Analysis and Design of Bituminous Pavements

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Lecture – 39

KENLAYER - Nonlinear Analysis

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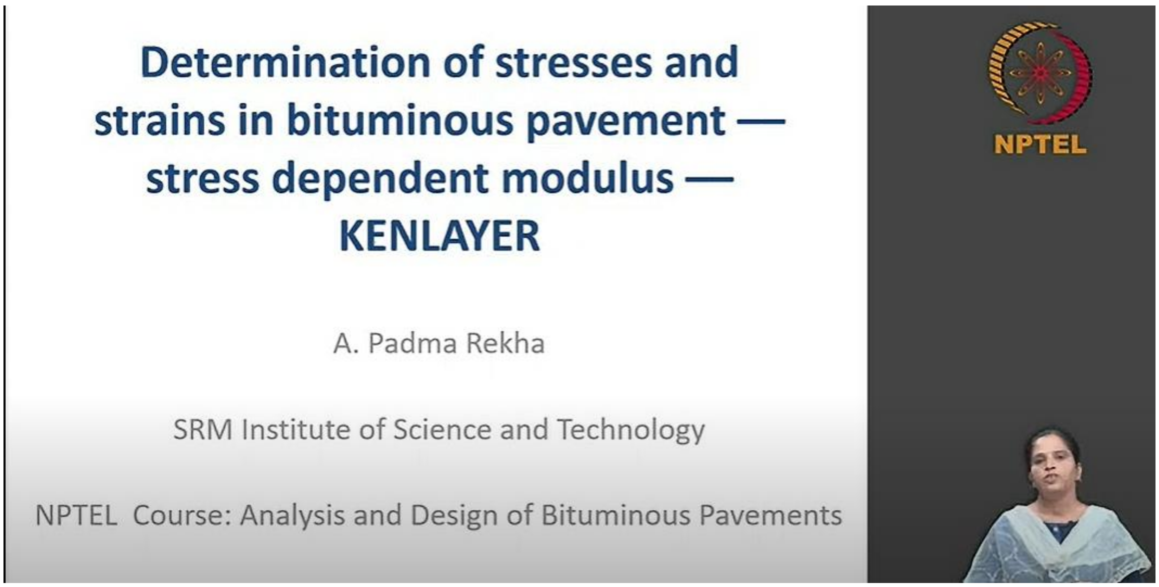

Hello everybody, in this course we introduced you to the KENLAYER software that is used for determining stress and strain at different locations of the pavement. In the previous exercise that we solved using the KENLAYER software, we used elastic modulus to determine stresses and strains at different locations in the pavement. Now, you know that we use a resilient modulus in place of elastic modulus in the pavement analysis. In such case, resilient modulus of a granular material or soil material is stress dependent. Now the question is, how to account for this stress dependent material property in the analysis of pavement. So, we will solve this exercise using the KENLAYER software.

You have been already introduced to a stress dependent resilient modulus value of the granular layer and soil layer by Professor Nivitha. Now, we will have a glance into these equations and we will focus on the material properties so that we can use these material properties in our analysis. So, you know that the granular layer and this soil layer exhibit a stress dependent modulus and modulus of the granular layer can be given by this expression.

$$E = k_1 \theta^{k_2}$$

Here, E is the resilient modulus. So, when you measure the resilient modulus of a granular layer for different stress invariant, you can see that the resilient modulus exhibits a straight-line function when you plot it in a logarithmic scale. So, the constant, the intercept here is called as k_1 and the slope of this line is k_2. So, this value of k_1 and k_2 depend on the type of the granular layer. So, you can see that for different types of granular layer, the k_1 value varies from 1620 psi to 7210 psi and k_2 value is somewhere nearing 0.5. So, you can determine this value of k_1 and k_2 by conducting a resilient modulus test in the laboratory but, if you do not have such kind of a facility you can infer to the values of k_1 and k_2 from this reference table.

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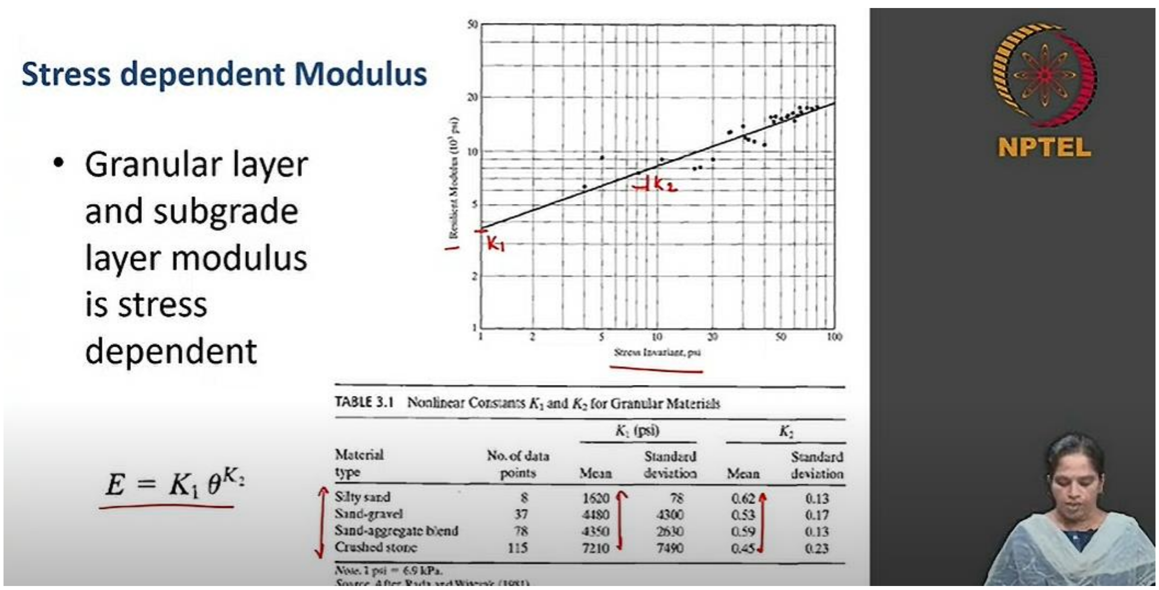

You can also see that the resilient modulus of a granular material increases when the stress invariant increases. This is the resilient modulus of a granular material. But if you see a resilient modulus of a fine-grained material or a soil value, it decreases with the increase in deviatoric stress and you can also see that there is a two-stage slope curve for resilient modulus of a soil layer. So, to define this resilient modulus of a soil layer as a function of deviatoric stress, you need 4 constants k_1, k_2, k_3 and k_4. The k_1 here, is the resilient modulus value at a point of slope change, k_2 is the deviatoric stress value at a point of slope change, k_3 and k_4 are the two different slopes.

So, you can mathematically represent this line using these two equations given here. So, again, you can determine the resilient modulus value in a laboratory for different deviatoric stress and measure this constant k_1, k_2, k_3 and k_4 for the analysis purpose. If you do not have laboratory values, you can infer to this chart for different k_1, k_2, k_3 and k_4 values. So, you can see that the k_1, k_2, k_3 and k_4 values vary depending on the type of clayey soil. So, you have for 4 different clayey soils - very soft, soft, medium and a strip clay, you have the material parameters listed here. You can also see that there is a minimum value of k_1 and minimum value of resilient modulus is defined for different materials here. So, we will see how to use these parameters in the analysis.

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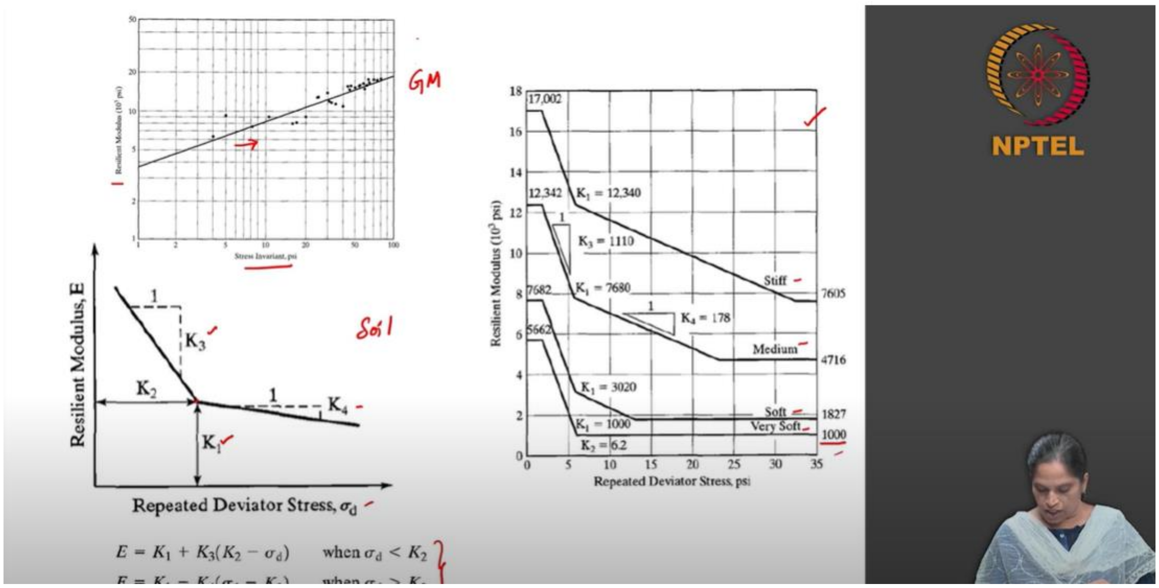

So, KENLAYER uses this pressure dependent material property in the analysis and it is called as nonlinear analysis. So, what exactly the nonlinear analysis in the KENLAYER means is, we use this stress dependent material property in determination of stresses and strains. So, this nonlinear analysis is carried out only for a granular layer and a subgrade layer. So, when we determine stresses and strains at different locations, we get 3 normal stresses and these 3 normal stresses are going to depend on depth. So, if the depth varies, the modulus at the depth is going to vary. So, in such case, the stresses and modulus are interdependent parameters. So, what KENLAYER does is, it assumes the initial seed modulus value and determines the stresses and back calculates the modulus value using the equations that we have seen previously and so this process is iterated many times till the solution converges. So, for this purpose, KENLAYER uses 3 different approaches.

