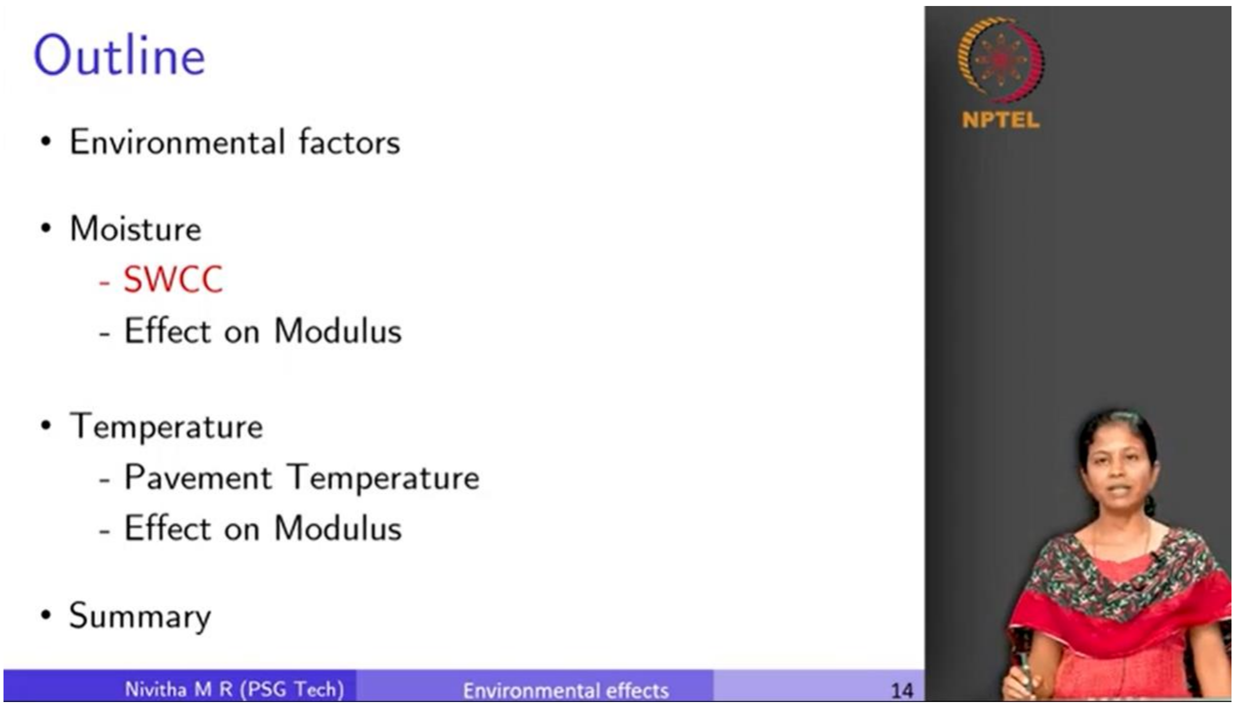
Analysis and Design of Bituminous Pavements

Dr. M. R. Nivitha
Department of Civil Engineering
PSG College of Technology, Coimbatore

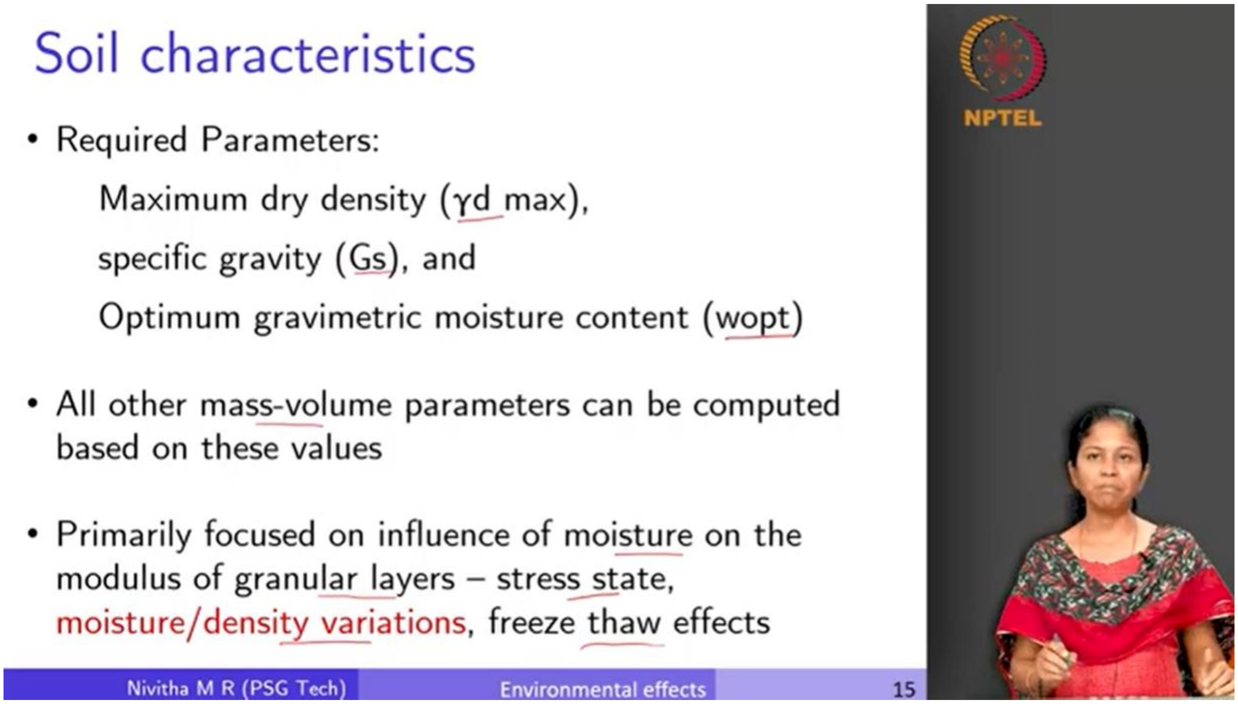
Lecture - 25
Environmental Effect - Part 02

(Refer Slide Time: 00:16)



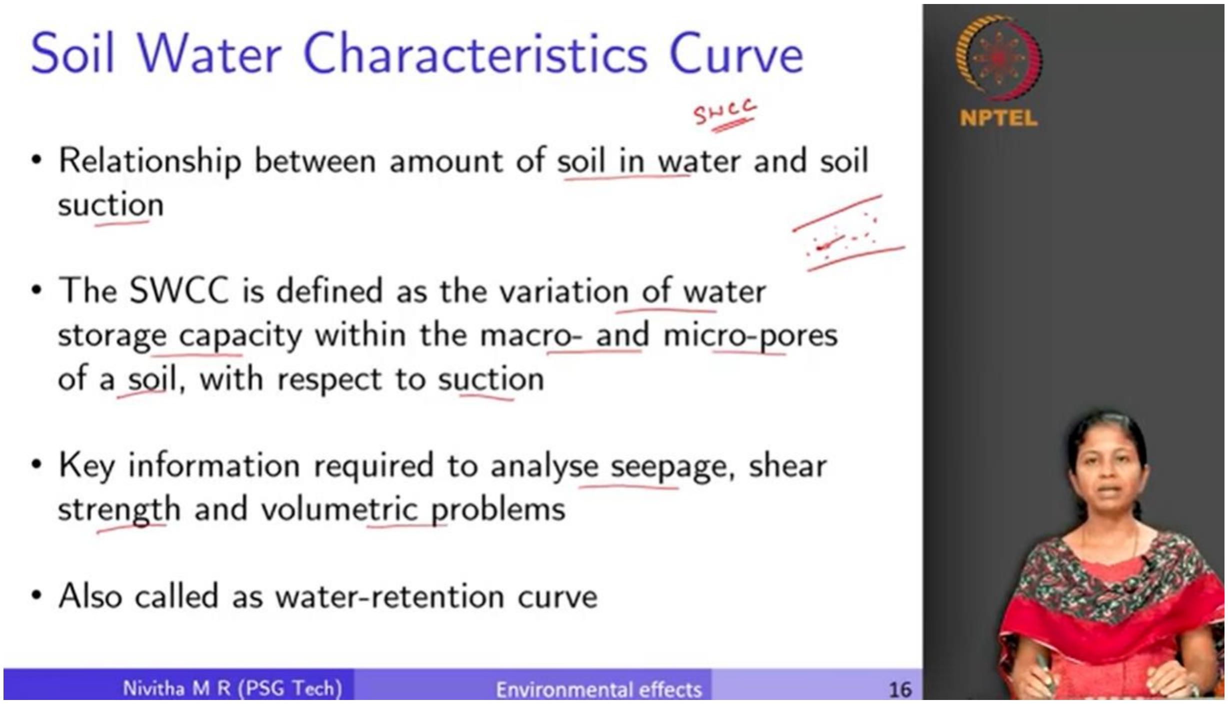
Welcome back, now we will start talking about the effect of moisture on the resilient modulus which is characterized using the soil water characteristic curve.

(Refer Slide Time: 00:34)



Typically for a soil when we are trying to compute any parameter, the basic parameters that are required for computation are the maximum dry density ($\gamma_{d\ max}$), specific gravity (G_s) and optimum moisture content (w_{opt}). If these 3 parameters are known to us, then we will be able to compute any other parameter related to soil which is required to compute its influence on modulus. Now all other mass, volume parameters can be computed based on these 3 values. So, it is primarily focused on influence of moisture on the modulus of granular layers. This effect of moisture on granular layer like we said is classified into 3 different aspects, one is the influence of moisture on the stress state. When the soil is in a dry condition, the stress state in the soil is different compared to it in a moist condition. The second one is the influence of moisture on the modulus variation. The third one is the freeze thaw effect. Here in this remainder portion of this lecture we are going to talk about the influence of modulus on the modulus variation.

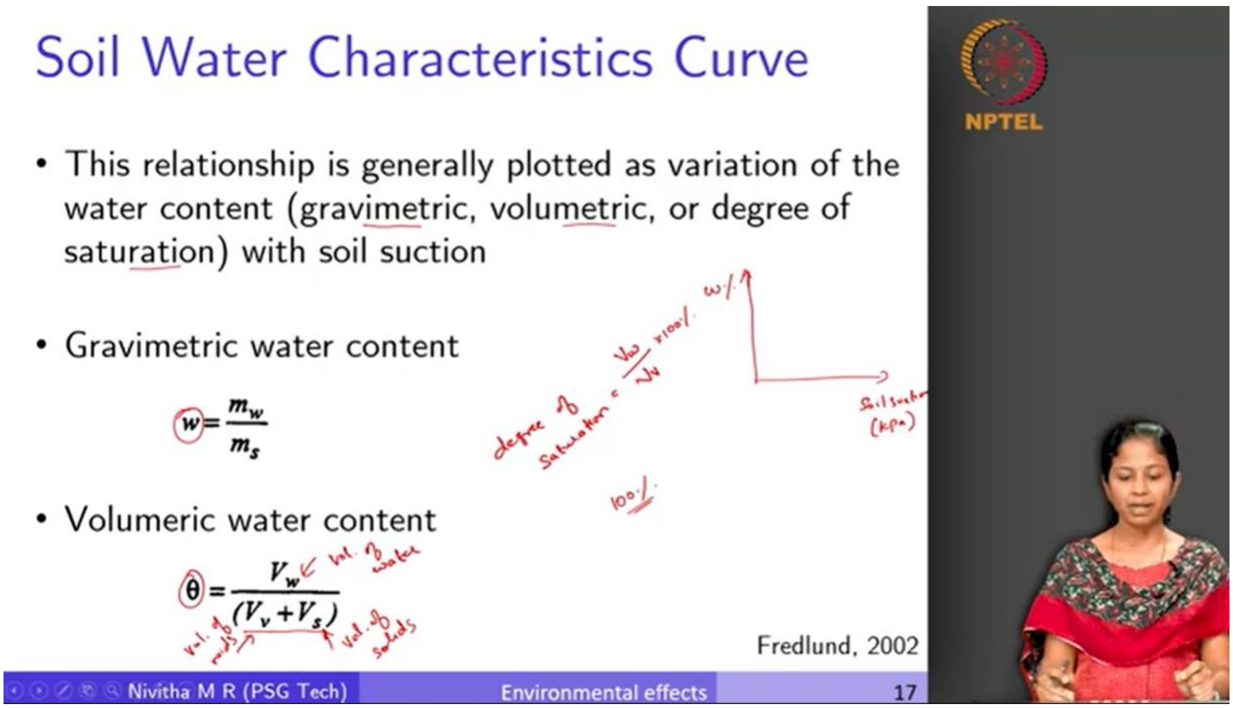
(Refer Slide Time: 02:03)



The relationship between the influences of moisture is given by a soil water characteristic curve which we typically call as SWCC. It is basically the relationship between amount of soil and water and the soil suction. Let us say that a system of soil is present, there is one soil particle here, what is the capability of this soil particle to absorb moisture which is present in this environment? So, that is quantified through this soil water characteristic curve. There are many definitions and interpretations that people make for this particular parameter. In another context, it is also defined as the variation of water storage capacity within the macro and micro pores of a soil with respect to suction. If it is able to suck some amount of moisture from the surrounding, how much of it is it able to withhold in the micro and macro pores of the soil? So, that is another interpretation which certain authors make to this soil water characteristic curve.

