Underground Space Technology
Prof. Priti Maheshwari
Department of Civil Engineering
Indian Institute of Technology, Roorkee

Module No # 08
Lecture No # 37
Application of Rock Mass Classification System: Rock Mass Quality System -02, NATM, NMT

Hello everyone, in the previous class we discussed about the application of rock mass quality index system, to the analysis and design of underground excavations we learnt about the support pressure determination. So, today we will continue this discussion related to the application of Q system to underground excavations. And today, we will learn how the deformations can be estimated in the roof as well as in the side wall of the excavation using the Q system.

And then we will learn a few aspects related to NATM which is a new Austrian tunneling method and, the other one which is an NMT, that is, Norwegian method of tunneling. So, let us start our discussion with the estimation of deformation or closure of the underground excavations.

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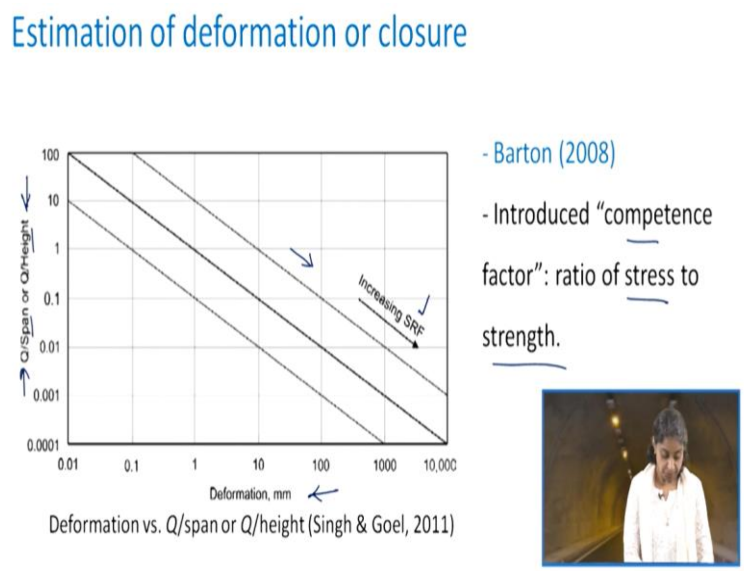

Barton in 2008, proposed the factor called competence factor which he defined as the ratio of stress to strength and also gave the plot between Q by span or Q by height versus the deformation. So, if we know the rock mass quality index Q for a particular rock mass and if we know the span or the height of the underground excavation. Then, we can determine this quantity on the y-axis, and accordingly, we can choose the deformation from this particular plot, we can estimate the deformation. And, you see that as we move in this direction the SRF value is increasing.

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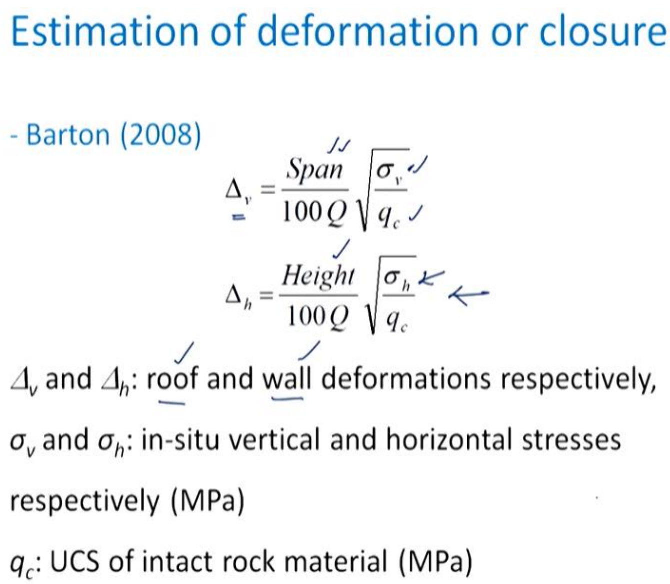

Now, Barton also gave the idea about the determination of roof and the wall deformations, so that was given by this expression that is

$$\Delta_v = \frac{\text{Span}}{100Q}\sqrt{\frac{\sigma_v}{q_c}}$$

Where this σ_v is the in-situ vertical stress in mega Pascal and q_c be the UCS of the intact rock material in mega Pascal. So, accordingly, we can find out, that what is going to be the roof and the wall deformation.

In case of the wall deformation, in place of span we consider the height of the excavation and in place of σ_v , it will be σ_h , which is in situ horizontal stress in megapascal.

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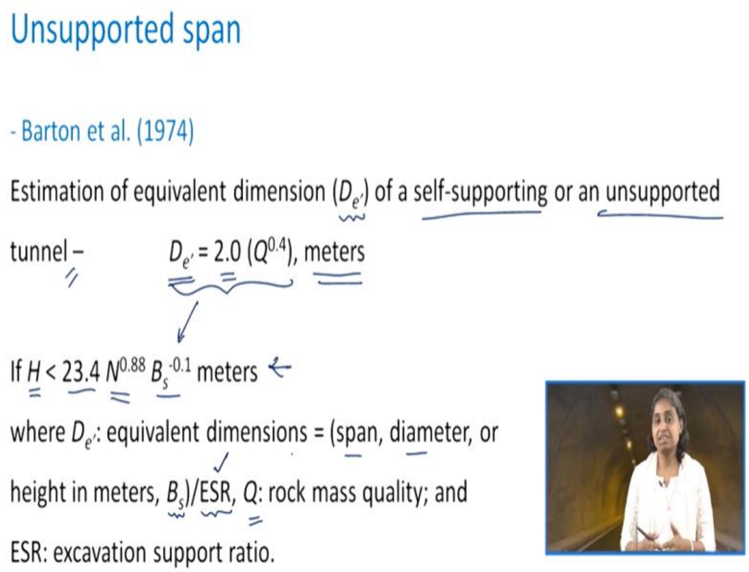

The estimation of equivalent dimension, that is De prime for the self-supporting or the unsupported tunnel can be done using this expression which is

$$D_{e'} = 2.0(Q^{0.4})$$

As you can see that, this is an empirical relationship so the unit is important which is in meter here. No, this will be applicable when you have the depth of overburden,

$$H < 23.4N^{0.88}\ B_s^{-0.1}$$

Take a note, this expression we learnt earlier as well and applicable to the self-supporting or the unsupported excavation case. Where this $D_{e'}$ is the equivalent dimension that is equal to either span or diameter or height in meter that is let us say represented by B_s divided by this excavation support ratio ESR, then this Q represent the rock mass quality. Now the question comes here how to determine the value of ESR? So, typical values of ESR for various types of projects have been recommended we will learn that in a short while.

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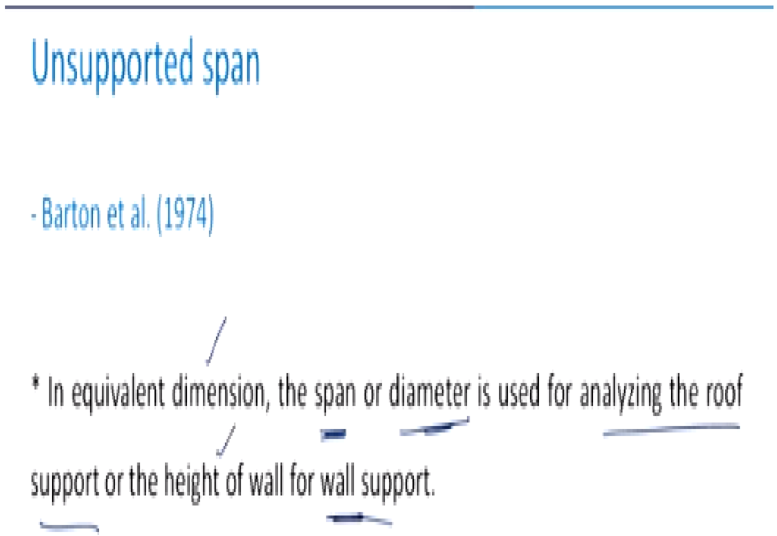

Now, when we have the equivalent dimension, we use the span or the diameter for analysis of the roof support and we use the height of the wall for wall support. Take a note, here in this expression I told you either you have to take span or diameter or height in meters. So, in if we are talking about the roof support then we talk in terms of span and the diameter, and in case, if it is wall support then we will go ahead with the height of the wall.