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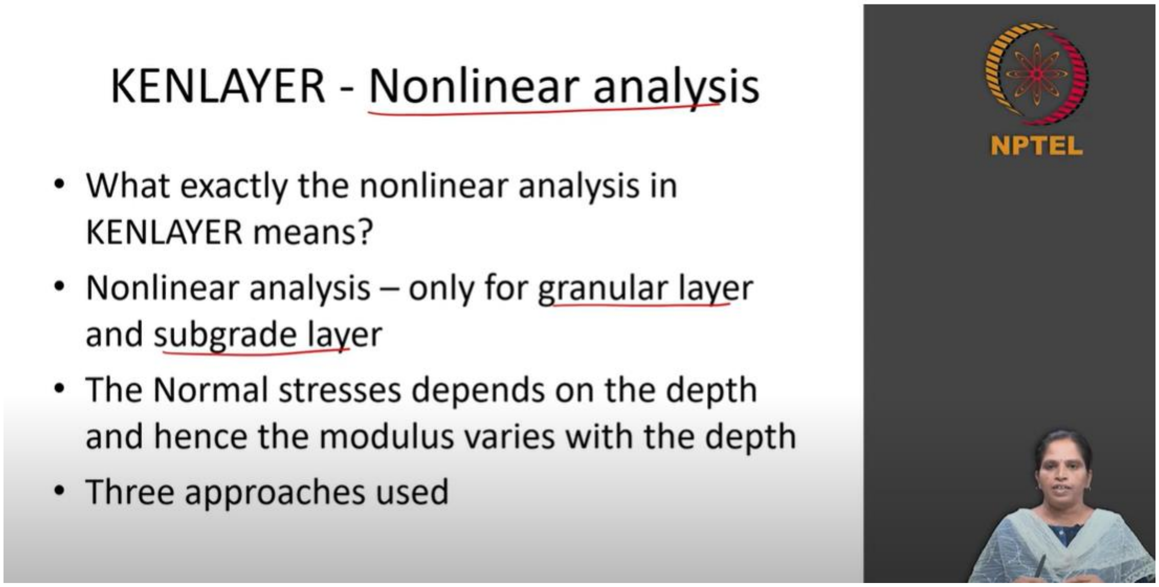

So, in the first approach, what it does is, the entire base layer is divided into small sub layers. So, after dividing into small sub layers, the center point of each layer is defined as a stress point. Now, knowing the seed modulus value, the normal stress value that is $\sigma_1, \sigma_2, \sigma_3$ or you can call it as $\sigma_x, \sigma_y, \sigma_z$ that is, normal stress at x, y and z direction can be obtained So, you get the normal stress value from this and you can compute the modulus value here and this process, you can iterate till the solution converges. So, in some cases, for determining the stress invariant, you can also include the dead weight of the material above where γ which is the unit weight of the material at a depth at which we are interested in (z) and k_0 is a passive earth pressure constant. So, you can see that the stress invariant depends on the normal stress. Sometimes, these normal stresses can also be a negative value. So, this negative normal stress occurs when you go deep below away from the loading conditions. In such cases if you get a negative normal stress, that negative normal stress value is adjusted to 0 value for determining the stress invariant in these conditions. So, this is a first method.

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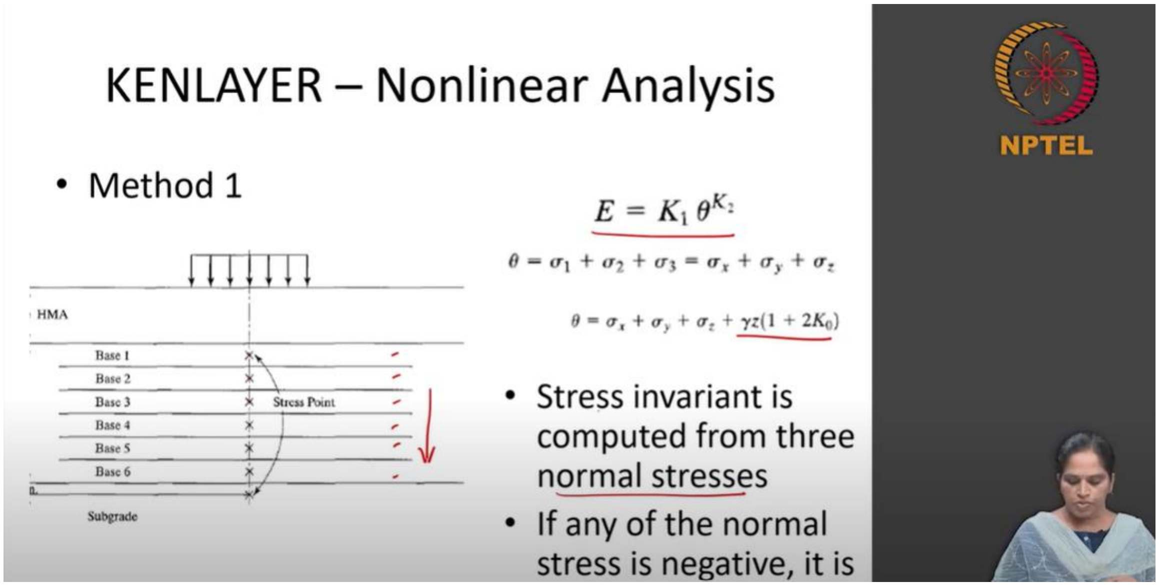

In the second approach, it is not divided into sub layer, the entire base layer is considered as a single layer. So, now when you consider entire base layer as a single layer, the next question is, at which point we are going to determine the stress and then the modulus value. So, the second method uses a stress point as one fourth of the height of the base layer. So, if h_2 is the height of the base layer, one fourth of the height of the base layer is considered as a stress point for determining the modulus value. So, you assume a seed modulus value, determine stress at these locations and then compute back the modulus value and iterate this process. So, while doing this process here, since this point is very near to the loading conditions, there may not be any chance for the negative normal stresses. So, you do not need any kind of adjustment here. So, you can consider a normal stress, even if it is a negative value, it may be a very small value. So, you can consider a negative normal stress as such. So, since you have a negative normal stress compensating on the vertical normal stress, we define a minimum modulus here. So, the minimum modulus here, is defined as the K_1 parameter that we have seen for the granular layer. So, the minimum modulus value is considered as K_1. So, the modulus will never go less than K_1. So, this is the method 2 approach.

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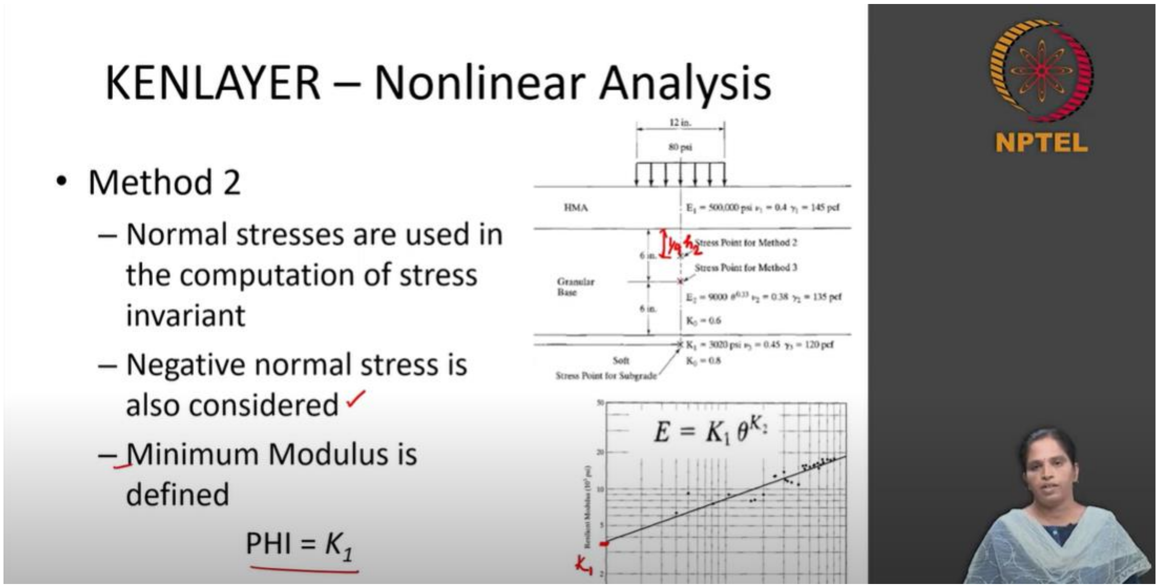

In the method 3 approach, the stress point is considered as the midpoint of the granular layer. In such conditions, the midpoint is away from the loading condition and so, there can be a chance for a negative normal stress. So, you need to adjust the principal stress values or normal stress value so as to avoid this negative value in the stress invariant. So, this adjustment is carried out using a Mohr-Coulomb theory. So, you have a relation here,

$$\sigma_h = \sigma_v \tan^2\left(45 - \frac{\varphi}{2}\right),$$

where, σ_h is the horizontal stress, σ_v is the vertical stress and φ is defined as the cohesion of the soil or cohesion of the granular material. So, when the φ is 0, you will get $\sigma_h = \sigma_v$. So, σ_h is adjusted and then modulus is recalculated. So, this is the third approach which the KENLAYER uses.

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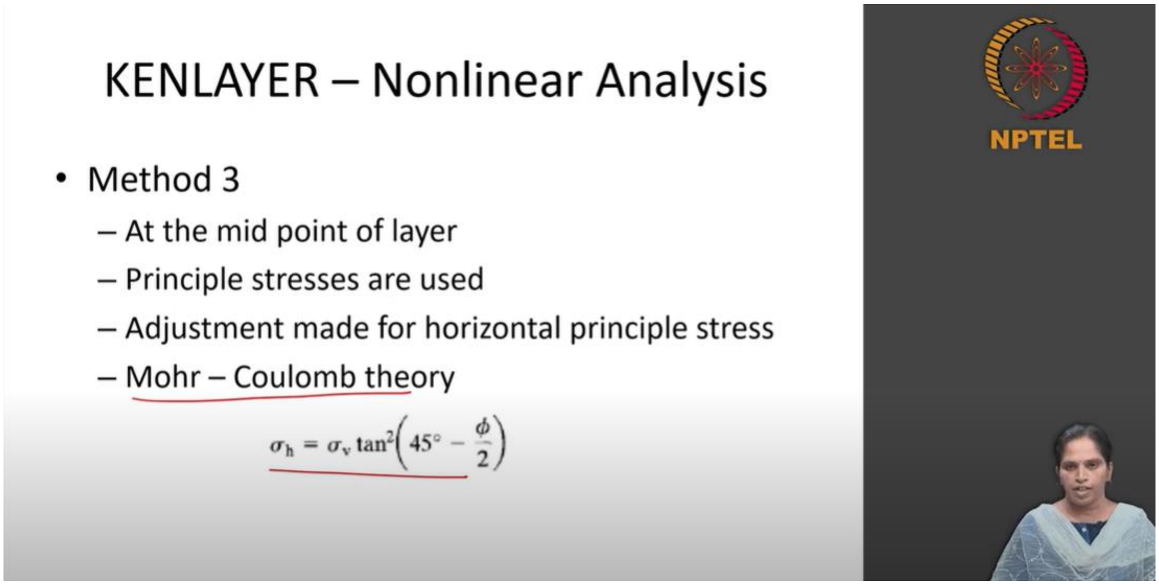

Now, we will solve this numerical using the KENLAYER software. So, you have a 3 layered structure as shown in the figure and it is subjected to a single wheel load and with a pressure intensity of 75 psi and the diameter of the load application is 9 inch. So, we will use inches and psi for the solution here. So, now we need to determine what is the maximum tensile strain at the bottom of layer 1 - HMA layer and maximum compressive strain at the top of layer 3 that is the subgrade layer. So, we will use method 1. So, method 1 is dividing the base course into multiple layers and determine stresses and strains at critical locations. And method 2 is, we consider the second layer as 1 layer and determine stresses and strains for the modulus determination is considered at upper quarter point of layer 2.