Ultimately, it is key information which is required to analyze seepage, shear strength and volumetric problems. If you look at this, it basically says how much water it is able to absorb and how much of the absorbed water it is able to retain in the pores? This is what is going to influence the seepage characteristics in a soil. Similarly, depending upon the moisture content that it is able to retain, the shear strength of the soil is going to vary. Again it is also going to influence the volumetric aspects of the soil. That is why this particular information is considered to be sufficient for representing the moisture aspects of soil. In some studies it is also called as a water retention curve because we said it is going to quantify the storage capacity within the pores.

(Refer Slide Time: 04:12)



What is this soil water characteristic curve? It is basically a plot wherein the water content expressed in percentage as a function of soil suction. So, it could be in kilopascals or megapascals. So, it is a graph between soil suction and how much of this it is able to retain. This can be expressed in terms of gravimetric water content or volumetric water content or degree of saturation. What is this gravimetric water content?

$$w = \frac{m_w}{m_s}$$

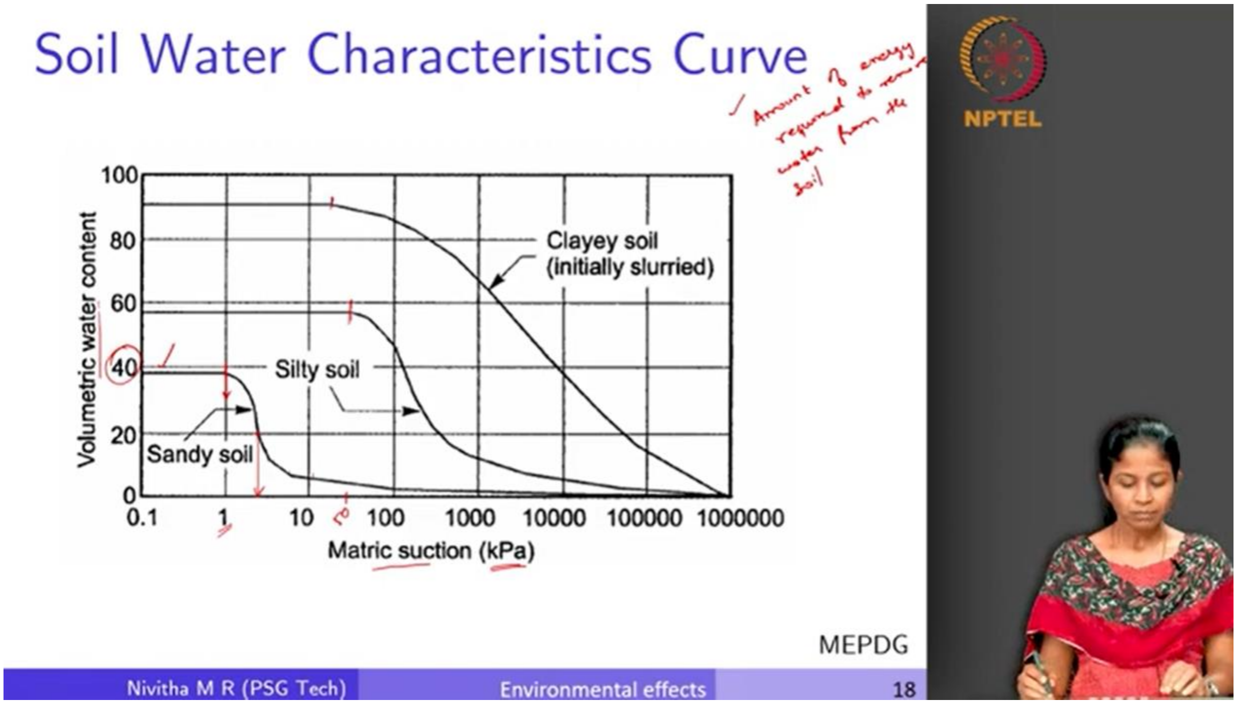
This water content is expressed as a ratio of mass of water to the mass of solids. Similarly, what is the volumetric water content?

$$\theta = \frac{V_w}{(V_v + V_s)}$$

It is defined as theta which is nothing but the ratio of volume of water to the sum of volume of voids and volume of solids.

What is degree of saturation? It is defined as volume of water to the volume of voids. What percentage of voids is filled with water? If all the voids (100%) are filled with water, then we call the degree of saturation to be 100. If there is a lesser percentage, then we associate a lesser value. So, this is what is called as the degree of saturation. These are the three parameters which could be used on the y-axis with respect to soil suction. Some textbooks also call this as matric suction.

(Refer Slide Time: 06:26)



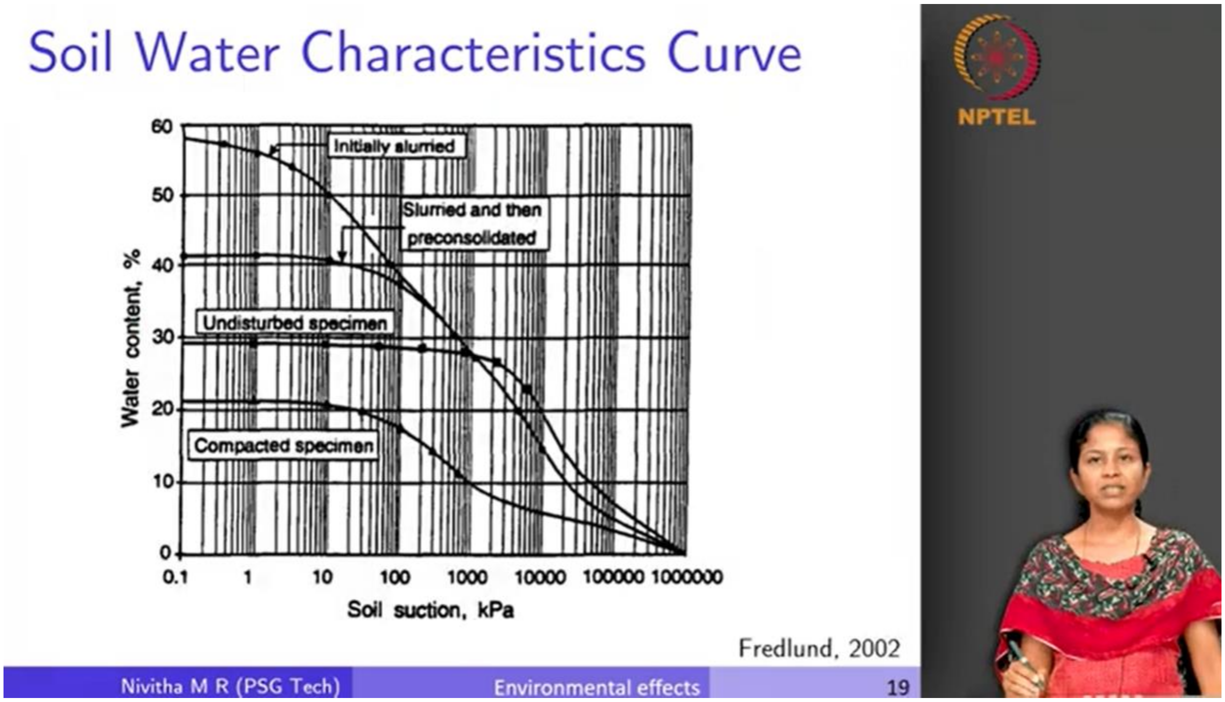
Now how does this soil water characteristic curve look like? You can see here this is volumetric water content and this is matric suction. There is other kind of interpretations also available for this soil water characteristic curve. One is the amount of energy required to remove water from the soil. How much of energy is required to remove water which is present in a soil system? And the other interpretation is, in the soil in a dry state, how much pressure it exerts to attract water from a nearby location?

So, these are two other interpretations which could be given for this soil water characteristic curve. Typically what is said is, when the soil is flooded with water, when there is more amount of water when it is in a saturated state, the matric suction will be very less. Say for example, let us take the condition of a sandy soil. You can see here when there is 40% volumetric water content, the matric suction is very less about 1 kPa of force only it is exerting. We can interpret it in any way.

We will use this particular interpretation with this amount of energy required to remove the water film from the soil particle. There is only 1 kPa of force which is required to remove this water content. Whereas once the volumetric water content reduces, we have to apply a higher amount of force to remove this water from the soil system. If we use the other interpretation which is the force exerted by the soil particle to attract moisture, which would also be valid for this particular graph. If you see when it is kind of saturated or when it has more amount of water content, the force that it is applying to attract more moisture is less.

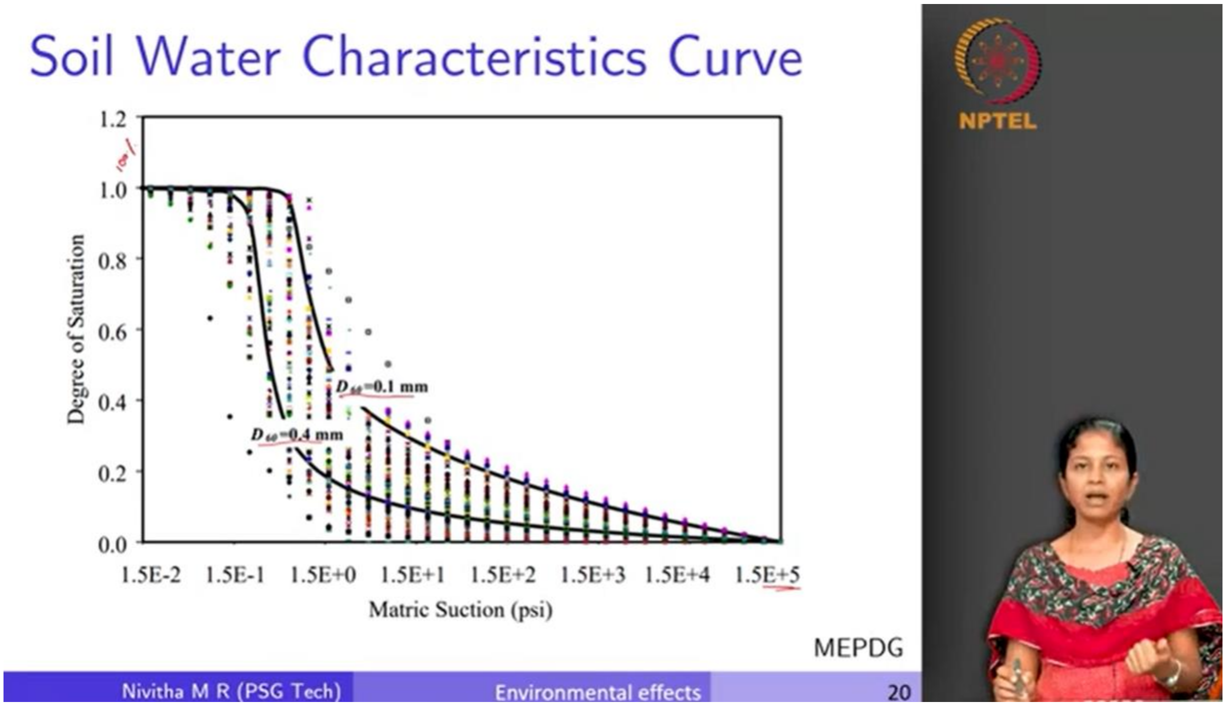
But in another scenario when it has 20 percent of volumetric water content, we can see that it exerts more force to attract water content. So this is the interpretation of this soil water characteristic curve. You can see here depending upon the type of soil, this SWCC curve is going to vary. So for a sandy soil you can see this remains constant up to 1 kPa matric suction. Whereas here it is linear up to 50 kPa matric suction. When the volumetric water content is 60, it remains constant up to a matric suction of 50. Beyond that only, it begins to increase. Similarly for a clayey soil also somewhere closer to that. So depending upon the type of soil this curve is going to vary.

