Analysis and Design of Bituminous Pavements

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Lecture – 35

Reliability in Pavement Design - Part 05

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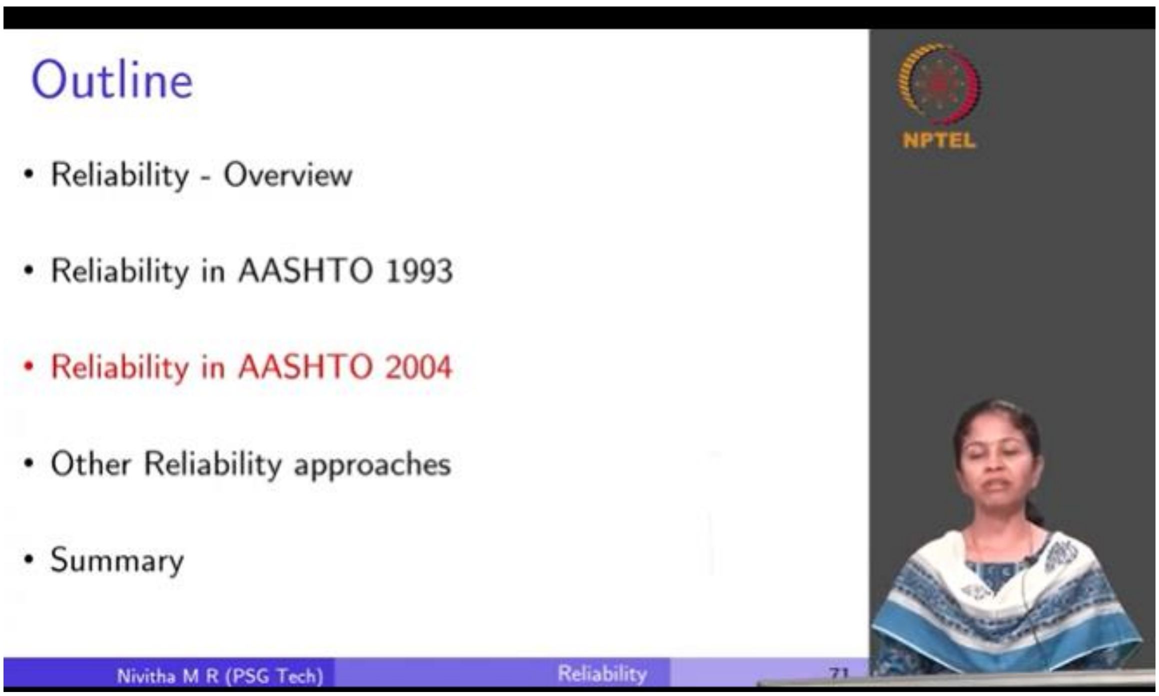

Hello everyone, welcome back. In this lecture, we are going to talk about the reliability aspects in AASHTO 2004 which is nothing but the MEPDG design procedure. Again, if you ask me is AASHTO 1993 not an MEPDG design procedure or even for that matter is IRC 37; all of them are mechanistic empirical pavement design procedures. So, in the first few lectures, you would have been introduced to what is mechanistic, what is empirical and why we call this design procedure as a mechanistic empirical pavement design procedure. So, this 2004 is also a mechanistic empirical pavement design procedure, except for the fact that it has detailed considerations with respect to traffic, climate, material properties, the design procedure as in. So, that is the advantage that is present in the 2004 version, but still it is commonly referred as MEPDG. So, I will just use it as AASHTO 2004 version. Again, this design procedure is very comprehensive, it is detailed. To completely understand the design procedure, we need to know the influence of all the individual parameters, how it is considered, there are a lot of aspects that have to be addressed, right. In fact, explaining all those concepts and completely understanding how this MEPDG works itself is a separate topic on its own, which we can cover in 4 or 8 weeks.

So, we will not get into the detailed aspects of the design procedure. Since our focus is here more on the reliability aspect, we will see how reliability is addressed in few of these aspects. Say for example, with respect to the input parameter or with respect to the distress prediction model, how reliability is addressed. So, that will be the focus of our discussion with respect to AASHTO 2004.

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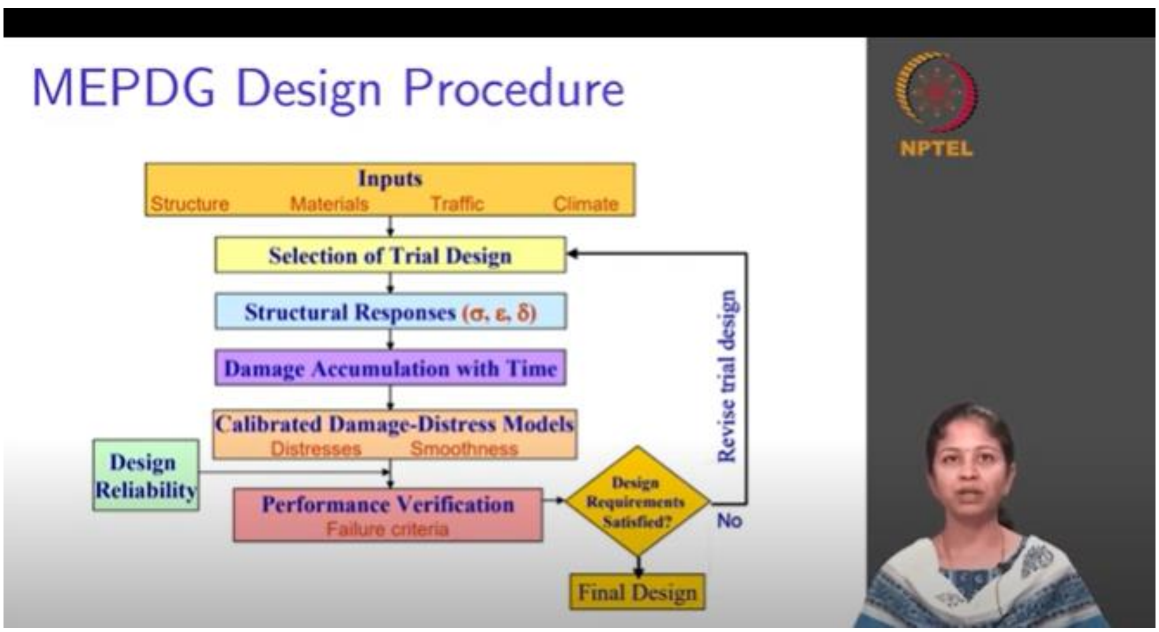

Now let me briefly show you the design procedure which is followed. This is again common and relevant for any mechanistic empirical design procedure. So, we have certain inputs which are used. This input is categorized into 4 different heads. One is the structure related inputs like what are the layers we are using, what are the properties of individual layers. The next one is material related aspects, the properties of materials that we are using, what are the traffic aspects in terms of axle load, in terms of traffic volume, the lateral distribution factor, wander, tire pressure, so many parameters. We have again seen all those things in detail in AASHTO 1993 design procedure. Then we also have the influence of climate. Structure and materials are common as in like similar to any design procedure, but there is detailed consideration with respect to traffic and climate. The influence of traffic and climate related factors on the material properties is discussed in detail or is addressed in detail in this particular design procedure.

Then after these inputs are provided, we select trial section for design. It is basically a proof checking kind of an exercise wherein we will choose an initial section. We will check for the adequacy of the section. If not, we will go back and revise, right. So, it starts with selection of a trial design. Then we obtain the structural responses, which is nothing but the stress strain at critical locations. Again, like the linear layered elastic analysis which is used in IRC 37, this particular design procedure also uses a linear layered elastic analysis. The distinguished feature in this design procedure is the critical strains are evaluated only at two locations for a given load in IRC 37. Whereas in this case, it is evaluated at multiple locations and the critical among those strain values or the stress value is used for the design. So, that is another advantage, but the design procedure is the same. Then the damage accumulation with time is computed here and then the calibrated damage distress model is also used.

As in the IRC 37 variant, we have the equations to predict N_f and N_R, which are based on 56 studies conducted by MoRTH. Similar AASHTO road test studies are, have been conducted in the US and based on those studies, the model calibration constants have been arrived at. And they have considered a lot of factors in the damage model or the distress prediction model, which only limited considerations are in other design procedures. So, that is another advantage with respect to the distress model. Then before we verify the performance, we have the design reliability that we should be using.

And for the design reliability, for the all these conditions, we are verifying the performance. If the performance is satisfactory or if it is below than the acceptable limit, then there is a design requirement is considered to be satisfied and the final design is arrived. If not, we go back and then we revise the trial design and repeat the same procedure. So, this is in a nutshell, the pavement design procedure that is followed in AASHTO-ware. More details related to the consideration of materials, traffic and climate have been discussed in the previous lectures. So, I will skip all these things and move straight away to the reliability aspect.

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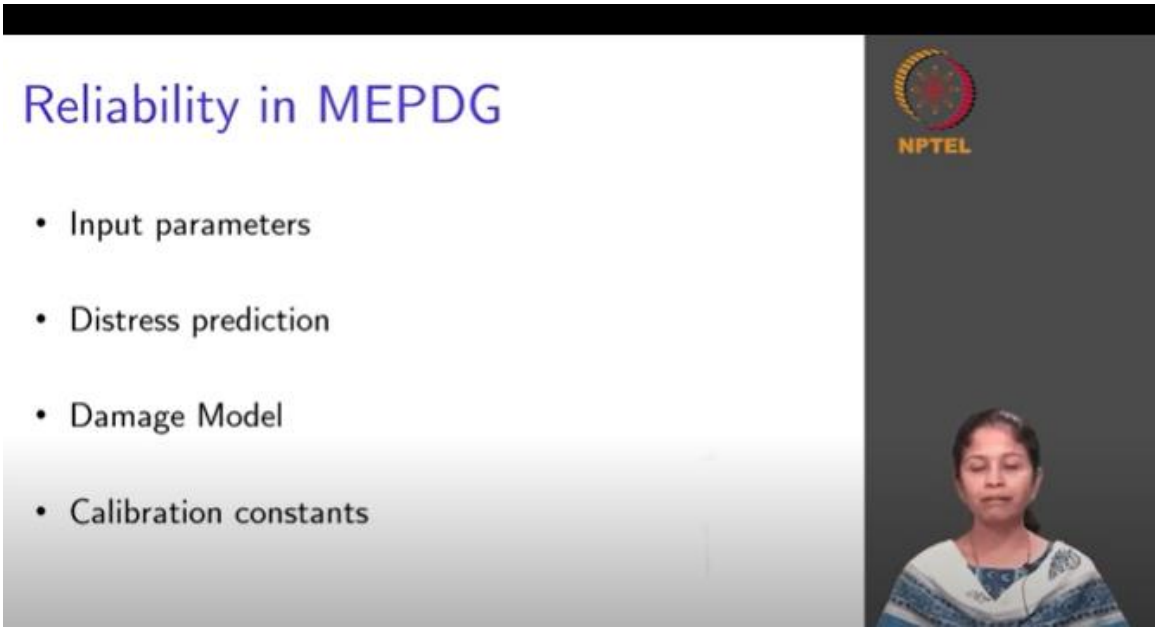

Now, what are the input, what are the aspects of reliability that we are going to discuss in this lecture? So, for ease of understanding, I have categorized them under four heads. One is input parameter related variations. The second one is distress prediction model. Third one is damage model. And finally, we have calibration constants. So, we are going to discuss the aspects of reliability in MEPDG or AASHTO 2004 under these four heads. So, now let us look at the input parameter.

