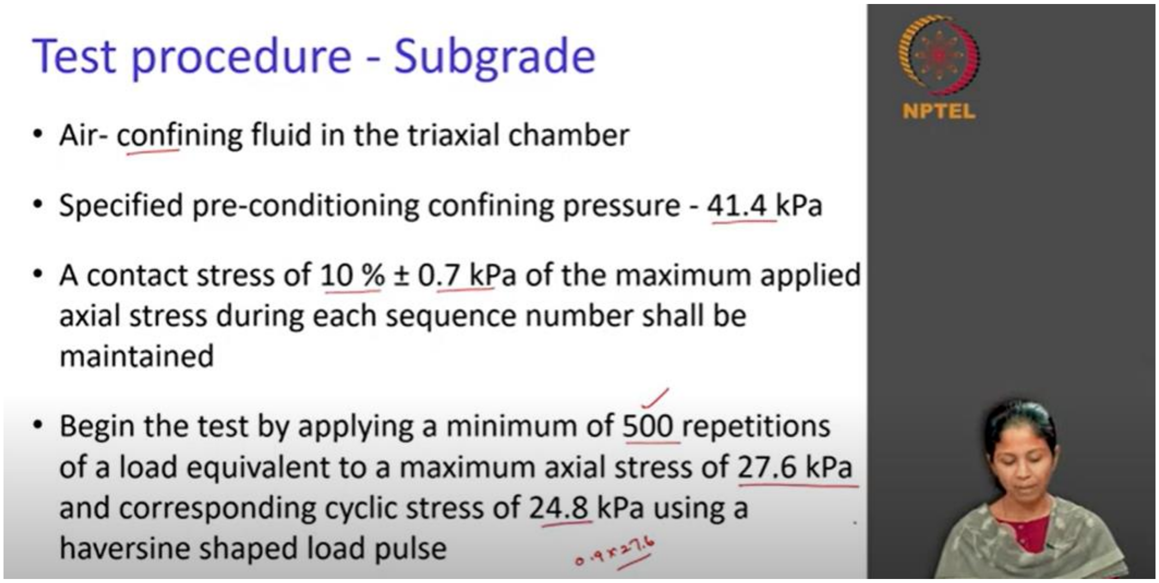

So, initially we apply 500 repetitions. If the sample height continues to decrease even after 500 repetitions which means that we have not reached the resilient state so far, then we can continue the initial conditioning cycle even up to 1000 repetitions. So, our ultimate aim is to reach that particular resilient state. If in this period, if in the initial first 500 to 1000 cycles, if the total vertical strain reaches 5 %, if the vertical strain has already reached 5 %, we stop the process and we check for probable reasons. We do not expect the strain to reach 5 % within this conditioning procedure. So, in the whole test procedure, wherever the strain reaches 5 %, we stop the test. So, that could be during the initial conditioning cycle or even somewhere during the middle of the test. Then if it does not reach 5 %, we continue the test and go as per the procedure specified in table 1. So what is this procedure specified in table 1?

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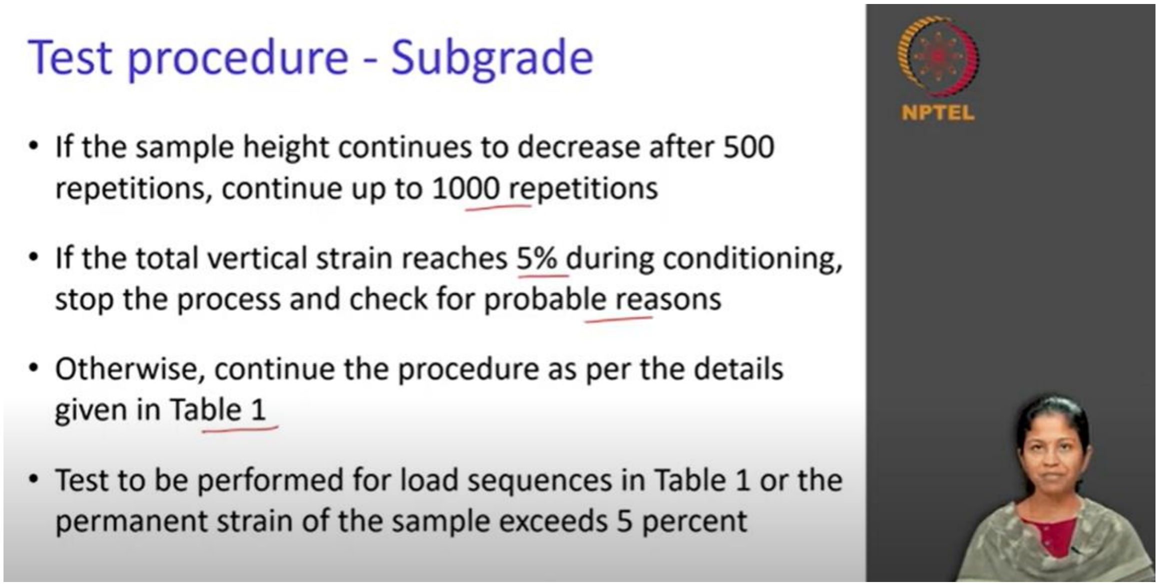

This is the testing sequence that is specified in table 1 for subgrade soil. So, let me go through the headings. We have the sequence number, the order in which we have to do all these things. What is the confining pressure which is S_3? What is the maximum axial stress? We know this cyclic stress, contact stress, the sum of these 2 will be the maximum axial stress and number of repetitions that we have to carry out for each case. So, the first sequence number 0 is kind of a conditioning. We have a confining pressure of 41.4 kPa. The maximum axial stress is 27.6 kPa. So, this is cyclic and this is the constant stress or the contact stress. So, we apply somewhere between 500 and 1000. So, this we have already discussed. Then, we have 3 cycles of 5 different load repetitions. So, we can see here, let me show you. So, for these 5 cases, the confining pressure is 41.4 kPa and for these 5 cycles the confining pressure is 27.6 kPa and for these 5 cycles it is 13.8 kPa. So, we keep varying the confining pressure. We start with a higher confining pressure and then we keep reducing it. The next one is the maximum axial stress. So, this goes in a cyclic manner. So, we go from 13.8, 27.6, 41.4, 55.2, 68.9. We have 5 set of values for the maximum axial stress. So, we repeat the same thing for all the 3 confining pressures. Then for each case, we apply 100 repetitions of load. So, this is only the initial case. So, we finish this and then once we start the sequence from sequence number 1, for each case we apply 100 repetitions. So, as I said earlier, at any point when the maximum strain reaches 5 %, we have to stop. It could be somewhere here or till the end of the test it may not reach 5 %, so we can continue. And there is one more note. You can see loading sequences, 14 and 15 which is nothing but these two loading sequences are not to be used for materials designated as type 1. So, if we are using type 1 material, we need not do loading cycles 14 and 15. So this is with regard to the loading condition. So, if the permanent deformation does not exceed 5 %, so at the end of the test we have completed all these, depending upon type 1 or type 2, we have completed all these sequences.

