Underground Space Technology
Prof. Priti Maheshwari
Department of Civil Engineering
India Institute of Technology – Roorkee

Module No # 9
Lecture No # 41
Rock Mass Support Interaction Analysis: Ground Response and Support Reaction Curves – 01

Hello everyone. In the previous class, we discussed some of the in-situ test for the determination of modulus of deformation of rock mass. So, today, in this new week, we will start a new chapter which is on rock mass tunnel support interaction analysis. So, today we will learn few concepts related to rock mass tunnel support interaction and also learn about ground response and support reaction curves.

The concept includes that what exactly do we mean by the rock mass and tunnel support interaction. So, for that we need to understand first the system.

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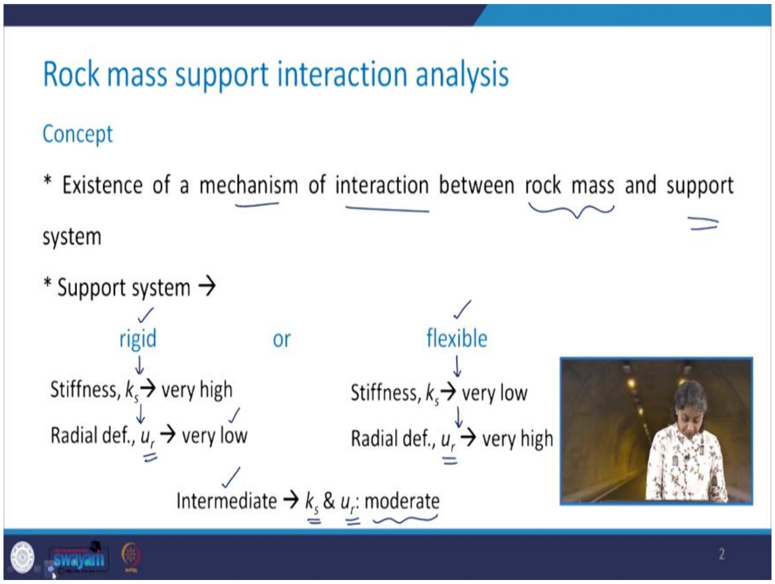

So, there is the existence of a mechanism of interaction between the rock mass and the support system. So, first, if we talk about the support system, it can be rigid or it can be flexible. What do we mean by rigid support system? That means that it is stiffness is going to be extremely high but in case of the flexible support system, we have very low stiffness of the support.

Now, since the stiffness of the support is very low, it is going to result into very high radial deformation which we are representing by u_r. And similarly, in case of the rigid support system, the stiffness being very high, so the radial deformation will be very low. Now, in case, if we want to restrict the complete deformation of the excavation then we have to provide extremely high stiff support system which may not be that economical.

And if we go for very flexible support system, then in that case, the deformations are going to be very large. And in that case, the system may fail because of the reason that the deformations are more than the permissible limits. So, what is the way out? So, here we need to choose the system having intermediate stiffness, where you have k_s, as well as the radial deformation being moderate in nature.

So, we are not going to adopt two extreme cases, maybe the rigid or the flexible but somewhere in between, we have to use the optimum type of the support system. So that it is neither too rigid nor too flexible.

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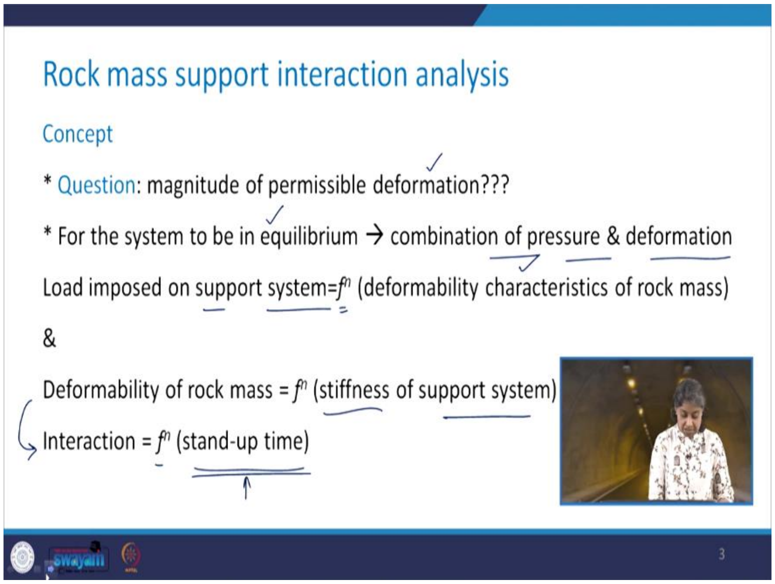

The question comes that what should be the magnitude of the permissible deformation? Then another thing which one needs to keep in mind that for the system to be in equilibrium, there is a particular combination of pressure and deformation. So, the load which is imposed on the support system, it becomes the function of deformability characteristic of rock mass. And this deformability characteristic of the rock mass in turn, becomes the function of the stiffness of the support system.

See, this is how it can be explained? That whatever is the load that is imposed on the support system, it will be the function of deformability characteristic of the rock mass. Let us say if it is more deformable then there is going to be more load which will be imposed on the support system. On the other hand, this deformability of the rock mass will be the function of the stiffness of the support system.

So, if you have very rigid system where the stiffness is more, obviously the deformability will be low. And there comes the interaction into picture, which is the function of the stand-up time. So, we have discussed what is the stand-up time couple of times in some of our earlier classes.