(Refer Slide Time: 09:44)



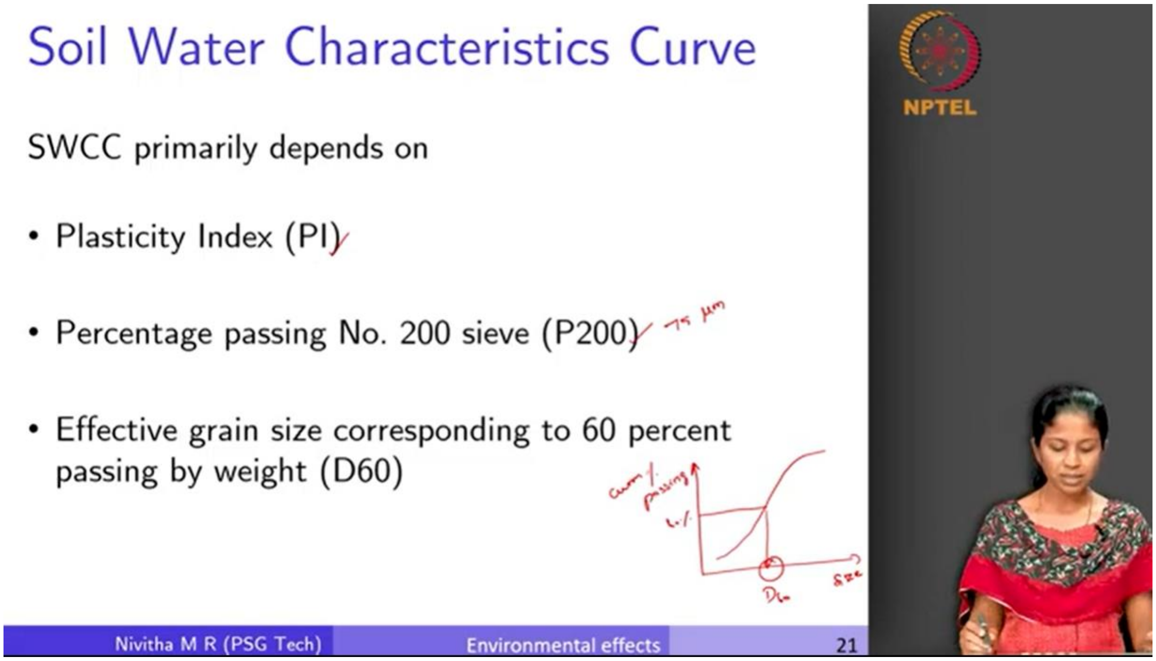
Similarly we can also see how the soil water characteristic curve varies for different kind of the state of soil. We have a compacted specimen which is a typical laboratory compacted specimen. We have an undisturbed specimen. We have a slurried and then pre-consolidated. We have a soil which is slurried in the initial condition itself. So, for a given soil depending upon the state in which the soil is present, this soil water characteristic curve will differ. Because in a slurry state the state of soil is different, the movement of moisture content will be different compared to a fully compacted state. So that is why for a given soil, also depending upon the state in which the soil is present, the soil water characteristic curve will differ.

(Refer Slide Time: 10:37)



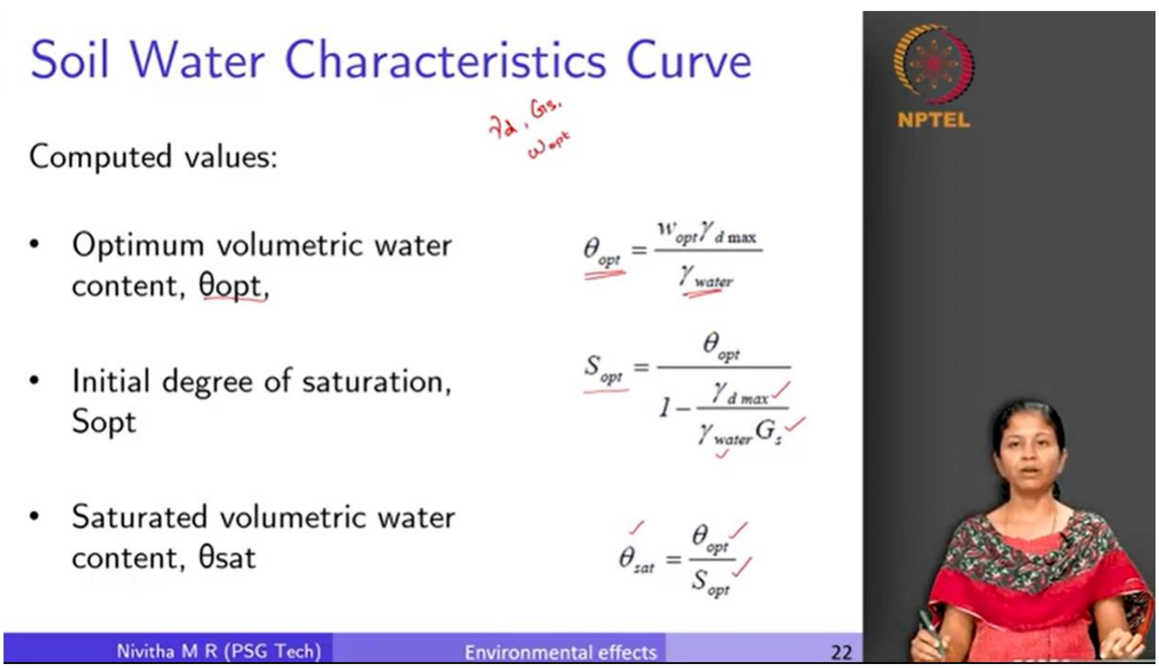
So this could also be expressed in terms of degree of saturation. When the degree of saturation is 1 or when it is 100%, the matric suction is very less. Then it increases, and when the degree of saturation is very less, this value is substantially higher. Again depending upon the gradation of the soil, the matric suction will vary. This curve is for a soil which has a D_{60} of 0.1 mm and this is for a soil which has a D_{60} of 0.4 mm. So this is highly sensitive to the type of soil, the natural condition of the soil and the particle size distribution of the soil.

(Refer Slide Time: 11:30)



This soil water characteristic curve depends upon 3 parameters, one is the plasticity index, the other one is the percentage passing 200 sieve. This number 200 is nothing but 75 microns sieve and the third one is effective grain size corresponding to 60 percent passing which is the D_{60} value. If we plot cumulative percentage passing, the size corresponding to 60% passing is D60.

(Refer Slide Time: 12:29)



So what are the computed parameters? Previously we said we need 3 other inputs for soil. For any soil characterization, we need the maximum dry density, specific gravity of soil and the optimum water content. In addition to these 3, if we know the plasticity index of the soil, if we know the percentage passing 75 microns sieve and if we know the D_{60} value, we can compute the parameters for a soil water characteristic curve.

There are three other parameters. One is the optimum volumetric water content.

$$\theta_{opt} = \frac{w_{opt}\gamma_{d\,max}}{\gamma_{water}}$$

Similarly we can calculate the initial degree of saturation. This depends on the optimum volumetric water content, maximum dry density, unit weight of water and specific gravity of the soil.

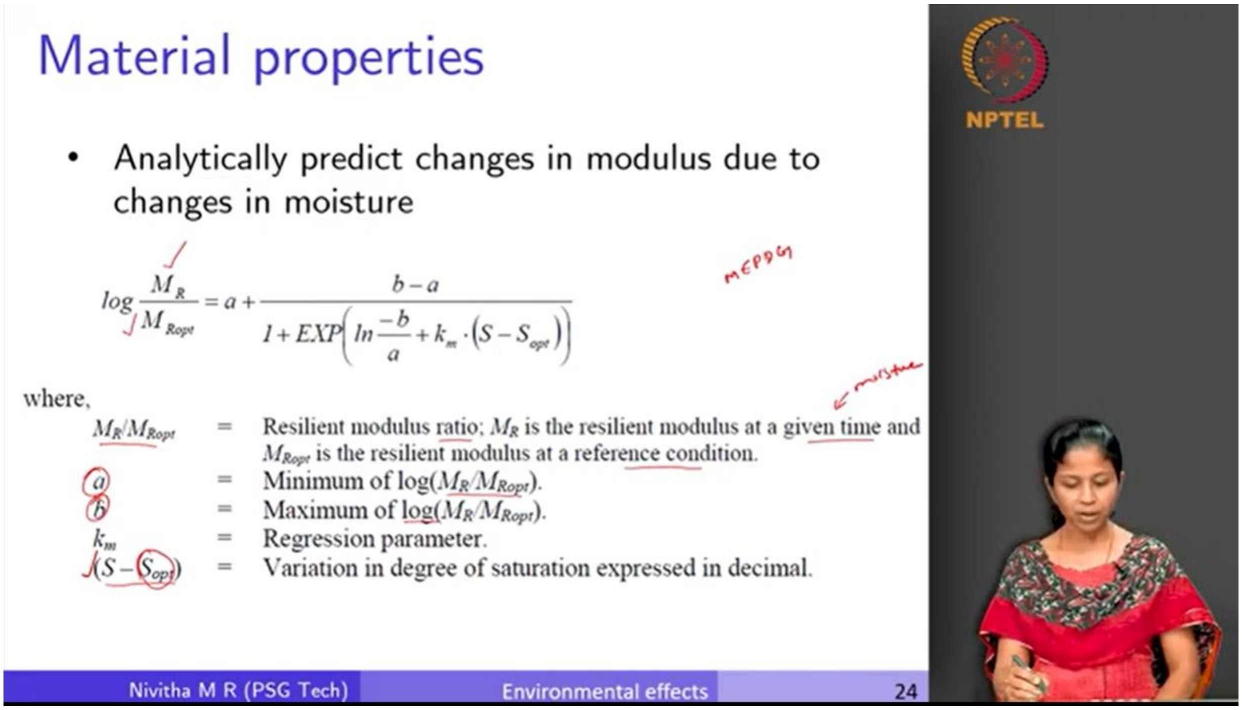
$$S_{opt} = \frac{\theta_{opt}}{1 - \frac{\gamma_{d\,max}}{\gamma_{water} G_s}}$$

Then we also can calculate the saturated volumetric water content, which also depends on the optimum water content and the initial degree of saturation.

$$\theta_{sat} = \frac{\theta_{opt}}{S_{opt}}$$

So depending upon all these things, we will know to what extent the soil is saturated and we will be able to compute the appropriate influence on the modulus value.

(Refer Slide Time: 13:53)

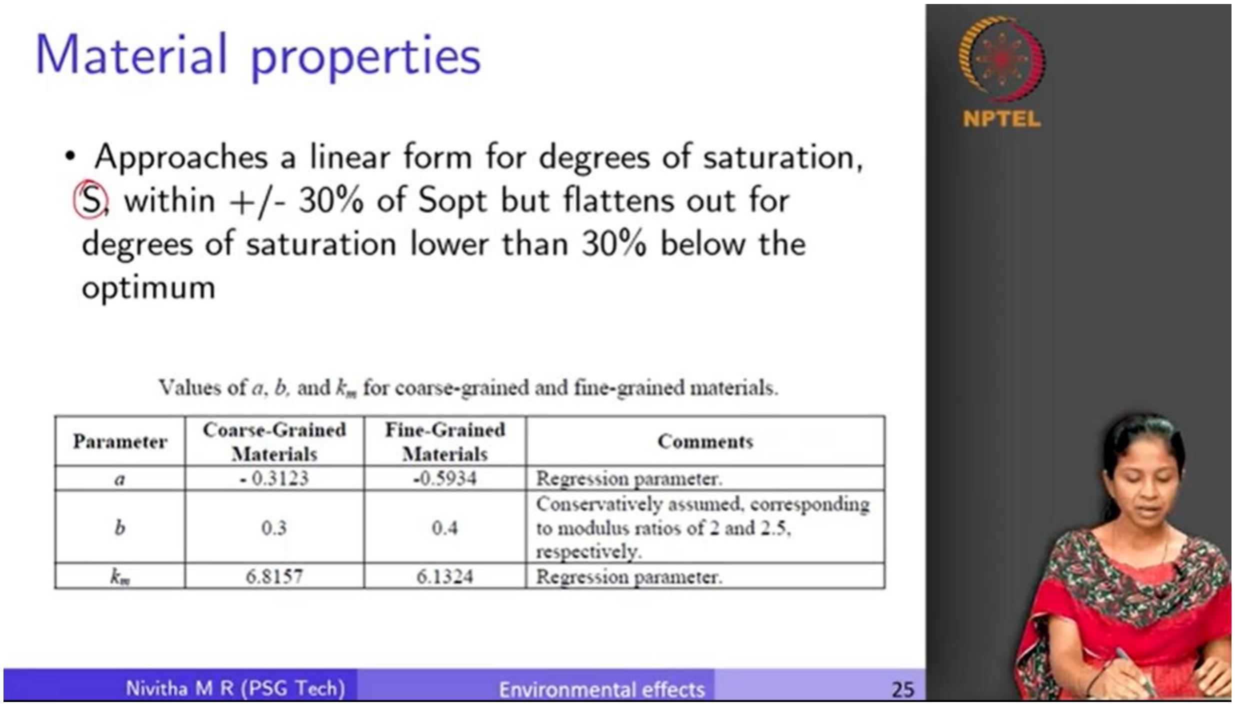


Now we will see the effect of moisture content and soil on the modulus parameter. So there is an equation which is given again this is from MEPDG which helps to correlate the resilient modulus at any given moisture content to the resilient modulus measured at optimum moisture content.