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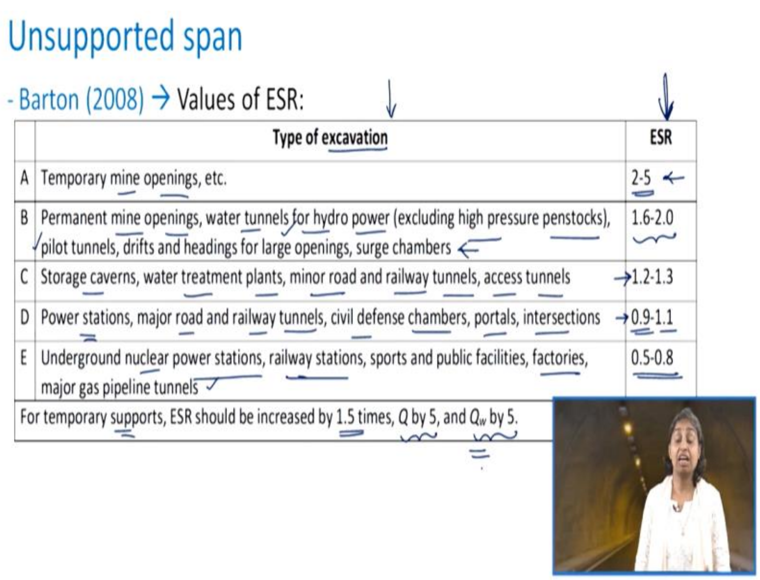

	Type of excavation	ESR
A	Temporary mine openings, etc.	2-5
B	Permanent mine openings, water tunnels for hydro power (excluding high pressure penstocks), pilot tunnels, drifts and headings for large openings, surge chambers	1.6-2.0
C	Storage caverns, water treatment plants, minor road and railway tunnels, access tunnels	1.2-1.3
D	Power stations, major road and railway tunnels, civil defense chambers, portals, intersections	0.9-1.1
E	Underground nuclear power stations, railway stations, sports and public facilities, factories, major gas pipeline tunnels	0.5-0.8
For temporary supports, ESR should be increased by 1.5 times, Q by 5, and Q_w by 5.		

As I mentioned that, the value of this excavation support ratio has been recommended for various types of excavation. So, the first column suggests here the type of excavation and the last column gives you the range of ESR value. So, if we take the temporary mine opening and the other type of excavation similar type of excavation in that case ESR will be varying between 2 to 5.

In case, if the type of excavation is permanent mine opening or water tunnels for hydropower projects excluding of course high-pressure penstocks. Or if these are related to pilot tunnels, or drifts and headings for large opening and surge chambers and search chambers. Then in that case ESR varies between 1.6 to 2. For these storage cabins, water treatment plants, minor road and railway tunnels, or access tunnels we need to adopt ESR between 1.2 to 1.3.

In case, if the excavation is done for the purpose of power stations, major road and railway tunnels, civil defense chambers, portals or intersections in that case ESR further reduces and it varies between 0.9 and 1.1. For underground nuclear power stations, railway stations facilities, used for the sports and public purpose, factories, and major gas pipelines tunnel in that case ESR is taken to be varying between 0.5 and 0.8.

In case, if you have the temporary supports, the ESR that is given in this column should be increased by 1.5 times Q should be increased by 5 and, Q_w also should be increased by 5. This Q_w is the wall factor we have discussed this in some of the earlier lectures.

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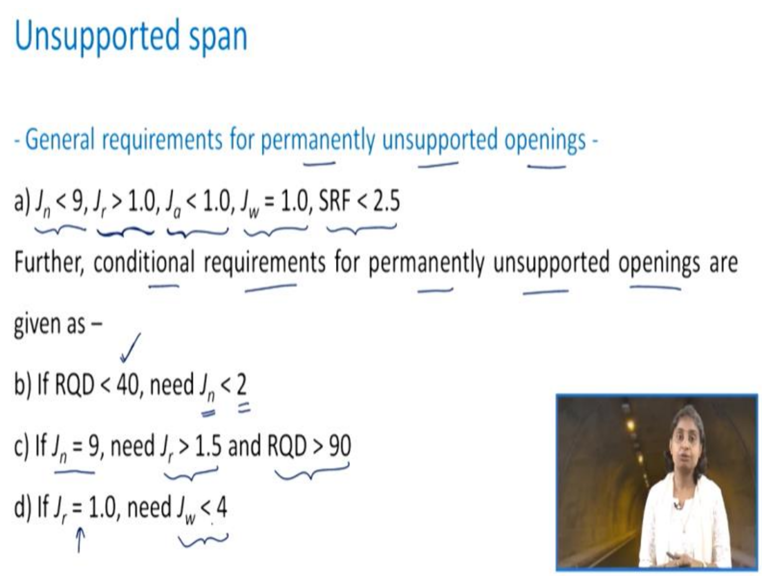

The general requirements for the permanently unsupported opening, if you have a very good rock mass then you may not need to go for any kind of support system the opening will be safe even when it is unsupported. But then what would be that unsupported span? So, for that general requirements are given here so for this purpose Jn should be < 9, Jr should be > 1, Ja should be < 1, Jw should be 1, and SRF should be < 2.5.

So, you see all the parameters of the Q system and you have the limit on if each of these for the permanently unsupported openings. Further, there are some additional requirements for permanently unsupported openings and these include that if RQD is < 40, you need to have Jn to be < 2. Then if Jn = 9 we need to have Jr more than 1.5 and RQD more than 90. If Jr = 1, that is joint roughness number is equal to 1 we need to have Jw < 4.

So, here these numbers, 9, 1.5, 1, 4, all these correspond to the rating which are assigned to these parameters as per the q system.

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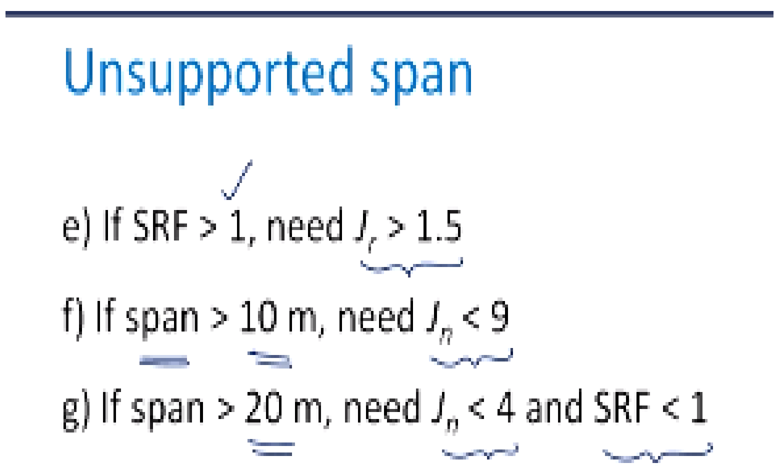

Further, some additional conditions are there, so in case if SRF is > 1 we need to have Jr > 1.5, if span of the opening is > 10 meter, we need to have Jn to be < 9. And in case, if span is > 20 meters, we need to have Jn < 4, and SRF < 1. So, these conditions should be satisfied to have the permanently unsupported excavation.