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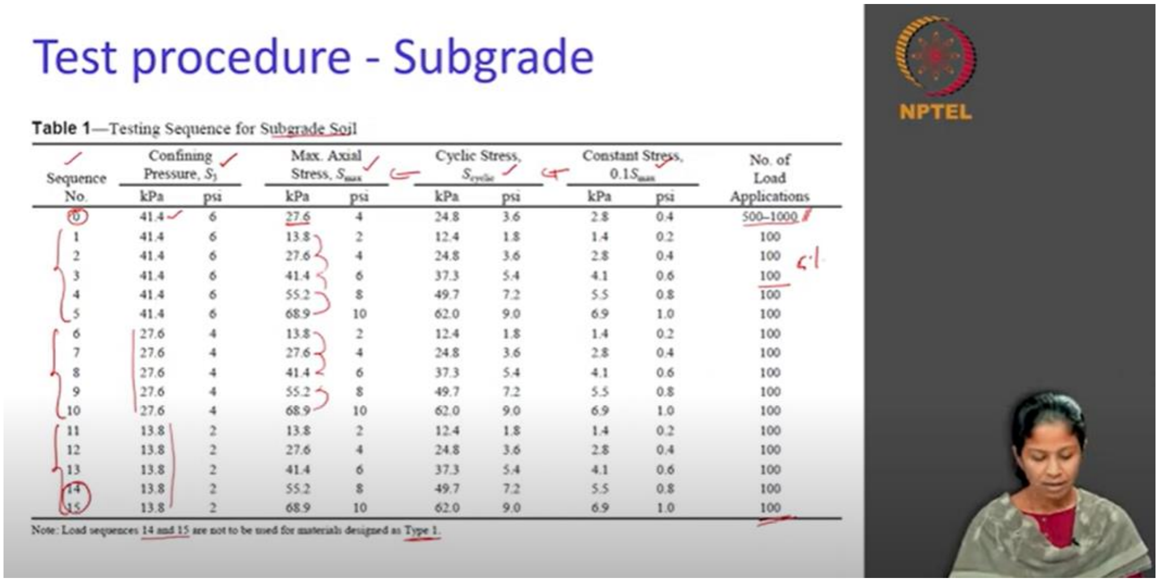

Table 1—Testing Sequence for Subgrade Soil

Sequence No.	Confining Pressure, S_3 (kPa)	Confining Pressure, S_3 (psi)	Max. Axial Stress, S_{max} (kPa)	Max. Axial Stress, S_{max} (psi)	Cyclic Stress, S_{cyclic} (kPa)	Cyclic Stress, S_{cyclic} (psi)	Constant Stress, $0.1S_{max}$ (kPa)	Constant Stress, $0.1S_{max}$ (psi)	No. of Load Applications
0	41.4	6	27.6	4	24.8	3.6	2.8	0.4	500–1000
1	41.4	6	13.8	2	12.4	1.8	1.4	0.2	100
2	41.4	6	27.6	4	24.8	3.6	2.8	0.4	100
3	41.4	6	41.4	6	37.3	5.4	4.1	0.6	100
4	41.4	6	55.2	8	49.7	7.2	5.5	0.8	100
5	41.4	6	68.9	10	62.0	9.0	6.9	1.0	100
6	27.6	4	13.8	2	12.4	1.8	1.4	0.2	100
7	27.6	4	27.6	4	24.8	3.6	2.8	0.4	100
8	27.6	4	41.4	6	37.3	5.4	4.1	0.6	100
9	27.6	4	55.2	8	49.7	7.2	5.5	0.8	100
10	27.6	4	68.9	10	62.0	9.0	6.9	1.0	100
11	13.8	2	13.8	2	12.4	1.8	1.4	0.2	100
12	13.8	2	27.6	4	24.8	3.6	2.8	0.4	100
13	13.8	2	41.4	6	37.3	5.4	4.1	0.6	100
14	13.8	2	55.2	8	49.7	7.2	5.5	0.8	100
15	13.8	2	68.9	10	62.0	9.0	6.9	1.0	100

Note: Load sequences 14 and 15 are not to be used for materials designed as Type 1.

And, even at the end of the test if the total permanent deformation does not exceed 5 % and if we require some kind of strength information from this particular test, it is suggested to do a quick shear test. What is this quick shear test? For this, we apply a confining pressure of 27.6 kPa. We load it so as to produce an axial strain at the rate of 1 % per minute. The strain should increase at the rate of 1 % per minute, under a strain-controlled loading procedure. So, in this case we load it. So, for increasing the strain at the rate of 1 % per minute, what is the corresponding load that has to be applied? So, this is calculated and it is applied in this manner. We continue the loading until the load value decreases with increase in strain. So typically, as the load increases, strain will also increase. It might reach a point wherein the load might reduce which indicates a failure of the sample. So, when we reach that particular point, we can stop the test or 5 % strain is reached or the capacity of the load cell is reached. For the load cells, the capacity is specified in this particular code. So, once we reach the capacity of the load cell we can stop the test.