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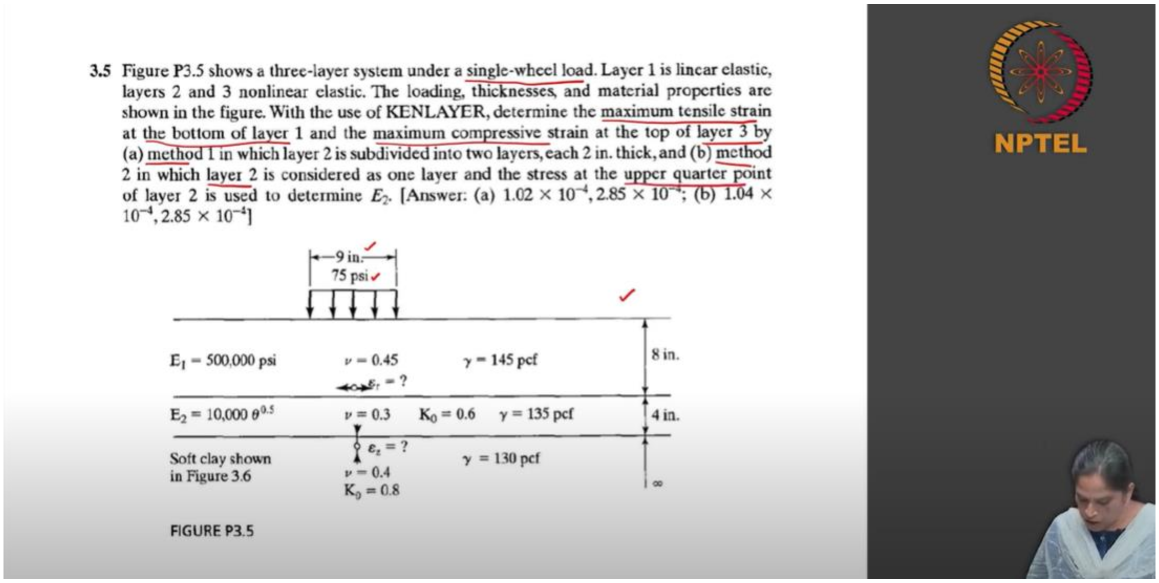

And so, when we go for this non-linear analysis, when you open a new file in the KENLAYER software, you will have the general menu option. When you click on this general menu options, this is what the information we have to give. So, type of material here is non-linear. This is called as non-linear analysis because we use the modulus as a stress dependent modulus. And so, we select 2 here and we do not perform any damage analysis here, so, we will keep this as 0, number of periods per year is 1, number of load group is also 1, we are not doing a multi group and a multi load analysis here. So, we will keep it as 1. Number of layers here, it is a 3 layered structure. But we divide the base layer into small layer. Let us divide the base layer with each layer of 2-inch thickness. So, the total thickness of the layer is 4 inch, we will divide into 2 layers each of 2-inch thickness. So, you will have 2 base layers, 1 HMA layer and 1 sub-grade layer, so total layers will be 4 layers here. Number of z coordinate for analysis, one is for fatigue strain corresponding to the fatigue damage, another is strain corresponding to rutting on the subgrade layer. So, you have 2 z coordinate for the analysis. So, these iterations, numerical integration, type of response, interface bounded and number of layers at the bottom tension and top compression this you are already aware of it.

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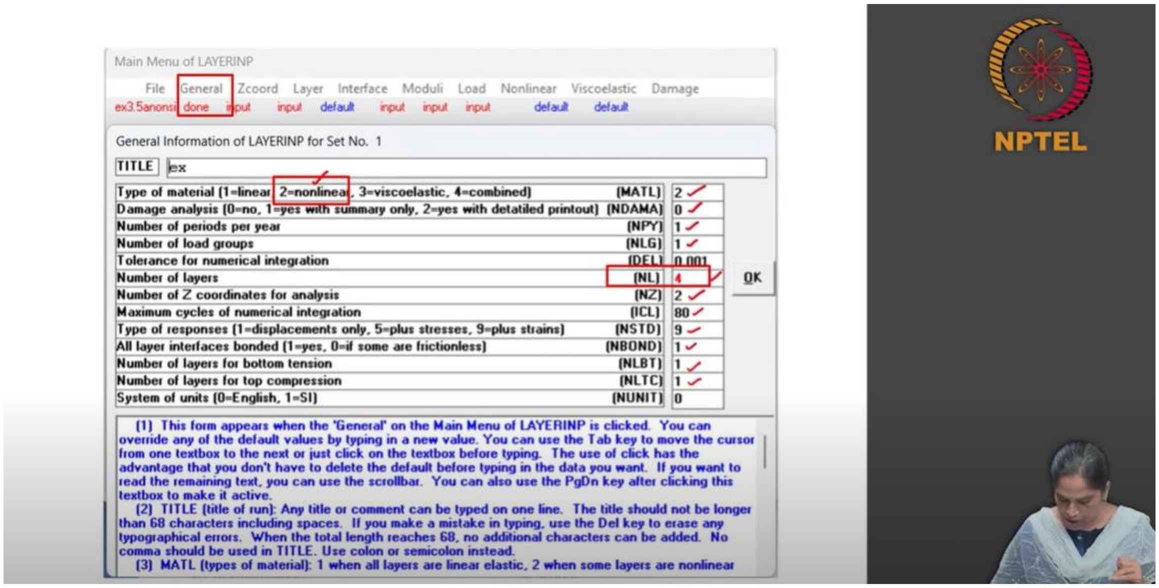

So, we will move to the next input - z coordinate. So, we are given 2 z-coordinates, one is at the top of subgrade layer. So, top of a subgrade layer which is nothing but 12 inches, so I have just given 12.0001, so that, the point exactly lies on the subgrade layer not at the interface and the other one is z is 8 inches which is at the bottom of the asphalt layer.

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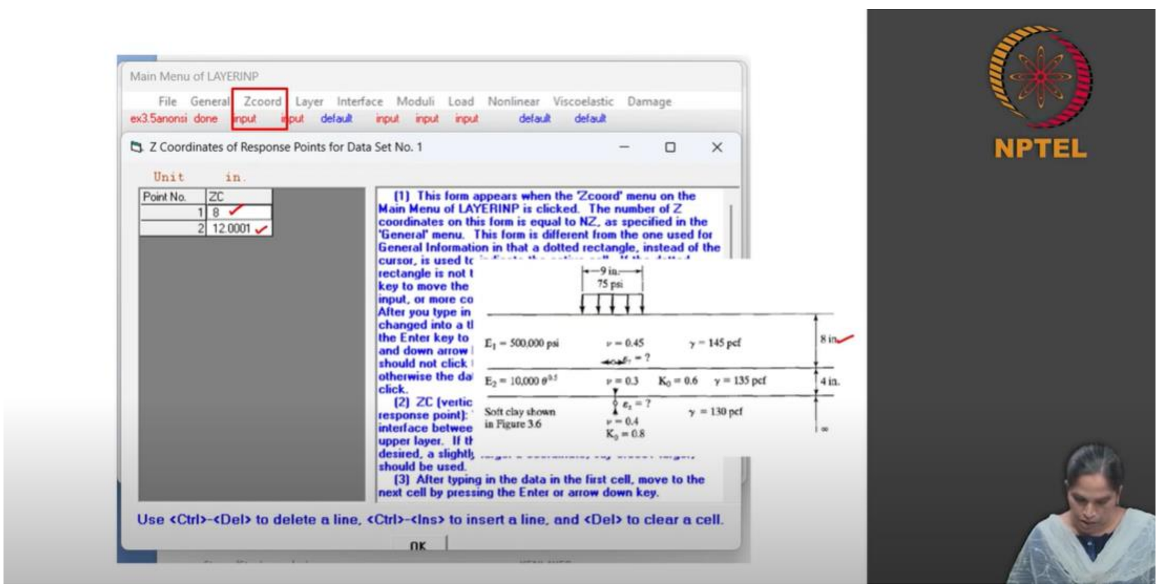

Now, the next input is the layer input which is the thickness of different layers. So, 8 inch first layer and the second and third layer are base layers. So, we divided into 2 inch, 2 inch each. So, the 4 inch base layer is divided into 2 layers and the third layer is of infinite thickness. So, you have an infinite thickness here already defined. Poisson's ratio of the first layer is 0.45. Second layer and third layers are base layer and its Poisson's ratio is 0.3 and the fourth layer is a subgrade soil layer that has a Poisson's ratio of 0.4. So, γ here is defined as the density which is lb/ft^3 values. So, the gamma value which is given in the numerical are given as input here for determining the self-weight of the material. And this self-weight of the material will be used in the computation of the stress invariant.