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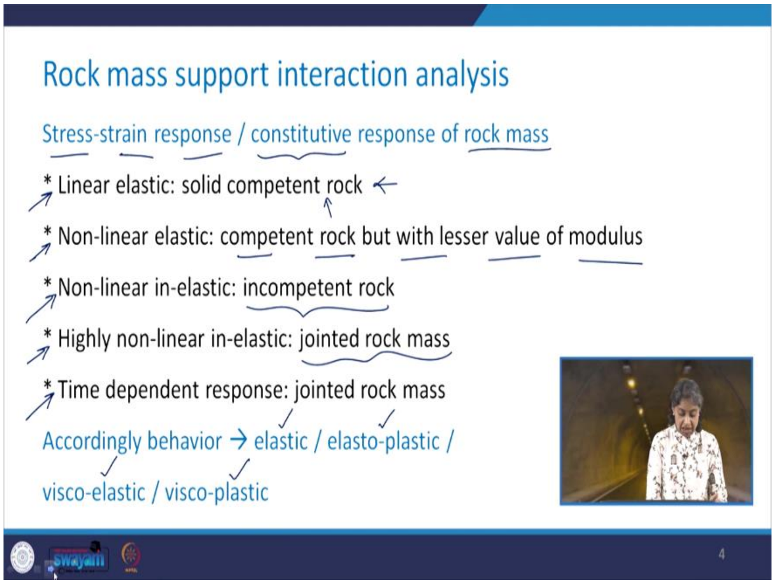

Now, before I go further, let us try to understand first the behaviour of the rock mass and then behaviour of the support system. Then we will try to understand their interaction phenomena. So, as far as the rock mass is concerned, it is material behaviour will be given by stress-strain response or we can call these as constitutive response of the rock mass. Any rock mass can behave in the linear, elastic manner, which is a particular case of the solid competent rock.

So, in case, if you have the solid competent rock at the site, it is expected that it will show the linear elastic stress-strain response. Similarly, one can have non-linear elastic stress-strain response in the case of competent rock but with lesser value of modulus as compared to this particular case which is solid, competent rock. In case, if you have the incompetent rock then one can observe non-linear, inelastic stress-strain response in case of the jointed rock mass.

One can have highly non-linear, inelastic, stress-strain response and some of the jointed rock mass. They also exhibit time-dependent, stress-strain response. So, based upon what type of rock or rock mass that you have? Accordingly, their behaviour can be either elastic or elasto-plastic or visco-elastic or visco-plastic. So, this is about the behaviour of the rock mass.

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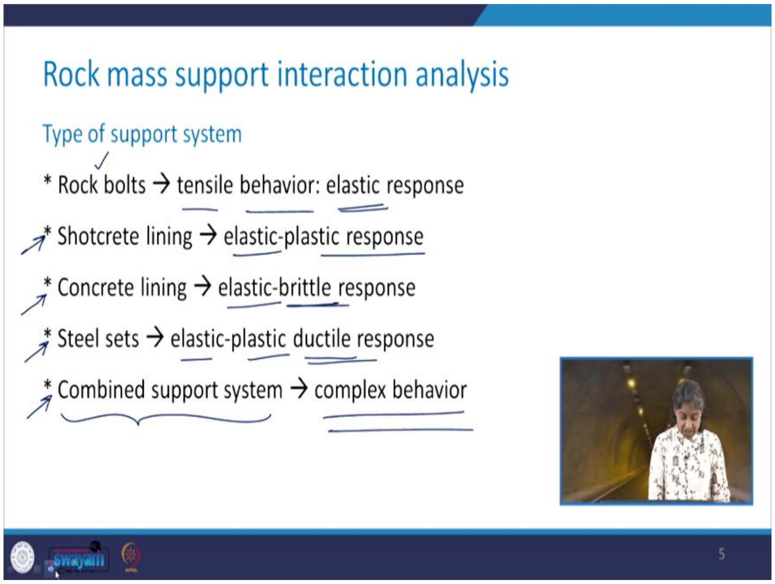

So now, coming to the support system. So, there are various types of support system we have discuss these earlier as well. So, let us see how on the type of the support system? How is going to be their behaviour? So, as far as rock bolts are concerned, they exhibit tensile behaviour, and their response is elastic. In case of the shotcrete lining, they show elastic-plastic response similar is for the concrete lining, but here it is elastic and brittle response.

For these steel sets, it is elastic-plastic but it is ductile response and in case, if you have the combined support system, then it is going to show you the complex behaviour. As far as the combined support systems are concerned, I mean the you can have the combination of shotcrete lining along with the rock bolts. So, such combined system fall under this category, and they will have highly complex behaviour.

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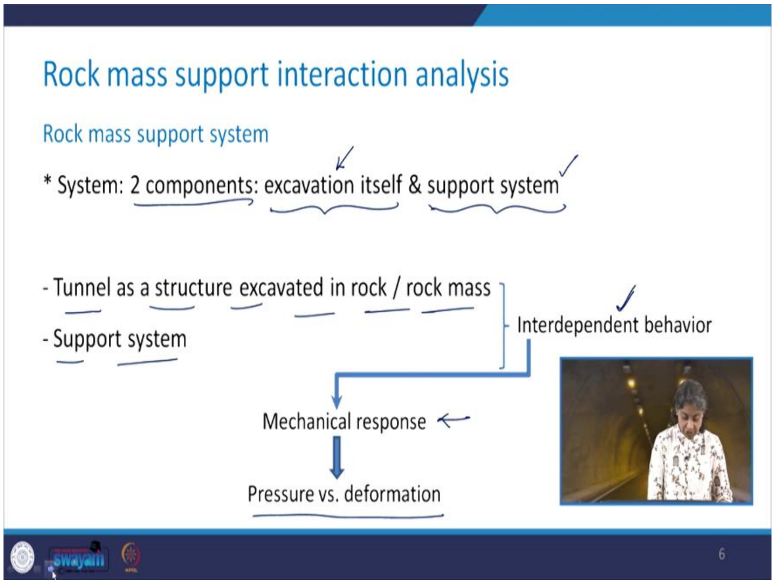

Now, let us combine the two-rock mass, as well as the support system. So, this complete system has two components, as we have seen that it is excavation itself and the support system. Now, depending upon what type of rock mass it is your excavation will show respective material behaviour. Similarly, what type of the support system is needed? Correspondingly, you will have the mechanical behaviour of the support system.