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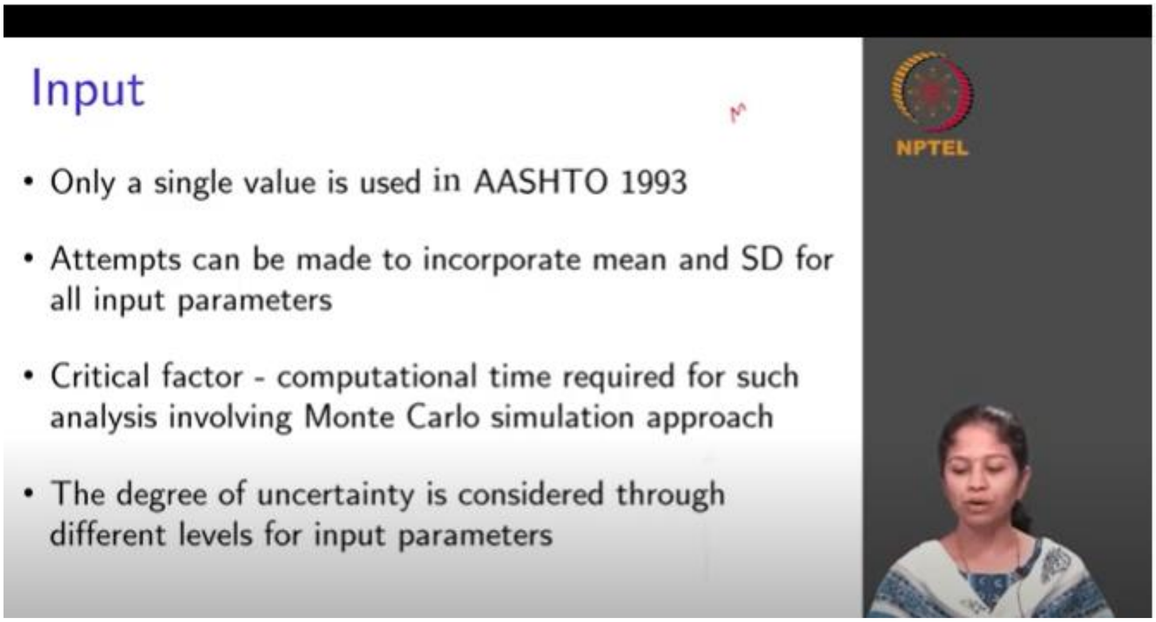

If you recollect in AASHTO 1993, only a single value was used. If you remember, we used MR value which is effective road bed resilient for the soil layer. And then we also used a Δpsi value which is loss of serviceability. So, only these values were used with respect to the material properties and the effect of environmental factor on loss of serviceability. There are a lot of attempts which have been made to incorporate the actual variability in materials. Again, in the previous lecture when we were discussing, we have seen that the variability in layer thickness, we have seen the variability in material modulus. So, all these things we saw that it could be approximated like a with any distribution. More commonly, a normal distribution can also be used to represent the variation in the data. So, when I plot a normal distribution, it can be characterized by the mean and standard deviation value. So, using these 2 parameters, we can obtain distribution for all our input parameters. So, this is something which we had seen in the last lecture. So, there are attempts to incorporate. So, if we have 5 or 6 material properties, for each of them I will have a distribution characterized by mean and standard deviation. So, like that I can arrive for all my parameters. In fact, if you remember the chart which I showed you which had lot of parameters listed separately and their mean and standard deviation, you can recollect how many parameters we will be using in design and how many mean and standard deviation values we have to input. So, in that perspective, if this is incorporated into the design procedure, then the design procedure will become highly time consuming. In fact, there will be like unrealistic time taken for computation of one particular design. So, this is usually executed through Monte Carlo simulation approach. In the next lecture, I will be discussing in detail about this Monte Carlo simulation approach. But if this kind of an attempt is made and it is incorporated into the design procedure, then the time consumed is enormous. It is not practical. So, that is why most of the times even though methods have been arrived at and the background related to incorporation of variability and input parameters is already known.

Considering these limitations, most of the design procedures and the associated software have not taken into account of the variability of input parameters into the design procedure. But however, the certainty with which we arrive at these input parameters is taken into account through a hierarchy of input. So, what do I mean by hierarchy of input? We have 3 levels for my input parameter, I can specify a level 1, I can specify a level 2 or I can specify a level 3. So, all 3 of them are not at the same level of accuracy, level 1 is considered to be more accurate. So, I can say it is more reliable and I am more certain about the outcome if I use a level 1 kind of data. On the other hand, level 3 is more approximate, so obviously less reliable and there is lot of uncertainty associated with it. So, whatever is the background related to reliability in terms of the assurance of the data and the uncertainty associated with it, it is kind of addressed through these 3 level of input parameters. Now, let us say what, let us see specifically about all these 3 levels.

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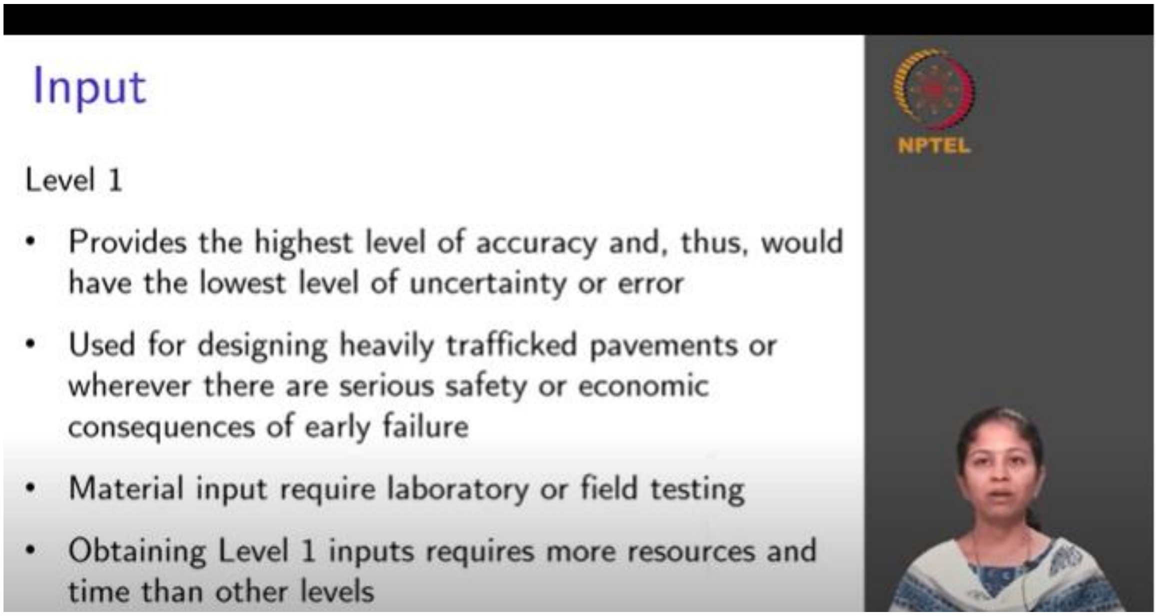

So, what is level 1? As I mentioned earlier, it provides the highest level of accuracy. So, it is the most specific information and thus would have the lowest level of uncertainty or error. So, it will more closely represent the actual condition that the material is going to be in field. Say for example, if I use an asphalt layer, right, we have a bituminous layer. So, I am using a bituminous mix and it has a mod, we have to associate a modulus value to the bituminous mix. Instead of making assumptions, I prepare a bituminous mix. Let us say dynamic modulus is the measure which is used for design for that particular bituminous layer.

So, how do I input the dynamic modulus? I prepare a bituminous mix sample as per the guidance, as per the CODEL provisions and I take it to my lab, I conduct a dynamic modulus test on it. Again, you know that this test has to be conducted at different frequencies and different test temperatures. So, I conduct the test at all those frequencies and test temperatures. I input this information into the design procedure and the design procedure will arrive at a master curve for this so that for any combination of temperature and frequency, the modulus value can be arrived. So, this is a closer representation of the modulus that the material will be experiencing in field. This is called as a level 1 data.

Similarly, if I measure the traffic volume, if I am inputting the traffic parameters, I have to measure the traffic volume for that particular highway. I also arrive at the axle load spectrum for that particular highway and I use all this information again the lane distribution factor and all other the lateral wander all those tire pressures, all this information I measure for that particular highway and I use it in my design procedure. So, this is a level 1 kind of input for example, for the material or for the traffic. So, it is used for designing heavily trafficked pavement or whenever there are serious safety or economic consequences of early failure. So, when the consequences of failure are very high or for highways wherein we do not want to make any compromise on the level of performance expected, then we go for a then we should be going for a level 1 input.

The material input requires laboratory or field testing. So, there is no assumption or there is no calculation of these values from already available or through using empirical equation. So, for that particular material, we have to do a laboratory or field testing arrive at the values and only use those values for design. So, obtaining a level 1 input requires more resources and time rather than other levels because we have to collect data which is specific to that site and then use it for our design. So, collection of data is going to require lot of time and resource but it is more accurate. So, this is a level 1 data that we will be using.

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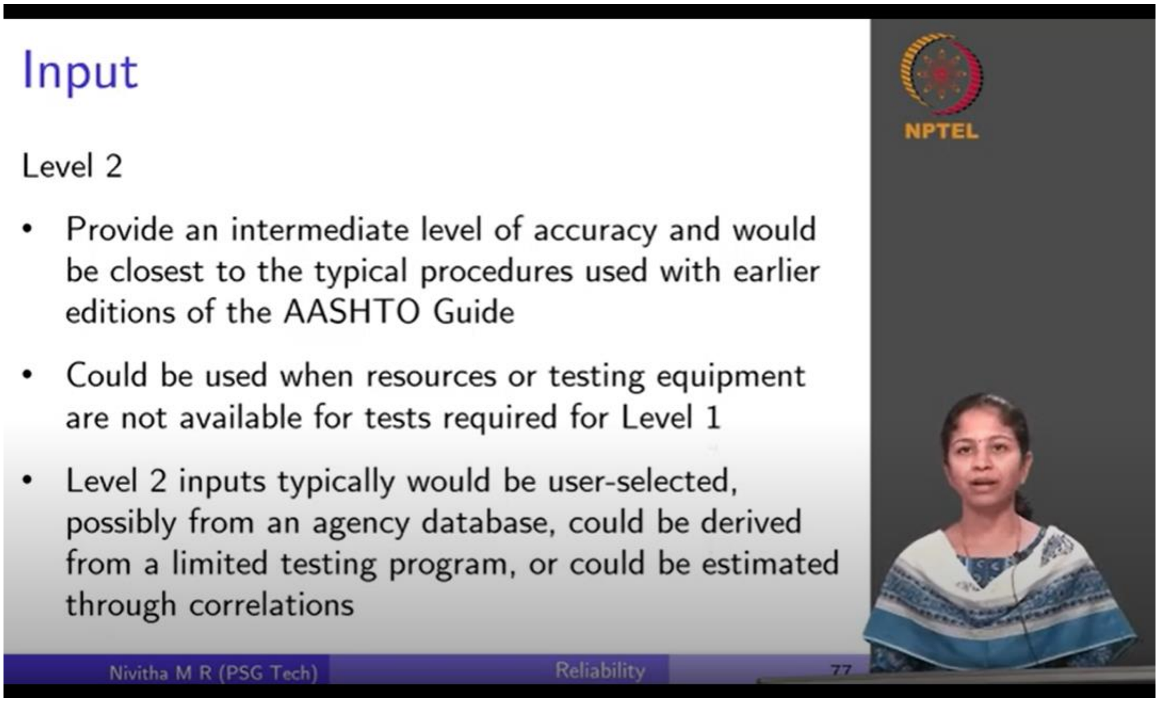

Then is a level 2 which is a slightly less accurate level of input and it is less certain compared to level 1 kind of input. So, it provides an intermediate level of accuracy and it would be the closest to the typical procedures which are used in previous editions. So, if you look at AASHTO 1993, it will be more related to the kind of procedures which are suggested in AASHTO 1993 wherein we sometimes resort to the use of empirical equations or say for example, for effective roadbed resilient modulus, we did not measure a different moisture conditions but used a damage concept to scale it. So, those kind of approximations will be used but still we are not deviating too much from the realistic condition.

It can be used when resources or testing equipment are not available for test required for level 1. Let us say if dynamic modulus is required for measuring the, is required as the modulus measure for bituminous mixture and I do not have an equipment to measure dynamic modulus. Instead what I can do is I can measure the property of binder, I can measure the property of aggregates and then based on these properties of the individual materials, I will use empirical relations to predict the property of bituminous mixture. So, I am not directly measuring, I am still using a modulus value but I am not directly measuring this value but I am predicting, it using other empirical equations. They may be valid but there are certain approximations which are used here obviously, so that we always have to keep in mind it is not as reliable as the level 1 measurement that we had done.

Similarly, let us say for traffic, I am able to collect traffic volume data which is relatively simple to do when compared to measurement of axial load spectrum. So, whatever is the parameters which I will be able to measure like axial load, like the lateral distribution factor, lane distribution factor, whatever is it, if whatever I am able to measure, I will measure it and whatever is tedious to measure like the axial load spectrum, I will assume from an agency data or from the historic data. So, here it is not as accurate as level 1 but still we are making some measurements specifically at that site. So, this is somewhere between level 1 and level 3. Level 2 inputs would be user selected, sometimes we will resort to user selected values possibly from an agency database or it could be derived from a limited testing program. The testing program may not be as exhaustive or as detailed as the level 1 and other things could be estimated through correlations. So, this is a level 2 kind of input. So, if you recollect reliability; we can determine the degree of uncertainty associated with level 1 input and the degree of uncertainty associated with level 2. So, it keeps increasing.