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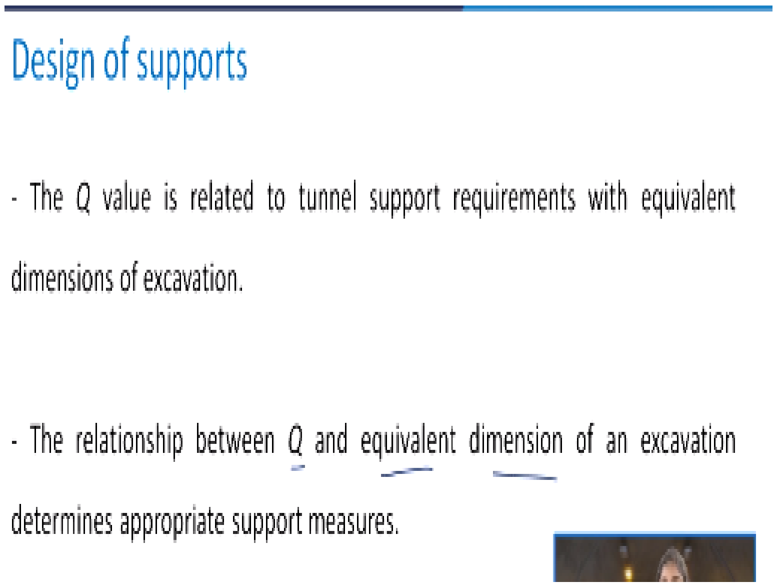

Coming to the design of supports the Q system is related to the tunnel support requirements with the reference to the equivalent dimensions of the excavation that we have seen earlier. The relationship between q and the equivalent dimension, it determines the appropriate support measure.

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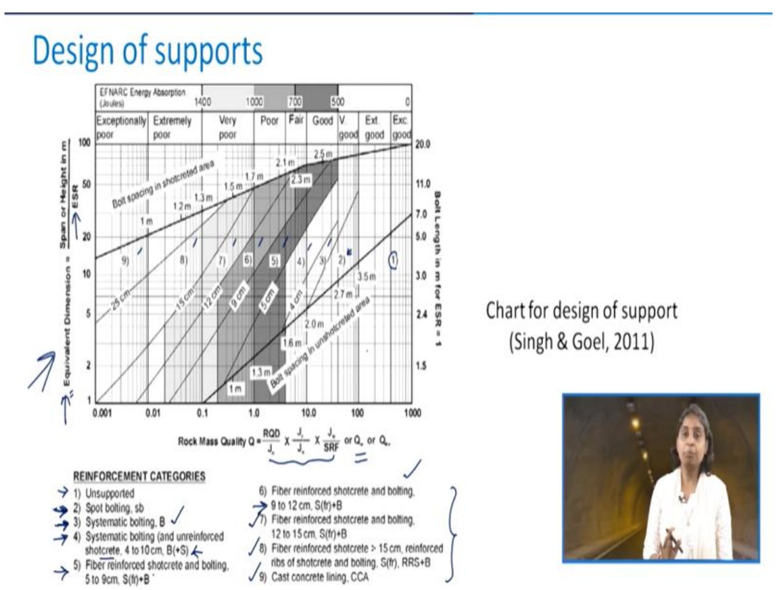
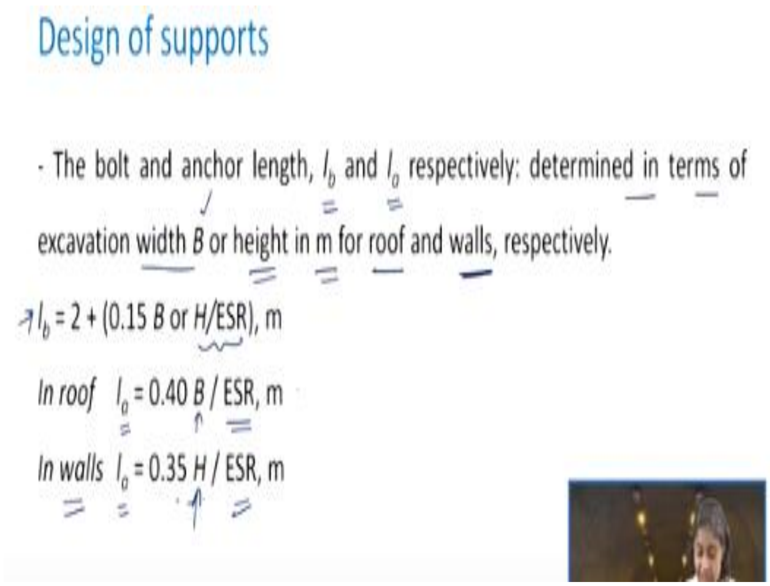


How? Take a look here on the x-axis you have either Q or Qw however on the y-axis you have the equivalent dimension, which we defined as span or diameter or height in meter, divided by the value of ESR. So, here you see that various reinforcement categories are shown with the numbers. So, these are represented here say 1 in this zone it is 2, 3, 4, 5, 6, 7, 8, and 9 so all the 9 categories have been mentioned here.

So, the first one corresponds to the unsupported category, and the second category is the spot bolting, the third reinforcement category is the systematic bolting. So, as against spot bolting where we provide the rock bolts only in a particular zone here in systematic bolting we design the wrong bolts throughout the cross-section properly, their spacing length everything. And throughout the section, it is provided then the fourth category of the reinforcement is a systematic bolting and the reinforced shotcrete.

So, this is represented by the symbol B and in bracket +s. Then the fifth category is, fiber-reinforced shotcrete and bolting here the shotcrete thickness varies between 5 to 9 centimeters. And likewise, here you have the categories 6 to 9 where the sixth one has the fiber reinforce shotcrete plus bolting. And the thickness of this fiber reinforced shotcrete varies between 9 to 12 centimeters.

Similarly, the description is given for 7, 8 and 9 and I also mentioned that this is how these categories have been mentioned in this particular figure. Now, if you know the value of rock, we know the type of the excavation. So, accordingly, we can find out the value of ESR we know the span or height of the excavation and hence we can find out the equivalent dimension. So, knowing the equivalent dimension as well as Q we can locate the point here in this space which is equivalent dimension versus Q. And accordingly, wherever that lies we can find out that which will be the most appropriate type of the reinforcement to be provided for such an excavation. **(Refer Slide Time: 13:49)**



The bolt and the anchor length is important and let us say that we represent them by lb and la respectively these are determined in terms of the excavation width b or height in meter for roof, and wall respectively. So, if we are going for the roof support, then we have to talk in terms of the excavation width and in case of wall it should be height of the excavation. So, this lb, which is the bolt length

$$l_b = 2 + (0.15B \text{ or } \frac{H}{ESR})$$

and in roof

$l_a = \frac{0.40B}{ESR}$ and involves

$$l_a = \frac{0.35H}{ESR}$$

So, you see that when we talk in terms of wall, we are dealing with this height H and in case of roof it is the span B and, all these are in meters.

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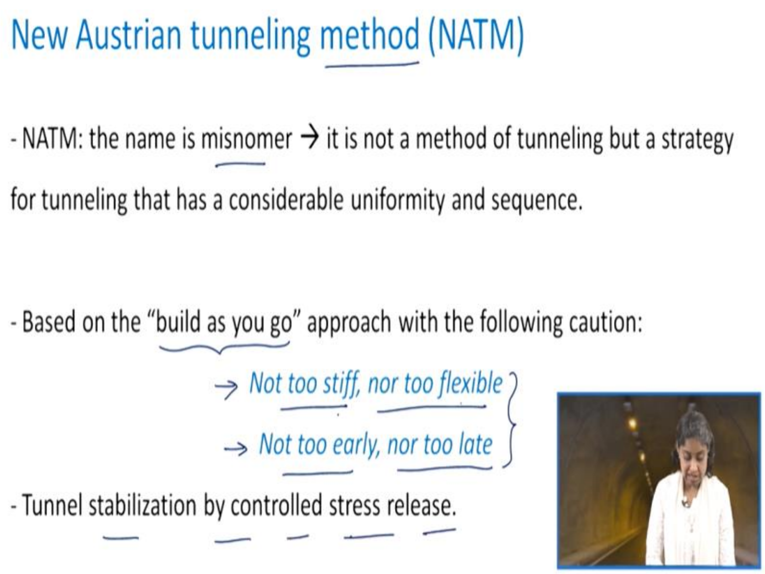

So, this was all about the design of support using the q system. Now we take a look on few aspects related to new Austrian tunneling method which we call in short as NATM. So, basically, here the term method is a misnomer basically NATM is not typically a method, but it is a strategy for tunnelling, which has a considerable uniformity and a particular sequence. So, this philosophy is based on the quote that is "build, as you go, with the following caution that is not too stiff, not too flexible, and not too early and not too late", this is in connection to the support system.