Now, the tunnel as a structure which is excavated in rock or rock mass, and then the second one is the support system. Their behaviour together is interdependent in what sense? In the sense of the their mechanical response. What do exactly we mean by that is? That we are going to focus on pressure versus deformation characteristic of these two components.

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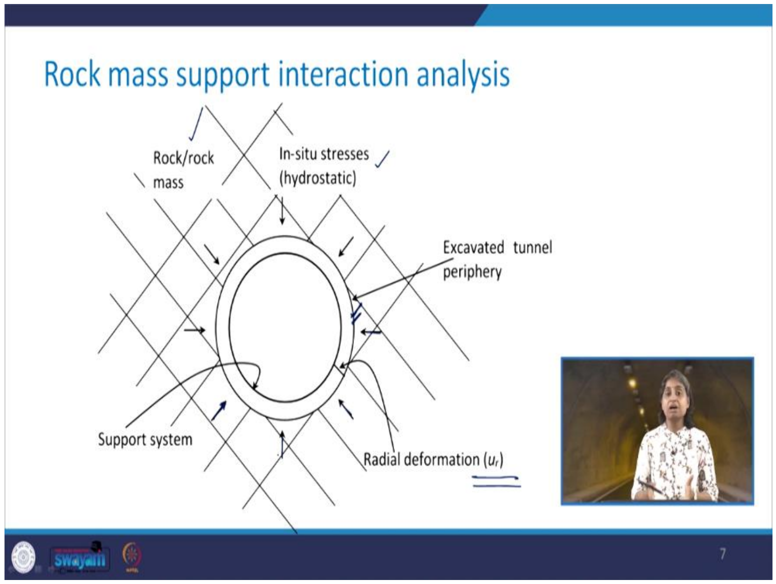

Take a look here. This is the excavation which is done maybe through rock or rock mass. The in-situ stresses are considered to be hydrostatic, so, since it is hydrostatic, you see in all the direction it is acting, and the magnitude remains the same. This is what is the excavated tunnel boundary. And then you allow some radial deformation to take place. So, this is how the radial deformation u_r will be measured?

That is from the excavated tunnel periphery. And then you have the support system. So, this is how our rock mass tunnel support system will look like?

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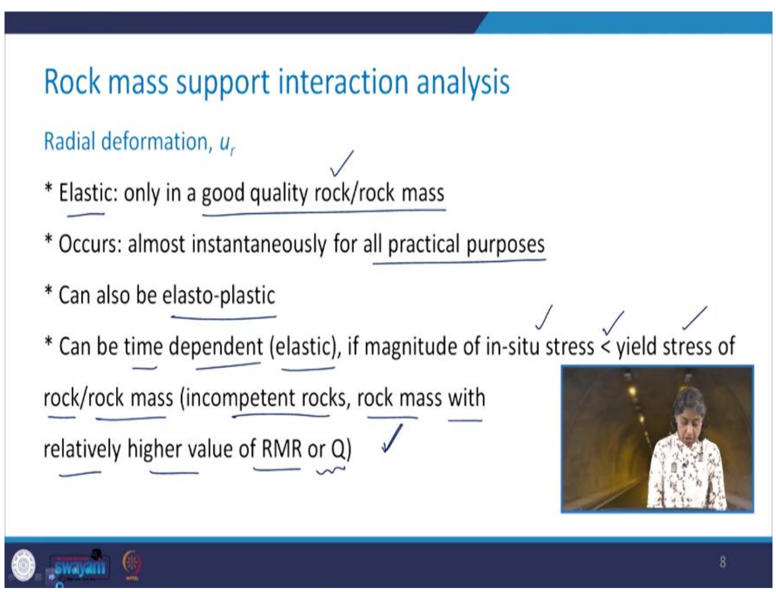

Coming to this radial deformation, it is elastic only in very good quality rock or rock mass. It occurs almost instantaneously for all the practical purposes in case if you have very good quality, rock or rock mass. Then this radial deformation can also be elasto-plastic. It can be time-dependent but elastic if the magnitude of in-situ stress is less than yield stress of rock or rock mass.

In case of the incompetent rocks/rock mass, with relatively higher value of RMR or Q they fall under this category. Now, what happens if this in-situ stress is more than the yield stress of the rock or rock mass?

