Underground Space Technology
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Module No # 07
Lecture No # 34
Tunnel Hazards

Hello everyone, in the previous class, we discussed the application of the rock mass classification system, that is, RMR in the case of the underground excavation design. And today, we will take up some aspects related to tunnel hazards, and then we will try to connect it with another classification system, which is the rock mass quality that is the Q system.

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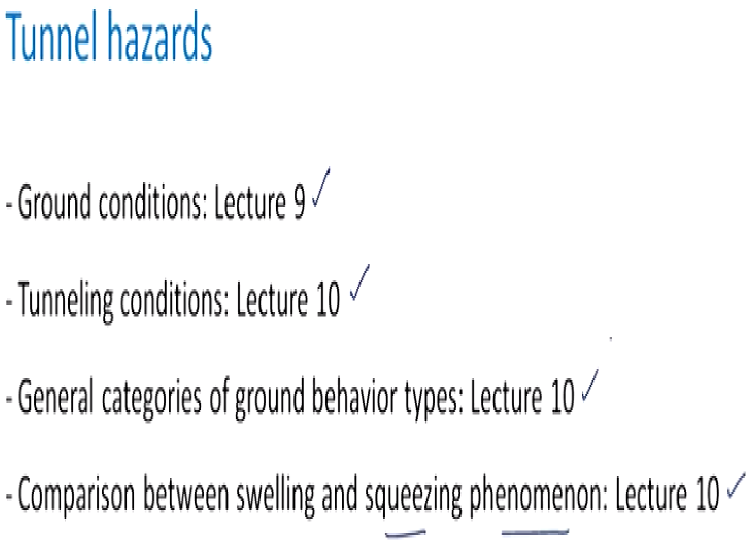

So, before we go to that, we have already discussed the ground conditions in lecture number 9 of this course and then tunneling conditions in lecture number 10. We also discussed the general categories of ground behavior types and the comparison between swelling and squeezing phenomena in lecture number 10. So, when we discuss tunnel hazards, I will be referring to some of the terms that we discussed in lectures 9 and 10. If you have forgotten, that maybe you can refer back to these two lectures of the same course.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
1	Ground collapse	Ground collapse near the portal	During the excavation of the upper half section of the portal the tunnel collapsed and the surrounding ground slid to the river side	Ground collapse was caused by the increase of pore water pressure due to rain for five consecutive days	- Installation of anchors to prevent landslides - Construction of counterweight embankment, which can also prevent landslide - Installation of pipe roofs to strengthen the loosened crown

So, quality aspects that are related to tunnel collapse that is what we are going to discuss. So, various types of tunnel collapse have been considered here and corresponding to each type. The phenomena have been explained, and what was the cause of that type of collapse that is also there and all the remedial measures that are to be adopted are also mentioned. So, we are going to discuss these in detail before we go to the Q-system.

So, the first one is related to the ground collapse, and then the ground collapse can also be for different categories. So, we take the various types of this. So, first, we discuss the type when the ground collapses near the bottle. You know what the portal is? We discussed it in some of the earlier classes. So, what are the phenomena that take place when the ground collapses near the portal?

So, during the excavation of the upper half section of the portal, the tunnel collapsed, and the surrounding ground it just slid to the riverside. So, the ground collapse was caused by the increase of the pore water pressure due to rain for five consecutive days. So, in case such a situation occurred. So, this caused this type of phenomenon, resulting in this type of ground collapse. So, what was the remedial measure that was adopted?

That was the installation of anchors to prevent the landslides and then the construction of counterweight embankments, which can also prevent landslides. The installation of pipe roofs to strengthen the loose-end crown is also one of the remedial measures to handle such type of ground collapse.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
3	Ground collapse	Collapse of the crown of cutting face	10 to 30 m^3 of soil collapsed and supports settled during excavation of the upper half section	The ground loosened and collapsed due to the presence of heavily jointed fractured rock mass at the crown of the cutting face, and the vibration caused by the blasting for the lower half section (hard rock)	- Roof bolts were driven into the ground to stabilize the tunnel crown - To strengthen the ground near the portal and talus, chemical injection and installation of vertical reinforcement bars were conducted

Now, the second type of ground collapse includes the landslide near the portal. So, in this case, what happens? That the cracks appeared in the ground surface during the excavation of the side drift of the portal, and the slope near the portal gradually collapsed. So, the cause of these phenomena was the excavation of the toe of the slope composed of strata which was disturbed by the stability of soil, and the excavation of the side drifts basically loosened this natural ground which resulted to the landslide.

