Underground Space Technology
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Module No # 10
Lecture No # 50
Calculation Sequence for Rock-Support Interaction Analysis-Example

Hello everyone, in the previous class, we summarized the Ladani's analysis for the tunnel and support system interaction analysis. And we discussed or we kind of noted down all the calculation sequence at one place. So let me explain you, with the help of an example taking the help of an excel sheet that how this type of analysis should be approached. So here, for your ready reference, we are going to take up one excel sheet.

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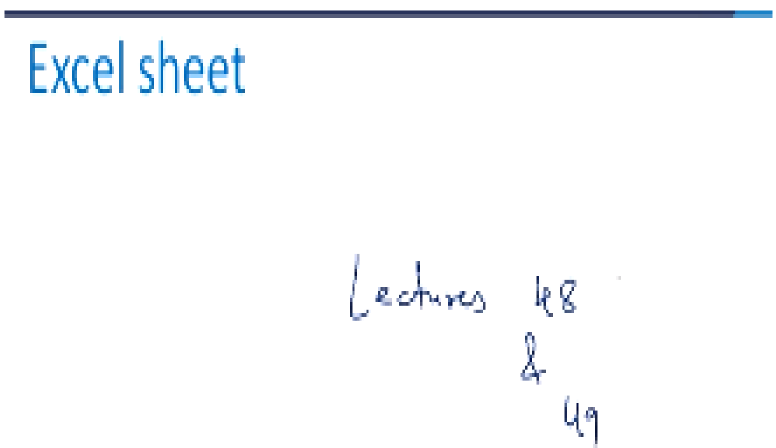

And I will be taking the help from our lectures 48 and 49; we will be following the various calculation sequence that we already discussed in lectures 48 and 49. And let us try to understand that how we can go ahead for the analysis using Ladani's method.

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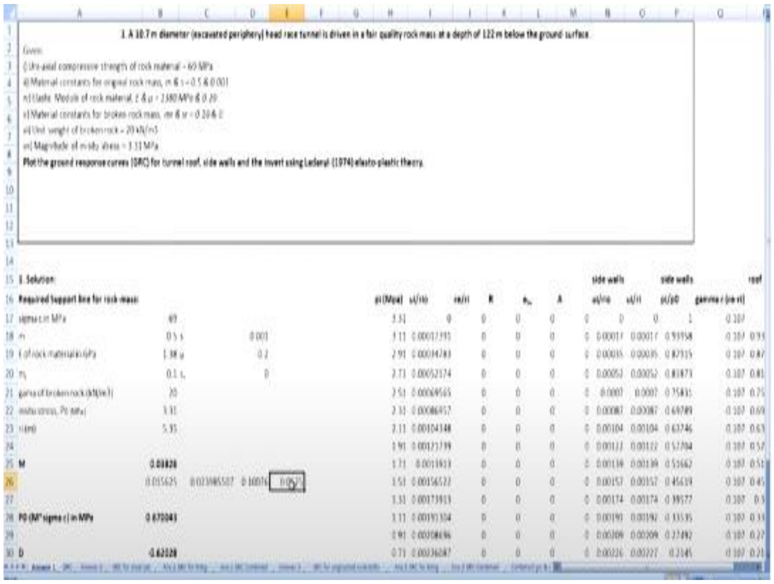

So here is an excel sheet in front of you let me just zoom this a little bit for you so that it is visible. We will be taking a few problems here, so the first one that we take with reference to the ground response curves. So, if you recall and if you take a look at our forty-eighth lecture, so I mentioned to you that we need some input parameters. So, the input parameters are given here.

You can see that this is the problem statement where we have a 10.7 diameter headrest tunnel which is driven in fair quality rock mass at a depth of, say 122 meter below the ground surface. And the data is given in the form that the UCS of the rock material as 69 MPa, then material constants for original rock mass. And this is the Hook and Brown material constants, of course, m and s they are given as 0.5 and 0.001, respectively. Then elastic modulus of the rock material is given as 1380 Mega Pascal and the Poisson's ratio for the rock material is given as 0.2.

The material constants for broken rock mass mr and sr are given as 0.1 and 0, respectively. The unit weight of the broken rock is 20 kilo Newton per meter cube and the magnitude of the in-situ stress is 3.31, Mega Pascal. So, our job here is to plot the ground response curve for tunnel roof, side walls, and the invert using Ladani's elastoplastic theory.

So here I do not need to explain you again that how this theory works that we have already discussed. All I am going to explain you is that if the data is there with you how you can plot the ground response curve. So, the first thing is the first step out of those 6, one was the required support line for the rock mass. So, the input data if you just take a look at forty-eighth lecture, so the input data which was needed was sigma c which is ucs so here I am putting this in this particular cell of the sheet which is 69 MPa as it was given in the problem statement. Then m and s they are taken as 0.5 and 0.001 and it has been put in these cells like s is put in D 18 cell.

Similarly, the E or the rock material in Giga Pascal it is 1.38 in Mega Pascal it was given as 1380 Mega Pascal. So, in Giga Pascal it is 1.38, and the Poisson's ratio here is 0.2. Similarly, we have the mr value as 0.1 and sr value as 0, then coming to the unit weight of the broken rock which is given as input in kilo Newton per meter cube that is 20. And the in-situ stress p naught is in Mega Pascal which is 3.31, now the diameter of the headrest tunnel is given as 10.7 meter, so we will have the radius here in this cell as 5.35.

Now the first step was to calculate m, which was half of m by 4 whole square + m p naught upon sigma c + s to the power half - m upon 8. So, what we have done here is I mean I have put here everything so that you can understand it easily. So, you see that here I calculate this as m by 4 square, so this m is 0.5 by 4 and its square. So, you can see here this is what is the formula, which is there so this is what that we will get.

And then we will find out the term m into p naught upon sigma c that is the second term in that equation, so here it is m into p naught which is m is 0.5 p naught is 3.31 divided by sigma c which is 69, so this will give you the second term. And the third one is of course s + s so here we find out the square root of m by 4 whole square + m into p naught upon sigma c + s. So, this s is your D18 you see here, so this is how we will be able to get the first term of this expression of M.

And then here I am finding out m upon 8 you see here m is 0.5 divided by 8. So here, M simply I will be getting as the term here which was half into square root of that complete expression - d m by 8; so, this is how we will be able to find out M.

Then we find out the value of p naught - m into sigma c in Mega Pascal, so here you see p naught is 3.31 Mega Pascal - this M, which I have calculated as 0.03826 here multiplied by sigma c which is the 69 Mega Pascal. So ultimately, this will be 0.670043 so then the next step was to determine the D.

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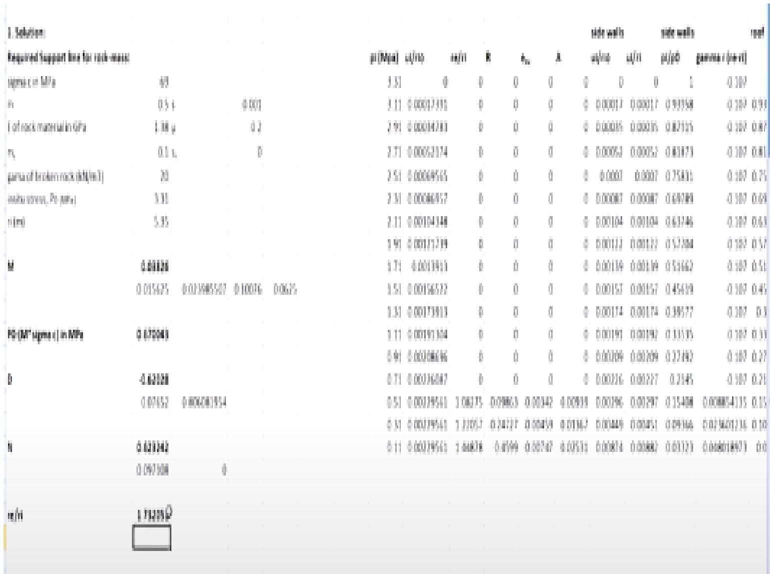

So, this is how we find out again. I have done it by parts so that it is easy for you to understand. So, we had the expression in the denominator as m into sigma c p naught - m sigma c + s to the power half. So here we are finding that out first so m, which is here as 0.5 which is b 18 multiplied by p naught - m sigma c which is this here b 28; see here b 28 and then this divided by sigma c which is b 17 here so that + s. So, s here is d 18 so this whole thing and its square root so this is what will work out to be 0.0765, and then we add like in the denominator, we had the complete expression as m + 4 times this expression.