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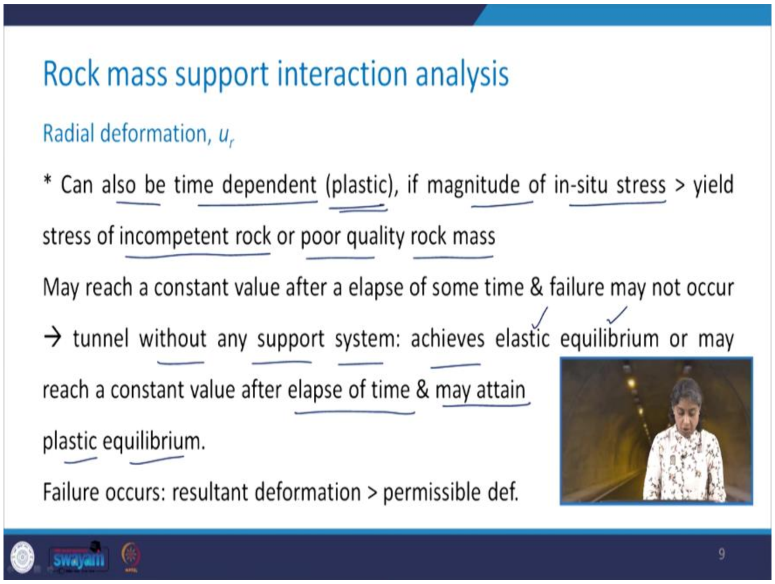

In that case, the radial deformation can also be time-dependent but plastic. So, this is the condition when magnitude of in-situ stress is greater than the yield stress of incompetent, rock or poor-quality rock mass. Then it may reach a constant value after some time, and failure may not occur. So, the tunnel without any support system it achieves the elastic equilibrium or it may reach a constant value after elapse of time and may attain the plastic equilibrium.

The failure occurs in such case as the resultant deformation becomes more than the permissible deformation. So, this gives the indication of occurrence of failure.

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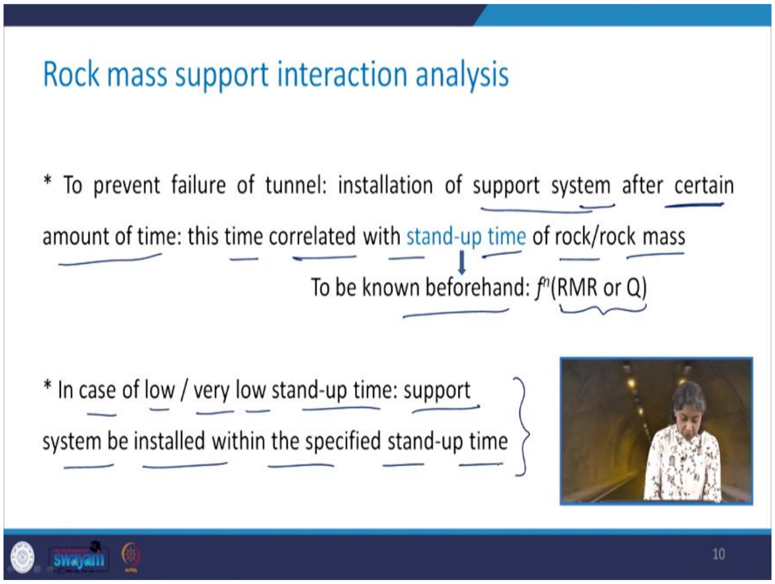

What should we do to prevent the failure of the tunnel? We should install the support system after certain amount of time. Now, why we should install the system after certain amount of time? Because if we apply the system immediately, there is going to be lot of support pressure on to the support system, and we need to go for extremely rigid support system and that may not be economical.

So, we provide the support system after certain amount of time. What should be this time? This time is correlated with the stand-up time of rock or rock mass, and it should be known beforehand. It is a function of RMR or Q which in a way showing you or telling you about the quality of the rock mass. So, in case you have low or very low stand-up time for a particular type of rock or rock mass.

In that case, support system should be installed within the specified stand-up time. Although, this installation of the system should be always within the specified stand-up time but why we are mentioning with reference to low stand-up time here is that that sometimes you have seen that the stand-up time can be as low as few hours after the excavation. So, there we should not wait for those many hours to get over but then we should start the installation of the support system as soon as possible.

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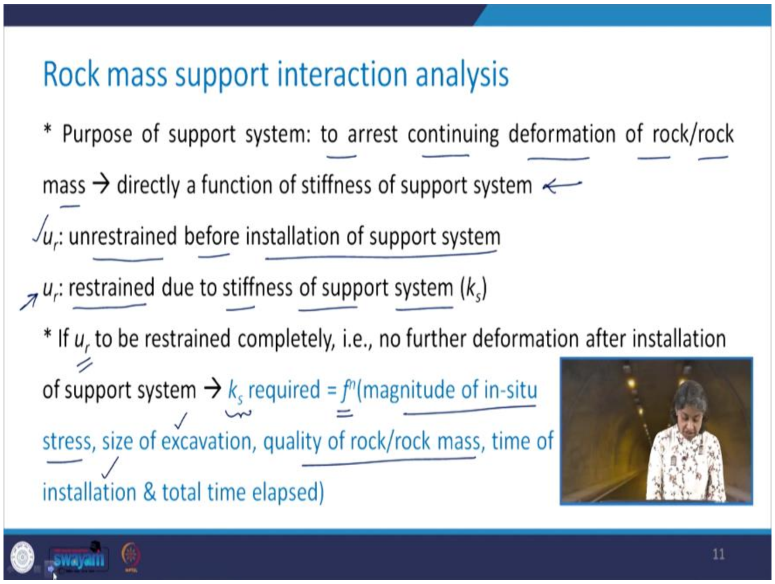

What is the purpose of the support system? This is to arrest the continuing deformation of rock or rock mass, and therefore, it becomes directly a function of stiffness of support system. So, the radial deformation is unrestrained before the installation of the support system. But then, this radial deformation becomes restrained due to the stiffness of the support system after it has been installed.