So, the remedial measure which can be adopted for this situation was the case on type pile foundations were constructed to prevent this unsymmetrical ground pressure, and the vertical reinforcement bars were driven into the ground to increase its strength. The third type of ground collapse included the collapse of the crown of cutting phase. This included the phenomena that 10 to 30 meters cube of soil it collapsed, and the supports which were provided it settled during the excavation of the upper half section.

The cause of this phenomena was that the ground loosened, and the collapse had took place due to the presence of heavily jointed fractured rock mass at the crown of the cutting face and the vibration that is caused by the blasting for the lower half section case of the hard rock. The remedial measure which were adopted in such situation was that the roof bolts were driven into the ground to stabilize the tunnel crown and strengthen the ground near the portal and talus. The chemical injection and installation of vertical reinforcement bars were conducted.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
4	Ground collapse	Collapse of the fault fracture zone	After completion of blasting and mucking, flaking of sprayed concrete occurred behind the cutting face, following which 40 - 50 m^3 of soil collapsed along a 7 m section from the cutting face; later it extended to 13 m from the cutting face and the volume of collapsed soil reached 900 m^3	The fault fracture zone above the collapsed cutting face loosened due to blasting, and excessive concentrated loads were imposed on supports, causing the shear failure and collapse of the sprayed concrete	- Reinforcement of supports behind the collapsed location (additional sprayed concrete, additional rock bolts) - Addition of the number of the measurement section - Hardening of the collapsed muck by chemical injection - Air milk injection into the voids above the collapsed portions - Use of supports with a higher strength

Coming to the fourth category of ground collapse, that is the collapse of the fault fracture zone. So, you see that all these are falling under the category of ground collapse. But then these are all different components, and they have to be treated in different manners. So, the phenomena that took place when the collapse of the fault fracture zone takes place is that, after the completion of blasting and mucking, flaking of the sprayed concrete occurred behind the cutting phase following which 40 to 50-meter cube of soil collapsed.

Along with the 7-meter section from the cutting phase and later it was extended to 13 meters from the cutting phase, and then, of course, the volume of the collapsed soil will also increase, and it reached as high as a 900-meter cube. So, the cause for this type of phenomenon was that the fault fracture zone above the collapsed cutting phase, it loosened due to blasting, and the excessive concentrated load were imposed on these supports causing the shear failure and collapse of the sprayed concrete.

So, which was provided as the support as a layer of concrete or the shotcrete so that failed. The remedial measure which was adopted was the reinforcement of the supports behind the collapsed section, which means additional sprayed concrete and additional rock bolting are to be done, then addition of the number of the measurement section. See, when we go for the excavation, one need to go for instrumentation as well as monitoring.

So, one can go for the large number of sections that are instrumented, and the monitoring can take place. So, hardening of the collapsed rock mass by the chemical injection was also one of the remedial measures and then air milk injection into the voids above the collapsed portions, then use of the supports having the higher strength.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
5	Distortion of supports	Distortion of tunnel supports	During excavation by the full face tunneling method, steel supports considerably settled and foot protection concrete cracked	Bearing capacity of the ground at the bottom of supports decreased due to prolonged immersion by groundwater	- Permanent foot protection concrete was placed to decrease the concentrated load - An invert with drainage was placed

Then the next category of failure is the distortion of these supports. So, the type includes here is the distortion of the tunnel supports. The phenomena that can take place which causes this distortion of the tunnel supports is that during the excavation by the full-face tunneling method, steel supports were considerably settled, and foot protection concrete it just got cracked. So, the cause of this was that the bearing capacity of the ground at the bottom of the supports it reduces due to the prolonged immersion by groundwater.