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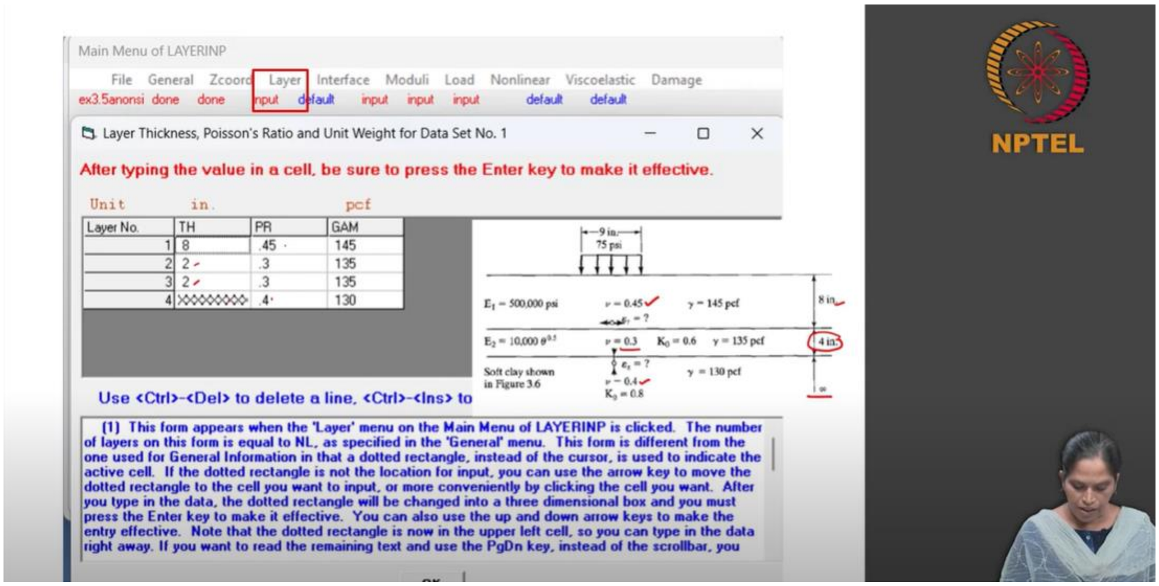

So, now, next input is the modulus value. So, now when you see the modulus value, we have used only one period here. When you click on this, you will get the modulus value. Now, if you see the modulus value, we used the modulus E_1 as the modulus of the asphalt layer. This asphalt layer is going to be an elastic layer with the same elastic modulus and it is only one value. Now if you consider the base course, now this is the resilient modulus value and it is a stress dependent resilient modulus and it is defined by this equation here. So, this equation says k_1 value is equal to 10,000 psi and k_2 value is equal to 0.5. Now, we need a seed modulus value, you can assume any seed modulus value for base layer. So, you have two base layers of 2 inch thickness. So, I have just given two different modulus values as seed modulus values. So, likewise you can take some other seed modulus value for the soil layer also. So, the soil is also considered to have a stress dependent modulus value. So, here it is given that we use a soft clay, I just assume some seed value modulus here to be 5000 psi for determination of stresses and strains.

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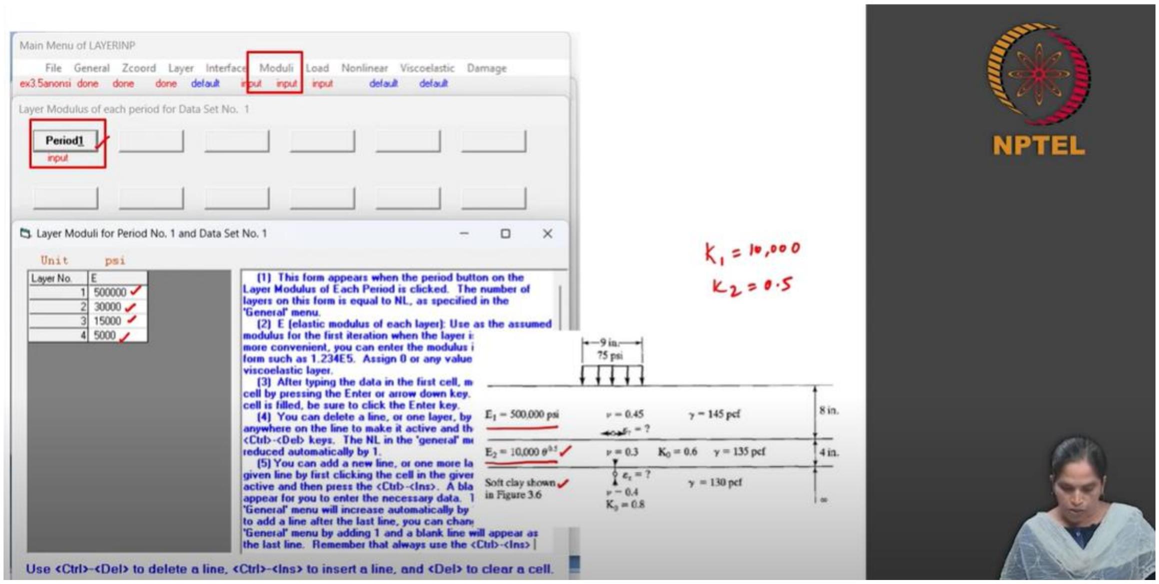

So, once you give the modulus value, the next input is the load parameter. So now, we have a single wheel load. So, single wheel single axle is defined by load group 0, contact pressure is 75 psi and contact radius is 9 by 2 which is 4.5 inches. Since it is a single axle single wheel, there is YW to be 0 as there is only one wheel. So, centre to centre distance between two wheels is 0, centre to centre distance between two axles is 0. So, we are interested in determining stresses and strain exactly at the centre of loading. So, you just click on this NR and give this input RC to be 0 which defines the centre of the pointer.

So, we define a stress value, we need to find out the critical stress values at the interface of two layers. But to compute this stress value, you need a modulus value. These modulus values are computed using the first method that is by dividing this sub base course into two layers each of 2 inch thickness and the mid of each layer is defined as a stress point and the modulus value are determined in the mid of this layer. So, now the next input is the nonlinear input which is something very new to you.

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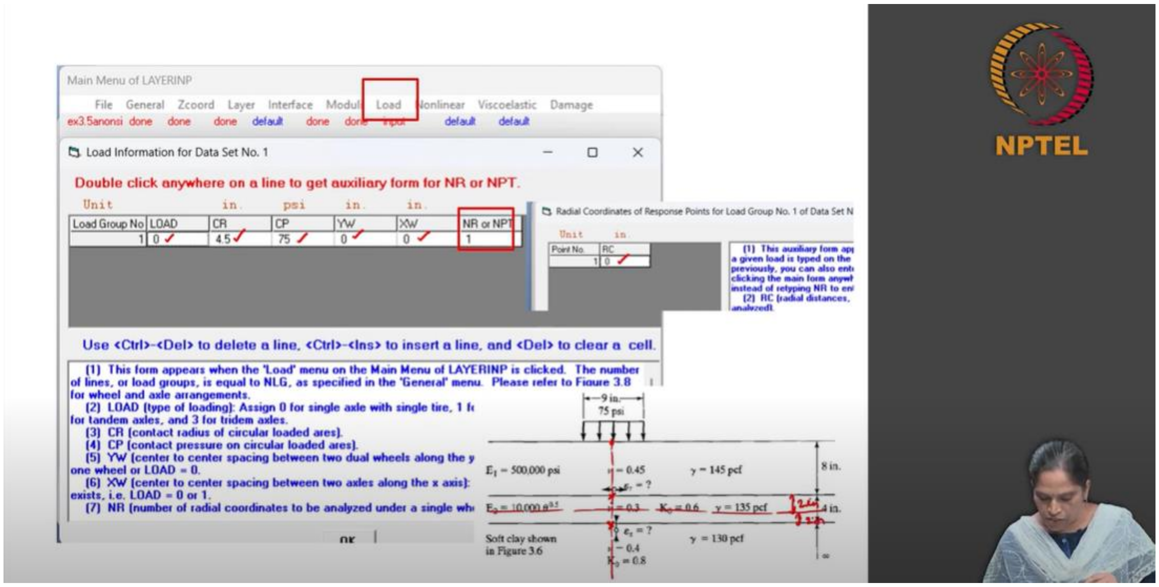

So, in the nonlinear input if you click, you will get these options, general relaxation, non seasonal input, seasonal input and Mohr-Coulomb theory input. So, when you click on this general input, this is the information you have to give in for the analysis. One is number of nonlinear layers. So, how many number of nonlinear layers we have? We have two base course and one subgrade layer. So, you have number of layers to be 3, maximum number of iterations as this modulus is computed based on the iterations. So, maximum number is restricted to 15 and tolerance for numerical analysis is 0.01.

So, now these radial coordinates, x coordinate and y coordinate values and slope of load distribution is defined in this figure. So, now assume like this is the radius of the load, as of now, this is 4.5 inch. So, now, the point at the top surface will get transferred at any depth z depending on the slope of load distributions. So, if you define the slope of load distributions, you can find out what exactly is the radius, x and y coordinate at any depth using these equations for r, x and y. So, you need the parameter to be defined here, what is ZCNOL or what is the slope value, what is the radius value, what is the x and y value, x and y is applicable in case if you have a 2-wheel loads. So, for this input, we assume that the slope here is 0 and we will give all these inputs to be 0. Since slope is 0 the capital R will match with the small r value here. We do not have x and y here because it is only a single axle single wheel.

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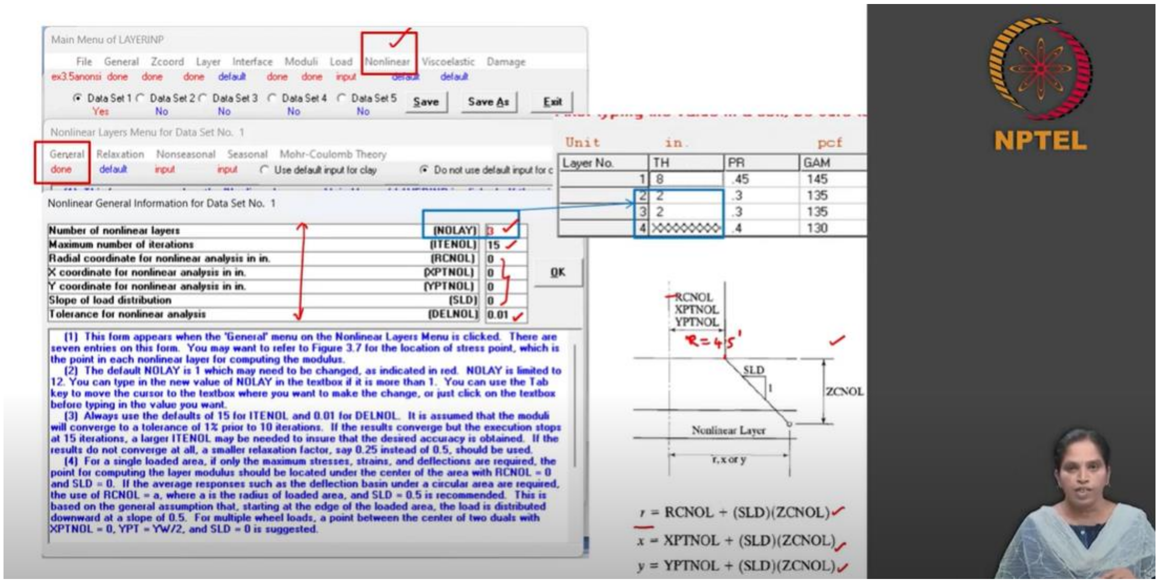

So, once the general input is done, the next one is the relaxation input. This relaxation input is a factor used for the convergence of the modulus value and the default value is given as 0.5. You can use the same default value.