So, this is what that we have obtained, and hence we can find out this d which is - m upon m + 4 times m upon sigma c p naught - m sigma c + s to the power half. I would suggest that you take the notes of lecture 48 and 49 with you, so that it becomes easier for you to understand or follow this excel file, so this is how that we can determine d. Now the next step after finding out d was to obtain N, so here also in that expression of N we had 2 terms or 2 expressions, so the first one was p naught - m sigma c upon m r into sigma c.

So, you see that we are obtaining that term complete term here we are here it is p naught - m sigma c divided by m r which is b 20 multiplied by sigma c which is b 17. Here you see it is already highlighted. So, this is how we can determine the first term and the second term which is s r upon m r square and being s r = 0, so this term will become equal to 0.

So, this is how you can determine the value of N by take by summing these 2 and taking the square root, and multiplying by 2. So, you see the same thing here we have done we added these 2 terms and took the square root of it, and then finally multiplied that by 2. So, this is how you can determine the value of N which in this case works out to be 0.623.

So now we are ready to go on the other side of this excel sheet where we will we need to compare the value of pi with the p naught - m sigma c and depending upon whether pi is less than or greater than p naught - m sigma c, which is the value as 0.67, in this case 0.67 MPa. We will decide whether the deformation around the tunnel is elastic or it goes into the plastic zone.

So here for the little bit of simplicity, since you know that r e upon r i is to be compared by square root of 3, so for the sake of simplicity, I am calculating the value of square root 3 here in this particular column. So, you can see it is nothing, no expression but only the value of square root 3 here.

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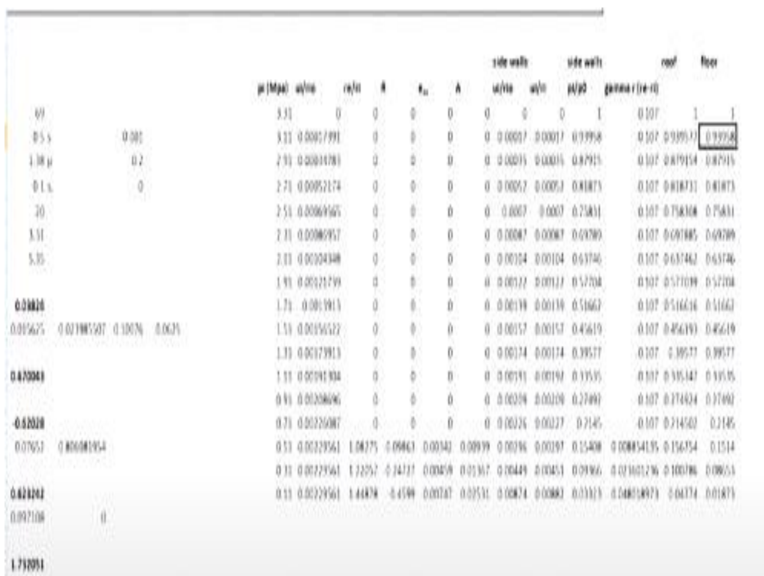

So, we go to the second part now if you recall, I mentioned to you that for pi greater than p naught - m sigma c. The deformation around the tunnel is going to be elastic and we can obtain a ui upon rio as 1 + nu upon e into p naught - p i. And in case if you have p i less than p naught - m sigma c then there is going to be the plastic failure around the tunnel. And accordingly, you can find out u e upon re as 1 + nu upon e into M times sigma c.

And then there I mentioned to you with reference to these 2-calculation sequence that there you have to give input as p i. So here you see that the in-situ state of stress was 3.31 MPa, and when i showed you that how the ground response curve is determined or it is plotted, so the first value is the in-situ stress like from there it starts. So here what we do is that we take the value of p i here in this column the first value becomes equal to the in-situ stress, which is 3.31 Mega Pascal.

And then to plot the ground response curve you need a few points so say here, for example, we took few values of p i with an interval of 0.2 Mega Pascal. Now, this interval is not fixed that you have to take 0.2 Mega Pascal, it depends upon you; you can take maybe 0.1 or 0.15 Mega Pascal also. All we need to have is to have enough points so that we can draw a smooth ground response curve.

So here we took the difference of 0.2 Mega Pascal, so you can see that here I mean from the earlier cell, we just kept on reducing 0.2 Mega Pascal. So, we just generate these values having known the first value as equal to the in-situ stress. So likewise, this is what this column can be generated. Now when I generate this column, the second one is ui upon rio, so what I do is I already have in one column or in one cell I already have p naught - m sigma c calculated here.

So, all I need to do is just provide a logic over there or then see whether this p i is greater than or less than this p naught - m sigma c value which is 0.67, in our case. So, if you take a look at various values of p i up to this much that is up to 0.71 Mega Pascal these values of p i are more than p naught - m sigma c which is 0.67 Mega Pascal. So therefore, what will happen since p i is more than p naught - m sigma c for all these values of p i that I have highlighted here there is going to be the elastic deformation all around the tunnel.

So, the rock mass beyond the tunnel will not enter into the plastic state, and therefore ui upon rio can be calculated using the expression 1 + nu upon e p naught - p i. But see here these 3 values which is 0.51, .31 and 0.11 Mega Pascal. All these values are less than p naught - m sigma c which is 0.67, Mega Pascal. So here, this is going to be entering into the plastic failure zone or the domain it, I mean the surrounding rock mass is going to be in the plastic zone, and also the deformations will be plastic.

So, in this case, we will have to use 1 + nu upon e into m sigma c, so accordingly, you see that I have put a logic here if h17 means this p i value is more than this value of p naught - m sigma c which is b 28 here. So, in that case, I have an expression, and if this is not satisfied, then I have another expression which is 1 + nu upon e into m times sigma c. So, all these expressions you see that I have put as a part of the formula here.

So, I mean, you do not need to know much programming for this it is simple logic, but if you know the programming, then maybe you can develop your own program. And there you can just put a logic to calculate the values of u i upon rio corresponding to each value of p i that you have given as input. So, you see like this following this logic, so once I write this formula, I can just drag it throughout the excel column, and I will be able to generate the value of ui upon rio corresponding to each value of p i.

Now the, we will have the next column as re upon r i because to draw the ground response curve, we need this ui upon r i o and r e also because the radius of the broken zone is also needed. So, in case if the rock mass is in the elastic domain, this re will not come into picture. So, wherever you have this p i more than p naught - m sigma c the deformations are elastic, and therefore re will be equal to 0. So that is what is happening here and if it is entering into the plastic zone, then we have the expression as r e upon ri = e to the power n - 2 times p i upon m r sigma c + s r upon m r square to the power half.