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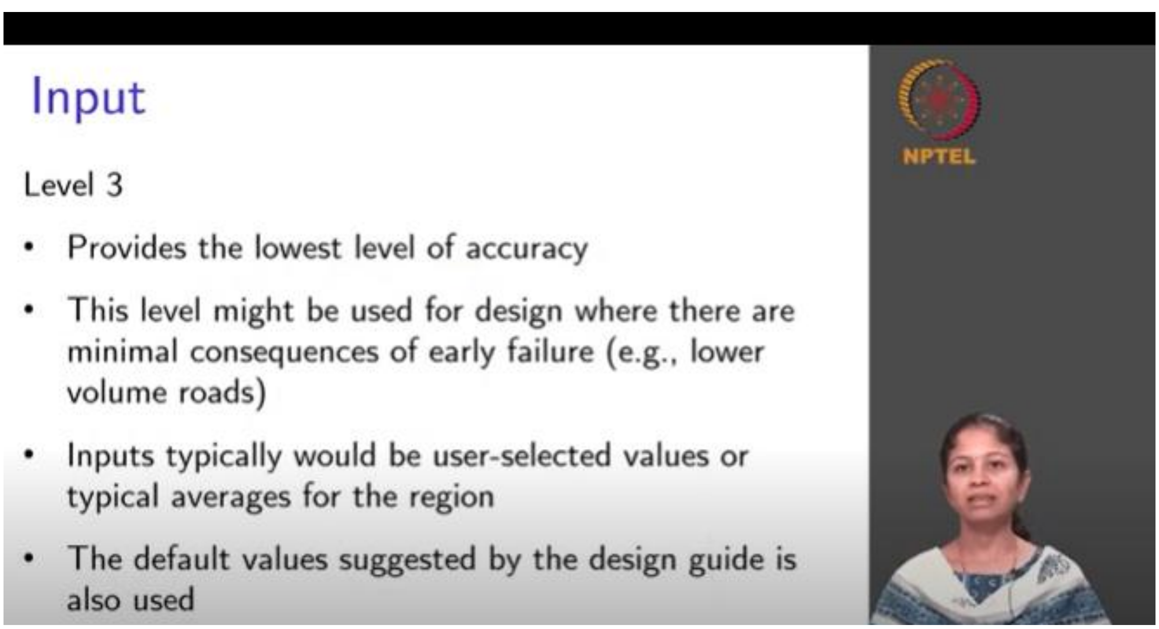

So, it is again higher in the case of level 3 wherein it provides the lowest level of accuracy. So, this level might be used to design when there are minimal consequences of early failure. Say for example, I have a low volume road and even if the road fails it is not a major consequence, then for those kind of roads we can use a lower reliability value. So, the inputs would be user selected values or typical averages for the region. Again, if I recollect the same example which we were talking about the dynamic modulus, I do not have an even have to measure a dynamic modulus, I might use a default value available for a bituminous mix. So, that kind of values could be adopted even for traffic, I can select traffic default, traffic data will be available for certain highways, whichever is more close or which represents more closely to the highway under design, I can use it, choose the default values and go ahead with the design. So, this is a very easy process wherein there is very little or almost negligible data collection involved but the level of accuracy is also relatively low. The default value suggested by the design guide can be used in most cases. So, whenever we do a design using this MEPDG procedure, it asks for the level of input. So, for every parameter I have to specify whether I am using a level 1, level 2 or level 3 input. This level of inputs can be different for different parameters. Say for example, for material properties I can do a level 1, for traffic I can do a level 2. So, all these combinations are possible even for materials for one layer I can give level 1, another layer I can use level 2. So, this is possible.

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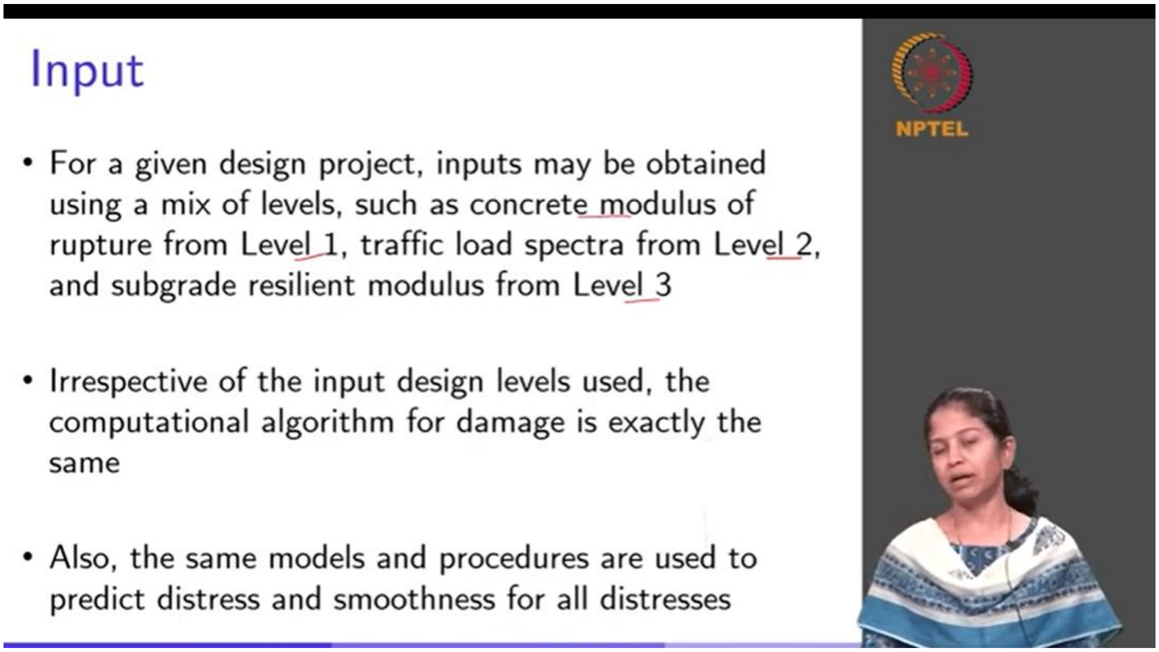

So, for a given design project, so input may be used as a mix of level. So, that is what I was mentioning about. Say for example, if I am designing a concrete layer, for concrete modulus of rupture I can use a level 1 kind of input, traffic load spectra I can use level 2 and for the subgrade resilient I can use level 3. If you recollect AASHTO 1993 or the 1993 design procedure, we had only one reliability level which was applied to the design procedure. But here we have flexibility in choosing the level of reliability for each layer, for each parameter that we are using in the design. Then another thing that should be noted is irrespective of the level of input that we are using, the computational algorithm for damage is exactly the same. So, once I give a modulus value, the variation comes in from how I arrive at the modulus value. But once I give the modulus value, then computation of strains will be based on that particular modulus value only. A similar procedure will be used irrespective of whether it is a level 1 input or a level 3 input. So, the computational algorithm is going to be the same. Also, all your damage prediction models and other performance prediction characteristics will be similar irrespective of the level of input. So, we do not have a separate damage prediction model if you are using a level 1 input or a separate damage prediction model if you are using a level 3 input. The damage prediction is going to remain the same irrespective of which level of input we are using. So, this is something with respect to the input data that we are using for design.

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So, next we will move on to the distress prediction. So, let me take IRI as, so I will go through this before I show you an example on IRI.

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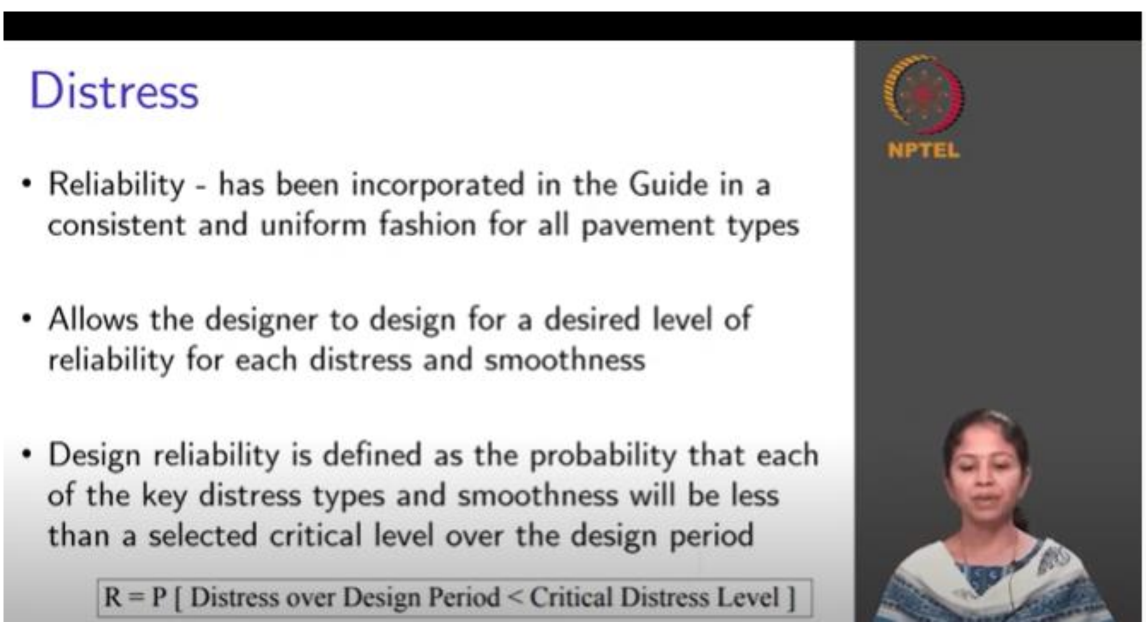

So, this reliability has been incorporated in the guide in a consistent and uniform fashion for all pavement types. So, how do we consider this? We always have a standard error and a standard normal deviate for any given reliability level. So, we always predict the, let us say I am predicting fatigue cracking, we predict it at 50% reliability using the mean value. We have seen in the previous lecture that if you use a mean value we are going to arrive at the reliability level corresponding to 50%. So, we will obtain the reliability level at 50%, then I am going to correct it with this particular parameter to get fatigue cracking at any reliability level R. Again, if you recollect in one of the previous lectures I would have shown this through a flow chart. So, this procedure is going to remain the same, instead of this fatigue cracking I can replace it with rutting. So, this is going to become rutting at 50% reliability. So, this format is the same except that the particular distress is going to vary. So, that is what they had said as a uniform fashion for all pavement types. So, it allows the designer to design for a desired level of reliability for each distress or smoothness. Since we have IRI also, the smoothness term is also included here. So, in MEPDG 2004 we have a number of distresses which are addressed. Say for example, we have the rutting and asphalt layer, then we have total rutting, we have top down cracking, we have bottom up cracking and then say we are also computing IRI. So, like that different distresses are taken into consideration. And so that is why the smoothness term is also given here to take into account of the IRI value.

Then the design reliability is defined as the probability that each of the key distress type and smoothness will be less than a selected level over the design period. So, this is how reliability is defined for a distress. So, if R is my reliability, this is the probability that the distress over my design period that is actually observed in field over my design period is less than the critical distress level or the acceptable distress level. So, then it is quantified through reliability. So, this is what they are defining as reliability in terms of distress.