$$\log\frac{M_R}{M_{opt}} = a + \frac{b-a}{1+\exp\left(\ln\frac{-b}{a} + k_m\left(S - S_{opt}\right)\right)}$$

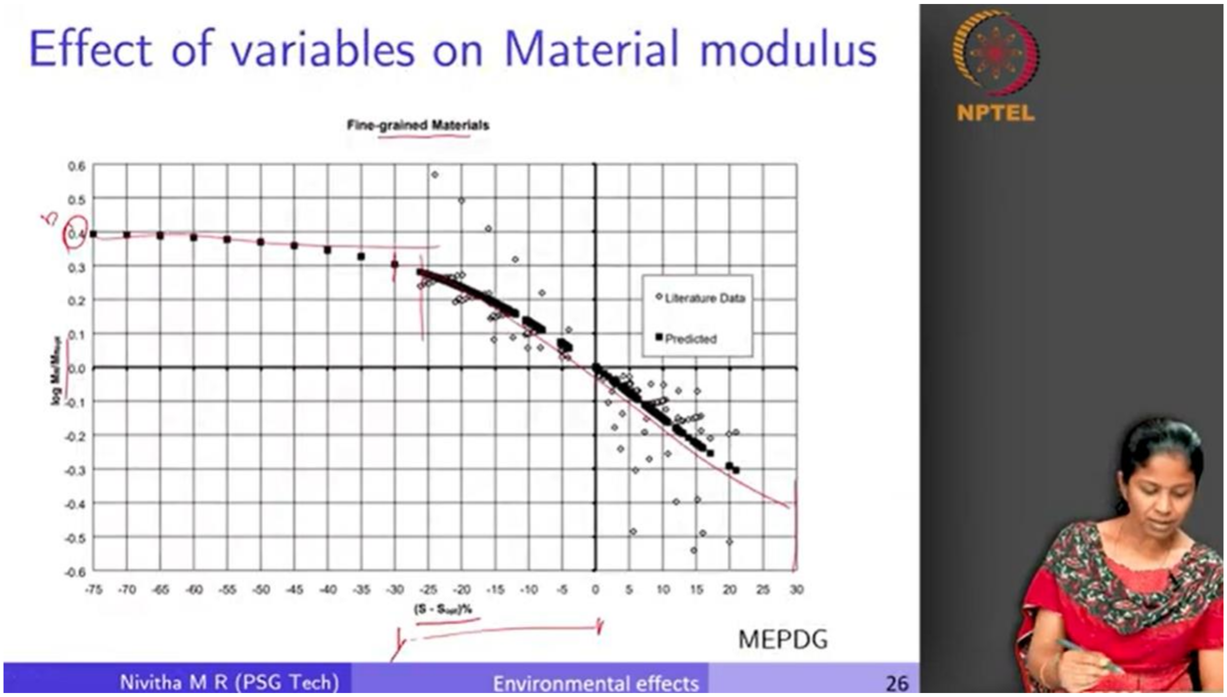
M_R is the resilient modulus at a reference condition. So at a given time means at any given time period in a year which is going to vary with respect to moisture at any given time period in the year we are going to have influences of moisture. So that is one effect and the M_{opt} is at any given reference condition which could be for the optimum moisture content or any standard moisture condition. And a is the minimum value of $\log\frac{M_R}{M_{opt}}$ and b is the maximum of $\log\frac{M_R}{M_{opt}}$. k_m is a regression parameter and $S - S_{opt}$ is the variation in degree of saturation. Initial degree of saturation is given as S_{opt} and this is for any given saturation. So based on this the variation in modulus is computed. So we know the modulus at a reference condition, so for the given condition we will be able to compute the resilient modulus. So this is how it is computed in MEPDG.

(Refer Slide Time: 15:54)



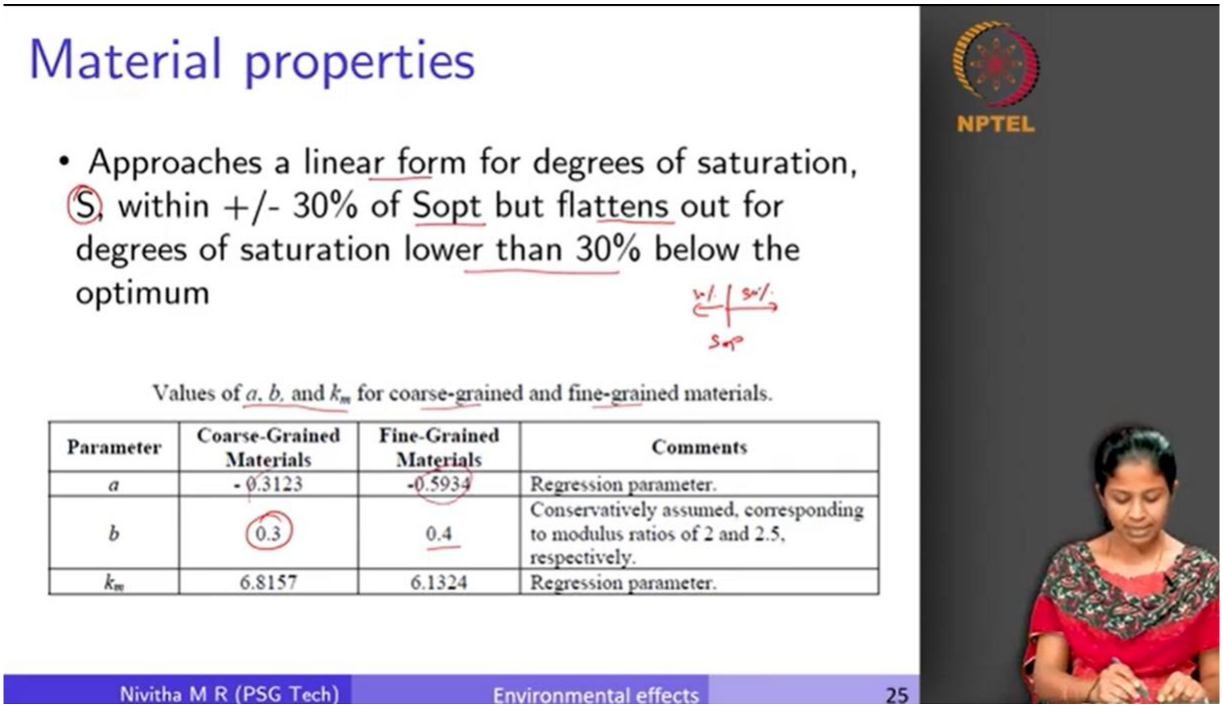
The equation which is shown here approaches a linear form for any given degree of saturation which is within plus or minus 30% of the optimum value. Let us say this is S_{opt} so whether it is this side 30% or this side 30%, it has a linear form but if it is less than 30% it flattens out. This is for degrees of saturation lower than 30% below the optimum value.

(Refer Slide Time: 16:28)



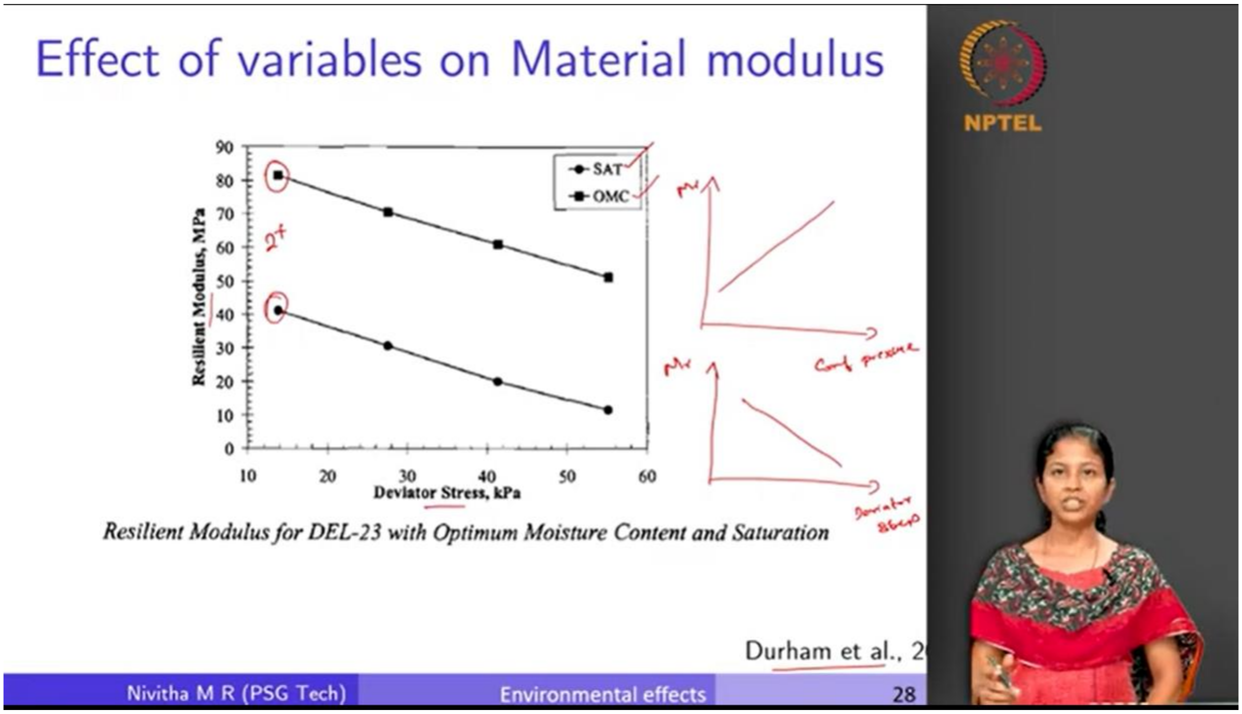
If you look at this graph, you will be able to understand this is for fine grained materials. This is the ratio which is $\log\frac{M_R}{M_{opt}}$ and this is $S - S_{opt}$. So if you see here, up to 30% has a linear form but if it is less than that, it kind of flattens out. For all the other cases, it is assumed to be a constant value. So this is how this model is proposed and this model is used in MEPDG to adjust the resilient modulus depending upon the moisture content of the soil. Similarly we have another graph for coarse grained soil, you can see here the ratio is 0.3 here and this ratio is 0.4 so the influence of moisture is more on the fine grained soil when we compare to a coarse grained soil.

(Refer Slide Time: 18:01)



And we can see here the values of a, b and k_m for coarse grained and fine grained soil for this particular equation which is given here. So, you can see the value of b which is the minimum of $\log\frac{M_R}{M_{opt}}$ so this is 0.3 in the case of coarse grained material and 0.4 in the case of fine grained material and a is different for both the materials. So, using this kind of an equation, we will be able to correct the resilient modulus for any given moisture content with respect to the moisture content at a known standard condition. So ideally we could use the optimum moisture content, measure the resilient modulus corresponding to the optimum moisture content using the codal provisions that we had discussed earlier and once we have these values and input in the system and we will be able to compute it for any other any other moisture content. The only thing is we should be able to compute the appropriate degree of saturation. So, that comes from the soil water characteristic curve.

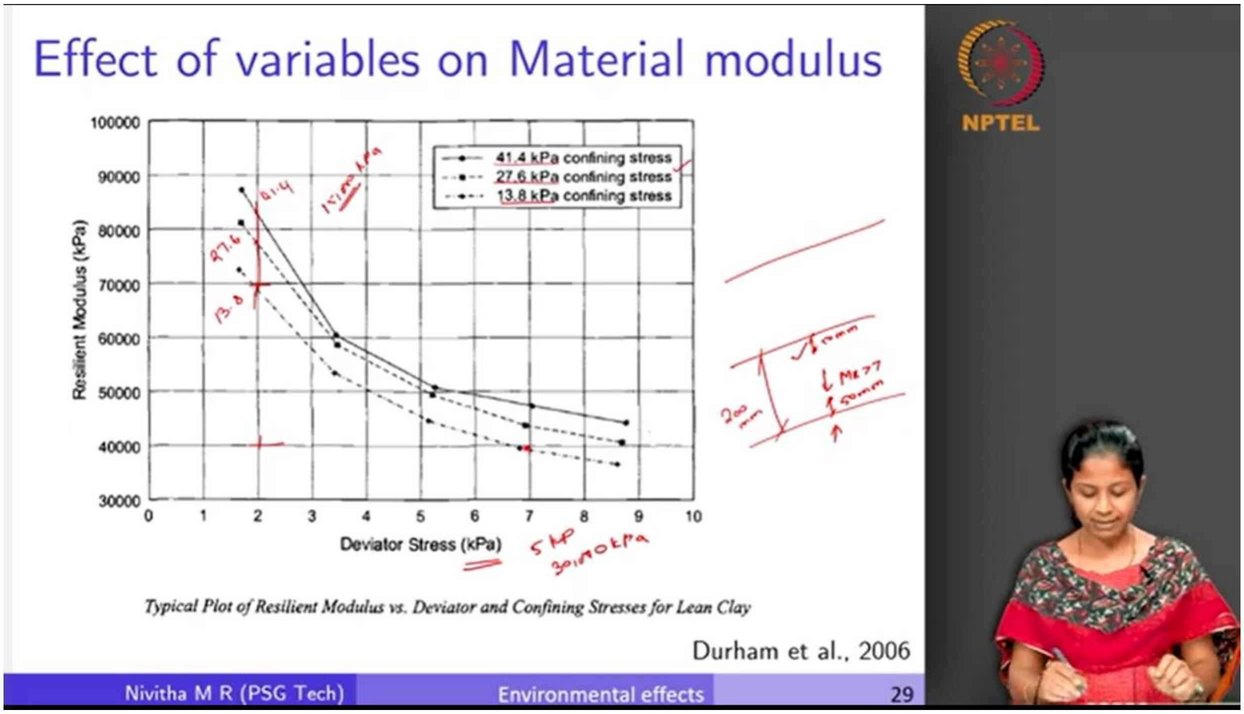
(Refer Slide Time: 18:47)



Now we will see the effect of some other variables on the modulus measurement. We can see this plot, these are all from taken from Durham et al. The first one is at saturated moisture content and at optimum moisture content, what is the effect of resilient modulus on deviator stress? We have seen what deviator stress is. It is the axial stress that we apply during the measurement of resilient modulus and it is a stress which is over and above the confining pressure in case of a confined test or if it is an unconfined test, it is simply the axial stress.