So, you see that here what we do is if this is less than this then less than means p i is less than this p naught - m sigma c. Then you see that this is what is the expression that is being followed that I have programmed, it is the same expression we have found out already n then mr, sr they are already given and then sigma c is also given. So, from there we calculate and if this condition is not satisfied then it will return a value 0.

So, this is what is happening at the top see this condition is not satisfied that is p i is not less than p naught - m sigma c and therefore r e upon ri = 0. So, like this we can determine re upon ri corresponding to every value of p i here given in this table. So, once we know re upon ri we can find out R; so how do we find out R so if re upon ri is less than square root of t is less than square root of 3. Then this R is 2 d natural log of re upon ri, otherwise it is 1.1 times t, so see here I have already determined the square root 3 value so all I need to do is compare this re upon ri with this square root of 3 value.

So, you see that here, from this first value to this value, all these are, in fact all the values in this problem incidentally, they are less than square root of 3 which is you see that it is 1.732 and here the maximum value is maybe approximately 1.45. So, all these values are less than square root of 3 so therefore, R can be calculated by the expression 2 d into ln re upon r i. So here we can say that we have again put a logic here, that if it is less than of a square root of 3.

Then we will have this particular expression which is 2 times d D here you know that - 0.62 that we have calculated. So, like that we can determine the value of R. Once I know the value of R, I have the expression of e average here with me so that also we can determine. So, i will just give you the idea that see how this is done that is 2 times u e upon re into re upon ri whole square divided by you have in the denominator re upon ri whole square - 1 into 1 + 1 upon r.

So that expressions i have put here you see that i am highlighting so based upon that you can determine the value of e average for each of these. Once I know this e average i can find out A which is 2 u e upon re - e average into r e upon ri whole square. So, you just see that here this is 2 u e is I 31, so here it is - e average so here it is l 31 into re upon ri whole square so this re upon ri whole square is this j column.

So, this is how that we can determine the value of a here. Then we can find out the value of u i upon rio which is 1 - 1 - e average upon 1 + a to the power half. So that we are finding out here, you see that the expression that has been put here completely, so finding that I mean you can find out ui upon rio all the values corresponding to pi.

Then I mentioned to you that once we determine the ground response curve for the side wall or once we analyze it for the weightless condition. Then we have to consider the weight of the broken rock in the grc for roof as well as for the floor. So that also we will do here so as far as the side walls are concerned this is what is the value that you will get for ui upon rio; ui upon r i and here this is p i upon p naught, so you have all the values now.

So, what i do is i determine gamma r into r e - ri here, so what we get is for the roof I will add it to the values of the side wall and for the floor I will subtract it so all I will get is if i just plot these.

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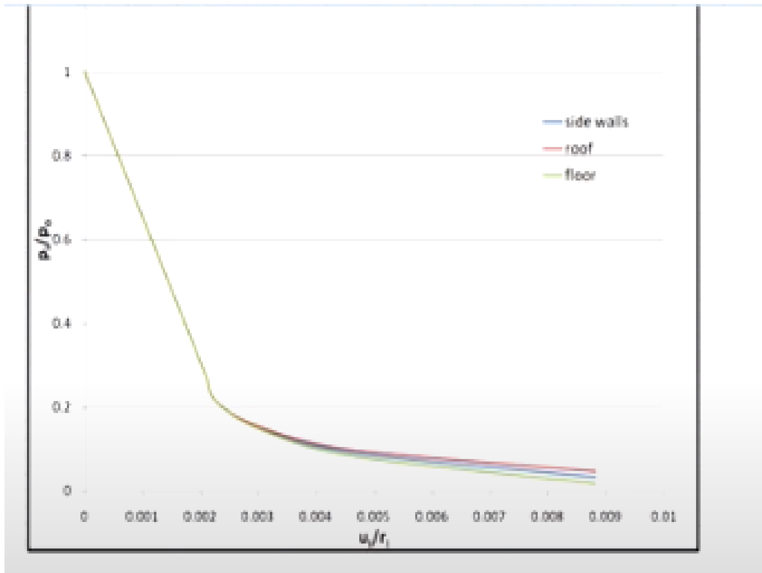

So take a look here, let me zoom it for you little bit so that, so here this is what is the grc for the sidewall roof and the floor they look like. So, you see the middle part is let me zoom it more, so here you can see that the middle part is for the side wall the top part is for roof and the bottom part is for the floor. Green one is for floor, so this is how the grc looks like.

So, this finishes the first portion of our problem that is to draw the ground response curve for side walls, roof and floor. So, I hope that now you get the idea that how to make use of the analysis that was given by Ladani for the elastoplastic analysis of the circular tunnel. So, this was all about the ground response curve. So now we focus on the support reaction curve, so for that purpose let me take you to the other example.

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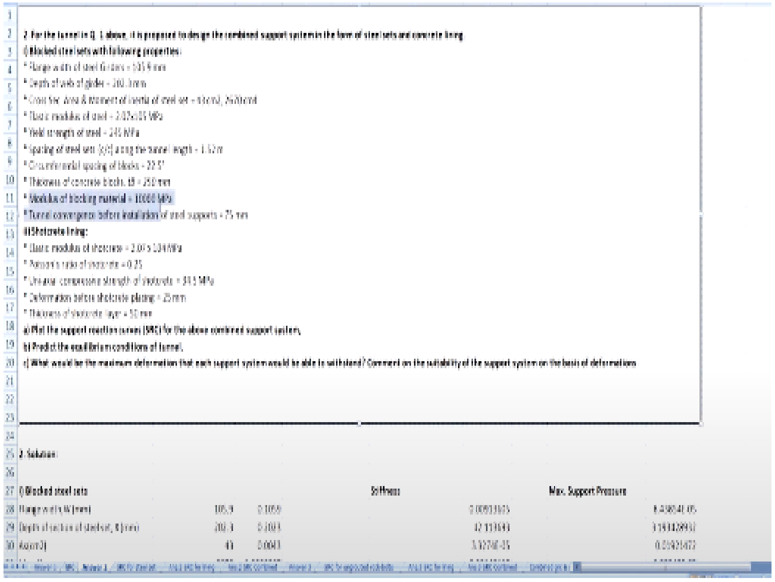

So here the question statement or the problem statement is given as here let me highlight this for you and also zoom it little bit, so that it is visible. So, you see that in this case it is required to design the combined support system in the form of steel sets and the concrete lining. So, we are taking 2 types of the support systems here steel sets and concrete lining. So, the input data which is given here as this flange width of the steel girder, is given, depth of the web of girder is given, cross sectional area and the moment of inertia of the steel set.

Then elastic modulus of steel it is 2.07 into 10 to the power of 5 Mega Pascal then yield strength of the steel is there. Then we have the spacing of steel sets along the tunnel length that is 1.52 meter. We have the circumferential spacing of the blocks then the thickness of the concrete block modulus of blocking material and all those things which are given.