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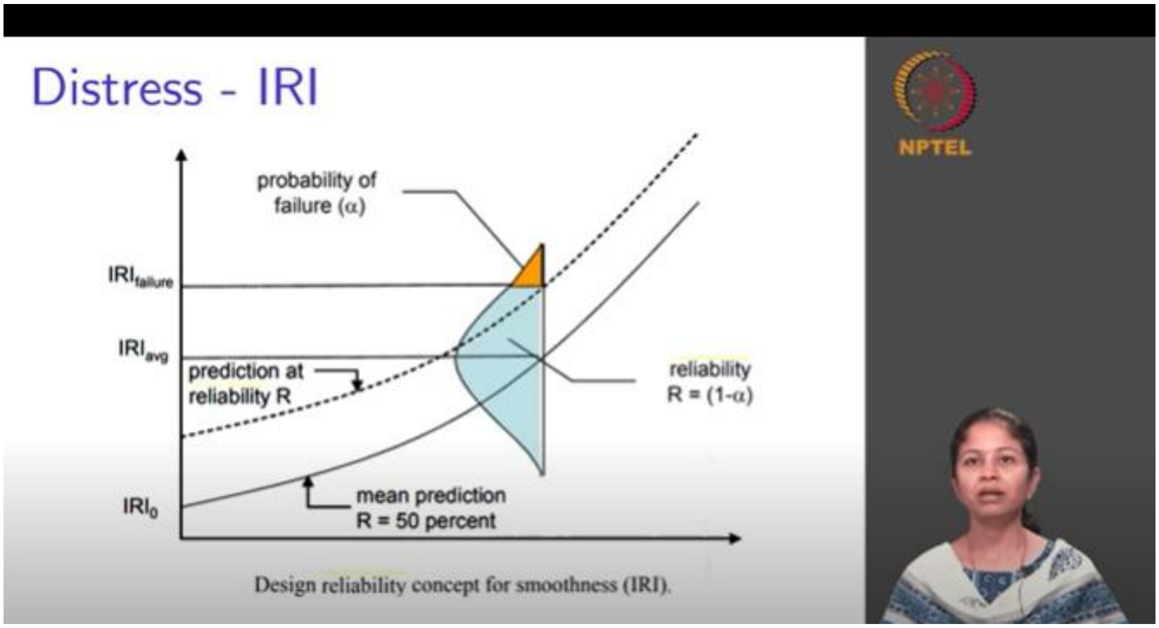

Now, let us look at this particular plot. This is indicated for IRI. Again, we can arrive at similar plot for any given distress. So, let me explain the axis associated with this. The y axis is my IRI value, x axis is the time period. So, this is how IRI value progresses with time. So, let us take this particular curve. This is at 50% reliability when I use mean values as input and I do not correct it for my desired reliability level. So, when I design it, this is my 50% value. So, this is the average IRI value I will be getting. So, I have this IRI average value. Then we also have another curve which is for a given reliability level R, it could be any reliability level. So, this is the performance curve at any given reliability level R. So, now if I observe this performance curve, this is the point at which we have defined failure in terms of IRI. So, this particular curve meets this, see this is my failure IRI.

So, my performance curve meets this at this point. So, whatever is the area to the right of this portion is my probability of failure. So, this is defined as probability of failure α and reliability is 1 - α which is this particular portion. So, this is how the probability of failure and the associated reliability is calculated.

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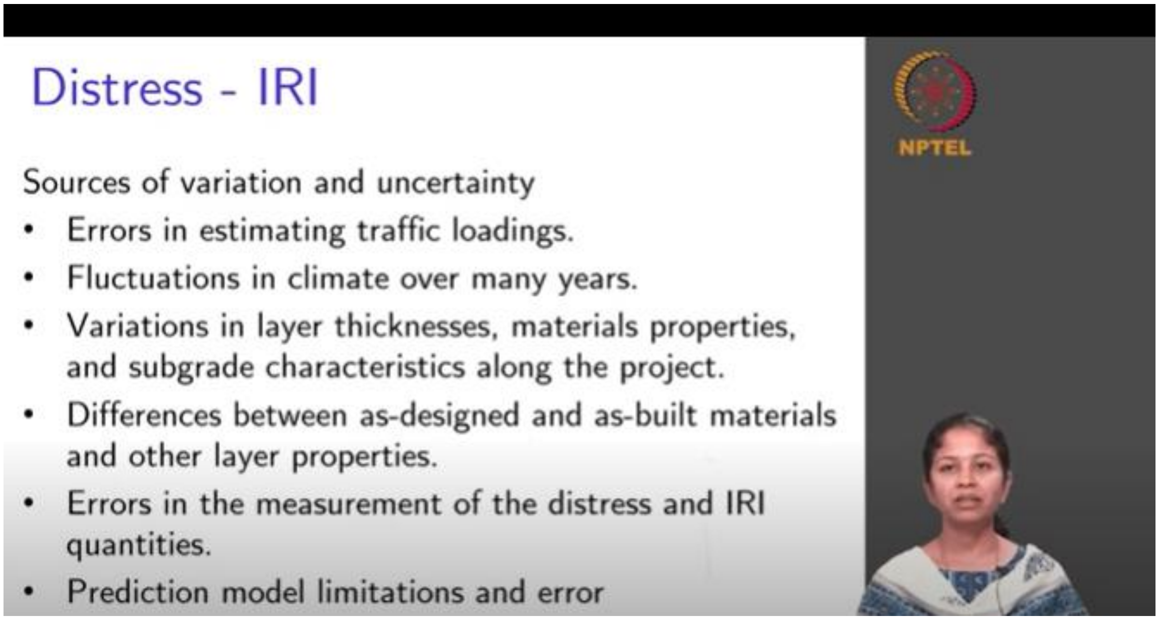

Now, let us see what are the factors which cause variation in this IRI. So, for the sources of variation and uncertainty are errors in estimating traffic loading. So, we have seen yesterday that let us see what are the sources of variation for this IRI value. So, if I use a mean input value, what factors would cause variation from this mean input value? So, one parameter is the traffic loading. We have seen in the previous lecture that the traffic loadings can vary over a range, we had seen that even for a given highway at different locations if we measure the AADT was varying. So, the errors associated in estimating traffic loading. Again, I said when we are using a sampling based approach, this has to be taken into consideration. Then fluctuation in climate over many years again, we would have had some climate as the base when we are designing the pavement, but there would be fluctuations from the assumed value. So, that is another parameter, variation in layer thickness, material properties, subgrade characteristics, etc. Again all that we had seen earlier. Then difference between as designed and as built materials. There is again this factor that has to be taken into account. It can come under the construction quality as well. We make some assumptions about the material when we are designing, but as I said earlier, it is not necessary that the same has to be translated into design. So, what is the deviation between as designed and as built materials? Then errors in measurement of distress again. So, when we are measuring distress also, especially when we are doing the calibration, there might be some errors associated with such measurement. So, errors in measurement of distress, IRI quantities, then even the limitations associated with the model, the error in prediction model, the constants which are used in the prediction model, as we discussed earlier are calibrated for certain locations, certain kind of materials in certain climatic conditions. So, when those things change, the accuracy of the model prediction also will change. So, the limitations associated with the prediction model and the error. So, these are some parameters which can influence the IRI value around its mean value.

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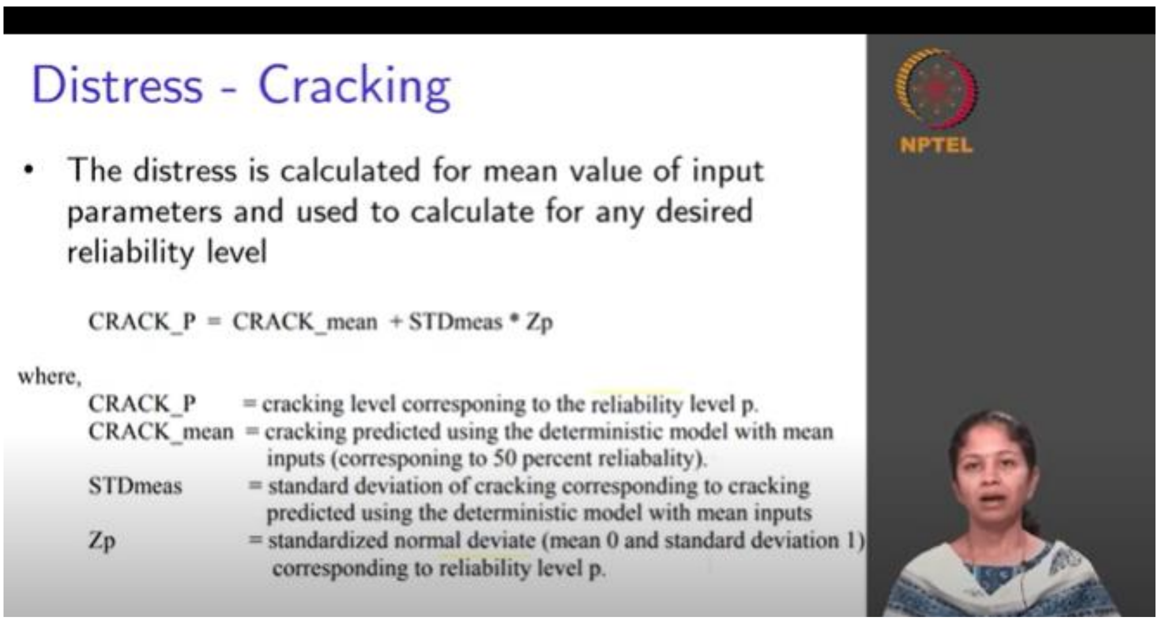

Similarly, we can define it for all distresses and look at how the required reliability level is taken into consideration in the distress prediction equation. So, this is explained for cracking. I will show you another slide wherein we have the same thing for rutting as well. This distress is calculated for a mean value of input parameter and used to calculate for any desired reliability level. Even in AASHTO 1993, if you recollect, we calculated w18, we had the equation for 50% reliability level and then we did an Zr into S_0 plus all the other terms. So, this was to convert that from 50% reliability into any desired reliability level. A similar exercise is carried out here also to take into account of the required reliability level. So, let us look at this equation.

$$CRACK_P = CRACK_{mean} + STDmeas * Zp$$

We have cracking at P. This is cracking level corresponding to the reliability level p. So, this is a function of mean cracking level that is cracking predicted using the deterministic model with mean inputs. As I said earlier, even in MEPDG, we are going to use a deterministic model with mean value for all the input parameters. So, I am going to take that value. So, that is my mean value and I am going to add this term to that. What is this? This is standard deviation of cracking corresponding to cracking predicted using the deterministic value with mean input. When I predict my cracking and I look at the values, I compute a standard deviation for the measured value. So, this is the standard deviation of measured value and we have a standardized normal deviate. It is with a mean 0 and standard deviation 1 corresponding to reliability level p. So, we have a standard normal table. If we look at the standard normal table, we will be able to arrive at the standard normal deviate value corresponding to any desired reliability level R or let us say here it is used as P. So, this is how we get the standard normal deviate. So, with that, we will be able to compute the cracking value for any desired reliability. Now there are certain differences between a deterministic approach and the probabilistic approach or a reliability based approach when we are calculating the distresses.

Let me explain that with an example. So, the specific information required for the design performance criteria depends on whether it is deterministic or it is a reliability design, wherein we take into account of the probability. If we have a deterministic design, there are only 2 pieces of information which are required for pavement analysis. The first is the limiting design value, like what is the critical value for which we have to design the pavement for and the design life. So, we will ideal let us say if I am interested in rutting and 20 mm rutting is my desired level and my design period is 10 years, I should design my pavement so that I do not reach this 20 mm in 10 years or my rut depth is less than 20 mm in 10 years. So, these are the 2 pieces of information that we require. So, performance criterion would thus be expressed as design should not exceed in HMA rutting level of 0.4 inches within a 25-year design period. So, that is how we define the performance criteria. So, if we look at let us say we look at we have different mixes and we are trying to choose a particular stiffness for the mix, so that the rut depth will be less than the required value.