That means we should not provide too stiff support system because in that case the allowable settlements or the allowable deformations are going to be very low and, to restrict complete deformation, we need to go for very heavy support system which may not be economical. But then, if we allow some deformation and if this allowable deformation is too large. Then, we have to go for very flexible kind of a support system which may not be good because, in that case, the deformations may be beyond the permissible limit.

And, therefore this line comes into picture that the support system should not be too stiff, nor it should be too flexible. So, we need to adopt somewhere in between that, yes, we will allow some permissible deformation to take place, and accordingly, we will design the support system. Then the second line is not too early and not too late you have excavated an opening now, when should we provide the support system this is related to that time.

Now we know that the concept of stand-up time, there this stand-up time, is the time up to which the tunnel can stand on its own after the excavation without any support system. I have mentioned this earlier also that, although based upon the quality of the rock mass the stand-up time may be larger. But then, you should not wait upto the last moment to provide the support system.

Therefore, the support system should not be provided too early not too late, because, if we provide it too early then we are not allowing any deformation to take place, we want to restrict all the deformation, and again then in that case we have to go for very stiff kind of support system. So, you need to keep these things in mind that the support system, should not be too stiff not too flexible, not too early not too late. Then, the tunnel stabilization should be done by controlled stress release.

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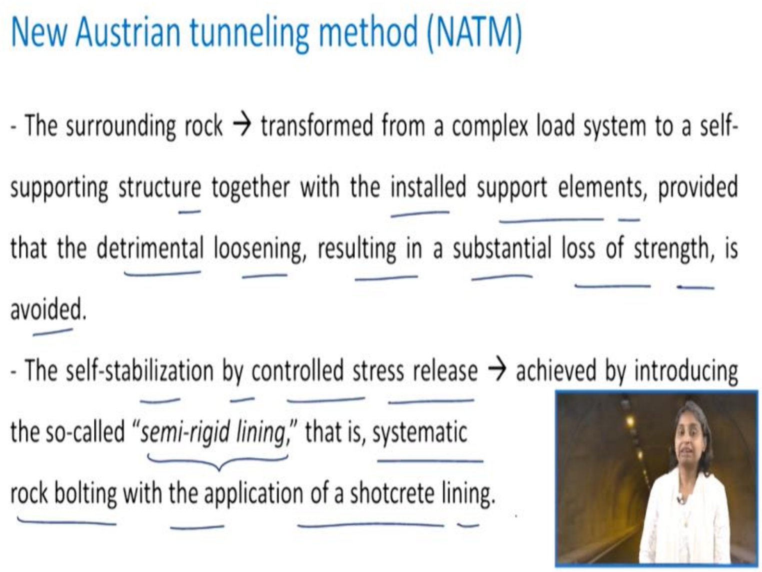

The main aspect related to NATM is that the surrounding rock is transformed from a complex load system to a self-supporting structure, together with the installed support elements. Provided that the detrimental loosening, resulting in a substantial loss of strength is avoided. So, basically what happens is when you excavate there is going to be the stress-free boundary and the surrounding rock mass will enter into the loosening state.

So, when we support or when we provide the support system the complete rock mass and support system should be transformed into the self-supporting structure, where rock mass along with the installed support system, they act together to resist the loading. Now, the self-stabilization by the controlled stress release is achieved by introducing the so-called semi-rigid lining. That is, systematic rock bolting with the application of a shotcrete lining.

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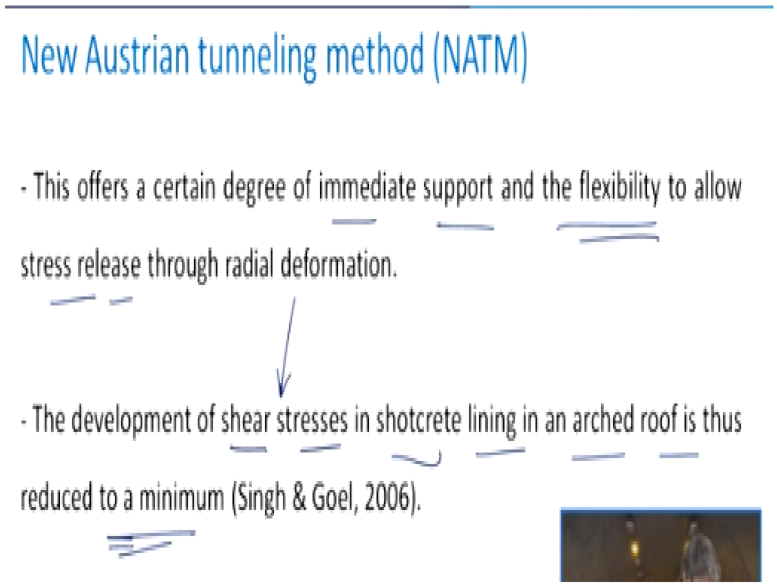

Now this kind of arrangement this kind of support system offers a certain degree of immediate support and also the flexibility. So that, the stress release can be allowed through the radial deformation see excavation is made if you do not allow any radial deformation to take place lot of stresses are going to be restored. What will happen if you allow the radial deformation to take place? As the deformation will take place, the stress release is going to occur.

Now, we cannot allow this stress release to be too large therefore we cannot allow very large radial deformation. The development of shear stress in the shotcrete lining in an arched roof is therefore, reduced to a minimum if we adopt this type of approach. I am not saying that, this will become equal to 0 because that we do not want, but then it will reduce to a minimum. All these concepts will become more, clear when we discuss the rock mass tunnel support interaction phenomena which we will take up maybe 3, 4 classes.

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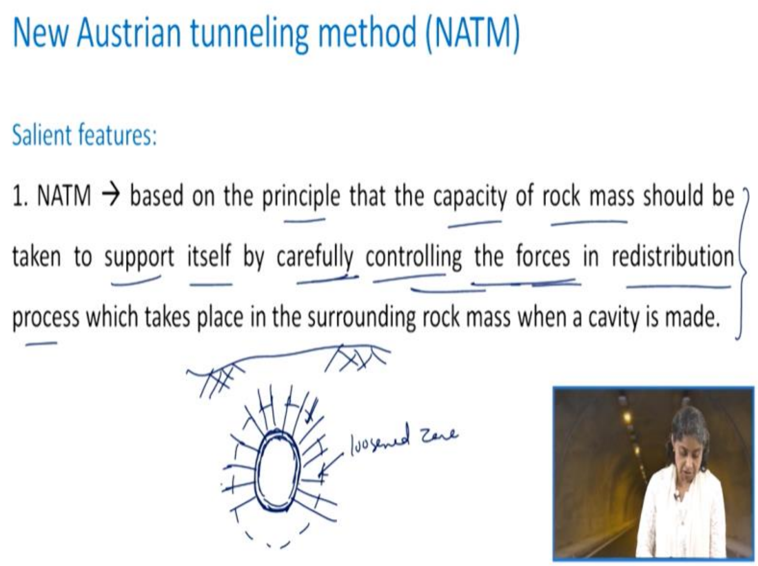

Coming to some of the salient features related to NATM. So, this is based upon the principle that the capacity of rock mass should be taken to support itself by carefully controlling the forces in redistribution process, which takes place in the surrounding rock mass when the cavity is made. Now, take a look here, let us say this is the excavation which is made and this is your say the ground surface and the excavation is made.

Now, what will happen immediately after the excavation is made, this boundary will be the stress-free boundary, and in the surrounding rock mass you will have a loosened zone. The question is, if I provide let us say a support system say the shotcrete layer plus maybe the, you know, the systematic rock bolting of course it has to go beyond this. So, now in that case we are very carefully controlling the forces in the redistribution process.

Because what happened when this was the stress-free boundary, immediately there is going to be the redistribution of stresses in this loosened zone. Now, we can control this by providing the systematic support system like shotcrete plus the rock bolting. So, that is what this is meant by that NATM is based on the principle that the capacity of the rock mass should be taken to support itself. That means that this excavation will be supported by this rock mass, which is all around it with the help of the careful control of the forces in the redistribution process.