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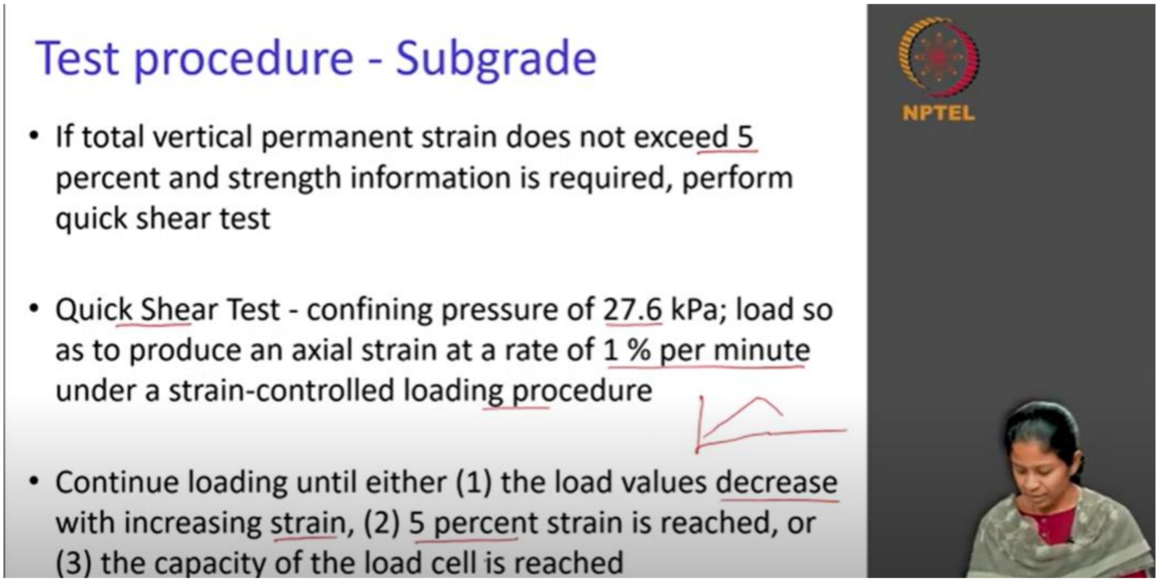

So, this is the test procedure for subgrade and this is the final table that we will be giving as a report. So, what is the chamber confining pressure? What is the nominal maximum axial stress? Again, you should remember that only for the last 5 cycles at each sequence, we will be using only those values for computation. So, we can give the cycle number, you can see for the sequence, what is the load, what is the cyclic load, contact load, maximum stress, cyclic stress, contact stress and this is the deformation from LVDT1, I showed you previously. We have 2 LVDTs mounted on, so you can see here. This is 1 and this is 2. So, from both the LVDTs, what is the deformation that is measured and we know we compute the average deformation. From deformation, we know how to compute the strain value and then finally, we compute resilient modulus which is nothing but S_3/ϵ_r or which is nothing but the first one is given here. So, this is nothing but the resilient modulus computation.

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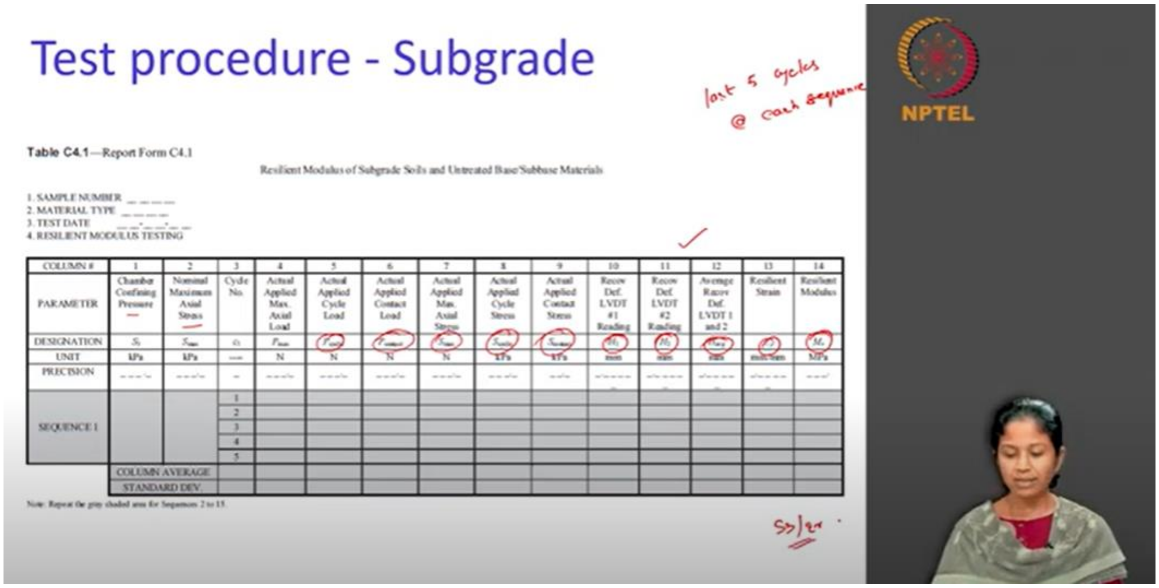

So, the axial stress for last 5 cycles is averaged as I told you. It is the ratio of amplitude of repeated axial stress by recoverable strain and once the test is over, we reduce the confining pressure to 0, remove the membrane sample and all those things.

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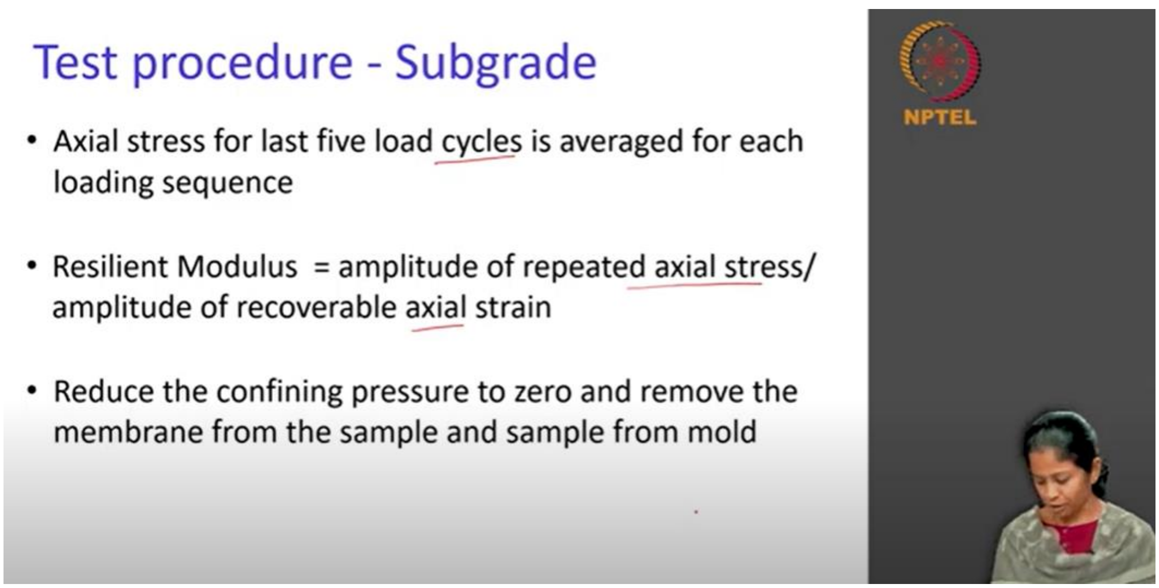