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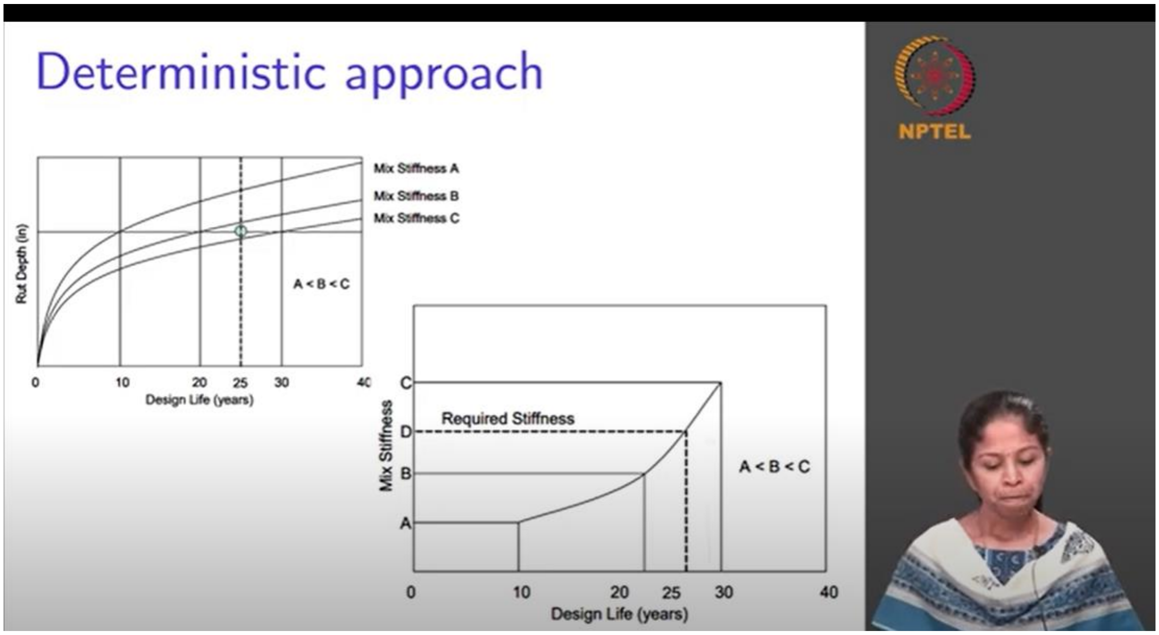

So, this is a graph which shows the design life on the x axis and rut depth on the y axis. Let us say that we have 3 different mixes, mix A, mix B and mix C. So, the for each of these mixes the rut depth is going to vary in the manner as indicated. So, this is for A, this is for B and this is for C. So, we see that the stiffness of mix A is less than that of B which is less than that of C. Now, if we have this as the critical rut depth, let me call this as rut depth critical. If we have this as the critical rut depth, we see that the critical rut depth is reached in 10 years if I use mix A, it is reached in 20 years if I use mix B and it is reached in 30 years if I use mix C corresponding to this particular. Wherever this critical rut depth is crossing the performance curve, we read the value corresponding to that and we see that we get different design life for each of the mixes. Now, our design life is 25 years, so we want this, right? The stiffness of the mix required will be somewhere between B and C. So, how do we arrive at that? We make another plot wherein we plot the stiffness of the mix. So, for 10, mix A is having 10 years, mix B is having 25 years and this is having 30 years. So, I join these points, I get a curve like this. So, 25 years is my required value. So, what is the value of the mix that I have to use if I need a design life of 25 years? Because if I use mix C, then I am overestimating the material property, I am using a higher or I am using a material with higher stiffness rather than what is required? So, to be on the economical side, we just want to use a material which will give us exactly our design life. So, I go for a mix D which has this particular stiffness. So, this is how we calculate the desired mix stiffness in a deterministic approach.

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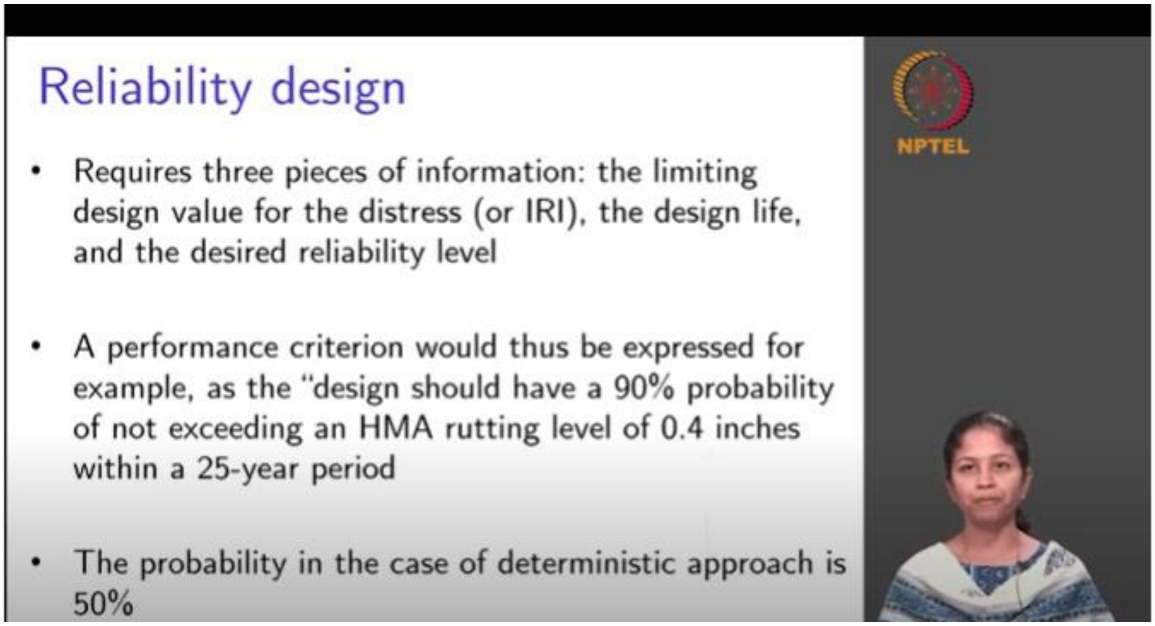

Let us see how we do the same thing in a reliability design also. So, this reliability design requires 3 pieces of information. So, what are those? The first one is limiting value. Again, as we said earlier, the first is going to be the limiting value for design. Second one, so first is a limiting value. Second one is the design life itself and the third one is the desired reliability level. In the previous case, we did not have any reliability level. So, now we are going to compute the same thing for different reliability levels. So, here the performance criterion will read like the design should have 90% probability of not exceeding a HMA rutting level of 0.4 inches within 25 year design period. So, it was the same thing except that we have this parameter introduced in the performance criteria. The probability associated with the deterministic approach is 50% that we have discussed multiple times in previous lectures. Now, let us see how to arrive at the, let us take the same example.

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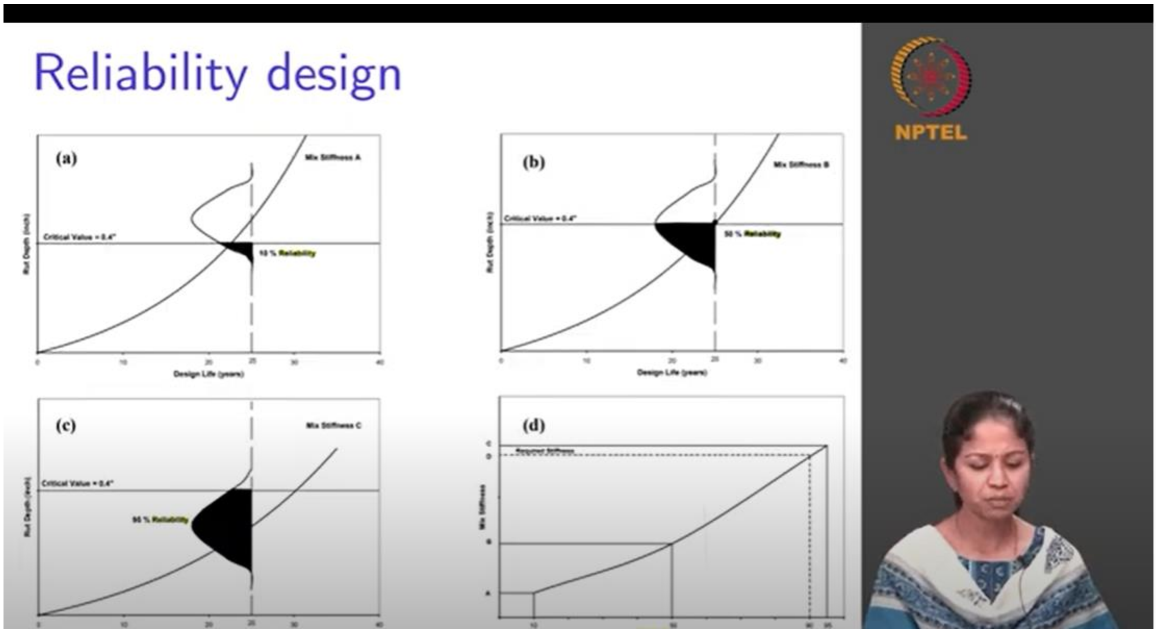

Let us see how to arrive at the required mix stiffness when we are considering a reliability design. So, now let us look at this particular plot. This is for a mix stiffness A. It is following the same order that we had seen in the previous case. So, stiffness of A is less than B, which is less than C. So, this is stiffness, right? So, this is my rut depth in inches on the y axis. Now, this is my performance curve; so, when I, my critical value is 0.4 inches. So, when I am meeting the performance curve, you can see here, it meets the performance curve at this point itself, right? So, if I draw a line corresponding to this, this is my reliability. So, my reliability is only 10% if I use a mix stiffness A, which means 90% it is going to fail, right? The probability of failure is 90% if I use a mix of stiffness A. It is going to reach the critical, there is a 90% probability that it will reach the critical value in 25 years. So, when we have a higher probability associated with that, then we should go for a stiffer mix.

Let us take a mix of stiffness B. This is the performance curve. So, it meets the critical value at this point. So, this is my reliability, right? So, it is 50%. See, if I use a mix of stiffness B, there is a 50% probability that this particular layer will fail by rutting, that is the rut depth will reach 0.4 inches. So, there is a 50% probability that it will reach 0.4 inches. So, if I still want to lower down my reliability, right? I choose even a further stiffer mix which is mix C. Again, this is the performance curve, it meets the critical value at this point. So, if I meet this with this reliability curve, so, this is my probability of failure and this is my reliability. I am getting a 95% reliability level, but ideally I was desiring only a 90% reliability. So, this is more than what I require. So, I want to limit it to 90% reliability. Then what we do is for each of the reliability levels. So, my x axis here is reliability level. For 10% I use the appropriate mix stiffness, then for 50% reliability what is the mix stiffness, then for 95% reliability what is the mix stiffness. Based on this, I will be able to calculate the required mix stiffness D. So, this is the difference between a deterministic approach and a reliability based design, wherein here we use the concepts of reliability in addition to the performance criteria and design life to arrive at parameters. So, that was about the distress prediction model and the different approaches which are used here.

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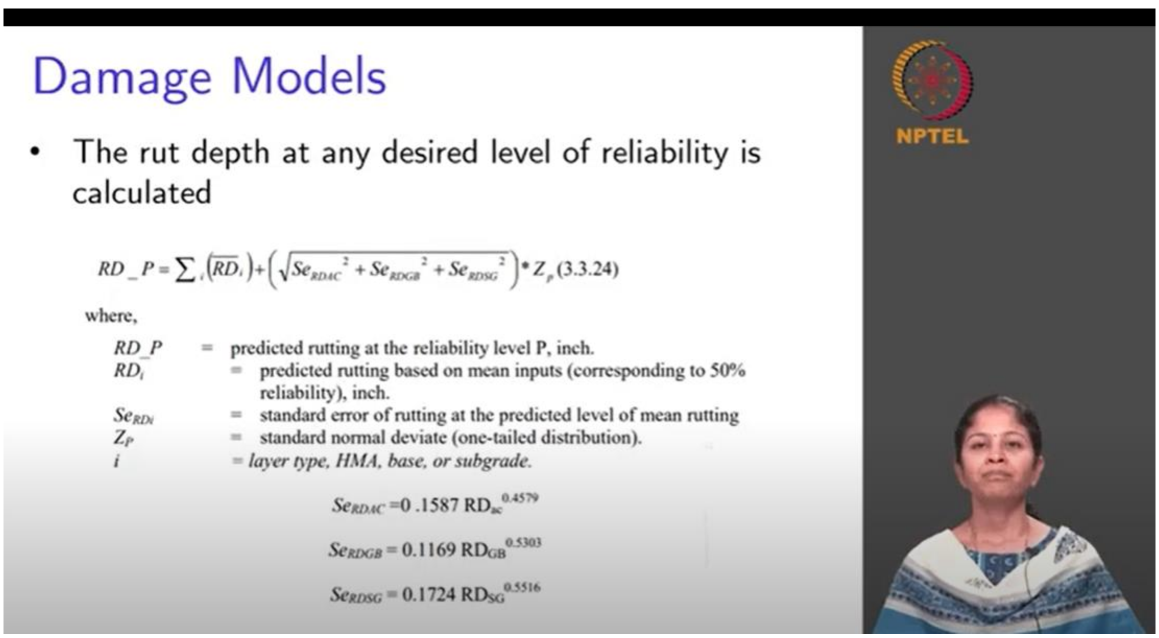

Now, we will spend some time looking at the damage model. So, what is this damage model? So, this is nothing but the equation that we had seen earlier, but in a more detailed fashion.

$$RD\_P = \sum_i (\overline{RD_i}) + \left(\sqrt{Se_{RDAC}^{\ 2} + Se_{RDGB}^{\ 2} + Se_{RDSG}^{\ 2}}\right) * Z_p$$

So, the rut depth that we had seen earlier that it is going to be at any reliability level is going to be at 50% + standard deviation × standard normal deviate corresponding to the reliability level. The same thing, but there is a detailed consideration how the standard deviation is addressed. So, this is addressed through standard error here, instead of standard deviation. So, you can see here the standard error of rutting at the predicted level of mean rutting, okay. So, how do we compute this? I will go through the procedure how the standard error is computed. So, you can see for the asphalt concrete layer, there are different models which are used to compute the standard error for rut depth in asphalt layer, granular base and subgrade. So, there are different models which are given here to calculate the rut depth. Now, how do we arrive at this standard error?