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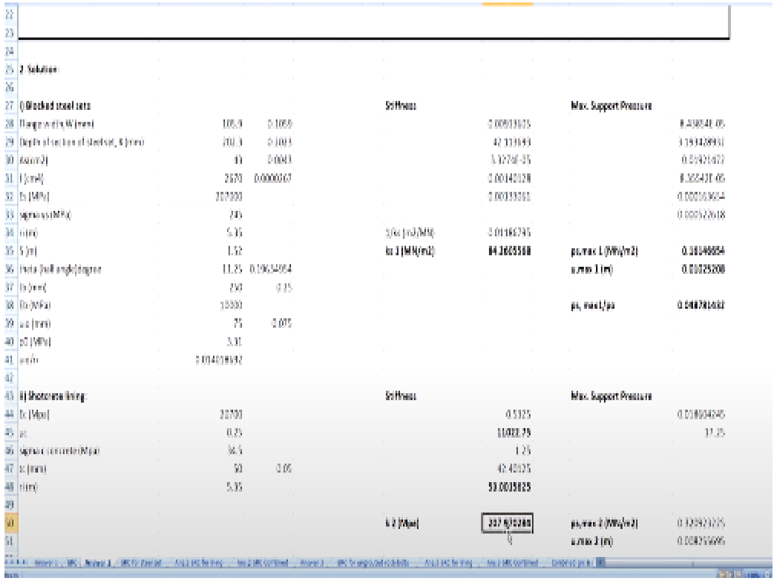

So, what we need to do is the plot the support reaction curve for the above-combined support system. Then we need to also predict the equilibrium condition for the tunnel and the maximum deformation also we need to find out. So let us first take the case of blocked steel sets so what we have here as input if you refer back to the lecture 49, so there we discussed that what all are the input parameters which are needed.

So, the first one was the flange width of the steel set, which is given as 105.9 millimeter; so, in the next column, I am converting these in meter to be consistent with the unit; so that we do not make any mistakes. Then the next one was X which was the depth of the section of steel set so that is given as 202.3 millimeter. So, I convert it into meter then area cross-sectional area of the steel set was given as 43-centimeter square, so I convert it into meter square. Then moment of inertia of the steel section was given as 2670 centimeter to the power 4 then we have the steel modulus of elasticity which is Es that is given as 207000 Mega Pascal. Then sigma y s which is the yield strength of the steel which is 245 MPa, again ri we have taken the same continuation with the previous example that we discussed.

So, they are the diameter was 10.7 meter, so it is the radius is going to be 5.35. Then the steel set spacing along the tunnel axis was given to be 1.52 meter, then theta half angle in degrees is given as 11.25 degree and that we can convert into the radians so that is what it is. Then thickness of the block is 250 millimeter, then the modulus of elasticity of block material is 1 into 10 to the power of 4 10 into 10 to the power of 4 Mega Pascal then u i o that is the initial deformation that is allowed is given as 75 millimeter, of course, the in-situ stresses is given as 3.31 Mega Pascal And then i can find out uio upon r i which is given here that is uio is 75 mm, so I convert it into meter and that divided by the radius of the tunnel, so this works out to be 0.014.

So how we can determine the stiffness? We had this expression s into ri upon e s into a s + you had the another term another 2 terms in fact. So, this is what has been done in a stepwise manner so the first one is see here, s into r i divided by e s into a s this is what is calculated here in this particular cell. So, you need to be very careful about the units. There is a mismatch of the unit, and you will not get the correct results.

So here you see that all the length, dimension, and area dimension, I have converted into meter or meter square, respectively. And then we are using these, then we have the second term and one part of it is s into riq by E s into I s. So, this is how that we are calculating s into uc riq which is b 34 divided by E s into I s so then we had this as theta into theta + sine theta cos theta divided by 2 sine square theta. So, this is the complete thing and this whole thing - 1 so that is what has been calculated here. And then we have another term which is 2s theta into t b divided by E b into w square, so that has been calculated in this particular cell.

Accordingly, there you will have to obtain 1 upon k s so it will just be the addition of the k terms because each and every component of that equation we have calculated separately, so that makes our task easy. So here, ks 1 therefore we can obtain as the inverse of this which is coming out to be 84.26, Mega Newton per meter square in this case. And similarly, we can find out the maximum support pressure in the first case which is this ps max 1.

So here you see we have again various terms that the expression was 3 a s into I s into sigma y s divided by 2 s r i theta into a complete bracket and you had 3 Is + x a s into ri - t b + half of x into 1 - cos theta. So, I mean you might not remember all this, but if you have those notes in front of your eyes, it will be easy for you to connect here with me and understand this excel file. So, you see that like we did earlier in parts, we are finding out some of these quantities and ultimately, we are finding out this ps max in this particular manner here.

That is the first term is 3 as is into sigma ys and then we find out by parts all the other terms and ultimately, we find out the denominator here as in this particular cell, which is j33. And hence we find out this ps max is simply the numerator divided by the denominator, and that is how we can find out the maximum support pressure for the blocked steel sets. Now once I know that you know how we can determine the u max 1 for the system one. Here you need to refer to the support system where you have only one support system that is the single support system.

And if you recall, I mentioned to you that you can find out this as uio upon r i + p i upon k that is going to be the available support curve. So here, in this case, this u max 1 you can determine as ri into p s max 1 divided by k1. So, you see the same way that we are doing that is ri is 5.35 multiplied by ps max which is 0.16 this divided by ks1 which is 84.26 and all this will give you in meters the value of u max 1 as 0.01. And knowing this ps max 1 we can divide it by the in-situ stress so we can determine this ps max 1 by p naught in this particular cell.

So, this is about the steel sets and here we have the other support system which is the shotcrete lining. So how do we find out the similar type of I mean similar type of calculation how do we perform which is the stiffness of the support system and the maximum support pressure. So again, I would suggest you to refer back the lecture number 48. There we had all these expressions.

So, the input data which was needed for the shortcut type of the support system for shotcrete lining was the modulus of elasticity of the concrete or the shotcrete. It is given as 207 into 100 MPa then poisons ratio for concrete is given as 0.25 sigma c of concrete is 34.5 Mega Pascal. Then tc, which is the thickness of the concrete lining that we are taking as 50 mm as an input parameter, and of course the radius of the tunnel is 5.35 being 10.7 as its diameter.

So here we find out the stiffness which is given by the expression Ec into ri square - ri - tc square divided by 1 + nu c, and in bracket you had 1 - 2 nu c r i square + ri - tc whole square. So here again, we find out the complete this is the denominator. So, you see that here we are finding out the term ri square - ri - t c whole square so this is coming out to be 0.5325 and then this i multiplied by Ec, so this is what is going to be the numerator of the expression for k c.

And then we find out the term in the denominator again it is simple calculation, but then you need to do it systematically without making any mistake for the units that is the most important thing. So here we find out the stiffness as this numerator divided by the denominator it works out to be approximately 208 Mega Pascal in the case of the shotcrete lining.

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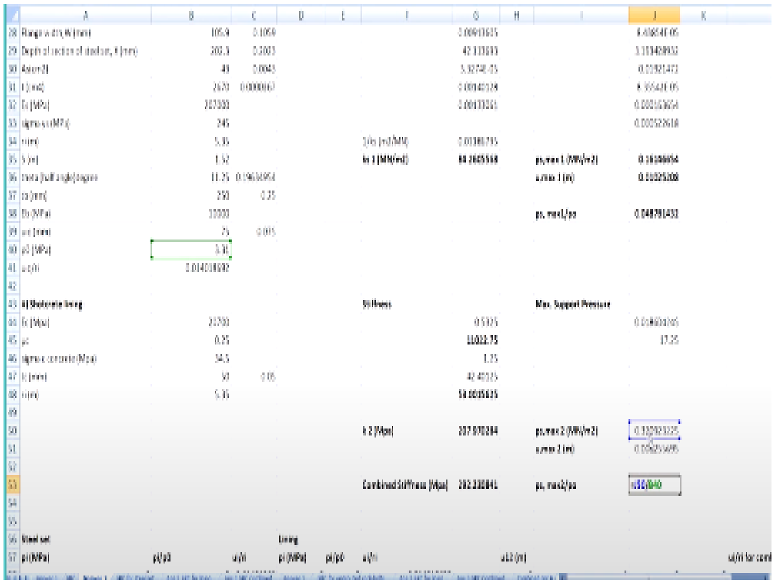

And here we have the maximum support pressure for that so that is what was 1 - sigma c concrete, sorry so the maximum support pressure for the shotcrete lining is half sigma c of concrete into 1 - ri - tc whole square divided by ri square. So, we that is how we find it out here. You see these are the values and ps max works out to be maybe 0.321 Mega Newton per meter square.