Now the same procedure is used for subbase and base materials except that there is a variation in the confining pressure and the maximum load. So, here the confining pressure used is 103.4 kPa, the same 10 % contact stress, the same 500 to 1000 repetitions except that the maximum axial stress was about 27 in the previous case. Here, we have 103 kPa. So, the same thing between 500 to 1000, if we do not reach resilience state in 500 cycles, we continue up to 1000 cycles and at any point if it reaches 5 %, we stop it.

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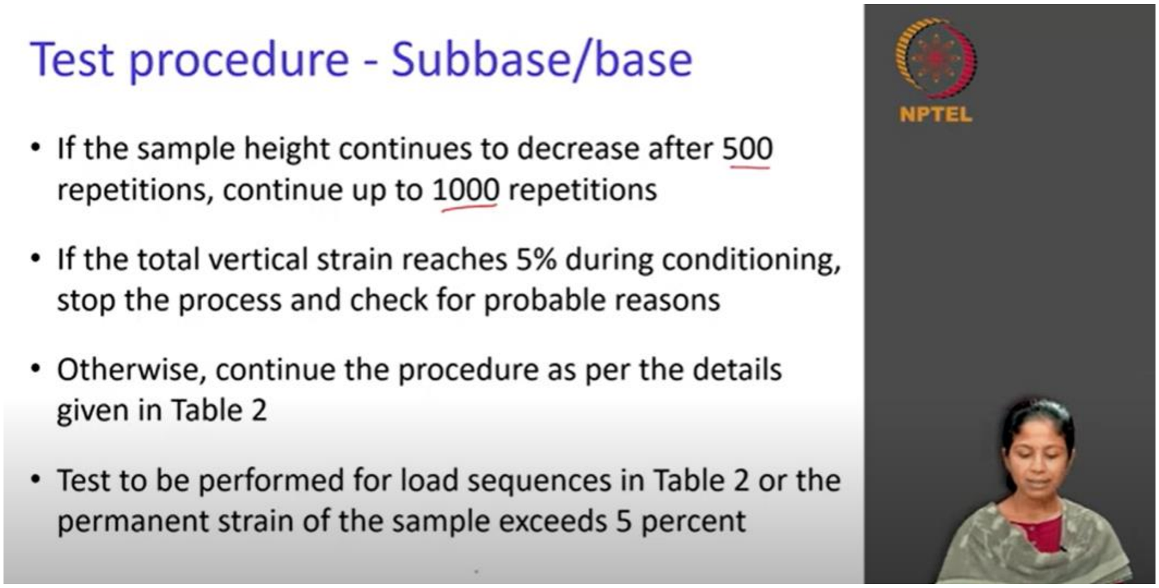

Then, the test sequence is given in table 2 of this particular code. For base and subbase materials, so this is the sequence 0. So, we use 500 to 1000 cycles to achieve the resilience state. So, you can see here this is the confining pressure and this is the maximum axial stress. Under this, we have 5 different confining pressures that we are using here in comparison to the 3 set of confining pressures that we saw here. So, this is 20, 37.5, 68.9, 103.4 and 137. So, for each case, you can see here the maximum axial stress is different here. It is 20.7, 41.4, 62.1, 34.5, then it is 68.9, 103.4, again 68.9, 137. So, it goes in a different manner. So, this maximum axial stress variation is carried out in a different manner in this case compared to the previous case wherein it is used for the subgrade materials. But again, for all the cases we have 100 repetitions. For each sequence we have 100 repetitions.

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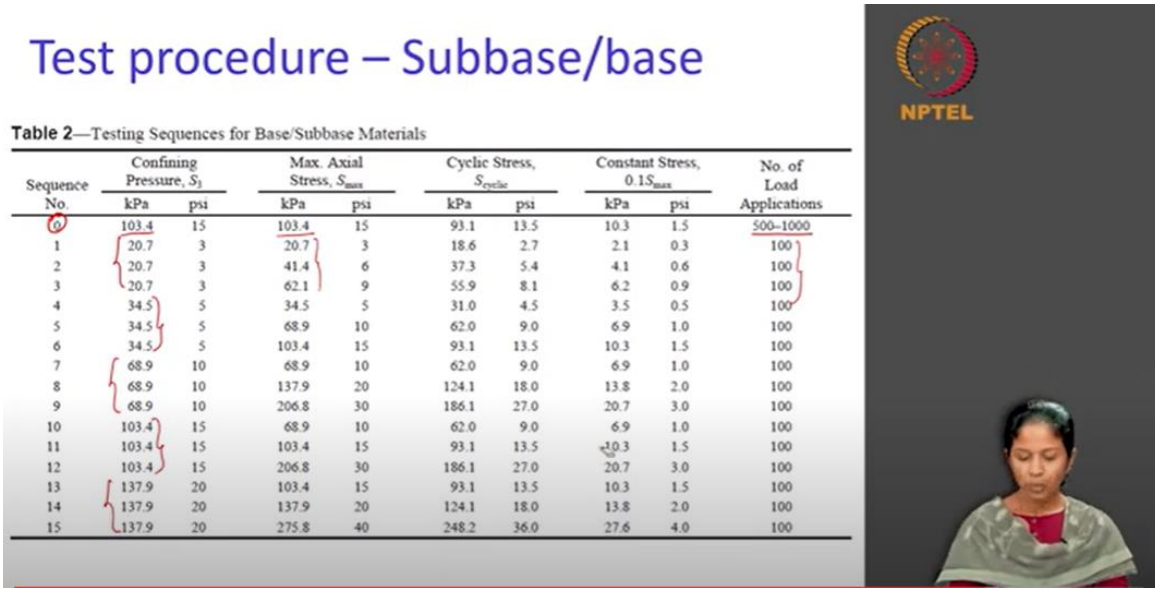