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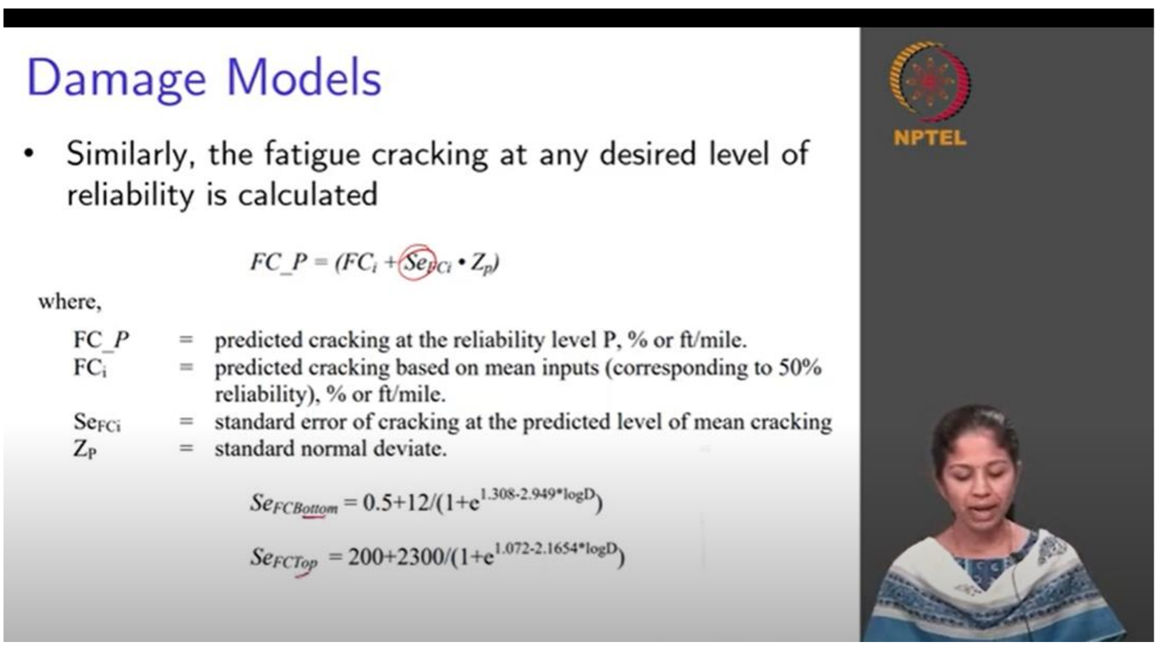

Yeah, again the same thing which is given for fatigue cracking.

$$FC\_P = \left(FC_i + Se_{FCi} * Z_p\right)$$

Here also we have a standard error term and we have different definitions for standard error when you have a bottom up cracking or a top down cracking.

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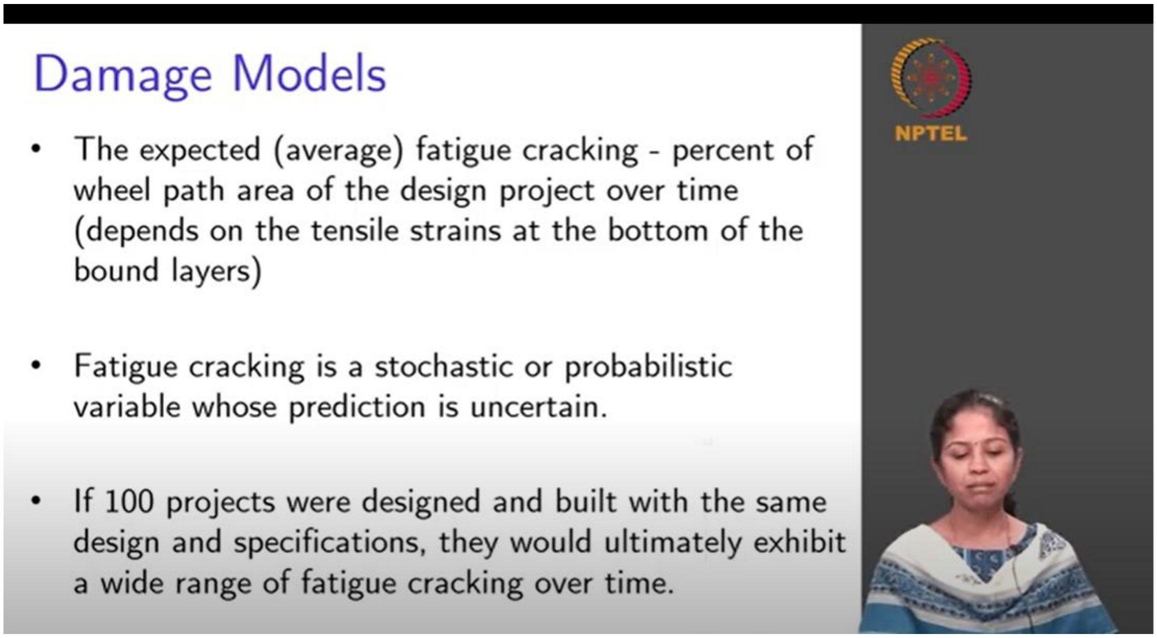

So, we will now see how to arrive at this standard error? So, the expected or which is nothing but the average fatigue cracking is nothing but the percentage of wheel path area of the design project over time. So, when we say the average fatigue cracking or fatigue cracking at 50% reliability, it is the percentage of wheel path area of the design project over time, right? Which depends nothing but on the critical strain at the bottom of asphalt layer.

Fatigue cracking is a stochastic or a probabilistic variable and the prediction is uncertain. We do not know exactly what is going to be the fatigue cracking. If I consider 100 projects, I use the same design and I use the same specifications, construct 100 projects, we all know that there will be some variability among the fatigue cracking that is observed in each of these pavements, right?

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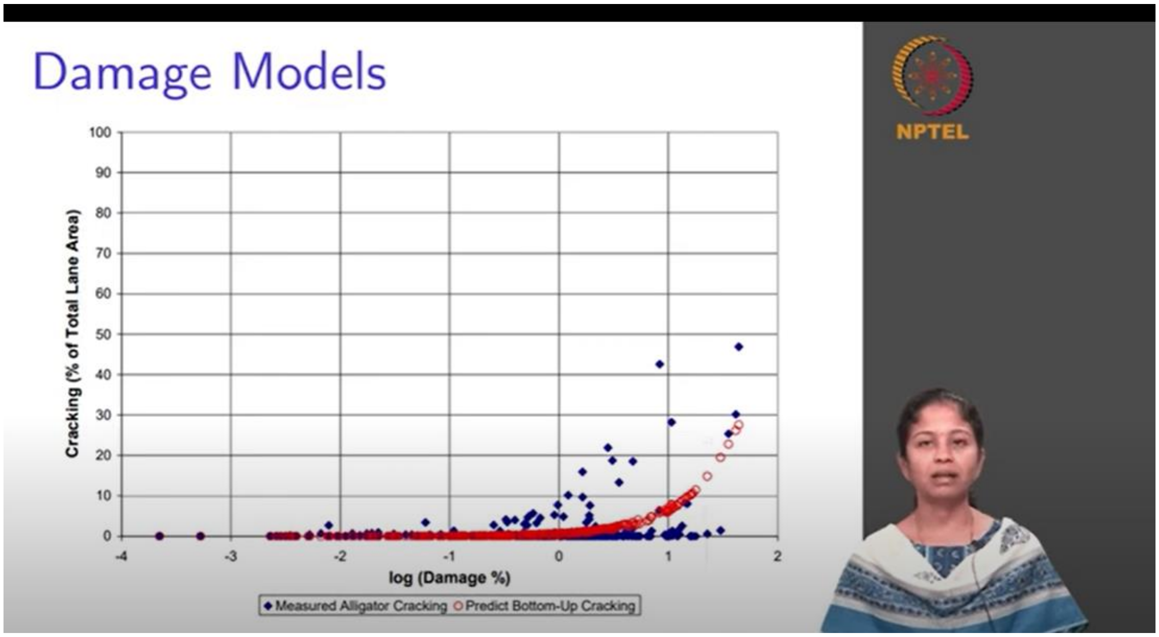

So, this is from the AASHTO study which was carried out and which served as a basis for this MEPDG 2004. So, such kind of a study was carried out, the fatigue cracking was measured from field and it was also predicted. So, you can see here, this is measured alligator cracking, these blue squares are measured values, measured value from field and these red ones are predicted using the design equation, right? So, they had used the fatigue cracking equation which was shown previously and they have also measured the value in field and try to compare both of it.

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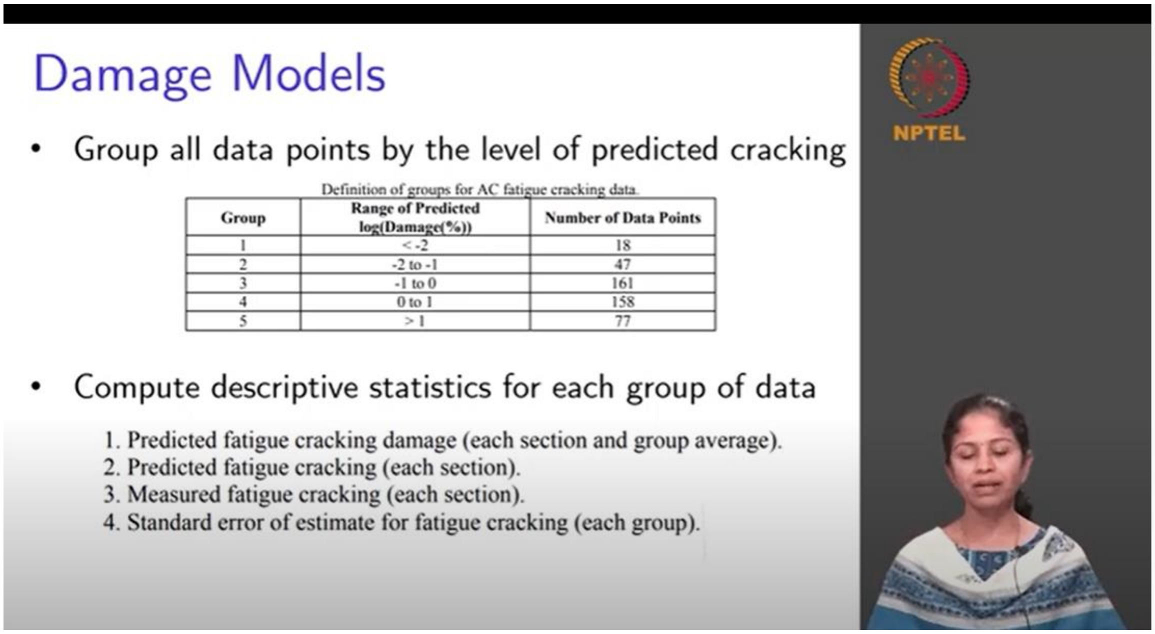

Now, based on the measured and predicted value, a damage index is computed. So, this damage index is computed for each particular data point corresponding to the measured value and the predicted value. Now, all these data points are grouped based on the level of predicted cracking. So, if the damage is less than -2, then it is group 1 and again this is log value of the damage and -2 to -1 it is group 2, -1 to 0, so like that it is grouped into different ranges and the number of data points falling in each of this range is also mentioned here.

Now the other parameters are calculated for each of this group. What are those parameters? Predicted fatigue cracking damage, so for each section and for each group average what is the predicted value? So, I take the average of the value within that particular subgroup, then predicted fatigue cracking for each section. So, again what is the predicted fatigue cracking? What is the measured fatigue cracking and standard error of estimate for fatigue cracking for each group?