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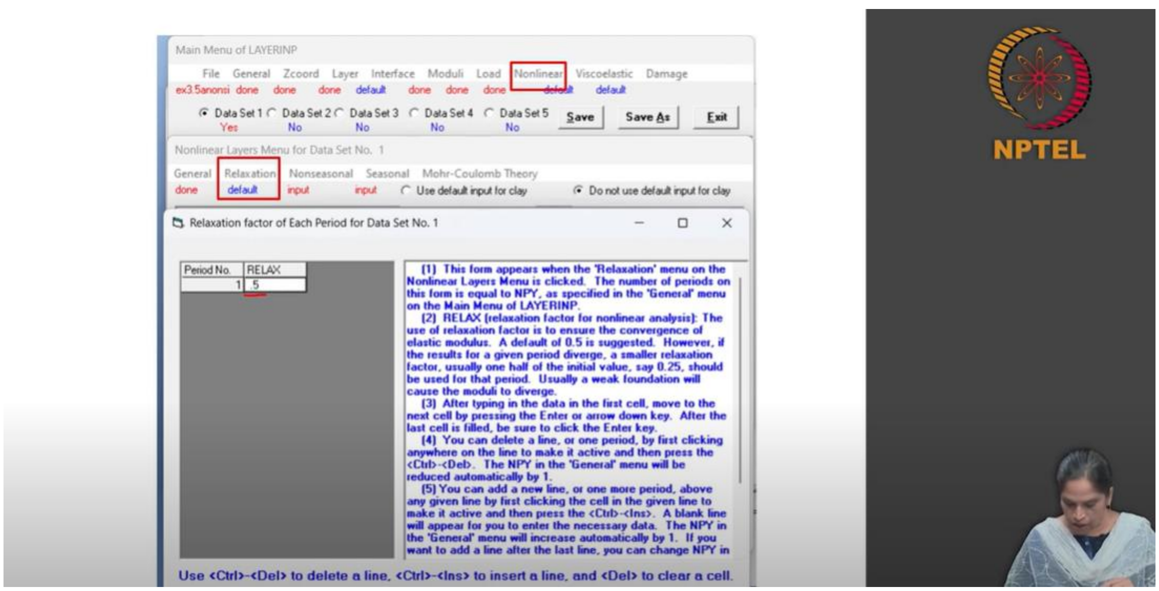

The next input from the modulus is the non-seasonal input in which we define the constants here. In the non-seasonal input, so you have parameters here, we define the layer number. So, second layer, third layer and fourth layer are non-linear layers. So, for second layer, now the value at which we need to find out stress is exactly 8+1 inch which is 9 inch. So, second layer is 8+2+1 which is 11 inches. So, the value where the modulus to be determined is the for the first layer, it is 9 inch, for the second layer it is 11 inch and for the subgrade layer, it is 1 inch below the interface. So, it is 4+8+1, so it is 13 inch. So, now, whether to define whether it is a fine grained soil or a granular layer, we use this NCLAY. So, if you give NCLAY to be 0, it represents the granular material. If you give NCLAY to be 1, it represents the clayey soil or a fine grained soil. So, now, when you click on this NCLAY value, you will get these parameters that is non-seasonal input parameter, that is the value of k_2 which is nothing but the slope of a resilient modulus value and we have seen that this value was close to 0.5. So, by default, this value will be taken as 0.5. If you have any other number other than this 0.5, based on the experimental results, you can use those numbers here and k_0 is the earth pressure constant and in the numerical values it is given as 0.6. So, we use the same number over here, 0.6. Now, for NCLAY which is a fine grained soil, you will have 4 constants that is the excluding k_1, you will have k_2, k_3, k_4. So, for all these 4 constants values, these are the default values which is used here and the earth pressure constant for the clay soil is taken as 0.8. So, these are the non-seasonal input which is going to be same for any number of periods. So, the value of k1 is dependent on the period.

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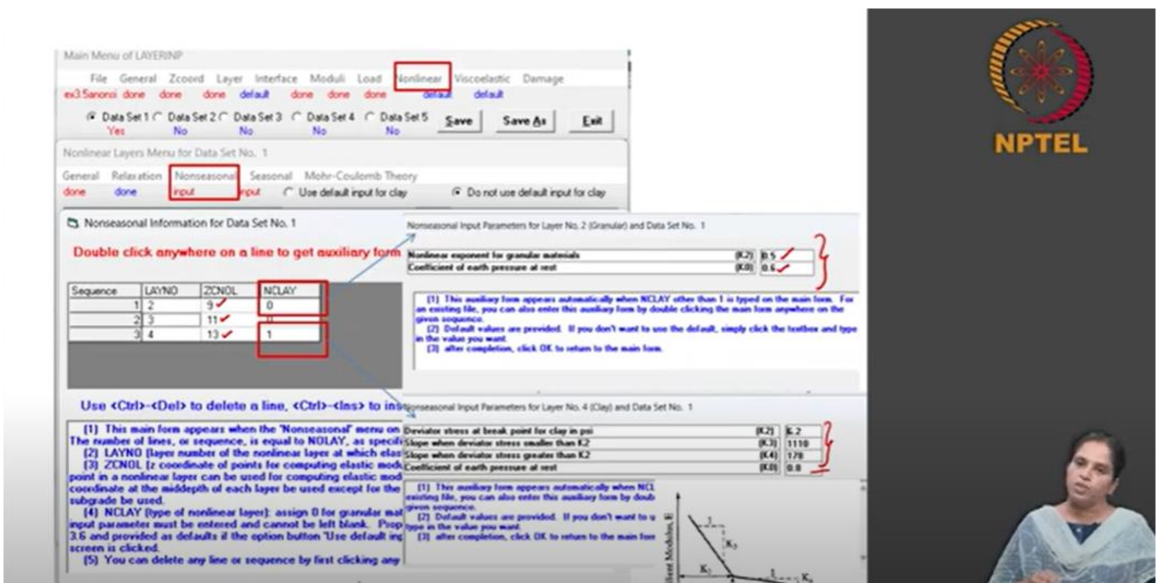

So, we have defined here only 1 period. So, we will give the seasonal input here for only 1 period and we have 3 layers. So, you can give the input for all 3 layers. So, when you click layer 2, second layer, so you have to give the value of k_1. So, the k_1 value as per numerical, it is 10000 psi and you also define a minimum value of k_1. So, minimum value of φ represents the minimum value of k_1 which is taken as 0 here. So, this is for the granular layer. Now, for a fine-grained soil or a clayey soil, now that is a layer four subgrade soil, you give what type of clay it is. So, for very soft from very soft medium and stiff clay, the number here defines what type of clay ranging from very soft, medium and stiff clay. So, you go from 1, 2, 3 and 4 here. So, you give it is a soft clay. So, when you click on the soft clay, these are the minimum parameters used. So, you already saw that you have a minimum value defined for a soft clay, maximum value defined for the soft clay and k_1 value used for the soft clay, we give that as input parameters, you can also get these parameters value from the experimental results. So, once you give this parameter, your non-linear input is done.

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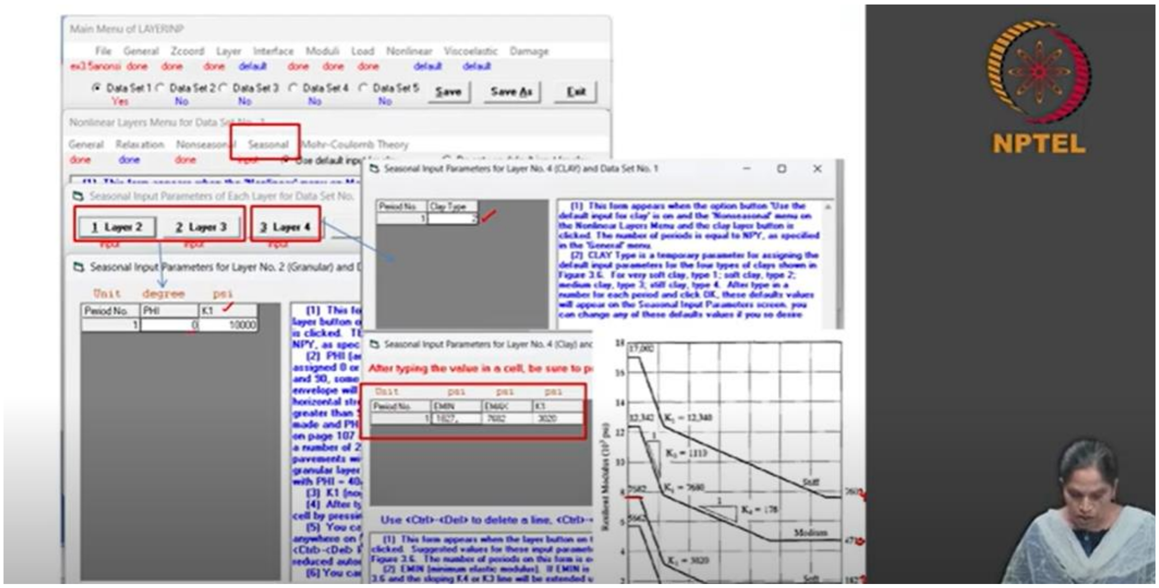

So, after giving this, just save and exit out of this main menu options and you run this program using the KENLAYER. When you compile it, so, you will get the screen something like this once the compilation is completed. So, this is the number of iterations which was taken to compute the modulus value at subgrade layer and the base layer.

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So, once the compilation is over, you will get the graphical representation of the results. So, this you can see that in plan and in elevations. The elevation of the section looks like this. So, you have different modulus, what you have assumed, different depth what you have assumed and the modulus value computed and also the input parameters are given here.