Now, if this radial deformation is to be restrained completely, this means that no further deformation of the support system is allowed after it is installation. So, this required stiffness of the support system is the function of many parameters. These include magnitude of in-situ stress then size of the excavation, quality of rock or rock mass, time of the installation, and the total time elapsed from the time of excavation.

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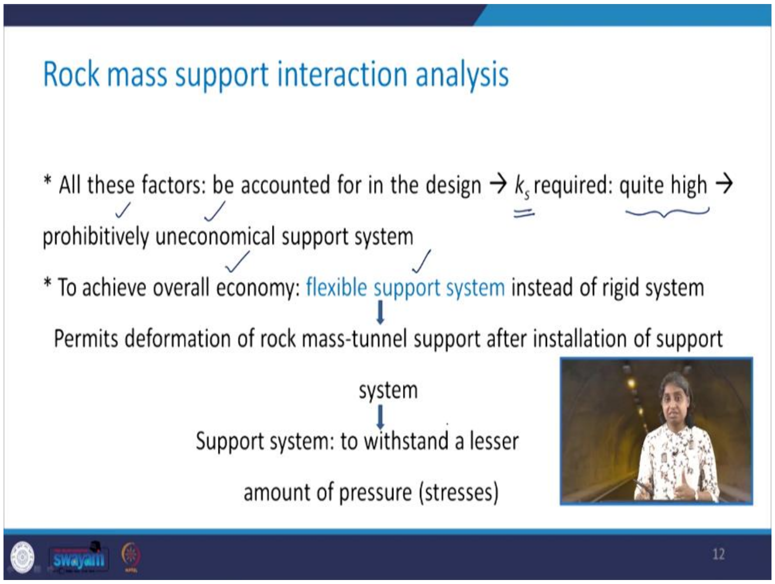

So, when we go for the design of the support system, all these factors should be accounted for. So, if you want to restrain the complete deformation, the required stiffness of the support system, which we are representing as case is going to be quite high. And this will make the support system prohibitively uneconomical. So, to achieve the overall economy, one should go for the flexible support system instead of a rigid system.

Now, what does this flexible system does? It permits some of the deformation of the rock mass tunnel support after the installation of the support system. And because the deformation is allowed, so the support system is to withstand a lesser amount of pressure or stresses. So, therefore, we do not need to provide that heavy a reinforcement system or the support system. So, we can go for the flexible support system rather than a perfectly rigid system.

The deformation of the support system it is governed by the load transferred by the surrounding rock or rock mass. We all know that if larger loads are applied, the deformations are going to be more.

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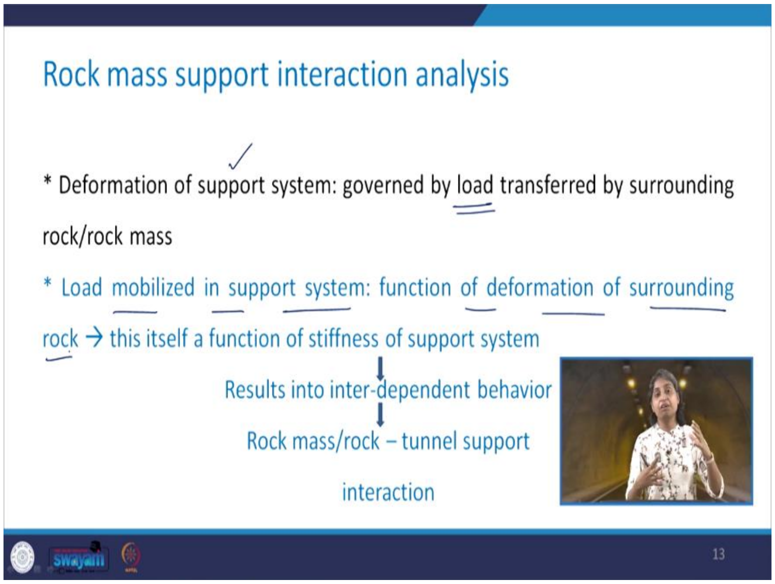

So, basically, the deformation will be governed by what is the load that is being transferred by the surrounding rock or rock mass. So, the load that is mobilized in the support system becomes the function of deformation of the surrounding rock, which itself is a function of stiffness of the support system. So, you see what exactly is happening here? That the stiffness of the support system is a function of deformation, and deformation is a function of the stiffness of the support system.

So, this basically is resulting into the interdependent behaviour, and we call this phenomena as the rock mass or rock tunnel support interaction. So, please understand that if somebody asks you that what do you mean by rock mass tunnel support interaction? You should not just say that, it is their interdependent behaviour that is incomplete definition. Of course, when the term interaction is coming, it is going to be interdependent behaviour. But what exactly do we mean by these interdependent behaviours? That should be absolutely clear to you.

So, there comes the load mobilized in the support system, and the other thing is deformation of the support system. How these two are interconnected? That you should always try to explain if somebody ask you what is rock mass tunnel support interaction. Coming to the rigid support system, the load which is mobilized in the support is very high and the resulting deformation is very, very small and so, vice versa.