You can see here, as the deviator stress increases the resilient modulus decreases. If you recollect in the previous lecture, we have seen that as the confining pressure increases, the resilient modulus was seen to increase. So, this is with respect to confining pressure. On the other hand, if we have deviator stress in the x axis and if we have resilient modulus here, it is going to decrease as it is shown here. Again the degree is going to be different for a saturated case and for an OMC case. When in a saturated condition, fully flooded with water, the resilient modulus is lesser compared to that measured at an optimum moisture content. So, you can see there is about a two times difference in modulus between the optimum moisture content and the saturated moisture content. So, this is the first parameter which is the influence of the moisture content present in soil.

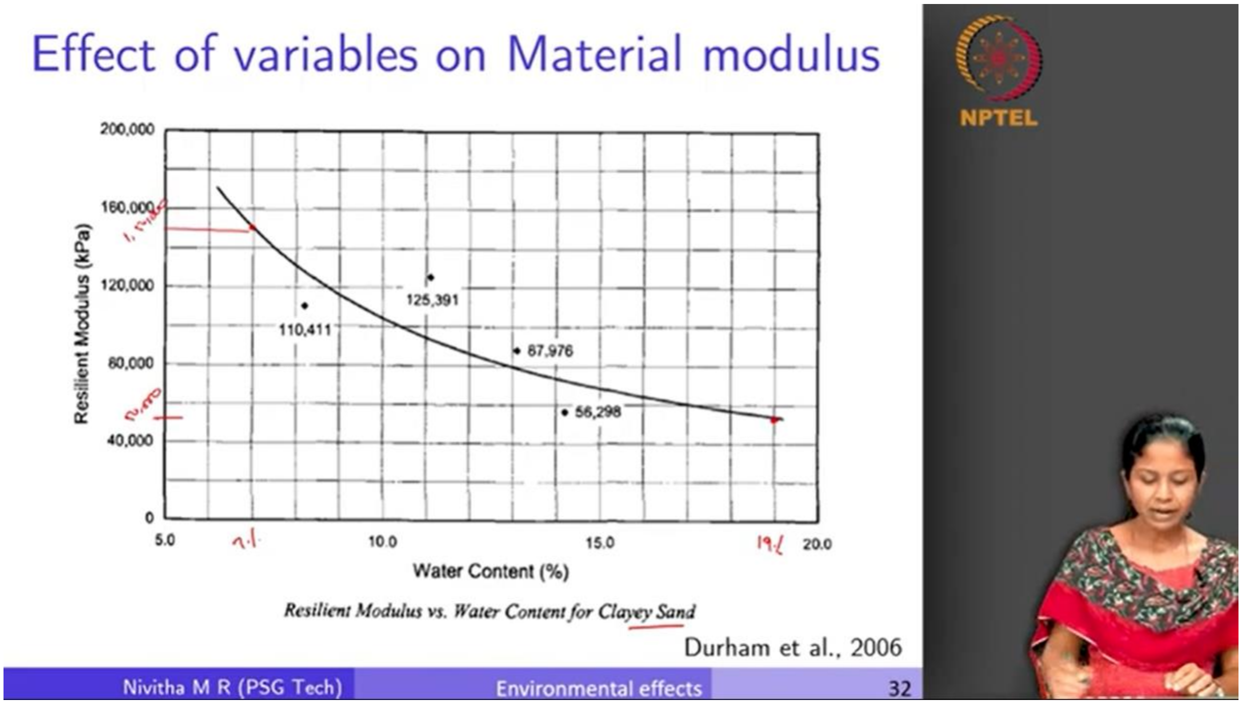
(Refer Slide Time: 20:35)



The influence of confining stress on the resilient modulus can be observed through the results obtained from laboratory tests. In these tests, different confining pressures are applied, such as 13.8, 27.6, and 41.4 kPa, while studying the variation in the resilient modulus with deviator stress of 2 kPa. The data shows that as the confining pressure increases, the resilient modulus also increases. This finding is crucial not only from a moisture perspective but also in the context of pavement design. In pavement design, different layers experience varying confining pressures based on their depth within the pavement structure. For example, a granular layer at a certain depth may experience a different confining pressure compared to another point at a different depth. The confining pressure that is experienced by a point which is present at 50 mm from the surface is different from the confining pressure experienced by another particle which is present at a 50 mm from the bottom.

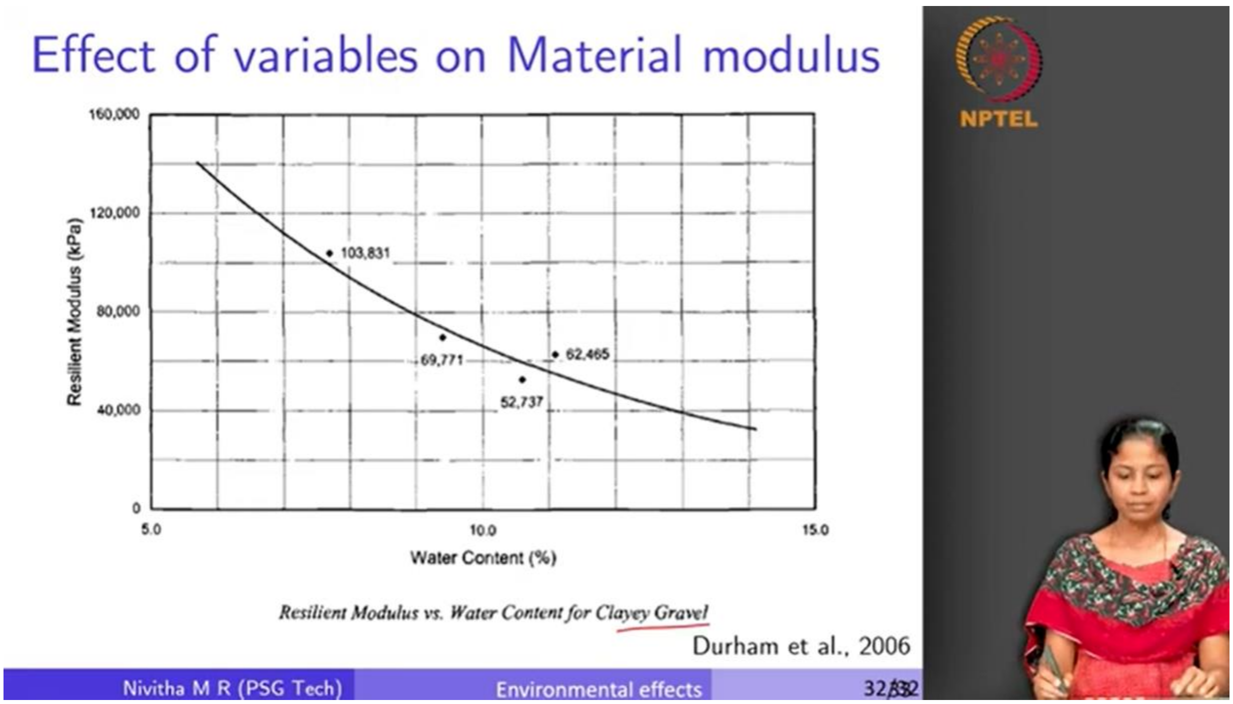
Due to this variation in confining pressure, the resilient modulus varies between different points in the pavement system. Therefore, it is essential to consider and accurately simulate the confining conditions while measuring the resilient modulus. Comparing the influence of confining stress to that of deviator stress, it is evident that the resilient modulus is more sensitive to changes in deviator stress. Even small variations in deviator stress can lead to significant changes in the resilient modulus. For instance, a 5 kilopascal variation in deviator stress can cause about a 30,000 kPa variation in the resilient modulus, whereas a similar variation in confining stress results in a much smaller change in the resilient modulus. So, compared to the confining stress the deviator stress is the resilient modulus is more sensitive to this deviator stress. So, again it is the load that is coming onto the pavement is having a more is having a higher influence compared to the confining condition.

(Refer Slide Time: 24:16)



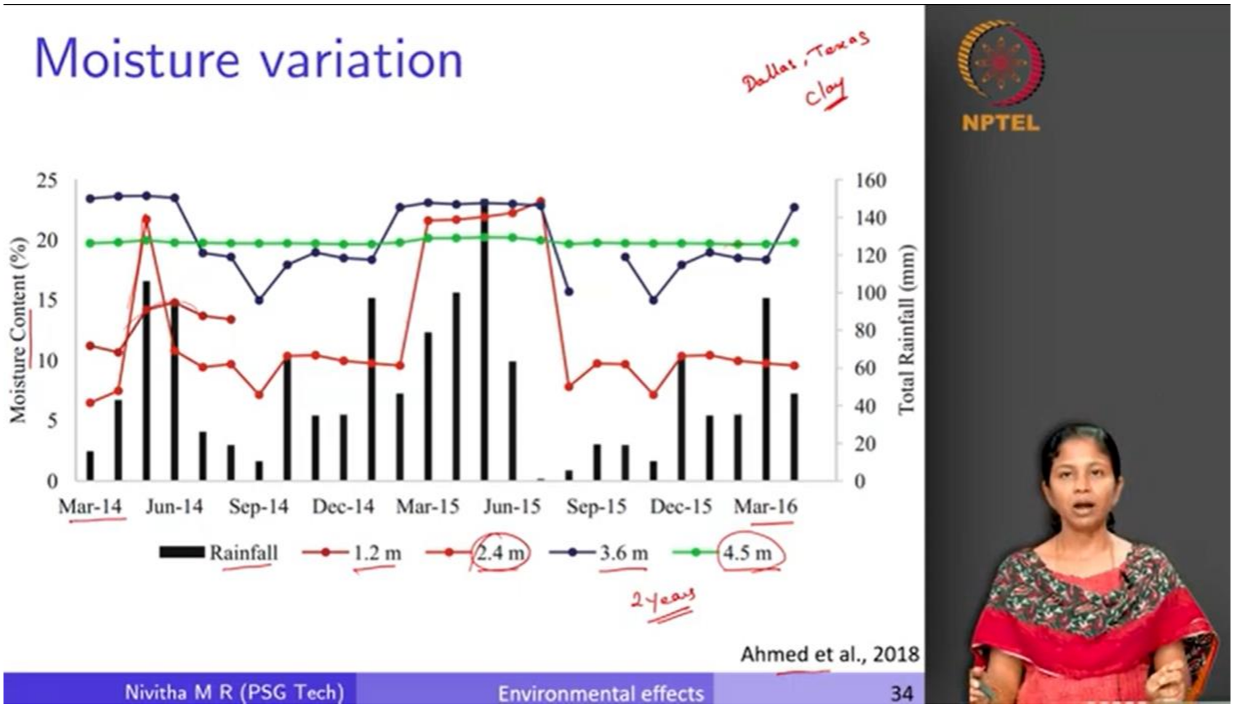
And this is also defined differently for different kind of materials. This is a same plot which is for saturated clayey gravel at a confining pressure of 17 kPa. So, we can see the variation for saturated clayey gravel depending upon the type of material, this relationship will again vary. Now let us see the influence of resilient modulus on the water content. So, ultimately that is what we are interested in quantifying. So, as the water content increases we can see here this is about 7% here and as the water content increases up to 19% we can see. There is a substantial variation in resilient modulus. As we mentioned earlier, moisture content is having a significant effect on the resilient modulus. So, this is the effect on lean clay similarly we can quantify the effect on clayey sand also. So, we are getting about a similar effect of 1,00,000 but depending upon the type of soil the sensitivity also will vary. So, this is from the experimental condition.