And once I know this ps max 2 I can find out the u max 2, again using the same expression which was given as ri into ps max 2 divided by k2. So, if i just double-click on this so that will give you the idea that what i am talking about. So here it is r i which is b48 multiplied by ps max 2 which is this j 50 this divided by g 50 which is 207.97. So, this is how we can determine the maximum deformation for the second support system, which we are considering as the shotcrete one.

So here we find out this ps max 2 by p naught so this works out to be you see ps max 2 which is 0.321 divided by 3.31 Mega Pascal which works out to be approximately 0.1.

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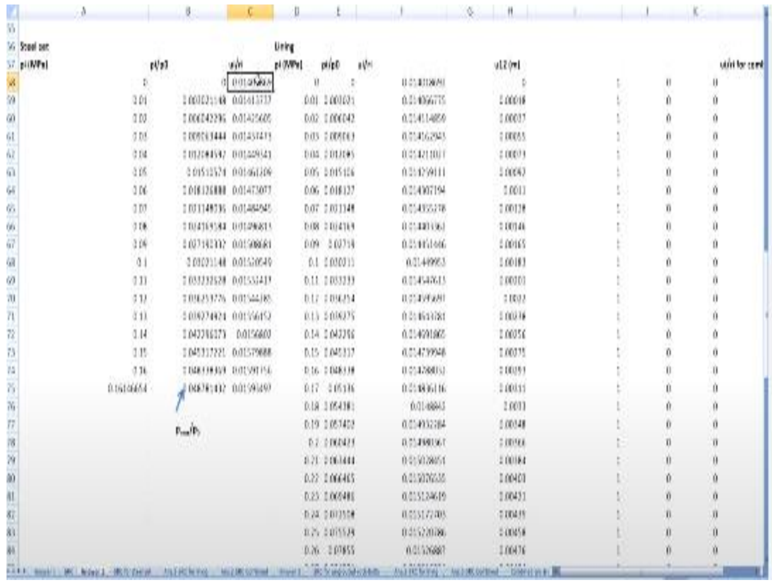

So this is how we determine the value of p s max 2. Now we find out the combined stiffness which is k1 + k2, so this is what that we are doing. So, you see here we obtained ks1 and this is what is ks 2, so combine stiffness in Mega Pascal works out to be 292.23 Mega Pascal in this case. So here now, if we just take a look that how this steel sets src will be developed so we have on the first column we have p i so this has to be given as input.

So, in this case, if you recall our discussion on grc and src. For the grc, which is the ground response curve, we start from the in-situ stress and then we keep reducing the support pressure which is like you start from p naught and then k kept on reducing. So that we saw in the previous example but in case of the support system, what we do is we start from the 0 value and then we go up to the maximum value for that support system. So, the maximum value for that support system that we have already obtained here.

So, if we are just considering the steel sets first so let us see that, what was the maximum support pressure for this steel set that was 0.16 Mega Newton per meter square. So, you see that p i we consider from 0, so to we go to the maximum value which is 0.16 that we determined here. You see here, this we determined already, so it should be the same value. So, p i upon p naught can be determined because p naught is given to you as 3.31 Mega Pascal. Again, I am repeating you need to be careful about the units here. Then we can find out ui upon r i how we can do this. So, you have ui upon ri as u i o upon r i + p i upon the stiffness of the support system.

So, when we try to find out this for these steel sets, instead of k we have to use the stiffness of the steel sets, so that is what that we are doing. You see the first term is uio upon r i, so this uio is given here in c 39 so this is what it is and then ri is b 34 so you see here is the first term + p i upon k; so this is the p i is your this a 58 for the first value and that divided by k.

So here I am using the stiffness for the first support system because we are dealing with the steel set which we considered as the first support system. So likewise, we can find out ui upon ri for steel sets. Then coming to the lining or shotcrete lining so we follow the same procedure, but in case of the shotcrete lining the ps max is 0.32.

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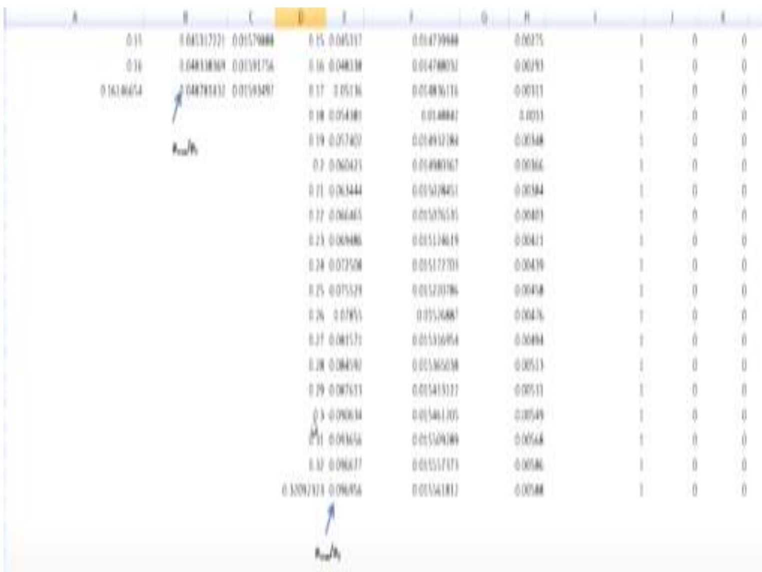

So what we do is we increase the value of p i from 0 to 0.3209 which was the value of p s max in case of the shotcrete lining. And accordingly, we find out p i upon p naught and there we find ui upon ri. So, in this case, we have to use the stiffness of the shotcrete lining when we calculate this ui upon ri. So accordingly, here we find out the corresponding value of ui upon ri just for lining. Now if I have to combine these 2 systems then we have to find out u 12, right? Please refer to the slide number 12 of lecture 49, and I mentioned to you that the expression for u12 is ri into pi upon k 1 + k 2.

So, you see that here this is what that we are considering that is ri into pi divided by k 1 + k 2; so, k 1 and k 2 here we have determined ri is this and pi is this. The question is up to which ps max that we will be going here, so for that here we are finding out up to 0.09096 we are doing this study so u12 this is how that we will find out.

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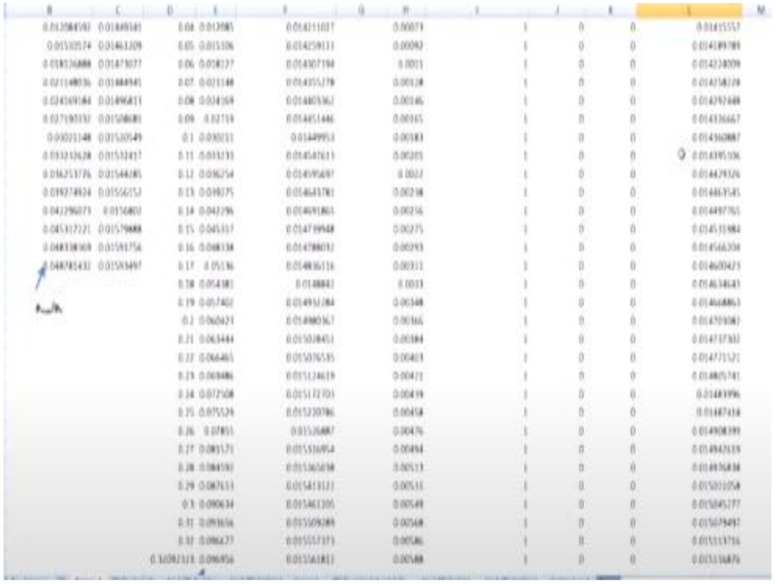

And then we will provide the logic that we have found out u max 1, we have found out u max 2, and we have also found out u12 all in meters, so I will just put a logic to find out either of the three which one is minimum. And accordingly, we will choose the value of ui upon ri, or we will choose the expression for ui upon ri to determine its value. So, these three columns where you see is 1, 0, 0 these are nothing but the kind of the logic that we have put that which one is minimum out of these three, whether u max 1, u max 2, or u 1 2 in all these values.