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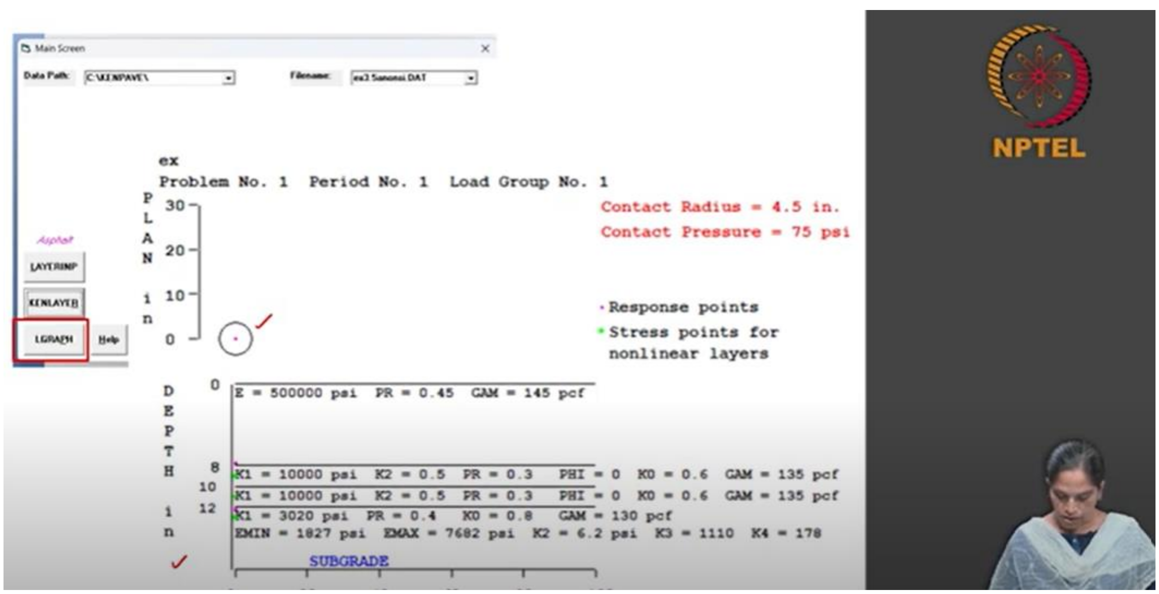

The results can be viewed as a text file and you can see that the modulus value of the second layer was computed to be 2.017E4 psi and the third layer it is 1.831E4. So, you know that second layer and third layer, both layers are the base layer. So, depending on the stress point you consider, the modulus values here are different. Fourth layer is a subgrade layer and the modulus of the subgrade layer after iterations was found out to be this. So, this modulus was computed at the locations of 9 inch, 11 inch and 13 inch and the normal stress computed at these locations is given here. So, at the second layer exactly which is at the 9 inch, this is the modulus value computed, you can see 3 normal stresses. So, you can see that these normal stresses value have a negative value. So, we said that negative value will be adjusted to 0 in computation of the modulus value. So, the negative values were adjusted to 0 for the computation of the modulus value. So, this is how the iteration goes on. And finally, once the result converges for the tolerance value, we mentioned, you will get the results of modulus at different locations. So, for this computed modulus, we have given two critical locations one is at the interface of asphalt layer and the base layer and second one is at the interface of base layer and subgrade layer. So, you will get the critical stresses. So, you can see that at the interface, a tensile stress is going to control the fatigue damage which is this ε_t value -1.024E-4, this is your critical stress which is going to control the fatigue damage at the asphalt layer. Now, rutting on the subgrade layer is controlled by ε_c which is vertical compressive strain at the top of the subgrade layer. So, these are the critical strains for this computed modulus. So, it is clear that these values depend on the modulus value. So, this process is iterated to compute the modulus value. So, we have to keep in mind that the modulus is determined at different locations. So, you get the stress at those points first and then modulus is computed from the determined stress. So, till this process is iterated till the solution converges.

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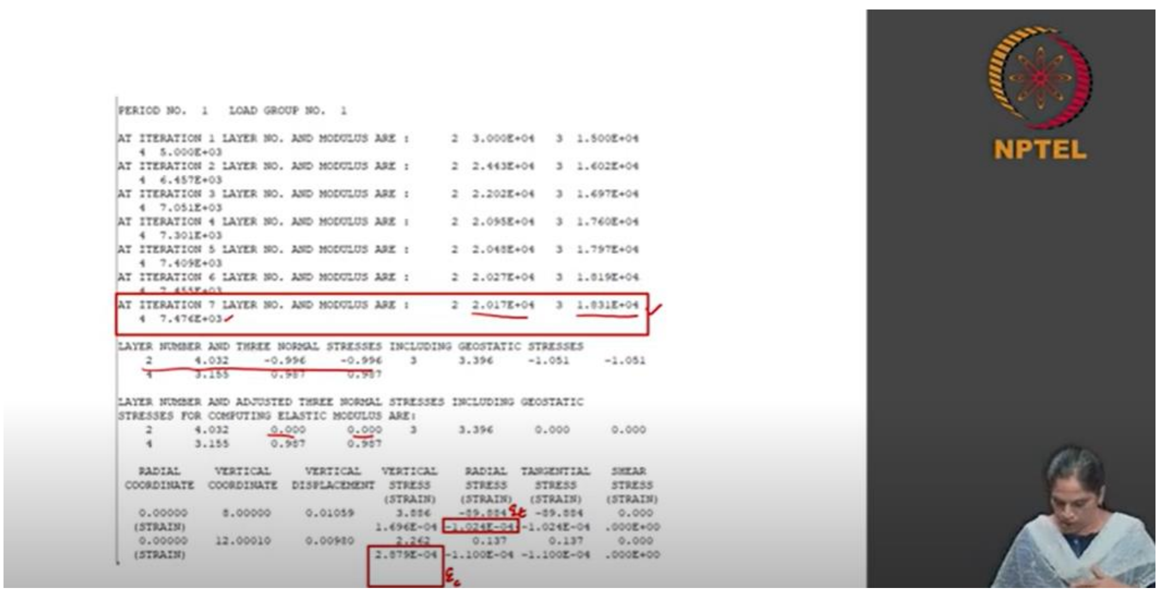

So, now, second part of the problem is by using a method 2 that is considering the base course as a single layer and considering the stress point to be at the upper quarter of the base layer. So, you have total 4 inch thickness. Now, from the base layer, you take 1 inch thickness and determine the modulus value at this point and further determine σ, ε_r and ε_z at two different locations. So, for these conditions, these are going to be your input.

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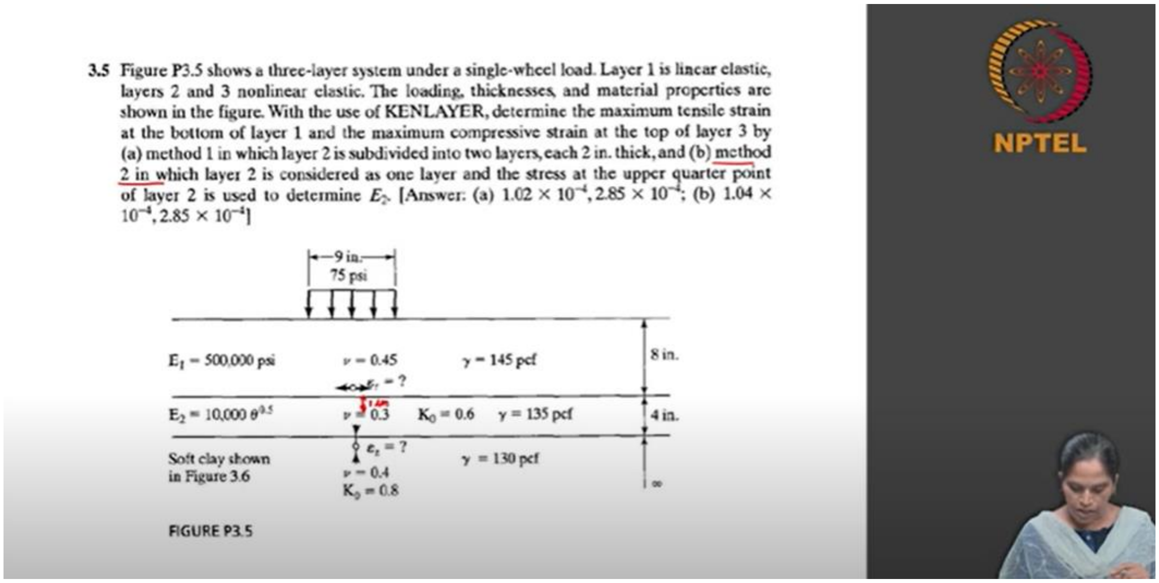

So, for the general information, we take the type of material to be non-linear. Damage analysis as of now we are not doing, so 0. Number of period and number of load group each is 1, tolerance of numerical integration, we keep it as the same as a default value. Now, number of layers is 3. In the previous case, we took it as 4 because we divided the base course into two sub layers. Here, base course is considered as a single layer. So, we take the number of layers to be 3 alone and number of z coordinates for the analysis is 2, 1 at the first interface and the second at the second interface. So, maximum number of integration - default value. So, this is the general information.

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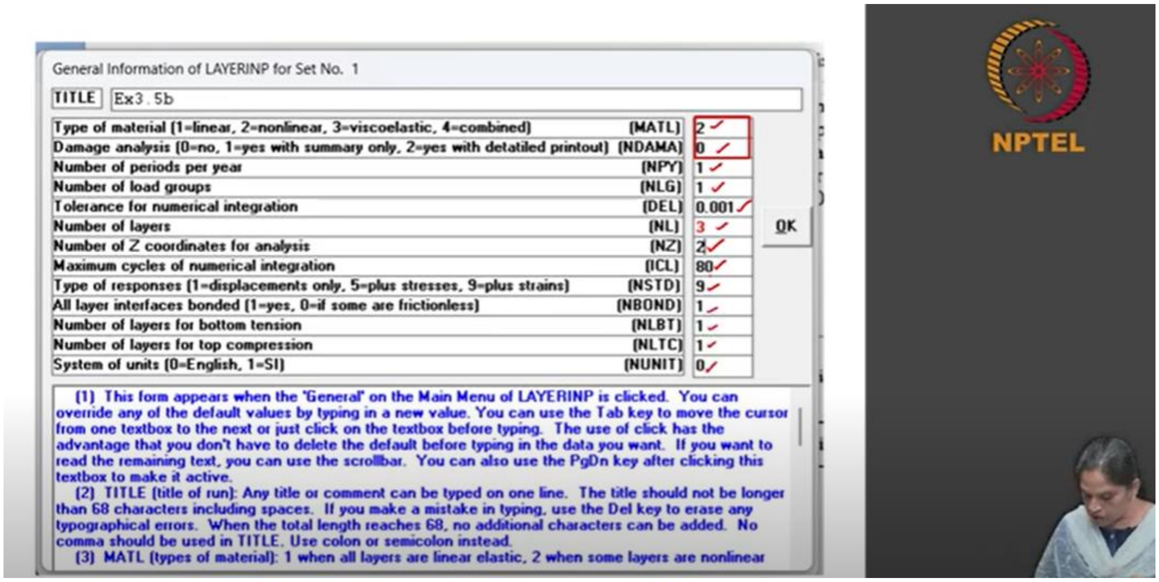

Followed by the general information, we give z coordinate that is the point where we need a critical stress and strain, one is at 8 inch from the top, another is second interface which is 12 inch from the top. So, it is 12.001 inch.