(Refer Slide Time: 26:17)



Similarly we have it for a clayey gravel also, the effect of moisture content is quantified.

(Refer Slide Time: 26:24)

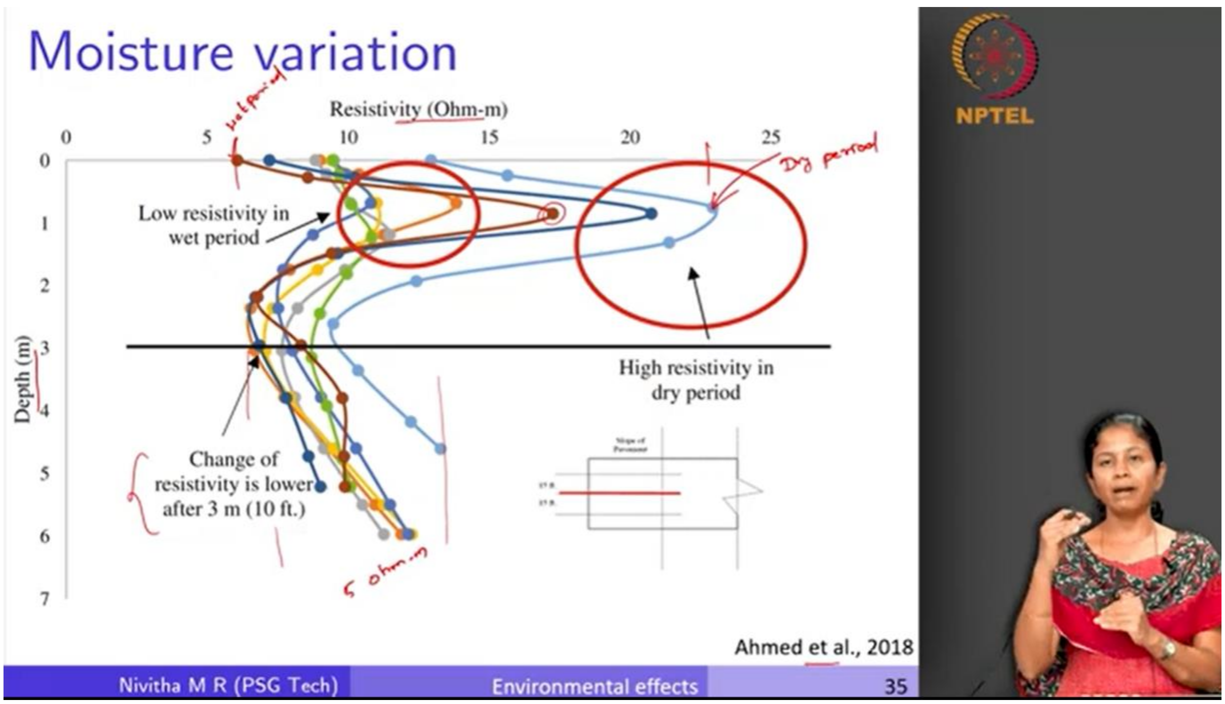


Now these are all tests carried out under laboratory conditions. Now we will move into some field data which people have measured to quantify the effect of moisture on the different variables in a pavement system. So, this study which is by Ahmed et al. is carried out at a location in Dallas, Texas. I am not able to recollect the specific highway number but if you look into this reference, you will be able to identify the specific highway on which they have carried out this test. Again I recollect that the soil that was present in that location is clay.

Now in this location, they have captured the moisture content as a function of rainfall. If you look at these black bar graphs here, this shows the amount of rainfall received at that particular location from March 2014 to March 2016. They have collected the data for a period of 2 years. So, for this 2 year period you can see how the rainfall pattern has varied. The corresponding moisture content is also measured at different depth 1.2, 2.4, 3.6 and 4.5 meters. Now if you see at 1.2 m, you can see how much the variation (red line) is. If you see at 2.4 meter, you can see when there is a higher rainfall, the moisture content has proportionally increased, reduced and then it has increased again when there is rainfall reduced again during the dry spell and then kind of varies. So, we will not be able to specify a particular pattern for this variation but we can see that it more or less varies with the precipitation.

So, if you look at another depth which is 3.6 m, there is also fluctuation because of the precipitation. Here you can see it is higher, lower, then higher and so on. But it is not as sensitive or it is not fluctuating as much as 2.4 meter depth. Similarly if you look at another location 4.5 meters which is far away from the surface, you can see here that it is almost a constant. It does not vary as much at all or it is almost insensitive to the rainfall. So, this is one important information which they had quantified it is not the effect of moisture is there on the pavement but the influence varies across the depth of the pavement.

(Refer Slide Time: 29:05)

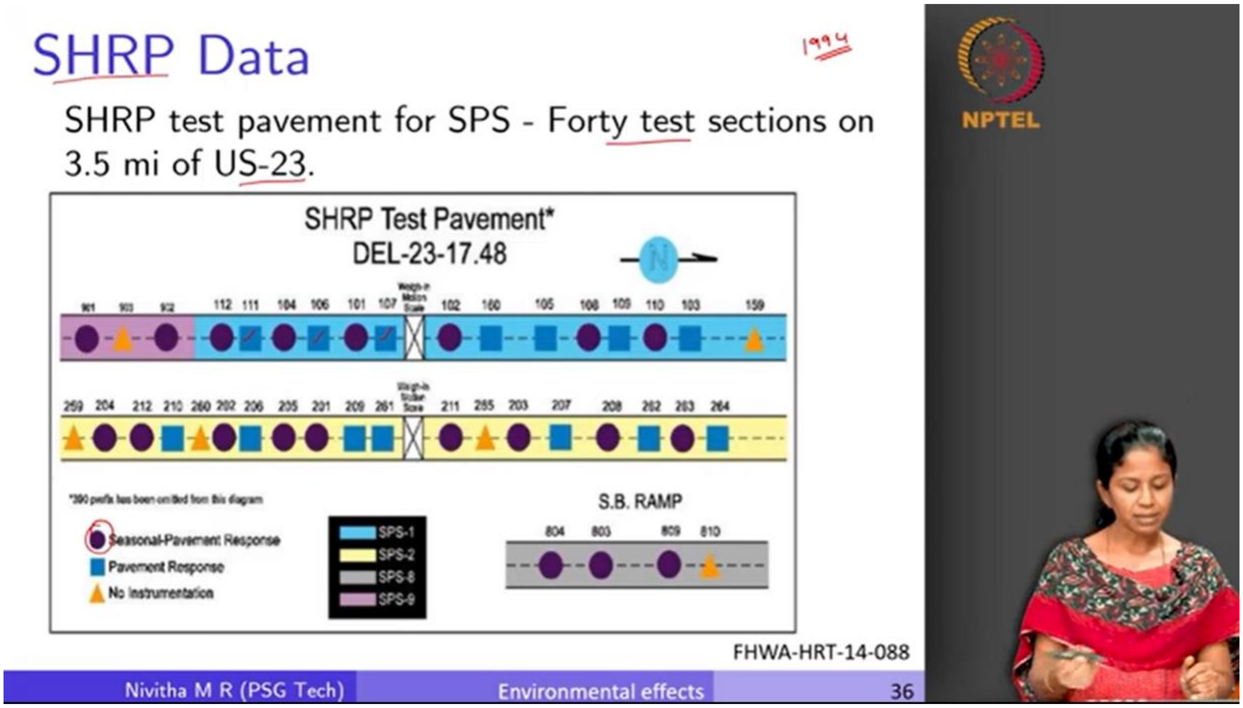


The study quantified the effect of moisture variation using indirect measurements obtained through resistivity measurements. These measurements were taken at different depths in the soil, with resistivity considered to be indirectly proportional to the moisture content. In the graph depicting resistivity versus depth, each line represents a different period over the course of two years. For example, the brown line corresponds to resistivity measurements during a wet period, while the blue line represents measurements during a dry period.

During the wet period (brown line), the resistivity increases initially and then decreases gradually. This indicates that the moisture content is high at the surface, leading to low resistivity. As the depth increases, the moisture content reduces, resulting in higher resistivity values. However, at some depth, the resistivity starts to decrease again, indicating increased moisture content. The pattern repeats for different periods throughout the year. The graph illustrates that the change in resistivity becomes minimal after reaching a certain depth, approximately 3 meters or 10 feet from the surface. Beyond this depth, the effect of moisture on resistivity becomes insignificant. The resistivity in this region shows very little variation, perhaps less than 5 ohm meter.

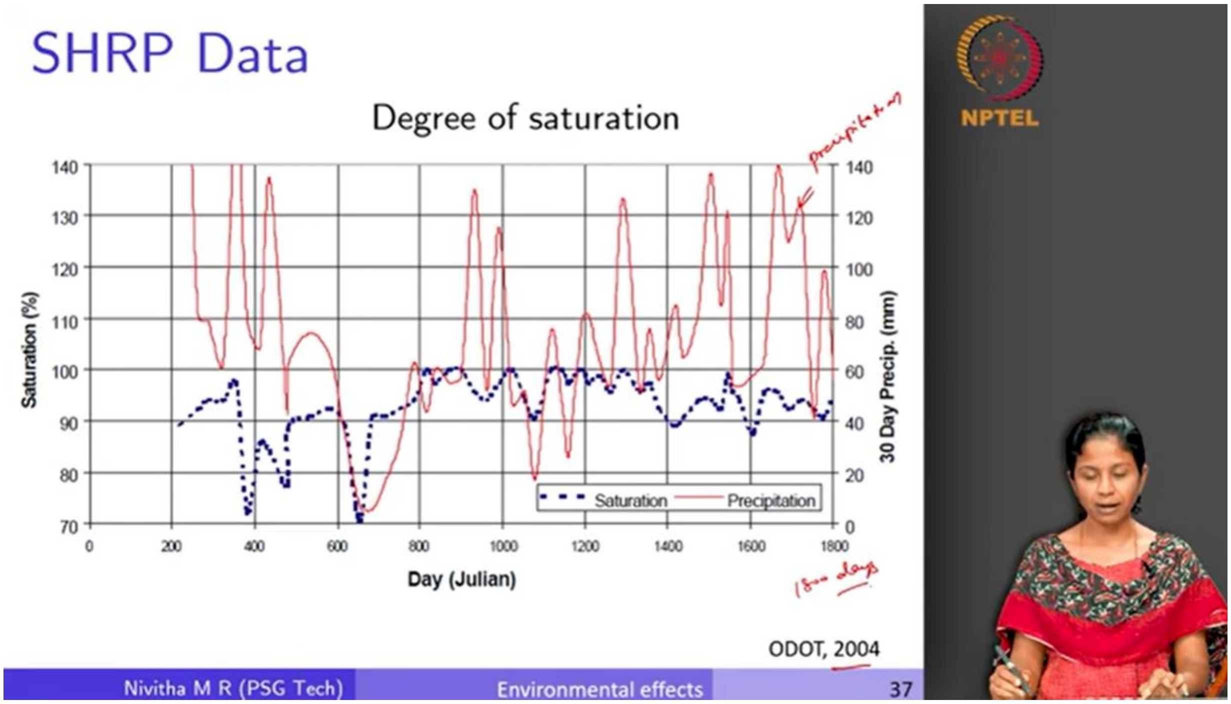
This finding aligns with the previous plot, which demonstrated that at a depth of 4.5 meters, the soil's response to variations in rainfall data becomes nearly insensitive. Therefore, it is evident that the influence of moisture on resistivity and soil behavior diminishes significantly beyond a specific depth, highlighting the importance of considering the appropriate depth when studying soil moisture effects.