Table 2—Testing Sequences for Base/Subbase Materials

Sequence No.	Confining Pressure, S_3		Max. Axial Stress, S_{max}		Cyclic Stress, S_{cyclic}		Constant Stress, $0.1S_{max}$		No. of Load Applications
	kPa	psi	kPa	psi	kPa	psi	kPa	psi	
0	103.4	15	103.4	15	93.1	13.5	10.3	1.5	500–1000
1	20.7	3	20.7	3	18.6	2.7	2.1	0.3	100
2	20.7	3	41.4	6	37.3	5.4	4.1	0.6	100
3	20.7	3	62.1	9	55.9	8.1	6.2	0.9	100
4	34.5	5	34.5	5	31.0	4.5	3.5	0.5	100
5	34.5	5	68.9	10	62.0	9.0	6.9	1.0	100
6	34.5	5	103.4	15	93.1	13.5	10.3	1.5	100
7	68.9	10	68.9	10	62.0	9.0	6.9	1.0	100
8	68.9	10	137.9	20	124.1	18.0	13.8	2.0	100
9	68.9	10	206.8	30	186.1	27.0	20.7	3.0	100
10	103.4	15	68.9	10	62.0	9.0	6.9	1.0	100
11	103.4	15	103.4	15	93.1	13.5	10.3	1.5	100
12	103.4	15	206.8	30	186.1	27.0	20.7	3.0	100
13	137.9	20	103.4	15	93.1	13.5	10.3	1.5	100
14	137.9	20	137.9	20	124.1	18.0	13.8	2.0	100
15	137.9	20	275.8	40	248.2	36.0	27.6	4.0	100

So, once the test is over, if the total vertical strain does not exceed 5 %, then we also do a quick shear test. Here, we use a confining pressure of 34.5 kPa and again load it so that we have an axial strain at the rate of 1 % per minute under a strain control loading condition. The same thing, we continue until the load value decreases with increase in strain or we reach 5 % strain value or we reach the capacity of load cell. Again, we summarize, so it is average for last 5 cycles. This is computation of resilient modulus and then once the test is over, we reduce the confining pressure and remove it.

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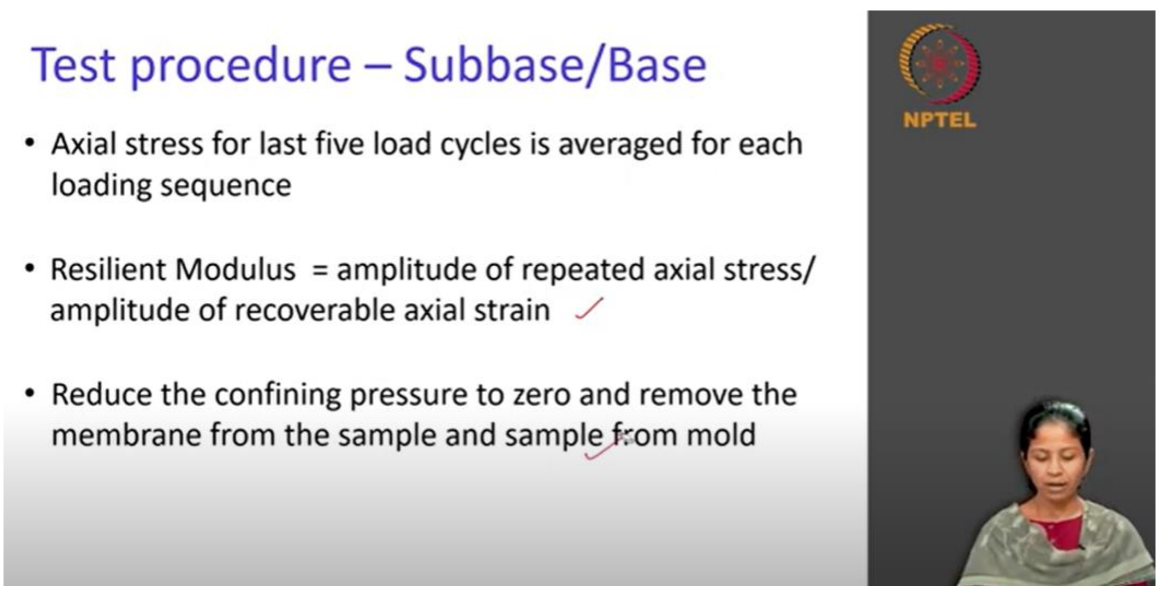

So, this is a table for subgrade soil and untreated base or subbase materials. A similar kind of table, similar set of parameters are given here. Only that the values would be different here. So, this is the testing procedure for subbase and base materials. Now, we have seen the procedure to compute the resilient modulus for subgrade materials separately, subbase and base materials separately. Similarly, the difference in sample preparation for type 1 and type 2 materials. So, this is the whole procedure for computation of resilient modulus based on AASHTO T307.