So accordingly, we find out ui upon ri for the combined system here you have to take the help of these steps d, e and f that i explained you in a lecture 49. So once i determine this, I am now ready to plot the support reaction curve. So let us see one by one how the support reaction curve for the steel set will look like.

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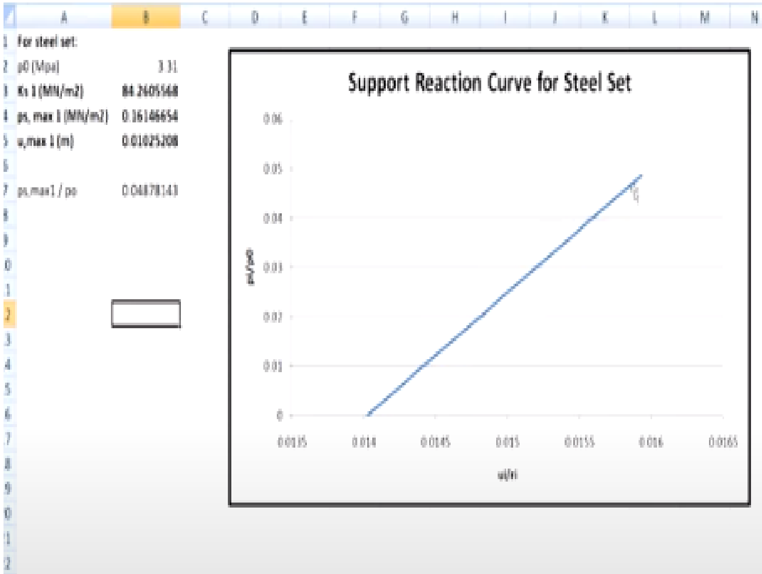

So when we talk about only the steel set this is how the support reaction curve for the steel set looks like. See here, we are going up to the ps max and beyond that what will happen you will just have a straight line beyond. That I mean the horizontal line because the maximum support pressure is this value it is the normalized value which is this, a particular value which is 0.04878 in this particular case. Similarly, you have also got p i upon p naught versus ui upon ri for the lining shotcrete lining.

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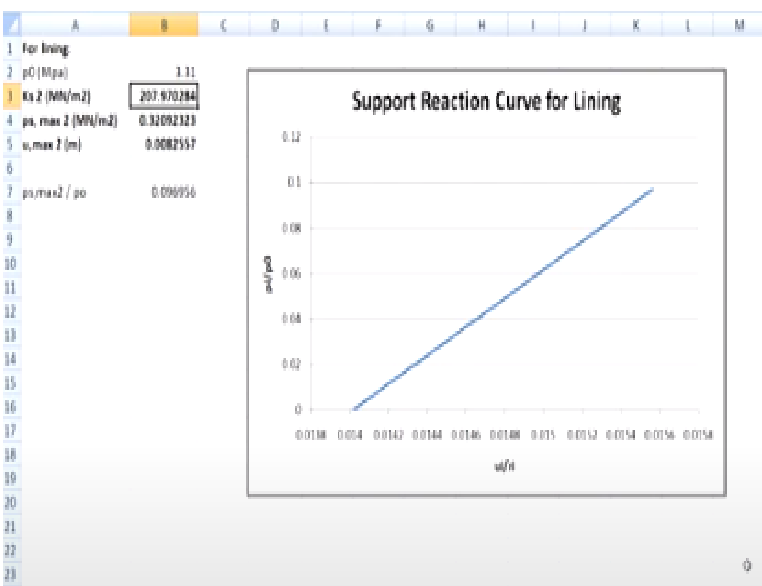

So this is how the support reaction curve for the lining looks like let me zoom it a bit. So here on y-axis, you have again pi upon p naught and then on x-axis you have ui upon ri. And we can have the support reaction curve for the lining. Now we have done this exercise for the single support system that as if there were only the steel sets or there is only the lining. But we have done the analysis when there are both the systems or we are finding out that what is the support reaction curve for the combined system.

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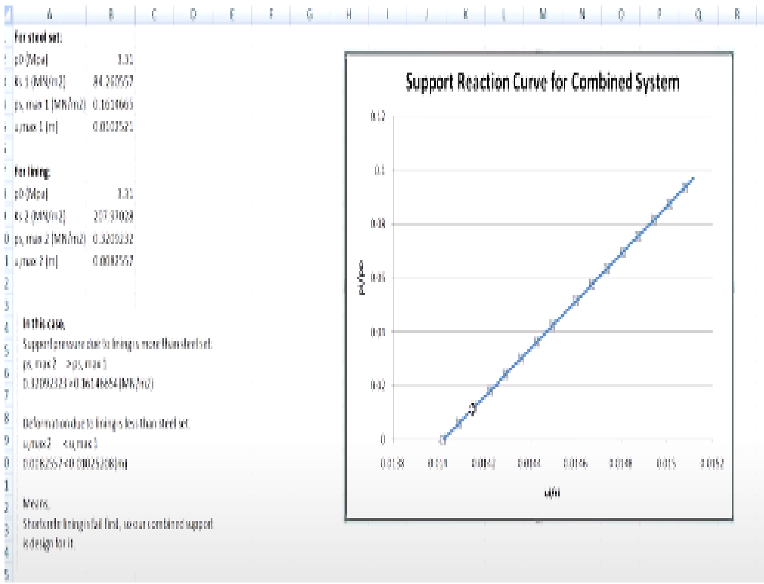

So, in that case you see we have already obtained the data for the support reaction curve for the combined system. So, we just plot it and then it looks like this, so in this case the support pressure due to lining is more than the steel set, so therefore in this case ps max 2, of course, it was more than ps max1. So, for your ready reference, here i have summarized all the values that we determined in the previous.

So, the deformation due to lining is less than the steel set, so in this case, shotcrete lining will fail first, so the combined support system will be designed for that so the support reaction curve, in this case, is going to look like this so this is for the combined system. So, this is how the support reaction curve for the combined system will look like. And here, when we say the combined system, we are dealing with the shotcrete and these steel sets.

But then we can have the other kind of combined system which can be maybe the combination of the lining and the ungrounded rock bolts. So let us see that how we can perform this similar analysis with reference to the combination of lining and ungrounded rock bolts.