(Refer Slide Time: 31:46)



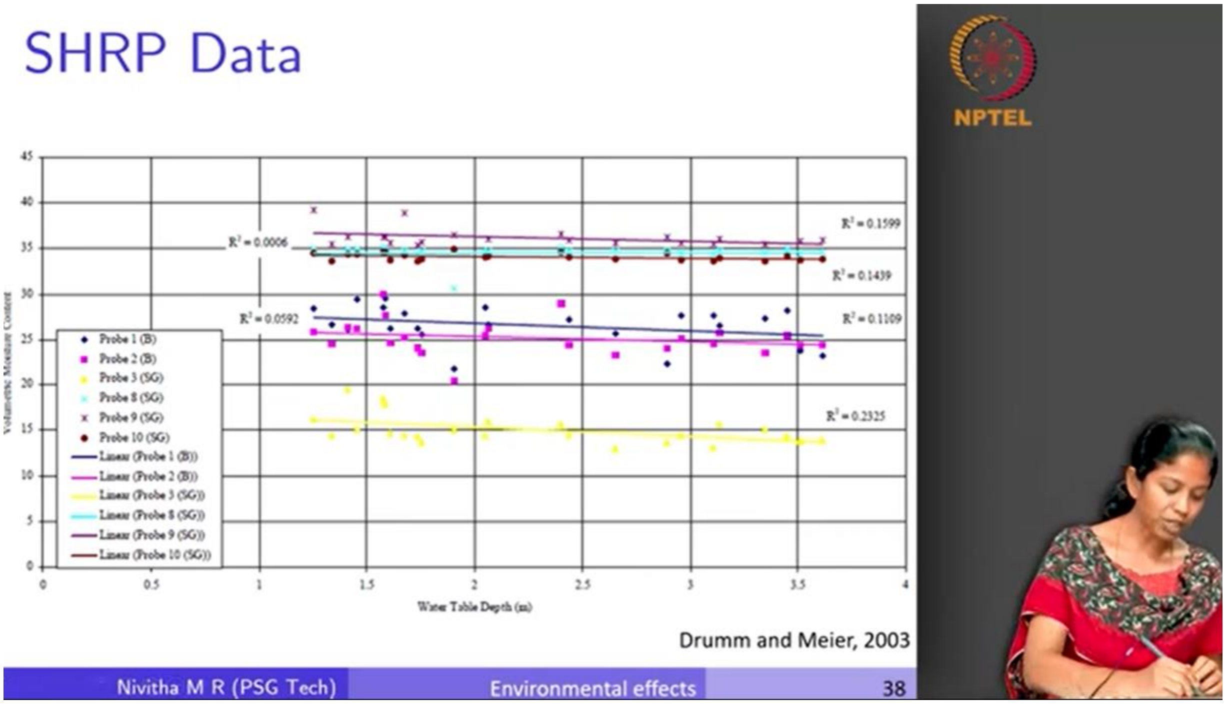
Similarly there is another study which was carried out by Ohio Department of Transportation. They had taken a strategic highway research program data. So if you recollect in 1994 the strategic highway research program data was published. It has a lot of pavement cross sections which was studied and they collected a number of data points across different highway. So this is one particular highway which is US 23 in the Ohio collected by Ohio Department of Transportation. 40 test sections were chosen and these were the data that were collected from these 40 test sections. The seasonal pavement response was measured for different seasons, the parameters like moisture, temperature and all those data was measured. And the structural response of the pavement was collected at these points which are indicated in the blue square and in some cases there was no instrumentation that was provided also. So this was the test section from which data was continuously collected.

(Refer Slide Time: 32:56)



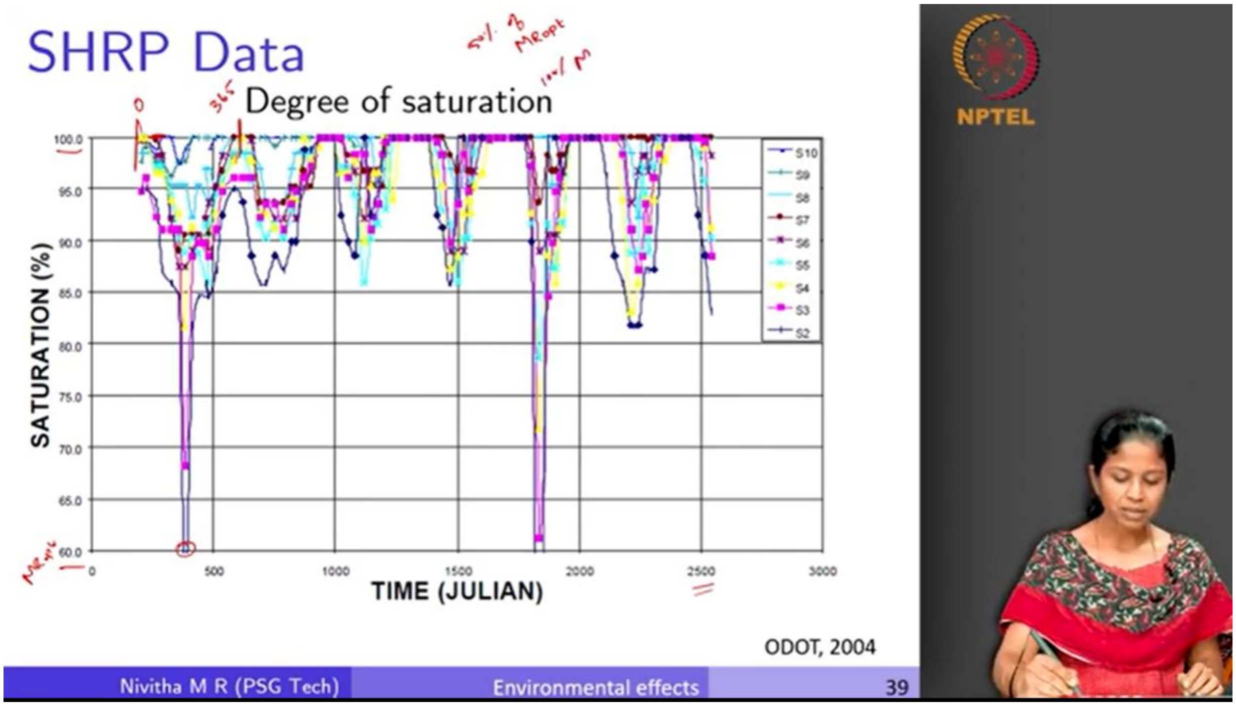
Again they have documented a different set of parameters. The first one or the more common one is the relation between precipitation and degree of saturation. Again if you see here, this red line is the precipitation and this blue line is the degree of saturation. It is again over an accumulated time period, they have collected it for 1800 days. So for some continuous 1800 days this data was collected and the exact time period is given in this particular reference. And if you look at this initially, the precipitation increases, so the degree of saturation also increases and once the precipitation reduces the degree of saturation also reduces. So you can see, it is more or less in line with the precipitation data. As seen earlier, the degree of saturation has a very close relation with the precipitation data. But we should also remember that this relation is valid only up to a certain depth. Beyond a certain depth it is highly insensitive to the precipitation data.

(Refer Slide Time: 34:06)



Similarly they had information which is about the volumetric moisture content which is present and the water table depth. For that particular case, they had collected data at different locations. It is in the base subgrade layers and all that. We can see here that as the water table depth has varied from 1.52, 2.53, 3.5 there is almost insignificant variation as the line kinds of remains flat. So for this particular case, they were not able to obtain any correlation between the water table depth and the volumetric moisture content.

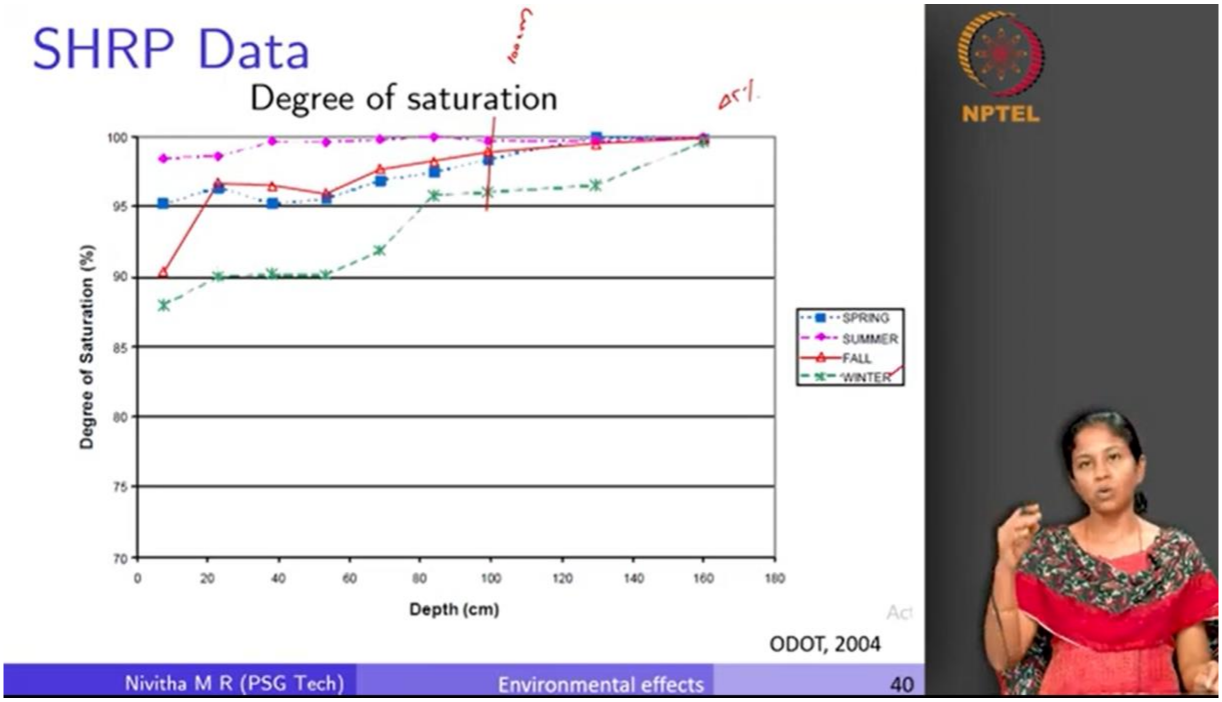
(Refer Slide Time: 34:43)



Another plot illustrating the degree of saturation over an extended period of 2500 days is presented here. It shows that by correlating this data with precipitation data, we can observe significant trends. During different seasons, such as the rainy season, the degree of saturation reaches 100%. Subsequently, during dry spells, it gradually reduces until precipitation occurs, causing it to rise again. These fluctuations continue over time. The focus here is to emphasize that over the given time period, let's say a year of 365 days, we can observe variations in the degree of saturation. However, it is essential to note that these are hypothetical variations, and there may be minor deviations. For instance, the degree of saturation may be 100% or 60%, leading to varying values of resilient modulus as we have seen before.

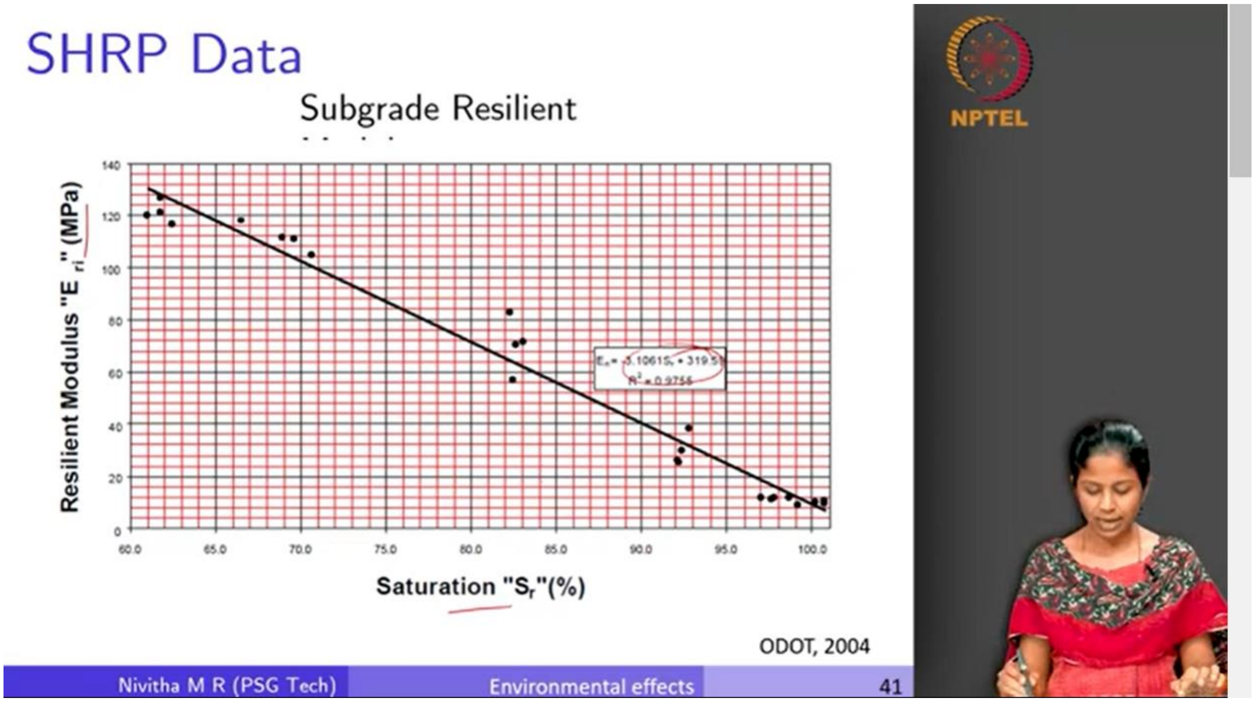
The resilient modulus exhibits a substantial variation, which must be considered. For instance, at a high degree of saturation point, the resilient modulus may be at least 50% of the resilient modulus at the optimum moisture content (MR optimum). Let's hypothetically label this value as MR optimum. When the pavement is loaded under fully saturated subgrade conditions, its ability to bear loads is reduced by 50% compared to the point when it is at the optimum moisture content. Assuming a single value for the modulus throughout the entire time period will introduce a lot of variability in the strains we evaluate. As a result, it may lead to underestimating or overestimating the total deformation that is expected in a pavement