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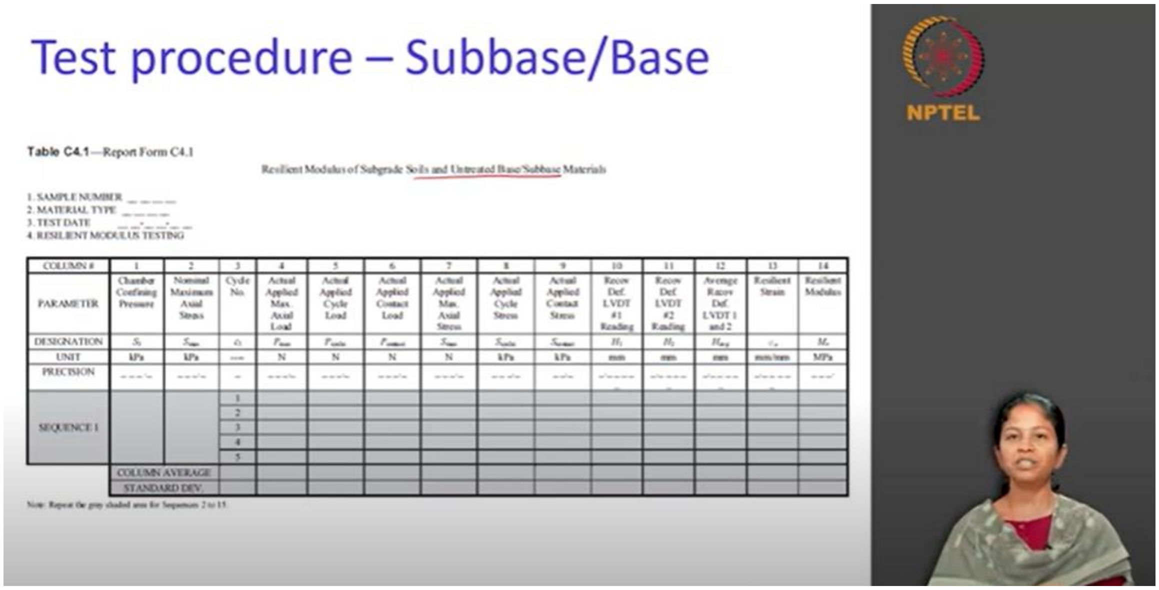

Now, we are going to see some models which are used to calculate resilient modulus, right. So, these models, the initial model which was proposed is called as a K-θ model, wherein the resilient modulus is calculated from θ which is sum of the principal stresses, which is nothing but the deviator stress or the axial stress which is over the confining pressure plus 3 times the confining pressure. So, this is called as the parameter θ and there are 2 other parameters which are K and n which are regression coefficients determined from laboratory data. So, this model was used to calculate the resilient modulus. Typically, in a pavement what happens is as the depth increases, the confining pressure on the material also keeps varying. So, for different kind of confining pressures, this model was used to compute the resilient modulus.

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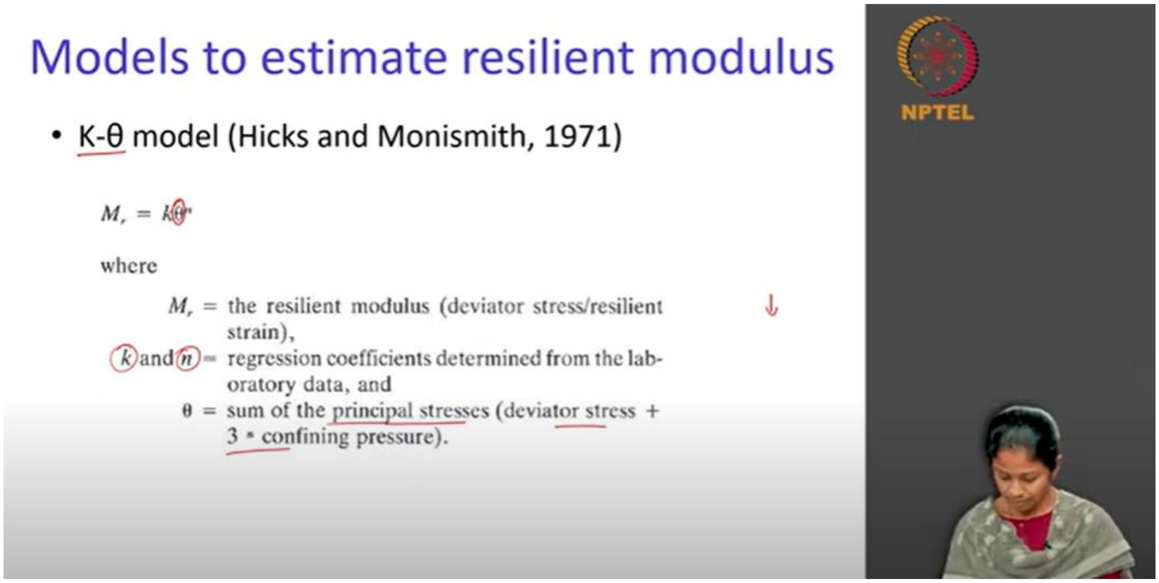

And there were a lot of modifications, you can see here. This is θ which is nothing but the sum of the deviatoric stress plus 3 times confining pressure. As the θ varies, you can see that there is an increase in resilient modulus. So, even in the resilient modulus test, when you increase the confining pressure, the resilient modulus is going to increase. So, for different type of soils, they have computed the values.

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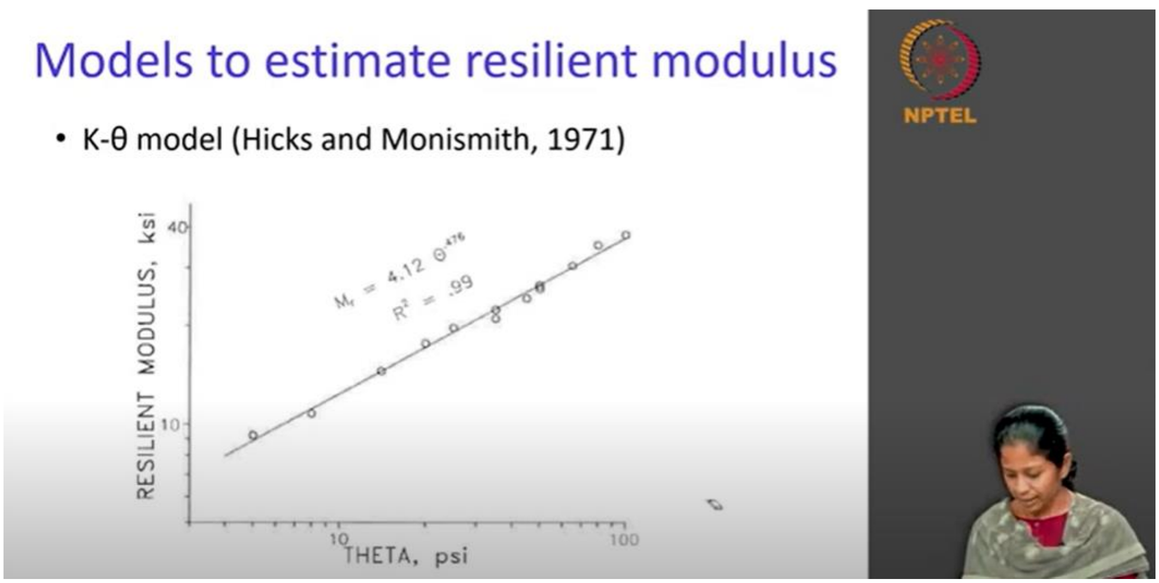