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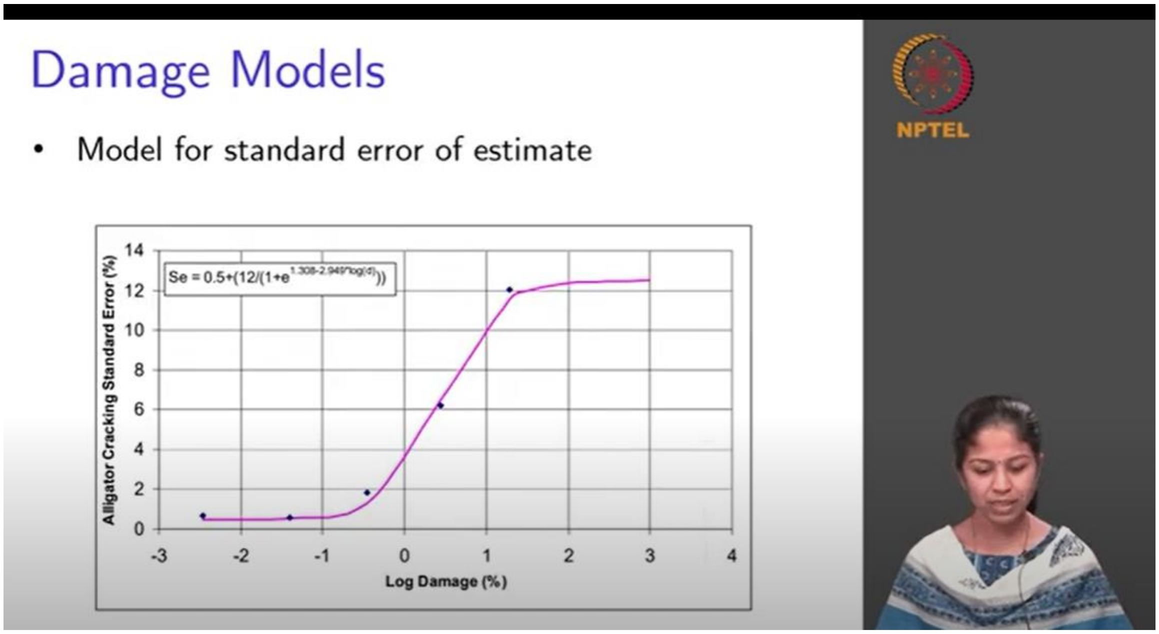

So, all these parameters are computed and here the standard deviation is also given here. So, this is for each of the group the average predicted value and the standard deviation of the measured value, so that is also plotted here. Based on this a relationship for the standard error is estimated for fatigue cracking? If I show you this graph you can see here, so there are 5 groups which we had defined here. So, we have 5 groups here, so these 5 groups are plotted as 5 points wherein the x axis is log of damage and y axis is the standard error associated with that, so which we have computed. So, using this we arrive at a relationship and that is obtained in the form of an equation which is used to compute the standard error (Se).

$$Se = 0.5 + \left(12/(1 + e^{1.308\ -2.941*\log(d)})\right)$$

Here, D is the predicted damage for bottom up cracking. So, this is nothing but a factor which takes into account of the variation between the predicted value and the measured value. So, this kind of an exercise is carried out for each of the distress and based on the relationship obtained between the standard error and the log of damage the equation for standard error is predicted here. So, like that for every distress the same thing is carried out and that is how we saw the Se equations which are defined for different cases.

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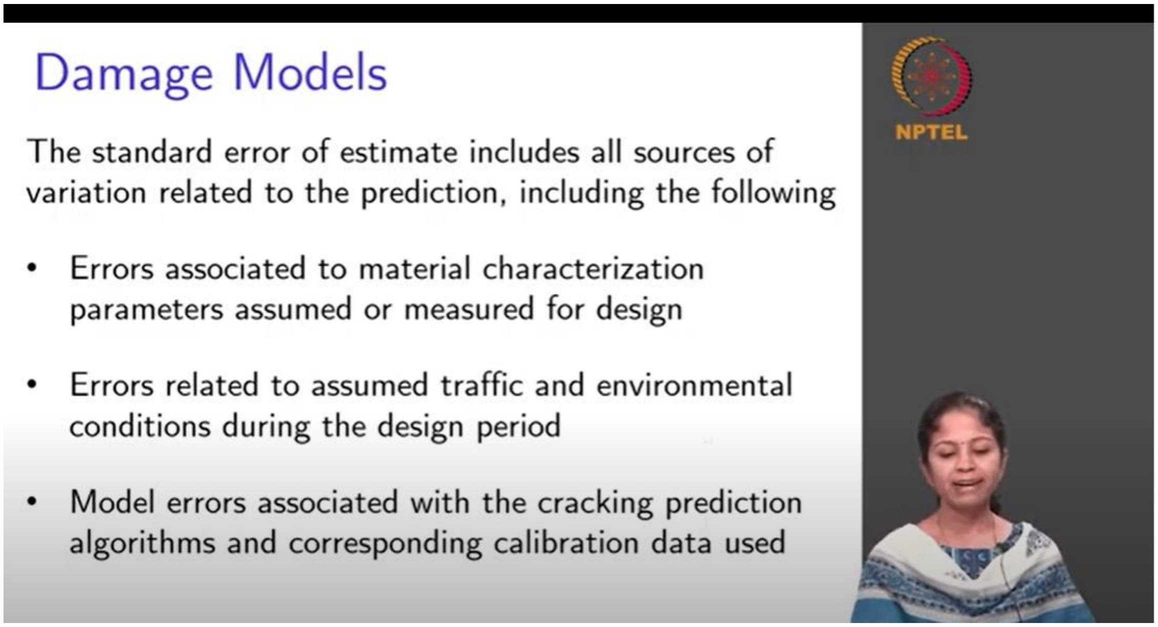

Now this standard error of estimate includes all source of variation related to the prediction including what are given below. So, what are these things? Errors associated to material characterization parameters assumed or measured. So, if I use a standard error value computed as shown here and if I use it, this is going to take into account of the variation in material parameters that were assumed during design and that is observed in field after construction. Similarly, errors related to assumed traffic and environmental conditions during the design period. Again this is going to take into account of the difference between the assumed traffic and environmental condition and that observed in field. Similarly, the model errors associated with prediction. So, all these three factors the standard error computed as shown here is going to take into account.

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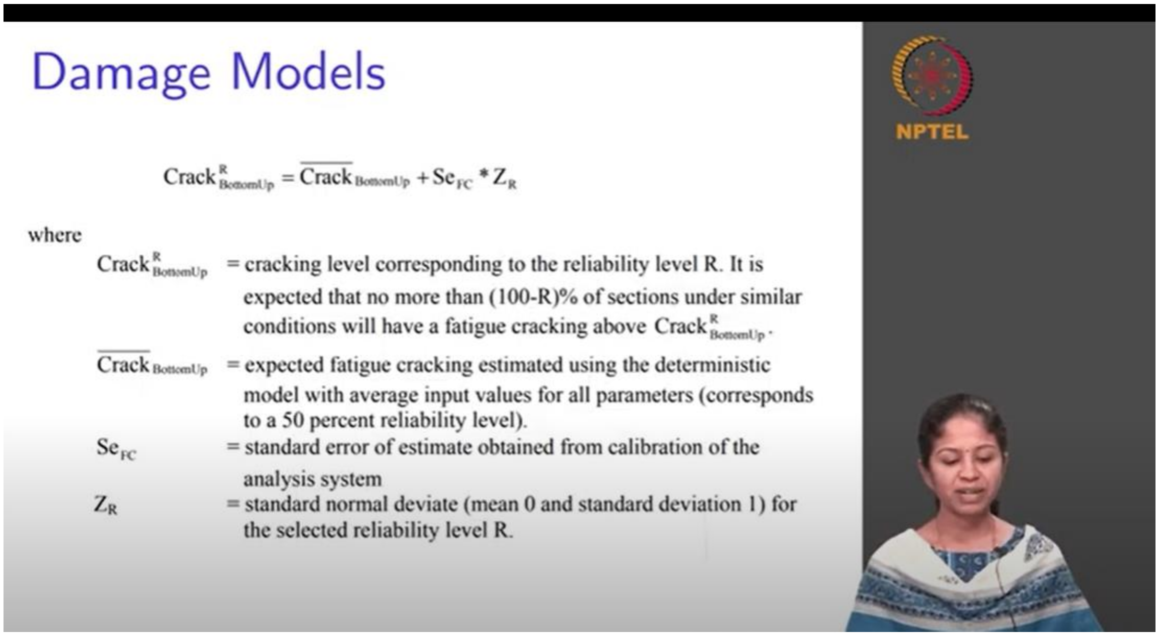

So, a same case is explained for fatigue cracking also you can see here. So, now let us see how it is translated into the terminologies which are used here.

$$CRACK^{R}_{BottomUp} = \overline{\overline{CRACK_{BottomUp}}} + Se_{FC} + Z_{p}$$

So, this term on the left hand side is cracking at a given reliability R the bottom up cracking at a reliability level R. So, how it is defined let me read it out. It is a cracking level corresponding to the reliability level R. It is expected that no more than 100 - R of the sections under similar conditions will have a fatigue cracking above this particular value. So, if my reliability is 90% it is expected that only 10% of the sections will have a bottom up fatigue cracking value higher than this particular value which is given here that is what this means. Similarly, what is this terminology which is given here? It is expected fatigue cracking estimated using the deterministic model with average input value for all parameters. So, if I use average input value we get this value and this corresponds to 50% reliability. Then this Se is standard error of estimate obtained from calibration of the analysis system. So, if you see previously it was defined as standard deviation of the measured value. So, it is corrected as standard error which is difference between the actual or observed value and the predicted value. So, Z_p is the standard normal deviate.

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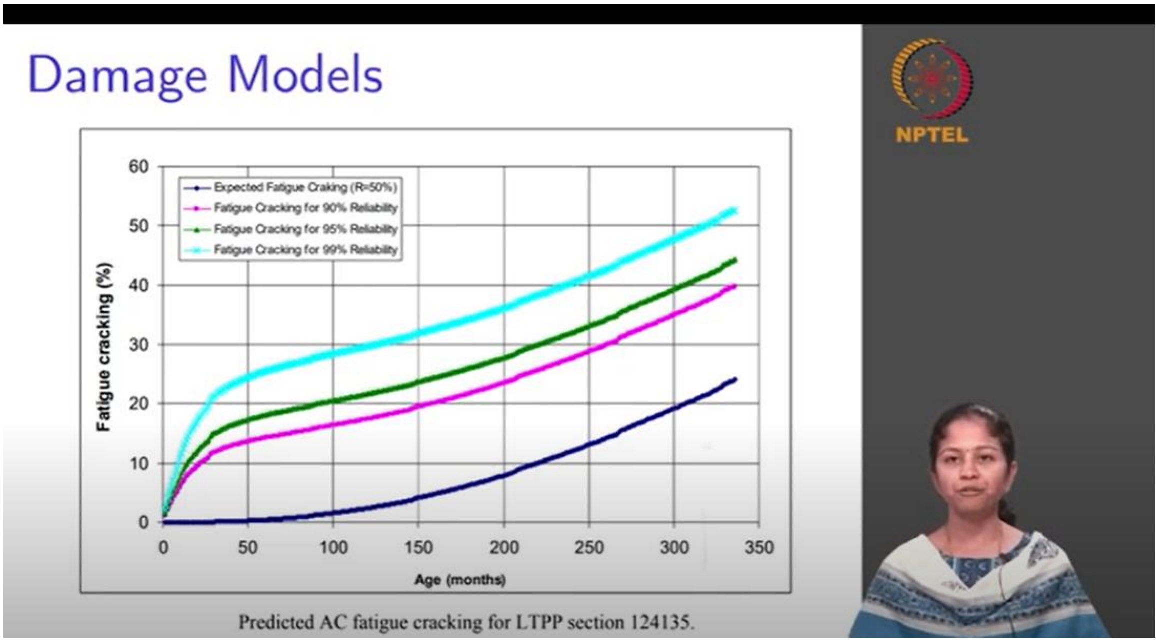

Now this is the fatigue cracking which is predicted for different reliability levels. You can see here this is for 50%, 90%, 95% and 99%. So, the age in months are given here for different reliability levels. So, if 20% is my fatigue cracking area let us say it is going to reach in maybe around 25 months. If I am using a reliability level of 99% I am going to reach the same thing in about 90 months if I am using a reliability level of 95% and so on. So, this is again explained here through this example.