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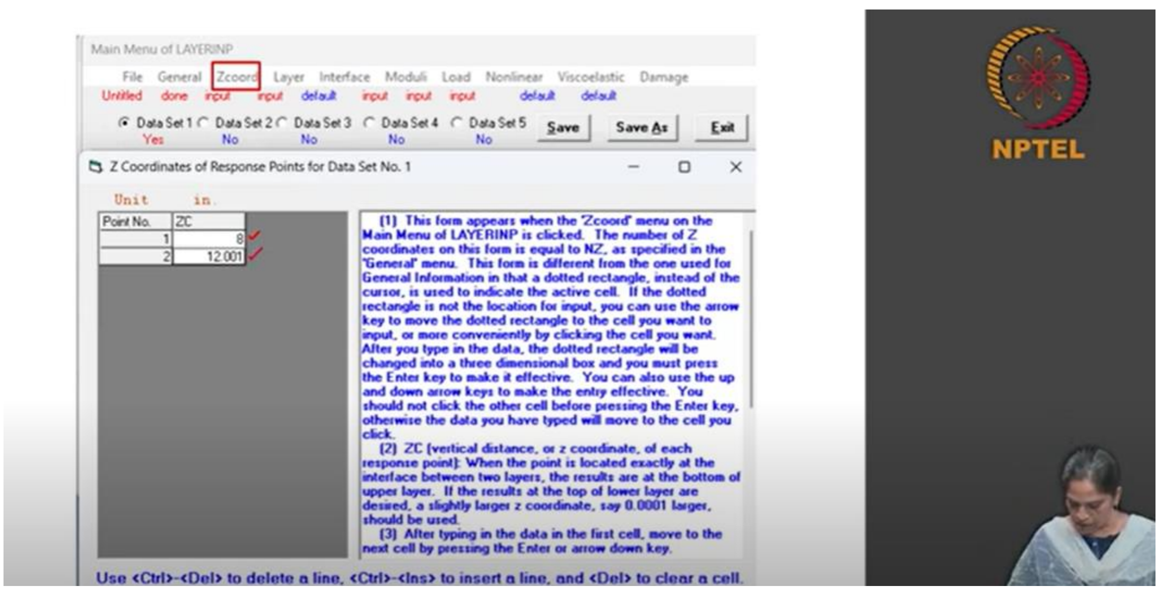

So, layer input, same as the previous case, you have thickness of different layer but the second layer, base course is not split into two it is considered as a one single layer. So, you have 4 inch thickness. So, otherwise the Poisson's ratio and the γ values are same as the previous condition.

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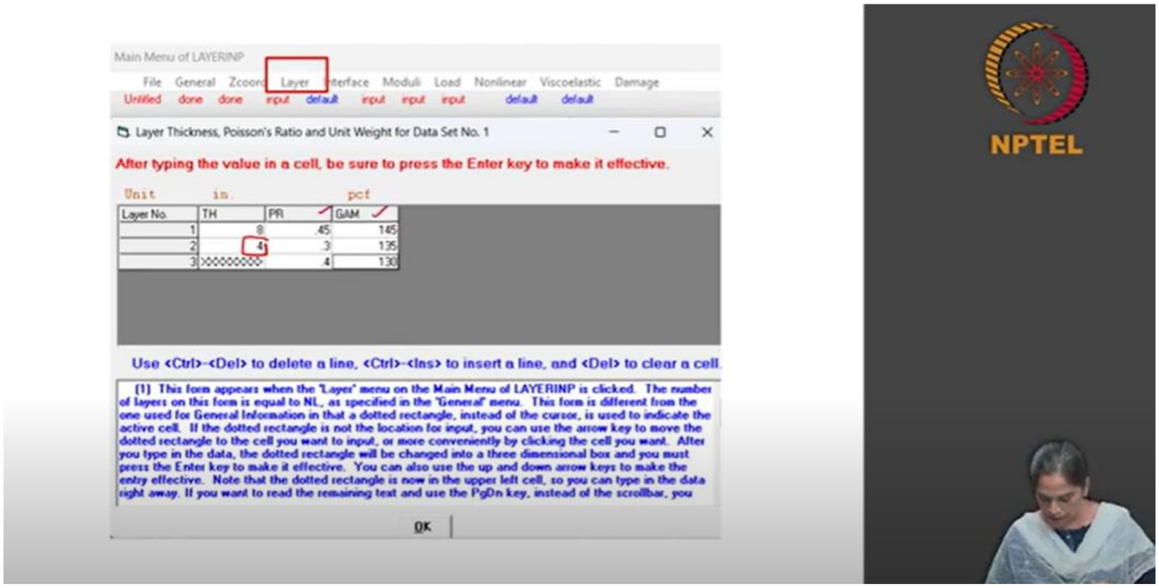

So, when you go to the moduli value, we define only one period and you can assume the modulus value again except first layer, the second and the third layer are a seed modulus which is assumed. You can assume to any nearest number.

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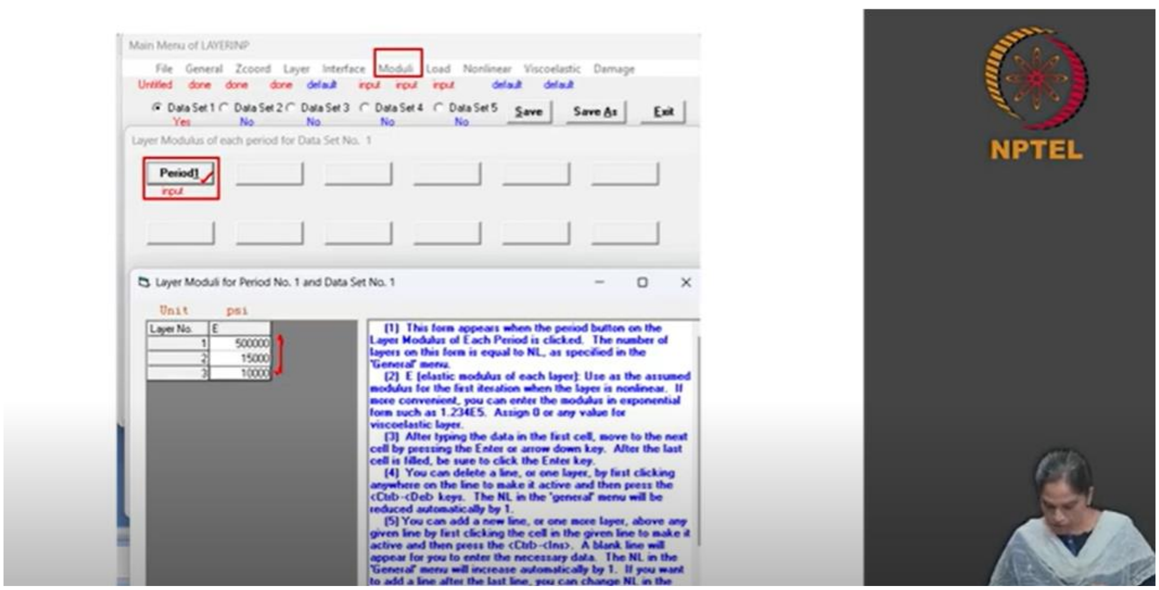

So, once the modulus input is done, the load input is same as the previous type, we give 0 load category as it is a single axle single wheel, contact radius is 4.5 inch, contact pressure is 75 psi and YW is 0 because there is only one axle and one wheel XW is also 0, NR is given as 1 and it is exactly at the center of loading. So, RC value is 0.

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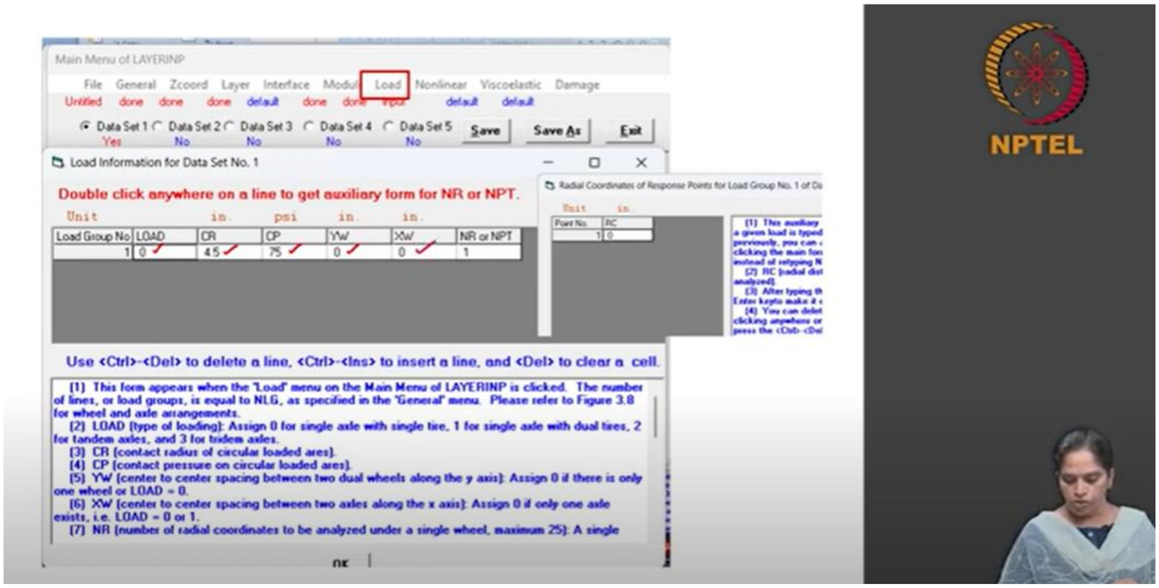

So, once the load input is given, next input is the non-linear input. In the non-linear general input, the number of non-linear layers is only 2. In a previous case we kept the number of non-linear layers to be 3 because we divided the base layer into 2. So, here, number of non-linear layers is only 2. Maximum number of iterations we will keep it as a default value and other parameters are same as that was explained previously.