So, this could be given as $K_1\theta^{K_2}$ or $K\theta^n$. So again, different people follow different notations. So, whatever is given here is based on this particular notation. You can see here for different type of materials, these K_1 and K_2 values vary. And these are called as nonlinear constants because the modulus value varies with the stress and that is why there is a nonlinear response. So, you can see here for silty sand, the K_1 value is 1620, whereas when you take a crushed stone, it is as high as 7210. And the K_2 value again, it varies from 0.53 for a sand or gravel to 0.45 for crushed stone and 0.62 for silty sand. So, these are the ranges of K_1 and K_2 values for granular materials. Again, for untreated granular materials from other reference, this is from one particular reference for different kind of materials. For other materials also, these values are given. So, it all kind of varies over a range. Many of the design procedures or at least a few of the design procedures have this model to compute the value of resilient modulus for different confining pressures. So, if you look at the MEPDG model, they divide the granular layer into different sub layers and for each sub layer the confining pressure is varied and the resilient modulus is computed. But if you see, as the state of stress varies for the material, the value of K_1 and K_2 are going to be different and thus the modulus value will be different. That is why most of the design procedures assume a confining pressure and then use the corresponding value of K_1 and K_2 and compute the modulus. Otherwise, the computation time is going to be substantially high.

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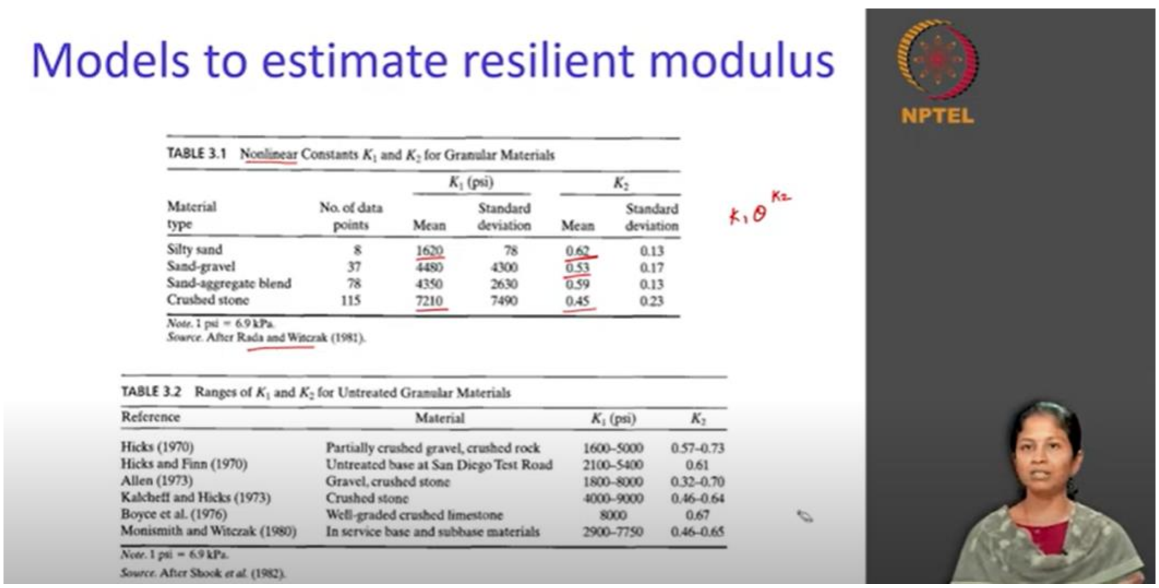

There are going to be other models which are improvements over this model. This is the Uzan model in fact. Previously, we said that for most materials as the θ value varied, the resilient modulus increased. But for some fine-grained soils, they observed that as the θ value increased, the resilient modulus decreased. So, to account for those kinds of materials, this parameter σ_d was incorporated in the model. So here, again resilient modulus which is a function of K and n which are regression coefficients determined in the laboratory, θ has a same meaning here, σ_d is the deviator stress in specific and a is also a regression coefficient determined from the laboratory. So, we have 3 constants here *K*, *a* and *n*, θ and σ_d.

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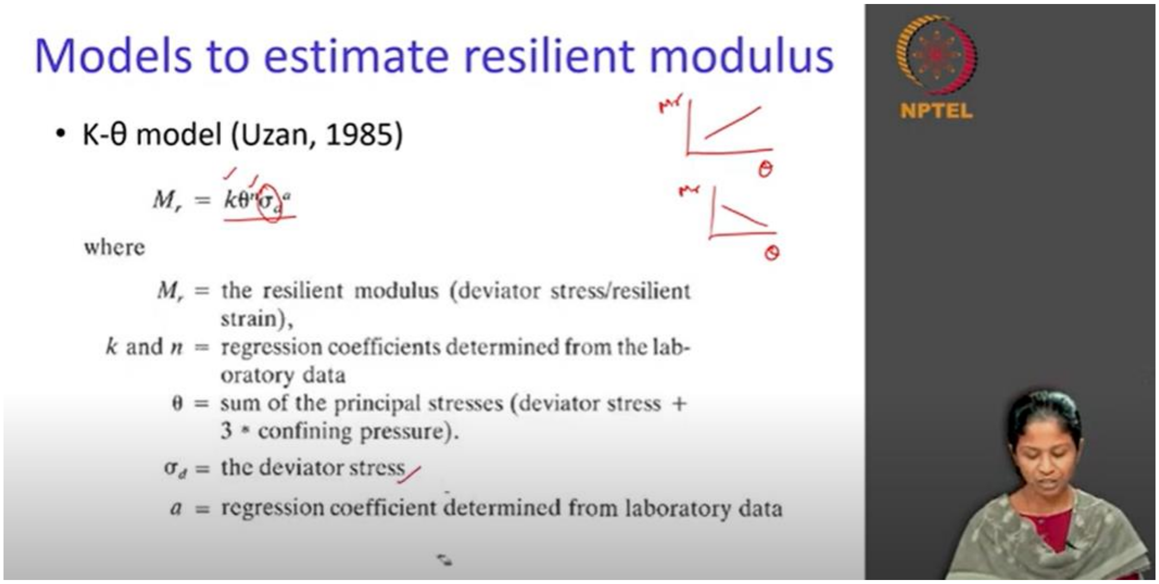