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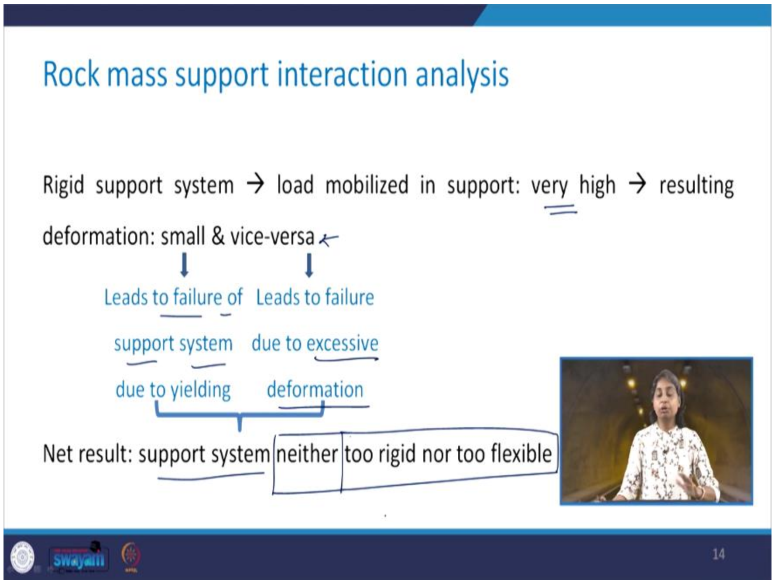

So, in case, if the resulting deformations are extremely small, these lead to the failure of support system due to yielding of the supports, but in case of the other one that is when you have very low load which is mobilized in the support and the resulting deformations are very high. In that case, the failure is due to the excessive deformation. So, the net result basically is the support system which is neither too rigid nor too flexible.

So, remember the code that I told you when we were discussing NATM, so there also this particular term came that neither too rigid nor too flexible so because if we go to the extreme sides, this is what is going to happen? Either the failure will take place because of the yielding of the support system or the failure will take place because of the excessive deformation at, and we do not want either of this to happen. So, we have to somewhere be there in the middle of these two extreme situations.

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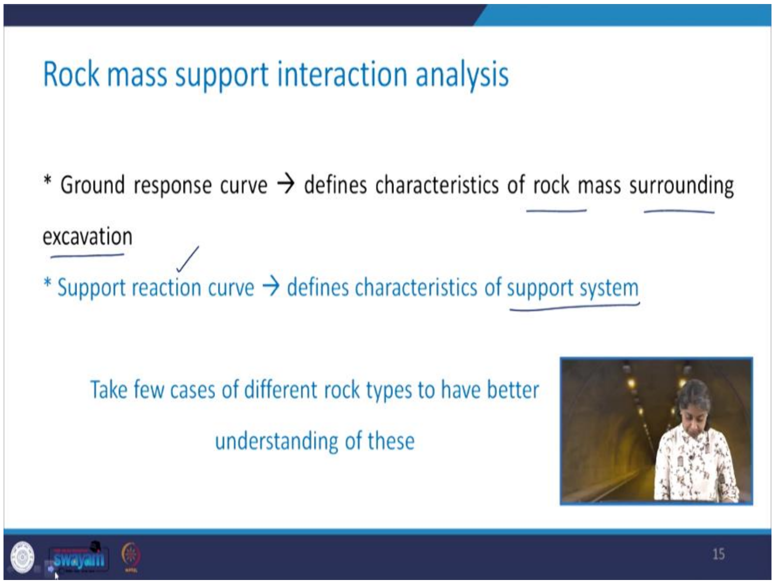

Now, the ground response curve is a term that clearly defines the characteristic of the rock mass surrounding the excavation. So, we have seen that when we talk about rock mass support, interaction or the rock mass tunnel support system, then in that case, we have two components one is the tunnel or the excavation itself, and the other component is the support system.

So, the characteristic of these two components are given by ground response curve and support reaction curve. Ground response curve gives us the idea about the characteristic of the rock mass which surrounds the excavation, and the support reaction curve it defines the characteristic of the support system. Now, to understand these in a better manner, let us take few cases of different rock types.

And first, let us discuss a 2-dimensional situation which will not be there in the field. But this I am discussing with you just to make sure that you first understand the concept of the rock mass tunnel support interaction properly and then we will go to the actual 3-dimensional case.

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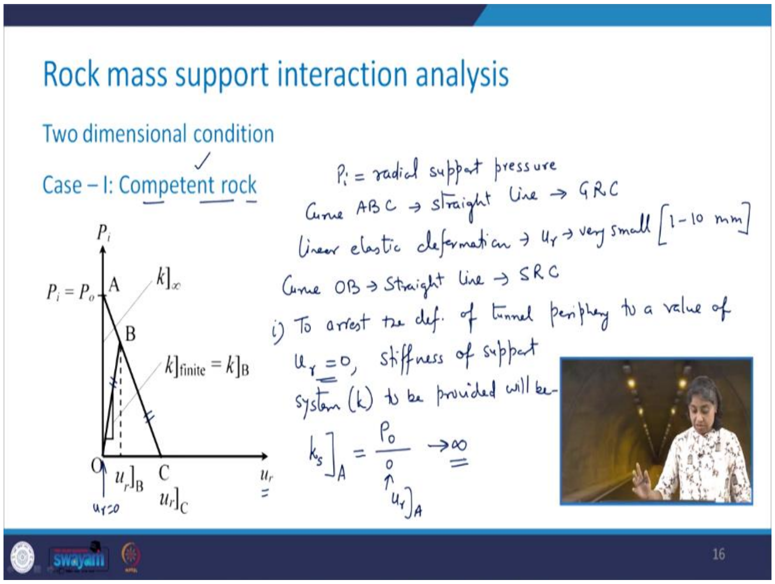

So, we take the 2-dimensional condition for all the cases that I am going to discuss. So, we take the first case of the competent rock. So, in that case, first of all, let us understand some of these terminology. So, here we are going to define P_i as the radial support pressure. In this case this curve A, B, C, see this one, this is the straight line. Why this is straight line? Because we are talking about the competent rock and this is going to be written as GRC which is the ground response curve in such case.