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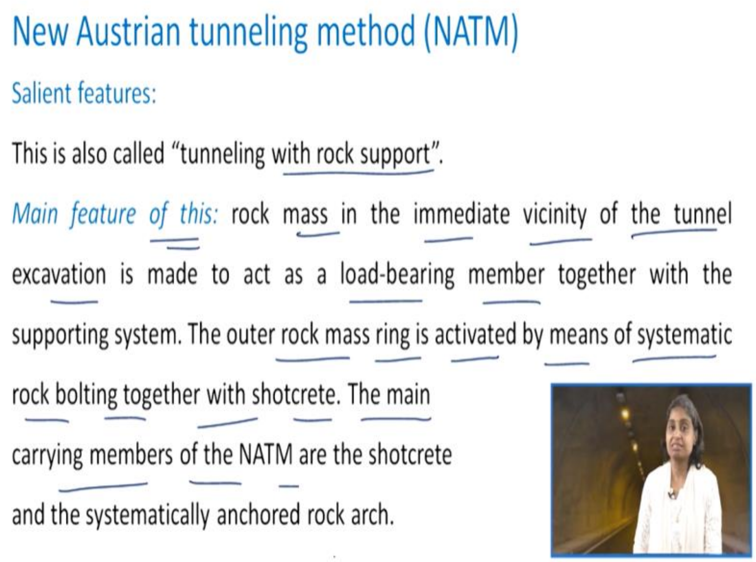

This type of the principle, this type of the phenomena is also called as a tunneling with rock support. The main feature of this is that the rock mass in the immediate vicinity of the tunnel excavation is made to act as the load-bearing member together with the supporting system. So, as I showed you that this is the loosened mass so not only the support system but this mass will also help as the load-bearing member.

The outer rock mass ring is activated by means of the systematic rock bolt together with the shotcrete, I already explained you the main carrying member of the NATM are the shotcrete and systematically anchored rock arch.

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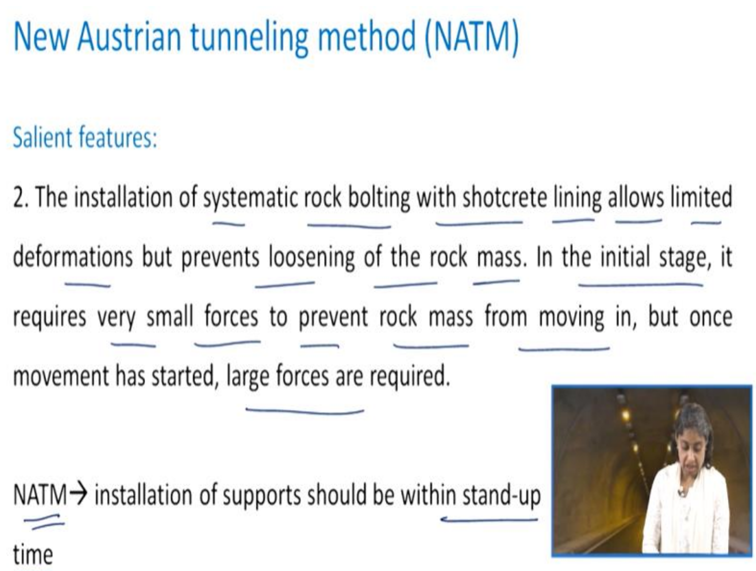

The second salient feature is the installation of systematic rock bolting with shotcrete lining, it allows the limited deformations but it prevents the loosening of the rock mass. So, in the initial stage, it requires very small forces to prevent the rock mass from moving in but once the movement has started you will need the large forces. So, the NATM considers the installation of supports which should be within the stand-up time, not too early not too long.

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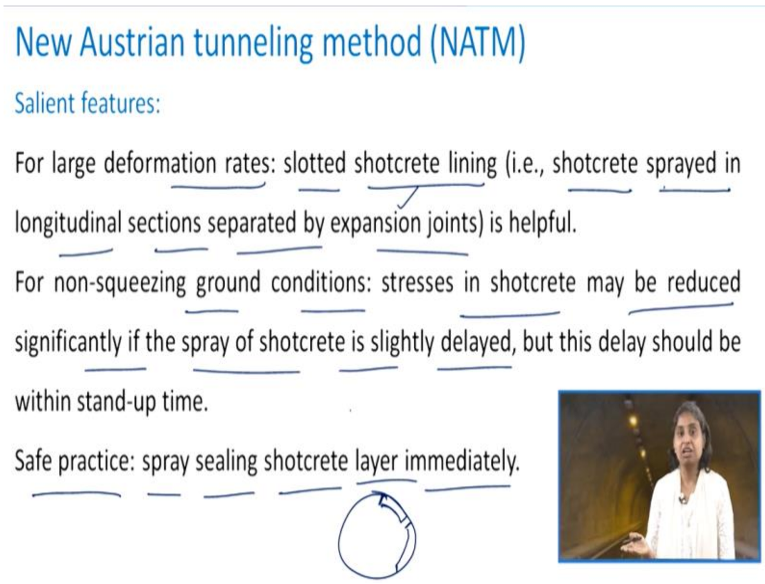

For the large deformation rates slotted shotcrete linings which means that the shotcrete sprayed in longitudinal sections separated by the expansion joint. So, let us say if this is the excavation so I sprayed in the longitudinal direction means direction perpendicular to the plane of screen. So, let us say I sprayed the shotcrete thickness up to this much of the area and then I leave a little bit of space as a part of the excavation joint and then further go ahead.

So, this is what is that the shotcrete sprayed in the longitudinal section which, are separated by the expansion joints. For non-squeezing ground conditions stresses in the shotcrete may be reduced significantly if the spray of the shotcrete is slightly delay but this delay should be within stand-up time. What happens when we delay the installation of the support or the spray of the concrete in this case some radial deformation takes place.

And, therefore, the release of the stresses also takes place and hence the load on the shotcrete is going to be little less. So, it is the safe practice that we spray the ceiling shotcrete layer immediately upon the excavation and the support system shortcut little later.

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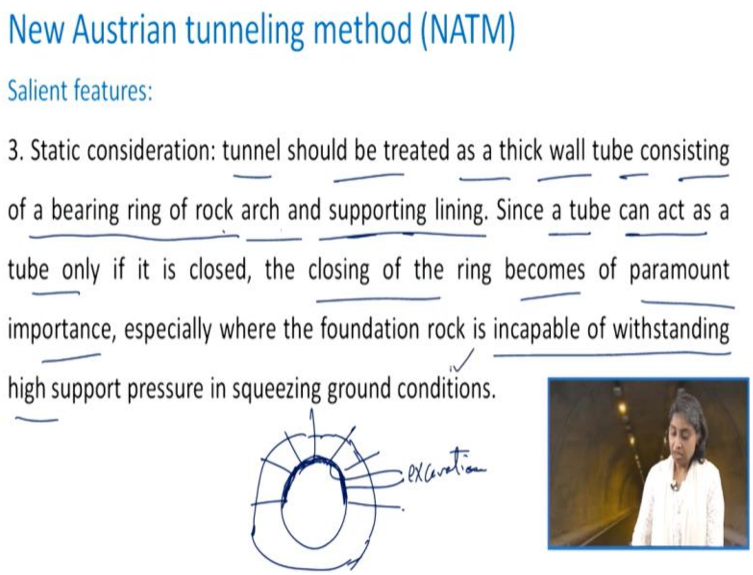

The static consideration involves that the tunnel should be treated as a thick wall tube consisting of a bearing ring of rock arch and supported lining, we saw this. So, it will be something like, this, so, this is the excavated boundary excavation and then you have a rock layer all around the periphery of this. And also, you have the support system, it can be let us say the shotcrete layer plus the rock bolting, so all these together they act as a bearing ring of rock arch and the supported lining.

Since, the tube can act as a tube only if it is closed, otherwise, it is it would not be acting as that the closing of this ring becomes a paramount importance. Especially in case where the foundation rock is incapable of withstanding the high support pressure especially in squeezing ground conditions. So, we need to be careful about this aspect.