So then, there was a modified Uzan model wherein the octahedral stress was used instead of the deviatoric stress. Again, all of them, even the previous Uzan model and the modified Uzan model wanted to incorporate the effect of both axial and shear stress. So, that is why these parameters θ and σ_d or τ_{oct} are incorporated in the model. So θ has nothing but the bulk stress which is σ_1, σ_2, σ_3, τ_{oct} is the octahedral shear stress and this is computed as $\tau_{oct} = \frac{1}{3}((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)^{1/2}$. So, this was the modified Uzan model. So based on this modified Uzan model, there were lot of other models with minor variations. So, if you see, there was one Pezo model, one model by Ni et al., one model by Ooi et al. and all those things. So, a number of models are available.

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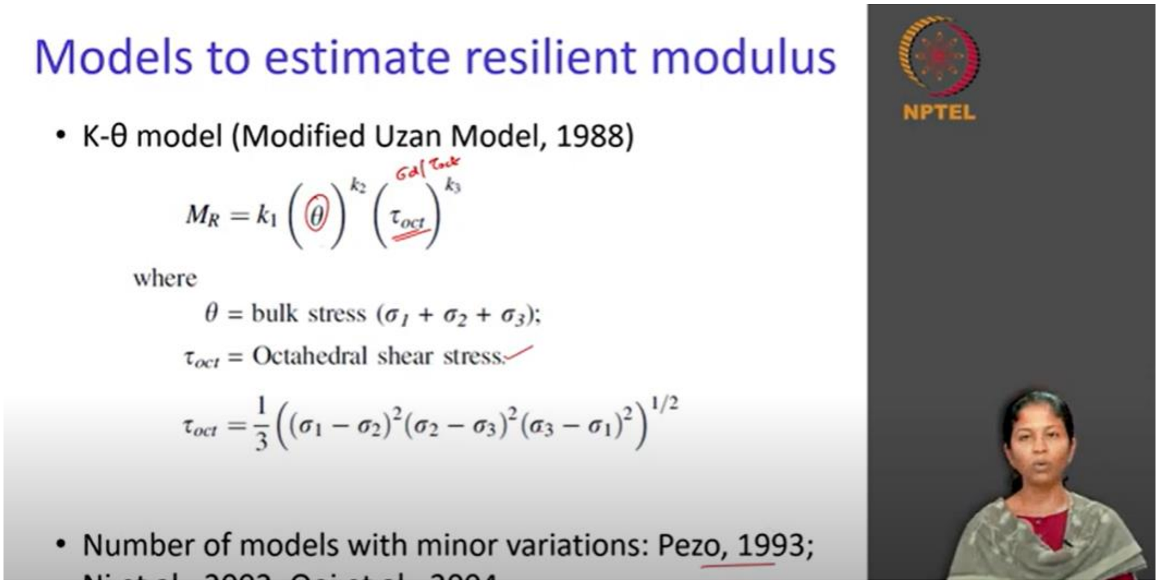

And the last one is the ME-PDG model which is used in the ME-PDG framework. Again, here it is a function of K_1 a constant, K_2 a constant, K_3 a constant and then there are 2 parameters θ and τ_{oct}. This P_a is used only as a normalizing stress parameter. We can just ignore it also. You can see it is multiplied on both sides. So, this is the ME-PDG model which is used here and here you can see these are the definitions for the bulk stress and this is the definition for the octahedral shear stress. So, to compute the resilient modulus for different confining pressures, it is difficult to measure each and every time. So, that is why these kinds of models are incorporated into design procedures to compute the resilient modulus knowing a particular confining pressure.

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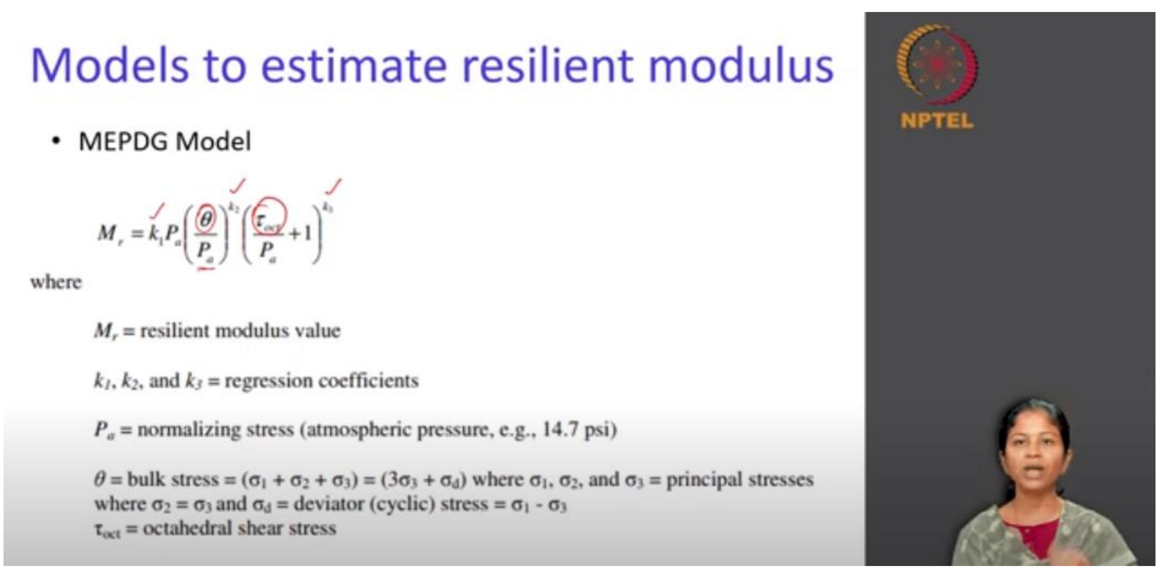

So, this is regarding the resilient modulus, its computation and the models used for subgrade and granular layers. I will stop this lecture here. In the next lecture, we will talk about the modulus measurement for bituminous layers. Thank you.