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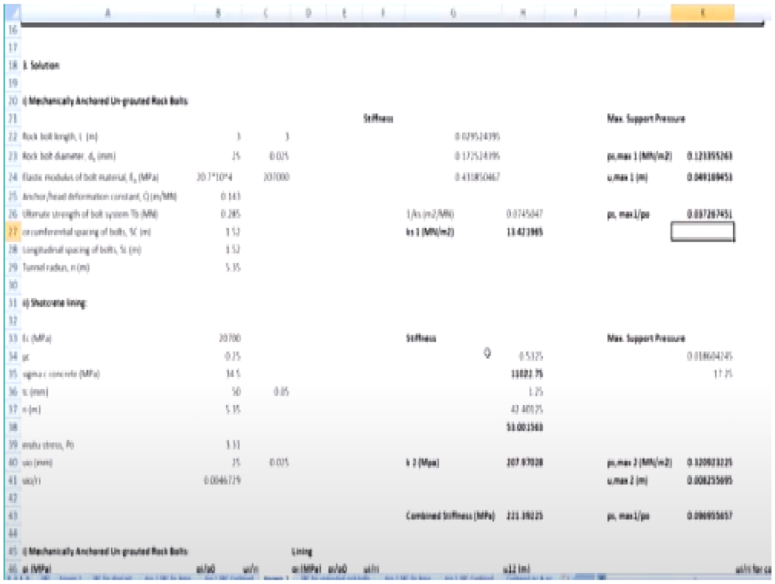

So here, the rock bolt length is given as 3 meter and then rock ball diameter as 25 millimeter. Then we have the Eb which was elastic modulus of the bolt material that is given as 20.7 into 10 to the power of 4 Mega Pascal. Then we have the load-deformation constant for anchor and head, that is given as 0.14, then the ultimate strength of the bolt system, which can be obtained from a typical pull-out load test that is given as 0.285 Mega Newton.

And then, circumferential spacing in meters and also the longitudinal spacing of the bolt in meters they are given as 1.52 meter. And since the diameter of the tunnel is 10.7 meter, so we have the radius here as 5.35. Now to determine the stiffness, if you remember, we had the expression as 1 upon kb = sc into sl upon ri and in bracket we had the 4i by pi db square into e b + q. So, this is how that we will determine these factors I mean these all these terms which are there for the equation.

So, the first term here 4l upon pi db square into e b is calculated here, you can see the expression and the different cell and the values. And this is what is, the term complete term which is in bracket which is this 4 l upon pi db square into e b + q. And then we multiply these by the spacing in circumferential and longitudinal direction and divided by the radius of the tunnel. So, this is what that we are going to get. And accordingly, we have the value of case where we multiply this term as c into s l by ri and the term in bracket, which is 4l upon pi db square e b + q. So then, inversion of this will give me directly the stiffness in Mega Newton per meter square, which is coming out to be 13.42 here.

And similarly, we can find out the maximum support pressure, which was simple expression that was given by t b f divided by sc into sl. So, you see that this is how that we are finding it out so t b is given here in Mega Newton and then sc and sl are here so this works out to be 0.12 Mega Newton per meter square. And from here, we can find out the value of u max as we did in the previous case by using the expression ri into ps max upon k. So, this is what is the expression this is ri which is 5.35 meter into the ps max, which is .12 divided by 13.42.

Please take a note here that we really need to be consistent with the units if you make that mistake, all your results will be erroneous. So here, this ps max divided by p naught that is we divided by the in-situ stress which was given as 3.31 Mega Pascal, so this is this comes out to be 0.037. Now we had the other support system at as the shotcrete lining this we have seen earlier as well with reference to the concrete lining.

So again what, all things which are needed here these are given as a part of the input data which is needed. So, we need the modulus of elasticity of the shotcrete which is written here, then poissons ratio then ucs of the shotcrete, then the thickness of the shotcrete layer, and the radius of the tunnel, along with the in-situ unit weight. And obviously, the initial deformation which is allowed permissible deformation that is 25 millimeter.

So, this is how we are finding out uio upon ri so just simply dividing it so you see that I am taking care of the units properly, so here it is 25 mm so i converted into meter and then only divide it with the value of radius.

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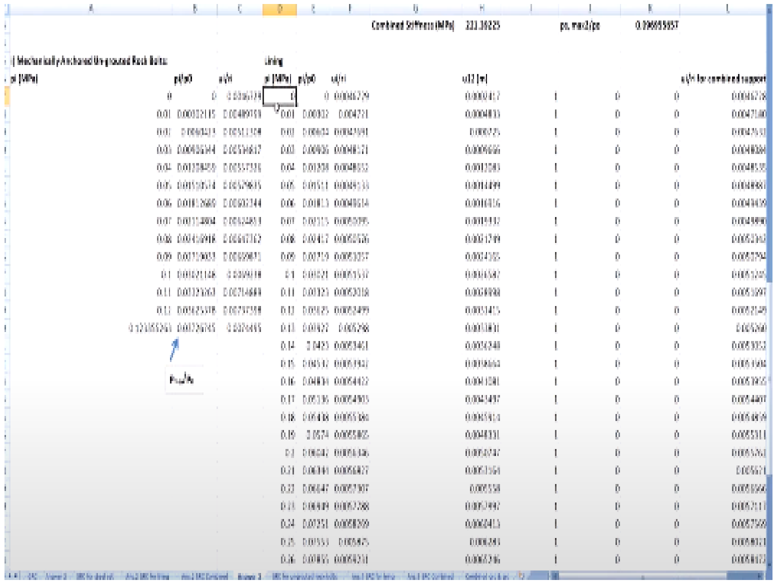

So here we find out the stiffness of the shotcrete lining, h so we had the expression as E c into r i square - ri - t c whole square and then you had a long-expression in the denominator. So, if you just substitute all these values, so accordingly there you will get you see that in parts, we are finding this out. So, this is r i square – r i - t c whole square which is one portion of the numerator, and this if I multiply by the modulus of elasticity.

So, I get the value in the numerator of that expression for the stiffness and then similarly, we have the value in the denominator here in this particular column. So simply, this stiffness will be numerator by the denominator, so this is what is the stiffness that we get in the Mega Pascal so it works out to be 208 MPa may be. And then we find out the combined stiffness, and I mentioned to you that when you have the 2-support system in a single application, then the combined stiffness is going to be the summation of the individual stiffnesses of these support systems.

So that is what that we are doing we are adding these stiffness as k 1 + k 2 here. So, this is how we can find out the combined stiffness of the lining as well as the ungrounded mechanically anchored rock poles. Then coming to the maximum support pressure for the lining, so that is the expression that you have is half sigma c of concrete and in bracket you have 1 - ri - tc whole square divided by ri square. So, use that expression, and then you will be able to obtain this, ps 2 which is the maximum one for the shotcrete.

And accordingly, then you obtain the deformation using the expression ri into ps max 2 divided by k 2. So, this is what that we are doing here. Here we have k 2 this is ri and we apply this formula, and we get the us max, u max 2, in meters. So, this ps max 2 here this should be 2, so this ps max 2 by p naught will work out to be you know this value divided by the in-situ stress which is p naught it works out to be 0.097 maybe. So here, what we need to do is we need to give the value of pi as input and if you recall, I told you that when we deal with the ground response curve, we reduce the support pressure starting from the in-situ stress. But in case of the support reaction curve, we increase this up to the value of ps max, so you see that in this case, we are getting this ps max as 0.037.

So, you see that here we have this ps max for the ungrouted rock balls as 0.123 Mega Newton per meter square. So, we start from pi to be equal to 0 and kept on increasing it by the increment as 0.01 Mega Pascal and we went up to the maximum value of this pi which is possible that is equal to ps max in the first case. And therefore, we can obtain pi upon p naught and as mentioned here the see this value corresponds to p max upon p naught which is 0.037, so you can see that is the same value here.

Now we find out the value of ui upon ri, which is equal to uio upon ri + p i upon k1, so this is what because we are right. Now talking about just the mechanically anchored ungrounded rock balls so what we have is see the uio, which is c 40 and then r i is of course b 37 because it is the radius of the tunnel + we have this as the p i divided by k1. So, we have here, in this case is this k s 1, so this is how that we can find out the expression for u i upon ri for all of these. And if we take this for the lining, then what we need to do is in the similar manner for the lining.