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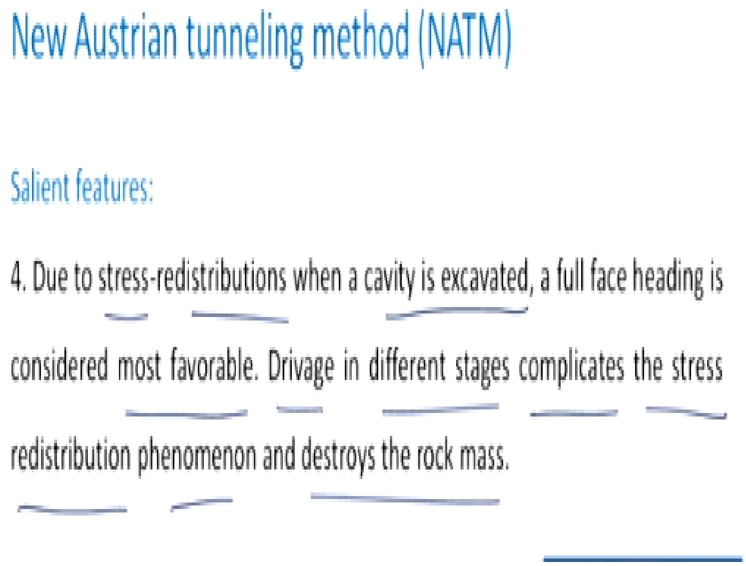

Then the fourth salient feature is the, due to stress redistributions when the cavity is excavated a full-face heading is considered to be the most favorable. Then drive it in different stages it complicates the stress redistribution phenomena and it destroys the rock mass, but then this cannot be done in all types of rock mass. So, what does this mean is that in case if you go for the full-face heading excavation?

That means the excavation is done in one go not in different stages, so what will happen that the stress redistribution process is not that complex. But in case, if you have the driving of the tunnel or the excavation in different stages then the stress redistribution is going to be quite complicated.

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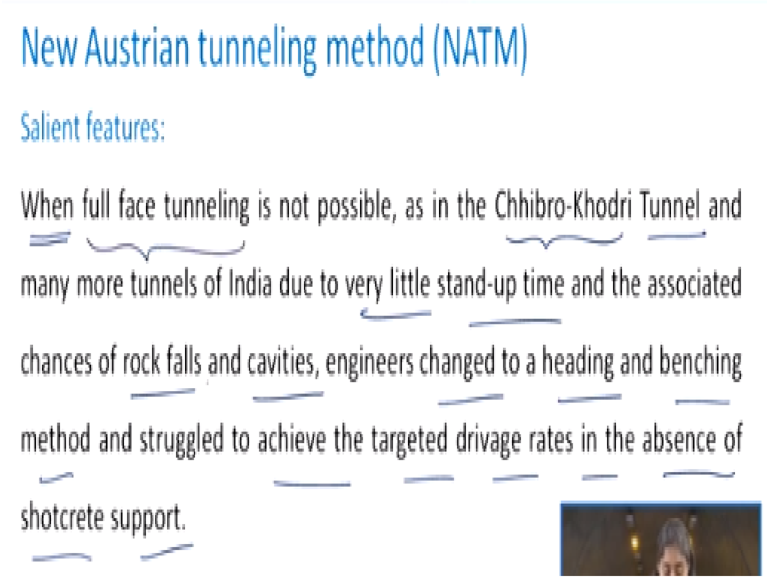

So, as I mentioned that in all the types of the rock mass the full face tunneling may not be possible. So, in case if it is not possible which is seen in many of the projects related to the tunnel construction in India. And, one name here I have mentioned is Chhibro-Kodri tunnel because of the rock mass quality, and hence very little stand-up time. In that case there are chances of the rock falls and the cavities what ingenious they do is they change to heading and benching method.

And, they really struggle to achieve the targeted drivage rates in the absence of the shotcrete support. So, it may not happen that for all the rock masses this is the best way to precede that is that you are able to go ahead with the full face tunneling, so if this is not there then we have few difficulties.

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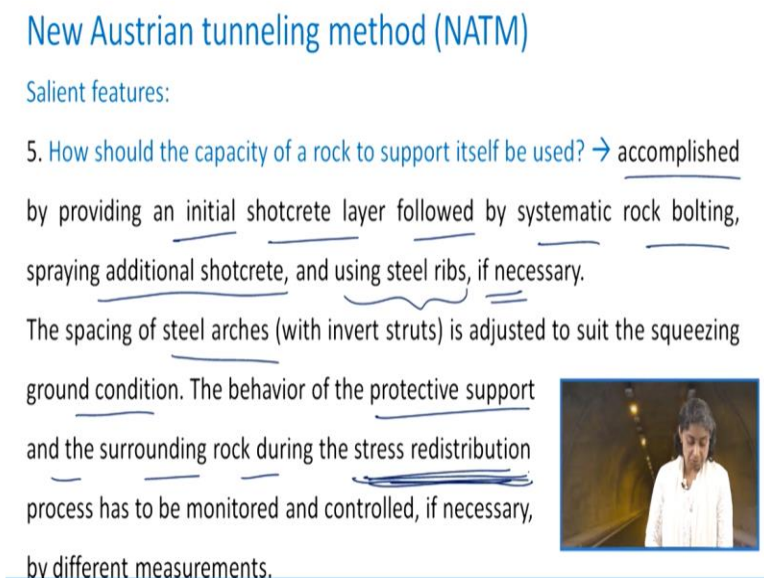

Now the question is, how should the capacity of the rock be used to support itself? that means as it was the principle of this philosophy NATM that it should be the self-supporting load member. So, this is accomplished by providing an initial shotcrete layer that is followed by systematic rock bolting. In this case spraying additional shotcrete and use of these steel ribs may also be there if it is necessary. Again, this will all depend upon the quality of the rock mass and the type of the excavation.

The spacing of steel arches within the inverted studs it is adjusted to suit the squeezing ground condition the behavior of the protective support and the surrounding rock. During the stress redistribution, process should be monitored and controlled by means of different measurement. Now, these measurements can be the measurement of the deformation the measurement of the in-situ stresses.

And, towards the end of this course in few classes I will tell you that, what all are the various instruments that are used for the measurement of deformation of the rock mass and also the stresses. So, why that monitoring and the instrumentation are important is this one of this reason that the behavior of the support system and the excavation should be observed during the stress redistribution process.

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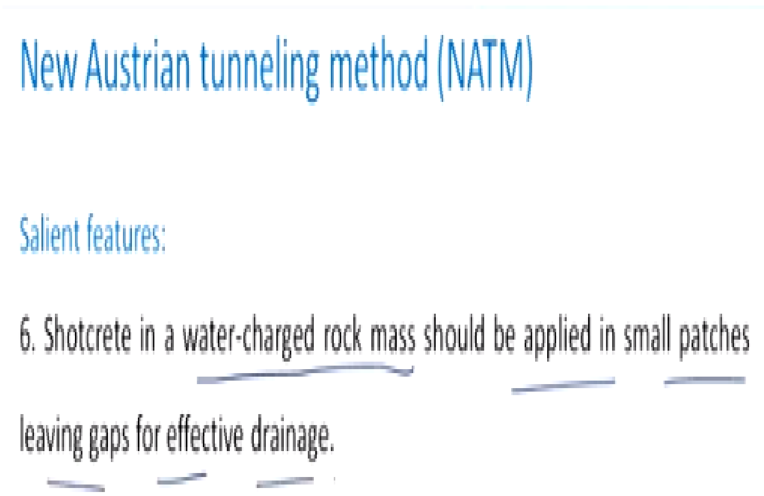

The shotcrete in a water-charged rock mass should be applied in small patches, leaving the gaps for effective drainage. Otherwise, because the rock mass is water charged the shotcrete will not get enough time to be hardened and start acting as a support system if the effective drainage is not there. The basic principles of NATM involve the mobilization of rock mastering. So, all I am going to do here is to summarize those, salient feature of NATM and the principles.