(Refer Slide Time: 37:03)



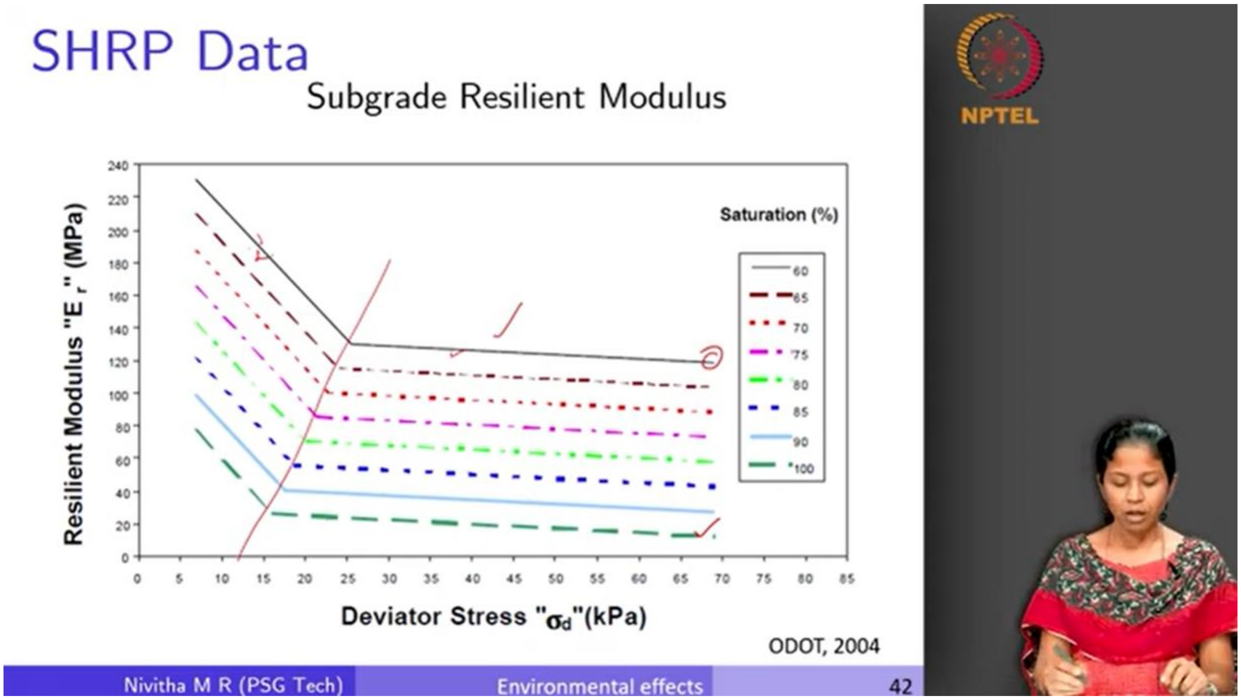
This graph also shows the degree of saturation during different periods. During winter, you can see that it is less because it is cold but the rainfall is less and during fall season you can see it is relatively higher. During summer probably this is where the rainfall has been higher, so the degree of saturation is higher and so on for different seasons they have quantified the degree of saturation and how the degree of saturation varies with the depth. You can see here maybe if I cross this particular point which is 100 centimeters, the degree of saturation the variation is less than 5%. So we should be taking into account of all of this only up to a particular depth and beyond that we can neglect the effect of the degree of saturation due to precipitation.

(Refer Slide Time: 37:56)



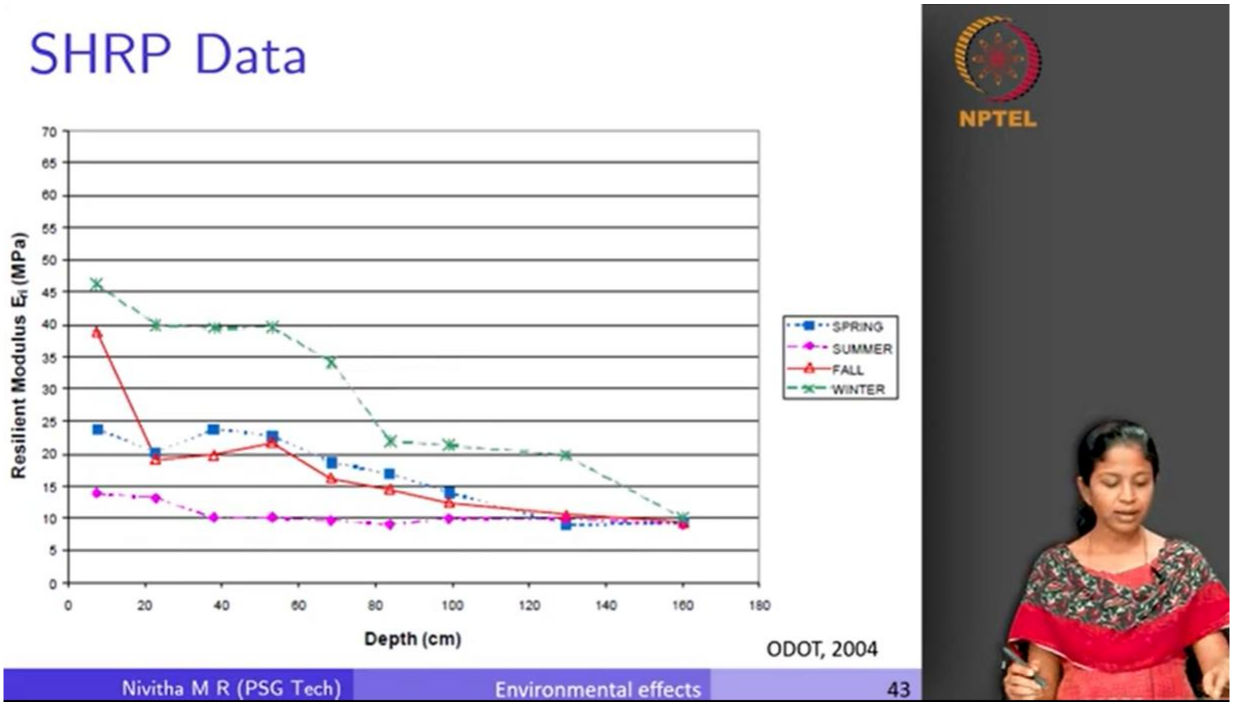
What is the variation of resilient modulus with the degree of saturation from another study we can see here? This is the equation which is computed for this particular case again how the resilient modulus varies with saturation. So when it is 100%, you can see it is about 10 MPa and when it is 60%, it is 130 MPa. So there is a substantial difference as we have been emphasizing before this is again from the same study which we are discussing now.

(Refer Slide Time: 38:25)



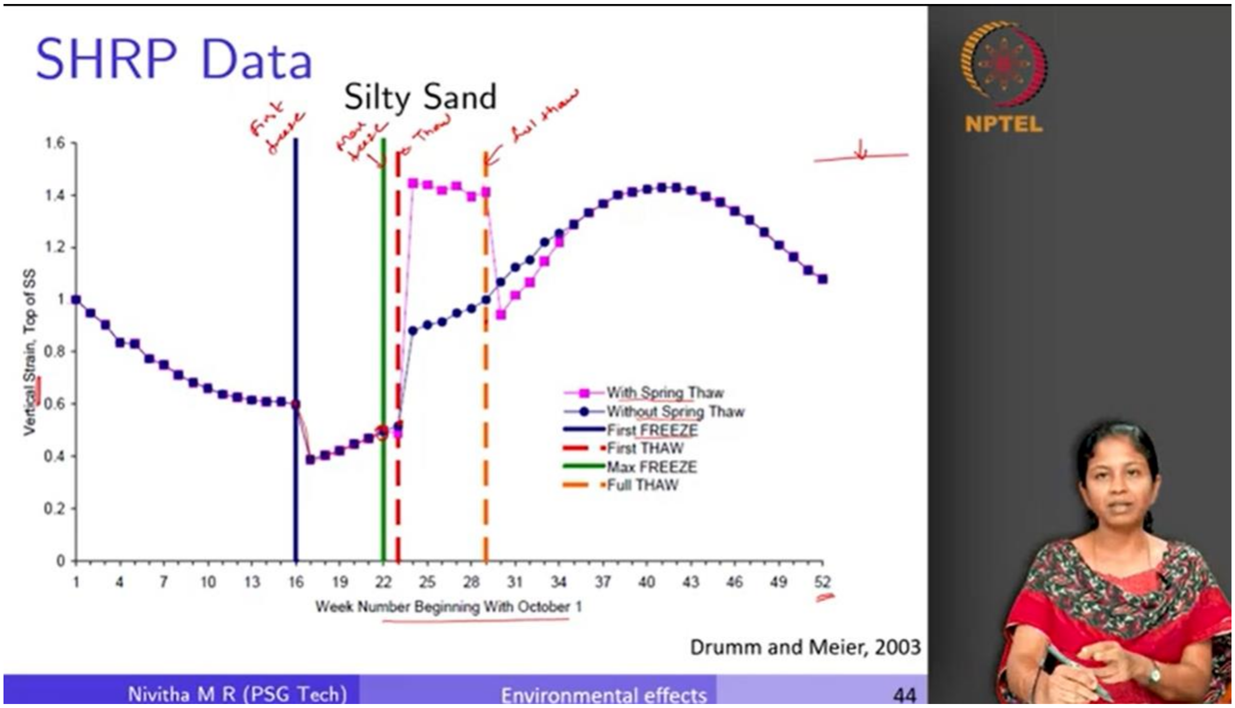
Similarly the variation of resilient modulus with deviator stress at different saturation conditions is also given. So we have seen already how resilient modulus varies with deviator stress and how it varies with confining pressure. This is also going to have a different influence depending upon the degree of saturation. For 60% saturation, this is the slope whereas for 100 percent saturation, this is the slope. You can see there is not much of a change in the slope that you can see here between these two states until a point here. Again the point of inflection varies with degree of saturation but these lines are seen to be offset by a constant distance which shows that the slope will more or less remain the same. So for both these cases the slope remains the same but this point of inflection is shifted depending upon the degree of saturation.

(Refer Slide Time: 39:20)



Similarly we are also seeing the variation of resilient modulus with depth. Previously we saw the degree of saturation. Now the variation of resilient modulus with depth is quantified from this study. So you can see, during a given season, it varies from season to season and for a given season, how it varies along the depth. So you can see the maximum variation is seen during fall and during winter wherein there is about 10 to 35 MPa variations in resilient modulus during winter and about 30 MPa variation during the fall season. Again all this data is for a particular location for a given type of soil, rainfall characteristics, drainage characteristics and so on. So this entire graph, the set of constants, the trend everything is subject to variations depending upon the specific conditions in a given location.

(Refer Slide Time: 40:25)



Ultimately the effect of all of it, especially the freeze and thaw on the strain and pavement is quantified. This is the vertical strain on the top of subgrade. What is the vertical strain on top of the subgrade and how it varies over a specific time period? So it is given over different weeks, we have 52 weeks which is a given calendar year. So there are different color lines given here. This is with spring thaw, after spring when there is thaw in the pavement. This is without thaw. Similarly, this is first freeze and the red line is first thaw, green line is maximum freeze and orange line is full thaw. So it has started to freeze at this particular point and the maximum freeze is observed at this particular point and at this point it has started to thaw and the maximum or the full thaw is over during this period. Now we can see how the vertical compressive strain on top of the subgrade varies for a case with where there was thaw experienced and for a case without thaw.

So you can see here once the freezing sets in the soil, the vertical strain has substantially reduced. There is reduction in the vertical strain and during the period of maximum freezing condition, you can see the vertical strain. Once it has started thawing, we saw that there are weak zones created in the pavement because of the thawing effect. So the vertical strain increases substantially then it reduces or it kind of remains constant. Once the full thaw is over and the water has been drained and evaporated, the strain reduces and then it keeps varying. So this is the effect of freeze and thaw which is the formation of ice lenses on the strain on top of the subgrade. So similarly you can see with spring thaw, the strain shoots up immediately after the thaw period whereas when there is no thaw, the increase in strain is very less. So the thaw period when the ice lenses defreeze and more water is present into the system, for a certain period of time, there is a substantial increase in strain.

So all these effects we have to take into account if we want to precisely quantify the strain response in a pavement system considering the impact of the environmental effects. So let me stop this lecture here. In the next lecture, we will talk about the effect of pavement temperature because that is what influences the modulus. Thank you.