You see that we had the, 0.321 Mega Newton per meter square. So likewise, here we had the p i value a starting from 0 and going up to the maximum value as ps max. And in the similar manner, we can determine this ui upon ri corresponding to the lining. And then when we have to find out this u12 so that was equal to ri into pi upon k 1 + k 2, so that is how that you can determine corresponding to every value of pi you can find out the value of u 1 2.

Now the question comes here as we did in the previous example that we had u 1, u 2, and u12, or maybe u max 1, u max 2, and u 12, and there we have to take a call that out of these 3 which one is minimum. And accordingly, we will find out ui upon ri for the combined support system. So, you see here that applying that logic here, we have obtained the ui upon ri for the combined system for all the values of pi so once I have this worksheet ready with me then I can plot the results.

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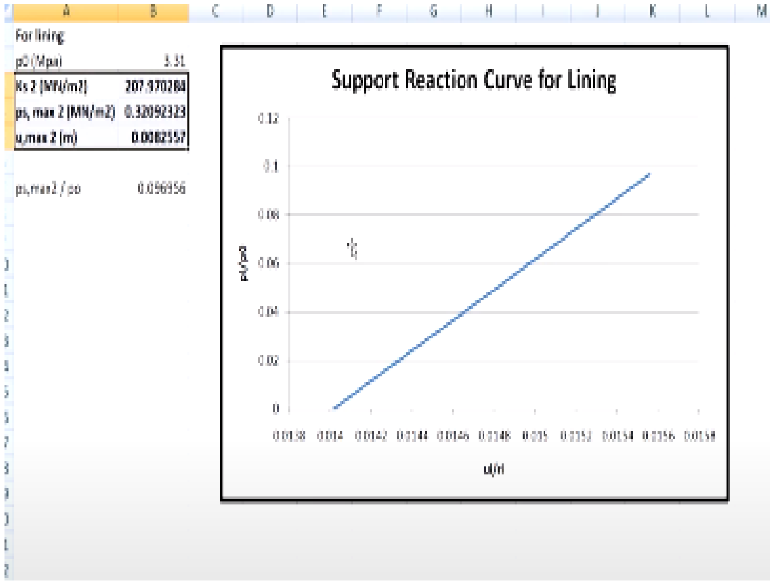

So you see, in this case, here it is the value of this is how this pi by p naught and ui by ri it looks like, and then we have the support reaction curve may be let me enlarge it little bit. So here you see that this is for the lining that we have.

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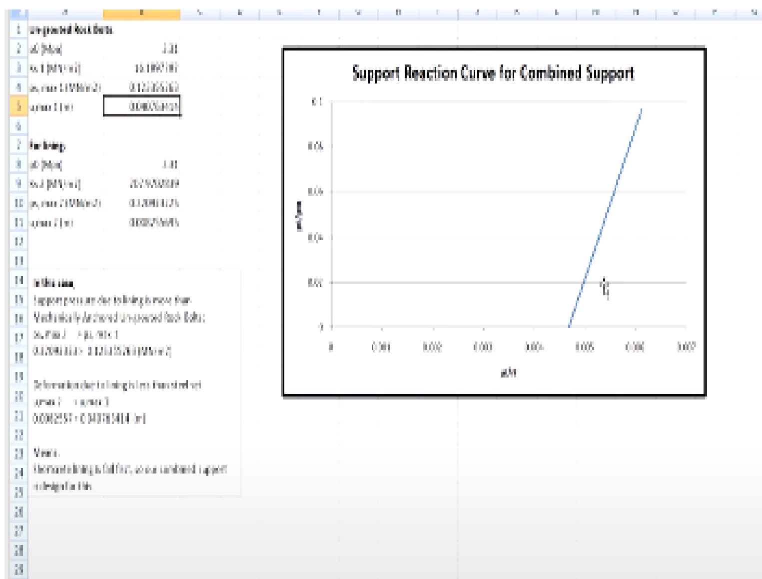

And in case if we want to have the combine support system that in that case this will look like this; this is what is the combined support reaction curve. So now, based upon these response curves, ground response curve, and the support reaction curve then you will be able to obtain that what will be the best choice of the various combination of the support system. So, in this case, you see the support pressure for the lining is more than the mechanically anchored rock bolt which are ungrounded.

So, the deformation due to lining is less than that of the steel set so that means that the deformation lining will fail first, so the combined support system will be designed for this. Now, if you recall, when we were discussing the grc that is ground response curve and the support reaction curve in one space only.

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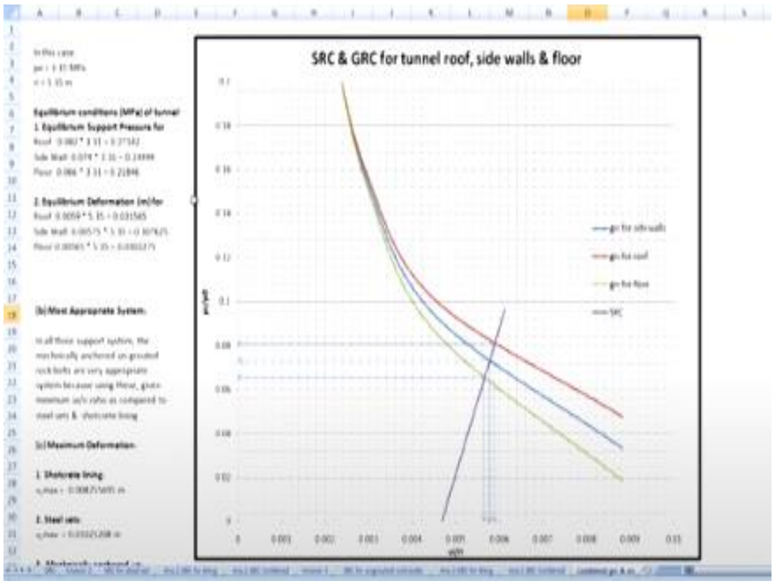

So let us do that here in this case, so this is how it low looks like, this is the support reaction curve, and this is the ground response curve, this one is for the roof. This is the second one that is blue one is for the side wall, and the bottom one, which is the green one this is for floor. Now to have the better clarity here, I have shown you see from this pi upon p naught as 0.2 because if i show you for pi upon p naught is starting from 1, then you know that these variation will not look very prominent.

So just to show you that how it will look so we have not here plotted or maybe we have restricted our scale from 0.2 to 0. So, this is how we can find out the ground response curve and the support reaction curve for the various support systems. So, we took not only the single support system but the combined support system as well, and I tried to give you the idea that how these problems can be approached. You for the use of the Ladani's analysis to account for the introduction phenomena between the rock mass and the tunnel support.

So, I hope after going through the theory portion which was covered in lectures 48 and 49, these examples give you the sufficient idea how to approach these problems. So, I hope that with the help of the demonstration with respect to the excel sheet, it is now clear to you that how we can generate the ground response curve and also the support reaction curve. If you have the single support system or the combination of the support system or combined support system. That combines support system can be the combination of shotcrete and steel set, or it can be shotcrete plus the rock bolt.

So, we have seen with the help of 3 examples how we can handle such type of problems and how we can analysis or how we can perform the analysis using the Ladani's method for the rock mass tunnel support interaction so this one was all about the interaction analysis.

In the next class now, we will focus on the method of excavation different types of the support system and finally, we will learn about the monitoring and instrumentation of the underground openings. Thank you very much.