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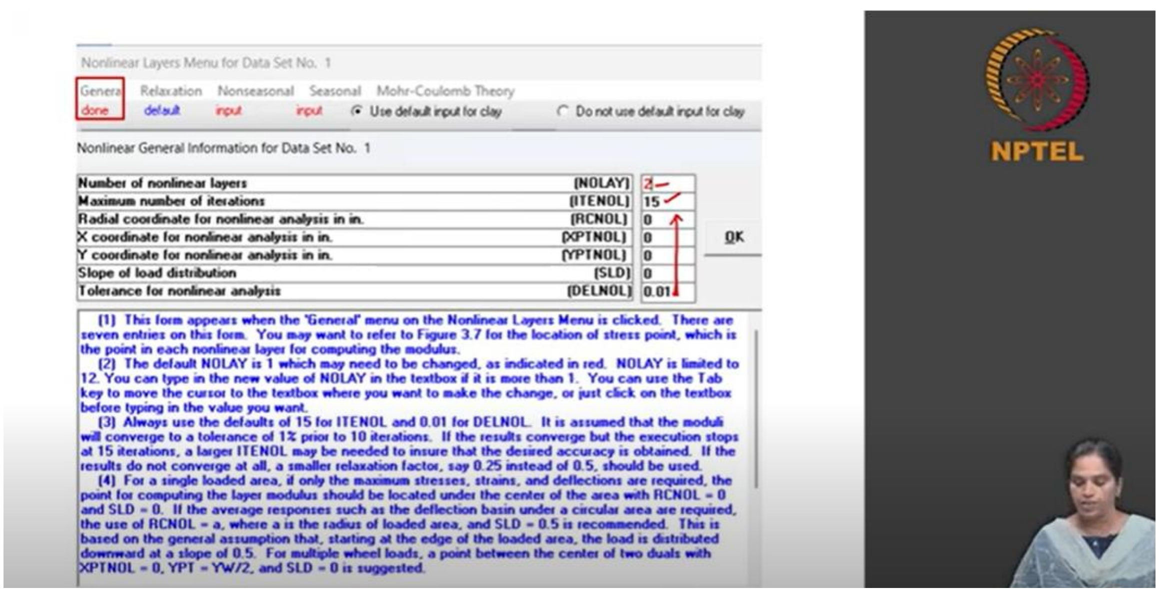

So, in the non-seasonal input, you have layer number 2 and layer number 3. Layer number 2, the depth at which we determine the modulus value is at the upper quarter. So, it is 8 inch and upper quarter is 2 inch. So, it is 8+2, 10 inch and at the subgrade layer, 1 inch below the interface, it is 13 inch. So, this is a value here is 13 inch. So, granular layer

NCLAY, you give it as 0 and soil subgrade layer you give it as 1 and the corresponding input for granular layer, that is constant k_2 and earth pressure constant are given as defined in the previous cases. So, you keep in mind you have only 2 layers here. So, for the seasonal input, that is for defining a $k_1$value and for the minimum k_1 value, it is same as defined earlier, but the thing is you have only 2 layers here and in the previous case, we had 3 layers.

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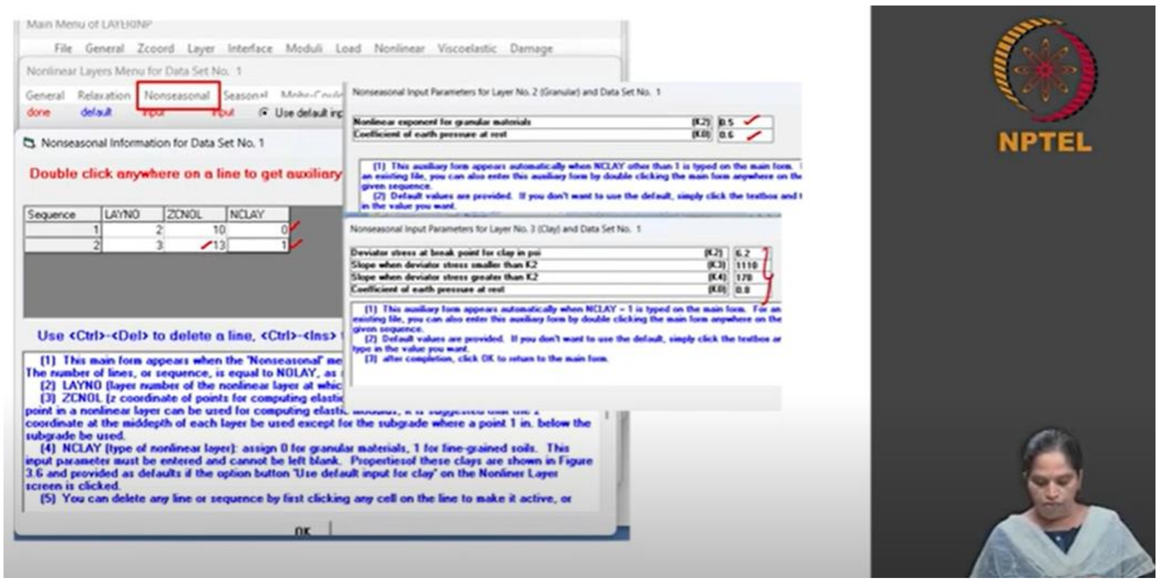

So, now, once you complete this input and compile the program this is the result you will get. So, a total of 6 number of iterations were made to compute the modulus value. So, these are the modulus values of the base layer and sub base layer at a computed depth and you can see that these are the values of normal stress you get. These normal stress value if you have a negative number are adjusted to 0 and the modulus values are computed at these specific locations. So, for these modulus values we determine critical stresses and strains. So, ε_t which is critical is this value -1.025E-4 which is same as your previous case and here vertical stress at the top of a sub grade is 2.861E-4 which is also nearing to the previous case that we determined. So, in a non-linear analysis to account for the stress dependent modulus value, we use the iteration process, we first give a seed value of a modulus, use the iteration process until the result converges and finally, we get the modulus at different depths and that modulus is further used in determining stresses and strain at critical locations.

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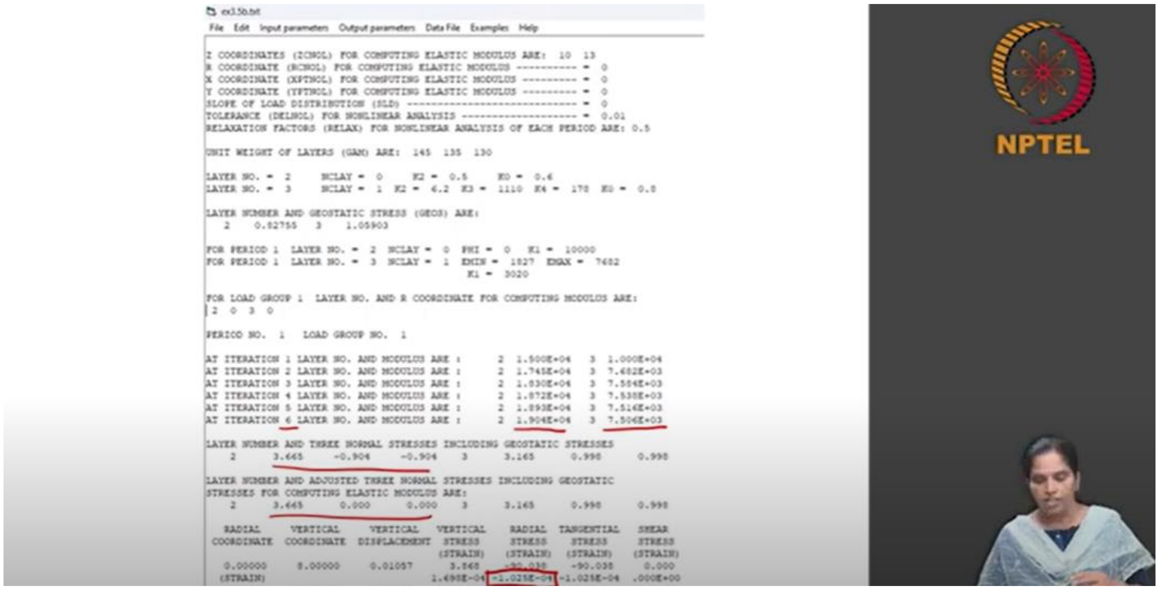

. This figure shows the influence of the stress dependent material on the critical stresses, that is the tensile strain at the bottom of the HMA layer and the compressive strain at the top of the subgrade layer. So, this computation is made for the pavement thickness as shown here. So, h_1 is considered as two different values, one is 2 inch thickness, another is 8 inch thickness, h_2 is considered as 12 inch thickness. So, the value of h_2 is considered to be stress dependent and the equation is given here, $8000\theta^{0.5}$, E_3 value is also considered as an elastic material. So, E_1 is elastic, E_3 is elastic and E_2 is considered to be a stress dependent material. In such case, when you vary the pressure intensity, you can see that the tensile strain and the vertical compressive strain increasing with the load value.

And you can also see that when the thickness of the HMA layer is thin that is for a 2 inch thickness, you can see that the influence of non-linearity of this case and this case is more pronounced compared to the thick asphalt layer. So, this is the same case even here when the layer thickness is small, the non-linearity influence is more pronounced when compared to the thick asphalt layer here. So, we can see that the stress dependent modulus value is more influential in case if you provide a thin asphalt pavement compared to the thick asphalt pavement and this value increases when the load value increases. So, that is what we see here the difference is more for a higher load category compared to the lower value.

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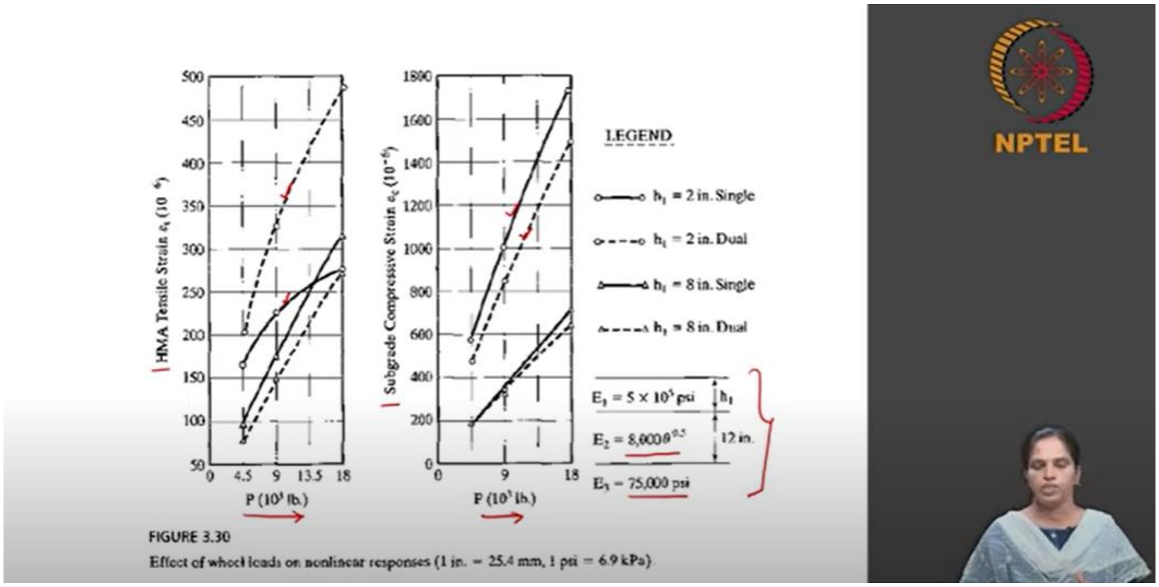

So, we have seen how the stress dependent modulus value influences the critical stresses and strains. In the next lecture, we will see damage analysis and how to do damage analysis using the KENLAYER software. Thank you so much.