Then we have the linear elastic deformation in this case because we are talking about the competent rock and I mentioned to you that based upon the type of the rock or the type of the support system, you may have elastic, elasto-plastic, elastic, plastic and the time-dependent kind of behaviour. So, in this case it is the linear elastic deformation, where u_r is very small, maybe to the tune of 1 to 10 mm. And then you focus on the curve OB which is again a straight line. And this we call as support reaction curve.

So, this line OB is giving us the idea about the characteristic of the support system. So, we have few cases here so, the first one is in if we want to arrest the total deformation of the tunnel periphery. So that this radial deformation is equal to 0, so, let us write that to arrest the deformation of the tunnel periphery to a value of u_r to be equal to 0. What should we do? We should provide the support system, of course, so, what will be the stiffness of the support system in that case?

So, the stiffness of the support system which I am writing as say k to be provided, will be what C here this is say, k_s at the point A because why I am calling this point as A point because corresponding to this, you can see that u_r here is equal to 0. So, case A is going to be:

$$k_s]_A = \frac{P_o]_A}{u_r]_A} = \infty$$

So, what is that deformation which is equal to 0? So, this is nothing but u_r at A this is the basic definition of the stiffness, and you see that this is tending to infinity. So, what does this mean that if we want to completely arrest the deformation, we have to provide very rigid support system and for all practical purposes. The stiffness is very, very high, and you can consider it to be tending towards infinity. So, what will be the result? That will be very uneconomical support system.

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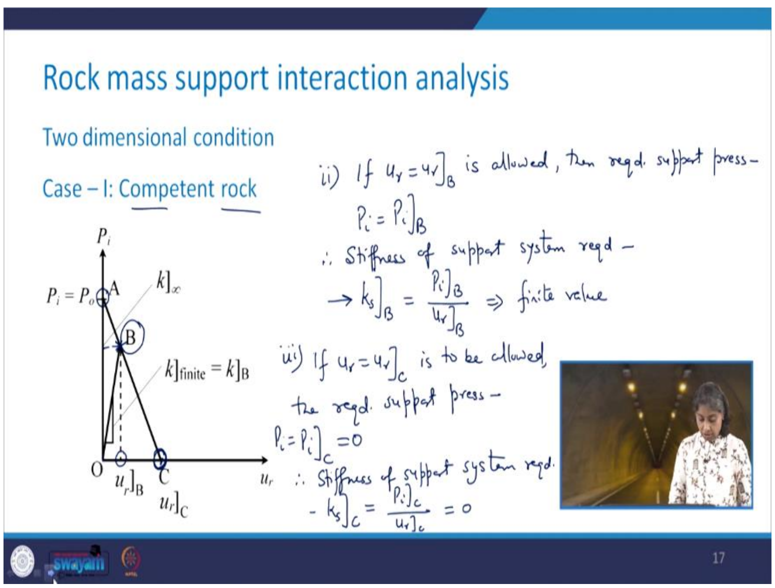

Then I take the other case that is the second one now, if $u_r = u_r$ at B means here this point. So, if this is allowed then the required support pressure. What it is going to be? It will be P_i will be equal to P_i at point B so, you see that here. So, what will be the stiffness of the support system in this case? Which is required is going to be case at point B will be equal to:

$$k_s]_B = \frac{P_o]_B}{u_r]_B} = Finite\ value$$

And we take the third situation where, $u_r = u_r$ at C this means here. So, see practically here what is the support pressure? Radial support pressure this is 0. So, if this is to be allowed then the required support pressure will be P_i which is equal to P_i at point C. And what is P_i at point C? This is equal to 0. So, we will have the stiffness of the support system apply the expression which is required, of course, so that is going to be k_s at C will be equal to:

$$k_s]_C = \frac{P_o]_C}{u_r]_C} = 0$$

So, you see that we have the competent rock and three situations in case if you want to arrest the complete deformation, which is represented by this point A. And in case, if you want to allow the maximum deformation such that the support pressure is zero, which is another extreme, that is point C.

And another point B which is somewhere in between and therefore, you will have the finite value of the stiffness of the support system. So, this is how we can find out for the competent rock?

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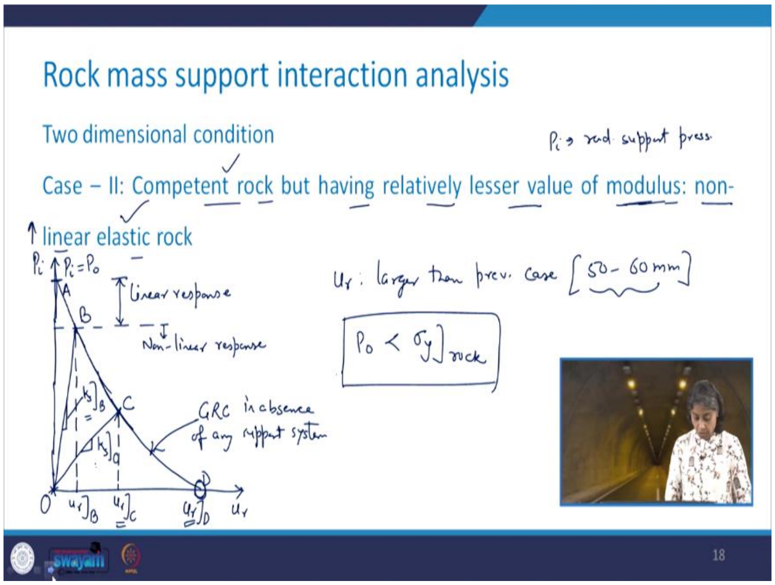

Let us take the next case of the competent rock, but it has relatively lesser value of modulus, and the behaviour is non-linear elastic rock. So, how does this look like the behaviour? Let us take a look here so, again on x-axis, we have the radial deformation, and on y-axis, we have the radial support pressure, say here. Of course, you have P_i and here this is where you want it to be completely arrested all the deformations, it is 0.