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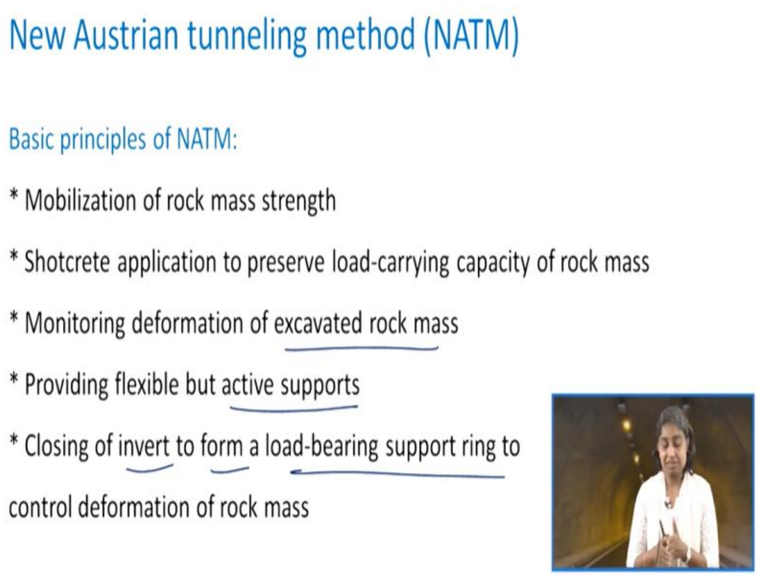

So, the first one is the mobilization of rock mass strength we saw that how this can be done. Then, the shotcrete application to preserve the load-carrying capacity of the rock mass, then the monitoring of the deformation of the excavated rock mass, we need to provide the flexible but active supports. So, it should not be that flexible that it is not able to restrain any deformation so we need to be careful.

Closing of inward to form a load bearing support ring to control the deformation of rock mass. So, you remember a tube will behave as a, as a tube only when its end is closed.

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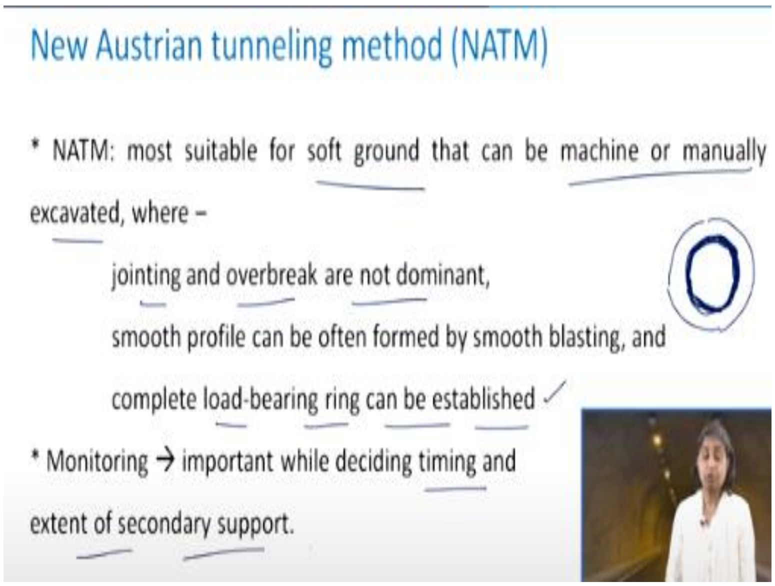

NATM is more suitable for the soft ground which can be machine or manually excavated, where jointing and over break they are not dominant. Where the smooth profiling can generally be formed by smooth blasting, smooth profile means upon the excavation. Of course, you will never get such a proper smooth surface it is going to be undulated but too many, undulation should not be there, more or less smooth profile should be there like this.

Complete load bearing ring, can be established like this, when you apply the shotcrete layer let us say here, in this manner, then this complete load bearing ring can be established. The monitoring is extremely important while deciding the timing and the extent of the secondary support system.

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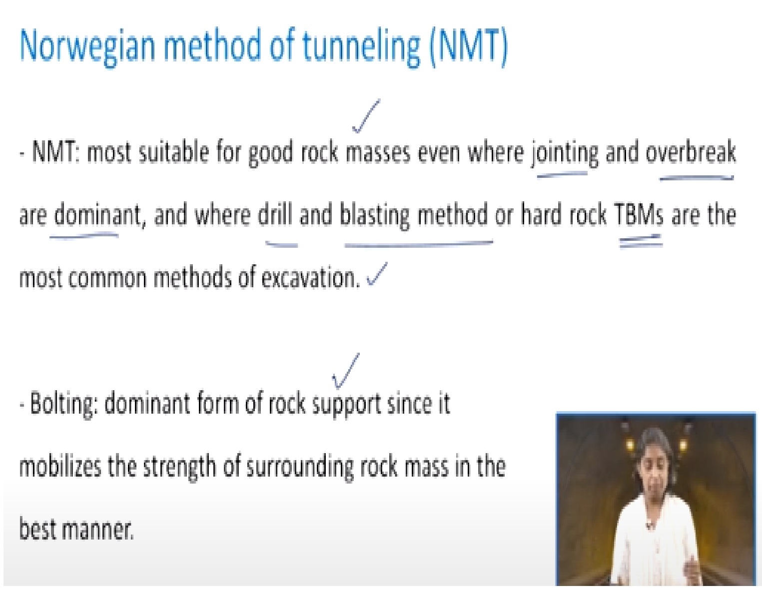

So, this was all about NATM, there is another method which is Norwegian method of tunneling we call in short as NMT. So, NMT is more suitable for good rock masses even where jointing and over break they are dominant. And where drill and blasting method or hard rock tunnel boring machines that is TBM's are the most common methods of excavation. In this case, the rock bolting is the dominant form of the rock support since it mobilizes the strength of the surrounding rock mass in the best possible manner.

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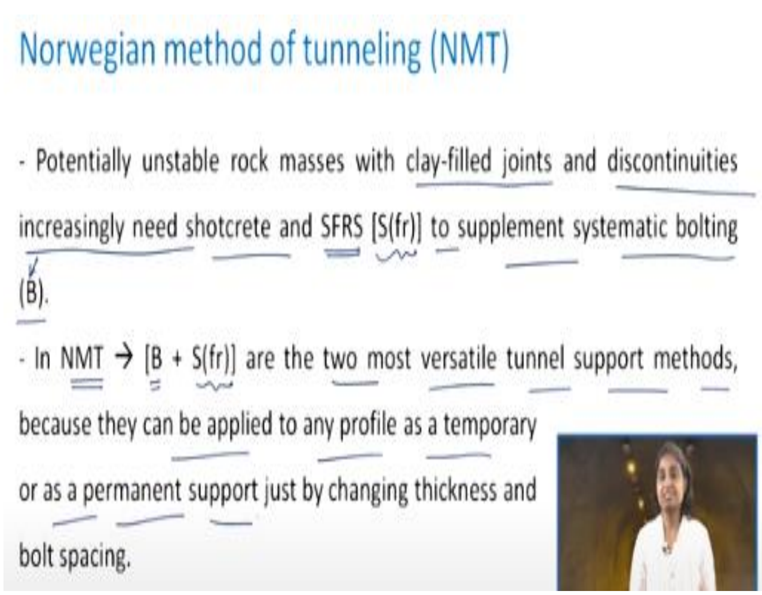

Potential unstable rock masses with clay-filled joints and discontinuities increasingly need shotcrete plus SFRS, that is a fiber-reinforced shotcrete to supplement systematic bolting which is represented by B. You remember I showed you a figure with reference to these various support systems and the Q. So, these correspond to that particular figure which we will be discussing once again here.

Then in Norwegian method of tunnelling, this systematic bolting plus SFRS they are the 2 most versatile tunnel support methods, because these can be applied to any profile as a temporary, or as a permanent support just by changing the thickness and the bolt spacing.