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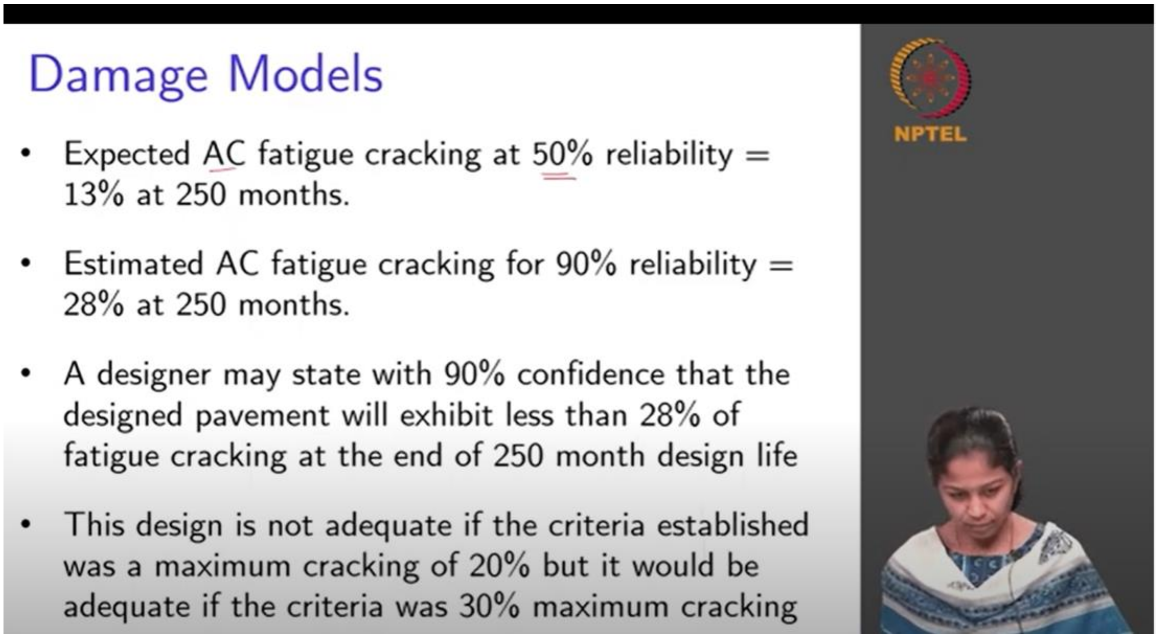

So, if we look at the expected asphalt concrete fatigue cracking at 50% reliability level, it is 13% here in 250 months. So, it is 13% in 250 months, but when it is estimated for 90% reliability level it is 28% in 250 months. You can see in graph it is 13% and 28% in 250 months. So, a designer can state with 90% confidence that the designed pavement will exhibit less than 28% of fatigue cracking at the end of 250 month design life. That is the total area that is subjected to fatigue cracking will be 28%. But if 30% is my cut off criteria then I am fine because my distress is only 28% less than my target value of 30%. But if the allowable cracking is only 20% then the design criteria is not adequate. We consider the pavement to have failed in fatigue cracking and we have to redo the design. So, this design is not adequate if the criteria established was a maximum cracking of 20%, but it would be adequate if the criteria was 30% maximum cracking. So, we look at this for a required reliability level and we go back and redesign the pavement if the required performance is not met over the design life. So, this is with regard to the damage and the last aspect is related to calibration constant.

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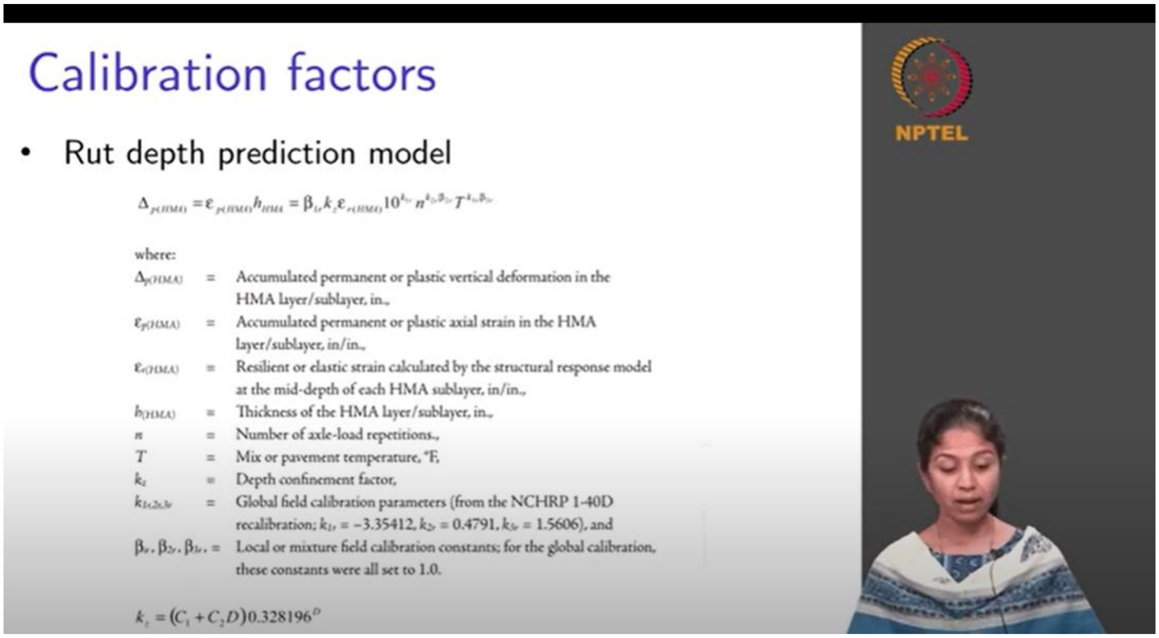

So, let us take a rut depth equation model which is given in MEPDG. So, this is the rut depth prediction model.

$$\Delta_{pHMA} = \varepsilon_{pHMA} h_{HMA} = \beta_{1r} k_r \varepsilon_{r(HMA)} 10^{k_{1r}} n^{k_{2r}\beta_{2r}} T^{k_{3r}\beta_{3r}}$$

This is permanent or plastic vertical deformation in the HMA layer. Again this is asphalt concrete rut depth prediction model. So, you can see here it has number of parameters which are listed here. You can see 3 β; β_{1r}, β_{2r} and β_{3r} and we have 3 constants k_z, k_{2r} and k_{3r}. So, this k_{1r}, k_{2r}, k_{3r} are called global field calibration parameters and β_{1r}, β_{2r} and β_{3r} are local or mixture field calibration constants. So, these are some constants which are used in this equation and these constants can be varied for any other location and that is how we take into account of the site specific conditions in the model. So, let us see how they are defined.

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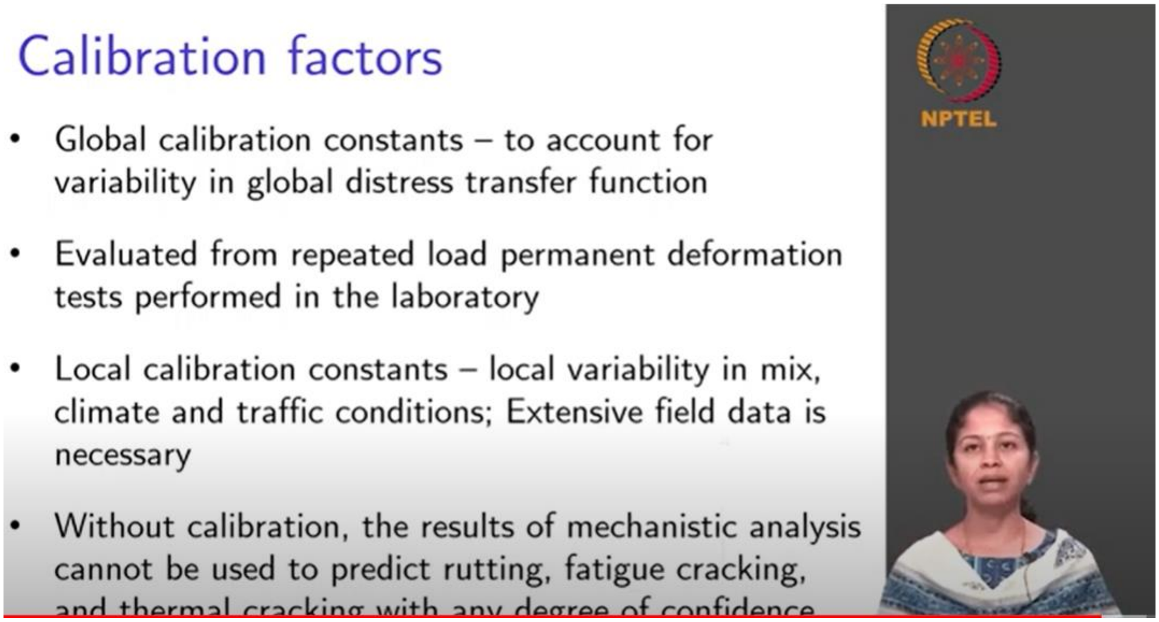

The global calibration constant is to account for the variability in global distress transfer function. So, we have this distress transfer function which was designed for a specific case. So, if we have a different set of mixtures then how is it going to vary? So, it is evaluated from repeated load permanent deformation test performed in the laboratory. We can calibrate the global calibration constants for the specific site. So, for that case we have to use the mix which is expected to be used in the site, do a repeated load permanent deformation test in the laboratory and there is a procedure to arrive at this set of calibration constants. Then we also have local calibration constant. This takes into account of the local variability in mix. So, though we have a mix which is defined in the laboratory, when we make it at site there is going to be some variations between the controlled conditions in which it is prepared in the laboratory and the field conditions.

So, that local variability is taken into account plus the effect of climate and traffic condition. So, if I have to take into account of the local calibration effect then we need extensive field data. We collect lot of data in field, compute standard error like how it was done previously and we will be able to accommodate the site specific conditions with respect to mix properties, climate and traffic. So, without calibration the results of mechanistic analysis cannot be used to predict rutting, fatigue cracking and thermal cracking with any degree of confidence. You do not even know what is the degree of confidence with which we will be predicting. If we do not calibrate the models for the local and global calibration constants. The global calibration constant can be done because it is based on some specific tests in the laboratory, but this local calibration constant requires a field data. Then only then this model can be or only then some reliability level can be associated with this model.

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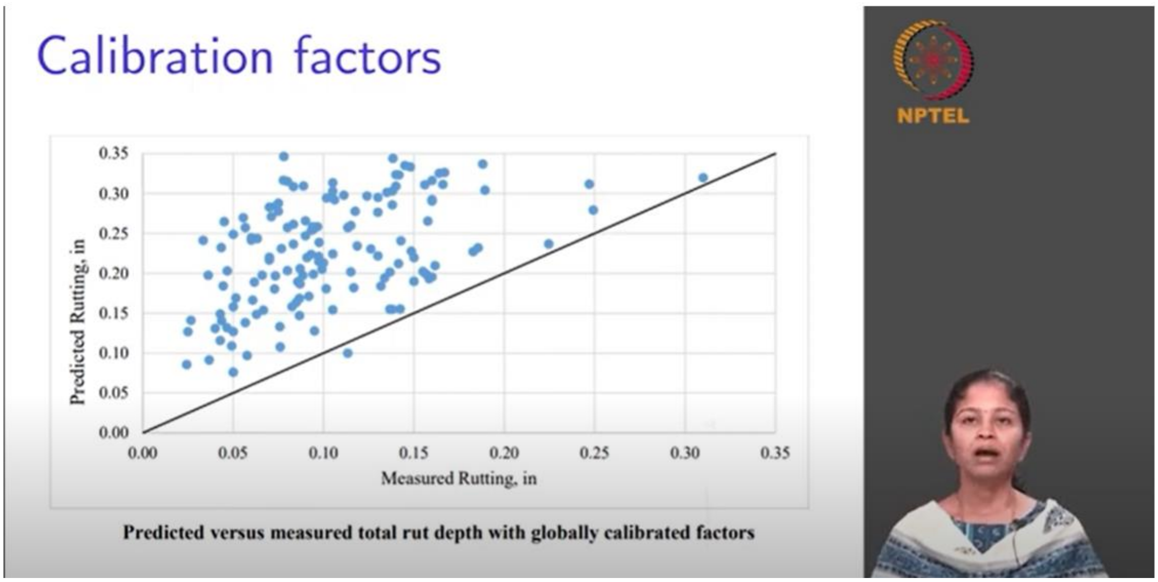

So, you can see here how the predicted rutting varies after correction for the local and the calibration constants. So, this is predicted versus measured total rut depth with globally calibrated factors. If we use a default values this is how we are going to get. Now, if they are corrected for locally calibrated coefficients then we can see how the predicted rutting varies. So, it is more or less close to the actual rutting value. So, this effect will be taken care by using appropriate calibration constants. So, before using the model it is necessary that we arrive at the specific calibration constant and then use the model. So, I will stop this lecture here. In the next lecture we will talk about other reliability approaches that we will be using. I will show you example of a Monte Carlo simulation wherein we will be seeing how the realistic variations and input parameters can be used and how the reliability can be estimated for a given traffic condition. So, that we will see in the next lecture. I will stop this lecture here. Thank you.