So, since it is non-linear elastic rock, so, how it is going to be? In the beginning, we will have some linear response, and then beyond that it becomes non-linear. So, up to this much point here, this is what is your linear response. And beyond this you have the non-linear response of the system. Of course, here you have P_i which is the let me write it here P_i is the radial support pressure. And then let us say I take this point so, just join this point with the origin, and I take maybe one more point here.

So, let us say that this point is point A, this is B, this point is C, and this point is D. So, I will just drop a vertical line from point B and from point C so, this is going to be u_r at C, this is u_r at B, this is of course, the origin. So, the stiffness here is going to be the slope of course. So, this I will write asks at B, and similarly, here we will have k_s at C, then here this is the GRC that is ground response curve in the absence of any support system.

So, this we know that because it is the competent rock but it it is having a relatively lesser value of modulus, and therefore, it shows non-linear elastic behaviour. So, this is how the GRC is going to be. So, in this case, u_r is larger than the previous case, which was case one. So, in this case, maybe it is of the order of, say 50 to 60 mm, and in this case, we have the in-situ stress to be less than yield stress of the rock. So, this condition is there so, depending upon what is the deformation? That is allowed accordingly, you can find out the stiffness.

You see that the more the deformation which is allowed less is the stiffness of the support system which is needed. So, here you see that at point D, it is u_r at D, which is very large, corresponding to which the support pressure which is needed is 0. So, in this case, this may be to the tune of say 50 to 60 mm and it is larger than the previous case of the competent rock.

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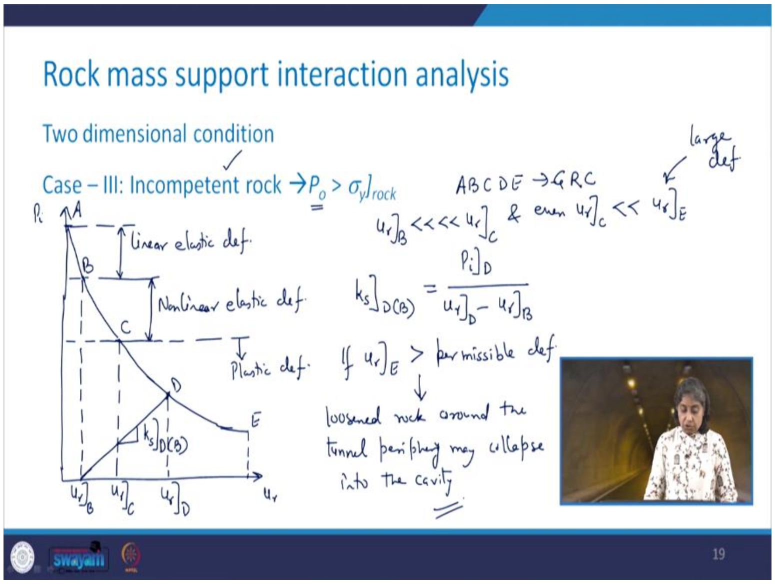

Then we can have the third case where we have incompetent rock, with P_o greater than the yield stress of the rock. So, let us take a look that how it is GRC and support reaction curve will look like. So, here we have u_r and radial support pressure P_i on this axis. So, here we will have in the beginning some linear portion and then the non-linear elastic deformation. Then we will have the plastic deformation.

So, say this point is A and say this point is B which is the linear, elastic deformation and then up to this point, say this is a point C. You have here as the non-linear elastic deformation, and beyond this you have the plastic deformation. So, corresponding to this point B may be you have here u_r at B, then corresponding to the point C you have u_r C and say if I take another point here which is D and in this case u_r at B is allowed.

So, corresponding to this we have u_r at D so, it is stiffness is written with a little bit different notation that it is k_s at D when the deformation at B is allowed. So, this is how it is behaviour is going to be. Now, let us try to understand some of the values here. So, basically, here this point I will mark as E. So, basically here, A, B, C, D, E is giving us the idea about the ground response curve u_r at B is much, much less than u_r at C. And even u_r at C is much smaller than u_r at E, u_r at E is pretty large deformation. So, we have this stiffness that is k_s at D when the deformation at point B is allowed. So, how are we going to do that? See:

$$k_s]_{D(B)} = \frac{P_o]_D}{u_r]_D - u_r]_B}$$

Now, if you have this, u_r at E more than the permissible deformation. So, what will happen? There is going to be the collapse because of the excessive deformation. So, in this case, this loosened rock around the tunnel periphery may collapse into the cavity. So, this is how, by looking at different types of rock, we can explain that how the stiffness of the support system can be determined if you have to completely restrict the deformation or if you allow some deformation, then how we can get the stiffness.

So, this was all about the 2-dimensional condition. And here ah I tried to explain you that how the stiffness and the deformation stiffness of the support system and deformation of the rock mass? How they are interdependent on each other? So now, in the next class, we will try to understand the same concept but with the help of a 3-dimensional problem which is more close to the real situation/field situation. Thank you very much.