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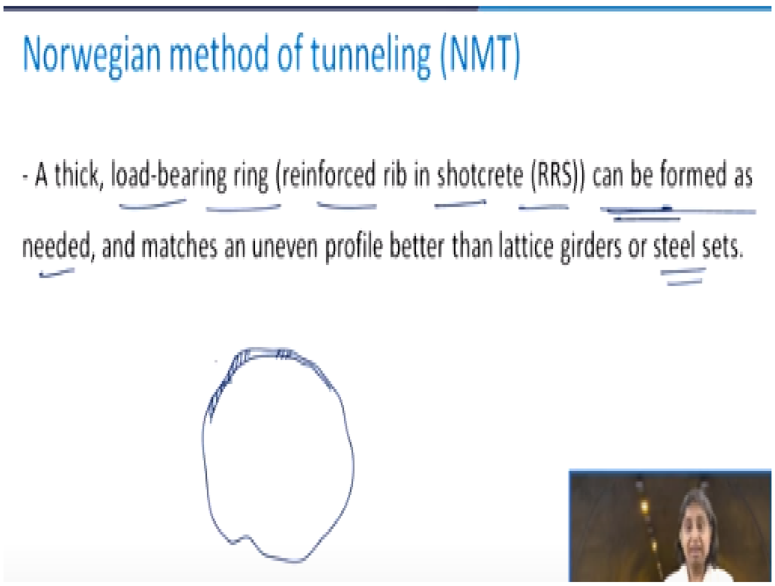

Thick load-bearing ring, which is reinforced rib in the shotcrete this can be formed as needed and it matches an uneven profile better than the lattice girder or steel set. So, you see that let us say the profile is something like this the excavated although this is again very smooth. But then when you are providing, let us say the steel set, so steel sets are going to be very nice girders which will be very smooth and see if you are going to provide.

So, what about these wherever these undulations are there these steel sets they will not be in touch with the excavated boundary. So, in that case, here this is a thick load bearing ring can be formed as and when needed, because it matches better as compared to steel sets or lattice girders.

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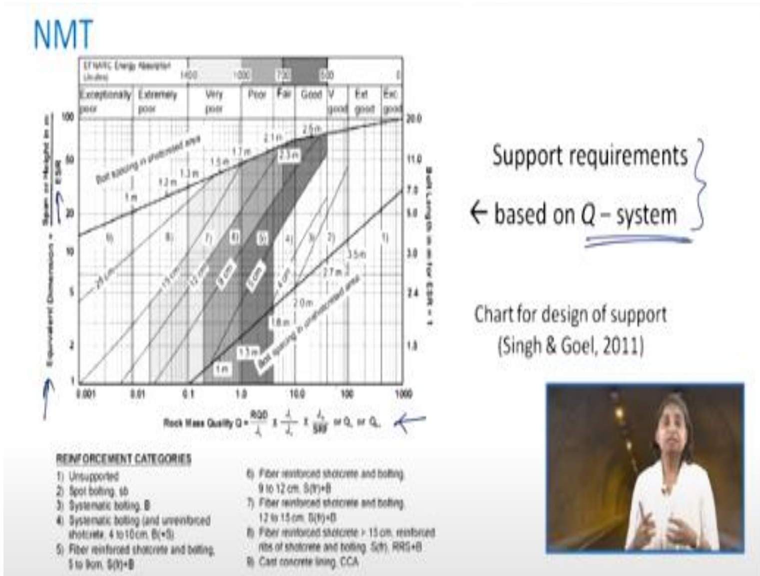

As I mentioned that I will come back to this figure again so here it is the support requirements which, is based on Q system I have already explained you this on the x-axis you have Q, y axis you have equivalent dimension. Which can be determined if you know the type of excavation and the size of the excavation. So, this is how we can choose what is going to be the most appropriate support system for a particular condition of course it is based on Q system. So, you see how these classification systems are applicable in the design of underground excavations.

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Norwegian method of tunneling (NMT)

Essential features of NMT (Singh & Goel, 2011)

S. No.	Features
1.	***Areas of usual application***
	Jointed rock, harder end of scale (q_c = 3-300 MPa)
	Clay-bearing zones, stress slabbing (Q is 0.001 to 10)
2.	***Usual methods of excavation***
	Drill and blast hard rock, TBM, hand excavation in clay zones
3.	***Temporary support and permanent support may be any of the following***
	Cast concrete arches (CCA), S(fr)+RRS+B, B+S(fr), B, S(fr), S, spot bolting (sb), None
	Temporary support forms part of permanent support
	Mesh reinforcement not used
	Dry process shotcrete not used
	Steel sets or lattice girder not used, RRS used in clay zones
	Contractor chooses temporary support
	Owner/consultant chooses permanent support
	Final concrete lining less frequently used, i.e., B+S(fr) is usually the final support

Coming to the essential features of Norwegian method of tunneling, the features include that there can be the areas of usual applications where jointed rock, harder end of scale Qc varies between 3 to 300 mega Pascal. Then you can have clay bearing zones or stress slabbing where Q is as low as 0.001 and goes high to 10 only here.

Usual methods of excavations which are there to be used in NMT is drill and blast hard rock, then TBM hand excavation in clay zones. What all are the temporary supports and permanent supports, which are used in NMT, these include cast concrete arches, then SFRE, bolting etc this we discussed. Temporary support, forms the part of the permanent support mesh reinforcement is not used in this case, dry process shotcrete is also not used.

So, you see that when the shotcrete is made there is, there are 2 processes one is the dry another one is the wet, so we will discuss all these things little later when we discuss the various support systems. The steel sets or the lattice girder they are not used, but RRS is used in clay zones. Contractor may choose the temporary support, and owner or consultant chooses the permanent support. So, the final concrete lining is less frequently used that is usually b+ that means bolting plus SFRS is usually the final support system in case of Norwegian method of tunneling.

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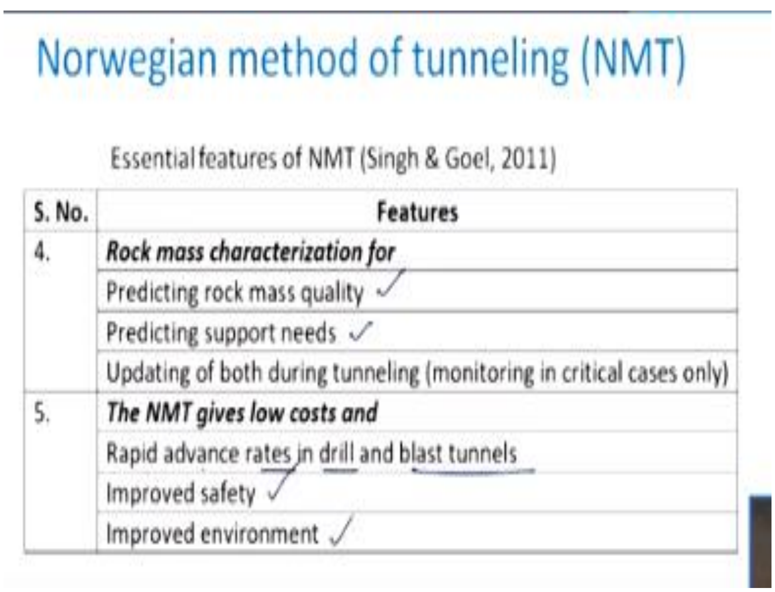
Norwegian method of tunneling (NMT)

Essential features of NMT (Singh & Goel, 2011)

S. No.	Features
4.	***Rock mass characterization for***
	Predicting rock mass quality
	Predicting support needs
	Updating of both during tunneling (monitoring in critical cases only)
5.	***The NMT gives low costs and***
	Rapid advance rates in drill and blast tunnels
	Improved safety
	Improved environment

So the, another essential feature for Norwegian method of tunneling is that the rock mass characterization is for the prediction of rock mass quality, and also for the support need. And then in case, if there are critical cases the continuous monitoring is done, and therefore even during the tunneling both of these that means rock mass quality and the required support system may be updated based upon those monitoring cases.

The NMT gives low cost, and there are rapid advance rates in the drill and blast tunnels, there is improved safety, and also the improved environment when we go for the NMT. So, this is what we I wanted to discuss with you as far as the application of rock mass quality Q system is concerned to the design of the underground excavations. Apart from this we also learnt about new Austrian tunneling method and Norwegian method of tunneling. Now, in the next class we will discuss few aspects related to the modulus of deformation, thank you very much.