We all know that the bearing capacity of the foundation or the shear strength parameter of the ground, how they reduce if they are exposed to the groundwater, so similar type of cause was there to trigger this phenomenon. The permanent food protection concrete was placed to reduce the concentrated load, and an invert with drainage was placed. So, that if there is a release of the pore water pressures, it will help.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
6	Distortion of supports	Distortion of lining concrete due to unsymmetrical ground pressure	During the excavation of the upper half section, horizontal cracks ranging in width from 0.1 to 0.4 mm appeared in the arch portion of the mountainside concrete lining, while subsidence reached the ground surface on the valley side	Landslide was caused due to the steep topography with asymmetric pressure and the ground with lower strength, leading to the oblique load on the lining concrete	- Earth anchors were driven into the mountainside ground to withstand the oblique load - Ground around the tunnel was strengthened by chemical injection; subsidence location was filled

The second category under the distortion of the supports includes the distortion of the lining concrete due to unsymmetrical ground pressure. The phenomenon that took place was during the excavation of the upper half section. The horizontal cracks appeared which were ranging in width from 0.1 to 0.4 mm in the arch portion of the mountainside concrete lining, while the subsidence took place on the valley side.

So, this landslide was caused due to steep topography with asymmetric pressure and the ground with lower strength. All these lead to the oblique load on the concrete lining. So, the remedial measures which were adopted include earth anchors, driven into the mountainside ground to withstand the oblique load, and the ground around the tunnel was strengthened by chemical injection therefore, the subsequent location was filled.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
7	Distortion of supports	Distortion of tunnel supports due to swelling pressure	Hexagonal cracks appeared in the sprayed concrete and the bearing plates for rock bolts were distorted due to the sudden inward movement of the side walls of the tunnel	Large swelling pressure was generated by swelling clay minerals in mudstone	- Sprayed concrete and face support bolts on the cutting face were provided to prevent weathering - A temporary invert was placed in the upper half section by spraying concrete

The third category of the distortion of supports includes the distortion of tunnel supports due to swelling pressure. So, wherever this kind of situation will come wherever, you have the minerals which have the tendency to expand in volume in the presence of moisture or water. So, there you will observe this type of tunnel collapse. The reason was that the phenomena that took place were the hexagonal cracks that appeared in the sprayed concrete and the bearing plates for rock bolts were distorted due to sudden inward movement of the side walls of the tunnel being the swelling ground condition.

Now, in this case, what is the cause here, it is very obvious that there was large swelling pressure which was generated because of the presence of swelling clay minerals in mudstone. So, the remedial measure which was adopted included the sprayed concrete and face support bolts on the cutting face to prevent the weathering. Then a temporary invert was also placed in the upper half section by spraying the concrete.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
8	Distortion of supports	Heaving of a tunnel in service	Heaving occurred in the pavement surface six months after the commencement of service, causing cracks and faulting in the pavement. Heaving reached as large as 25 cm	A fault fracture zone containing swelling clay minerals, which was subjected to hydrothermal alteration, existed in the distorted section; plastic ground pressure caused by this fracture zone concentrated on the base course of the weak tunnel section without invert	- To restrict the plastic ground pressure, rock bolts and sprayed concrete were applied to the soft sandy soil beneath the base course - Reinforced invert concrete was placed

Then the next category of the distortion of the support includes the heaving of a tunnel in service. So, this heaving occurred on the pavement surface 6 months after the commencement of the service. This caused cracking and faulting in the pavement, and the heaving reached as high as 25 centimeters. So, you can imagine that when the heaving takes place, it is as large as 25 centimeters.

So, obviously the cracks are going to come. The cause for this type of phenomenon was that a fault fracture zone containing swelling clay minerals was subjected to hydrothermal alteration. It existed in the distorted section, and there was the plastic ground pressure which was caused by this fracture zone, which was concentrated on the base course of the weak tunnel section without inverting.

So, wherever the invert was not provided in the base course of the weak tunnel section, there was the fracture zone. So, the remedial measure which was adopted was to first restrict the plastic ground pressure, and for this the rock bolts were provided, and the concrete was sprayed this was applied to the soft sandy soil beneath the base coarse. And in this case, the reinforced inward concrete was also placed.

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Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
9	Adverse effects on the surrounding environment	Adverse effects of vibration due to blasting on the adjacent existing tunnel	During the construction of a new tunnel, which runs parallel to the side wall of the existing portal, cracks appeared in the lining (made of bricks) of the existing tunnel	The voids behind the existing tunnel loosened and the lining was distorted due to the vibration of the blasting for construction of the new tunnel	- Steel supports and temporary concrete lining were provided to protect the existing tunnel - Backfill grouting was carried out - Excavation was carried out by the non-blasting rock breaking method and the limit for chemical agent was set to mitigate the vibration

Now, the third category involves the adverse effects on the surrounding environment, and the type corresponding to this is the adverse effect of vibration due to blasting on the adjacent existing tunnel. So, let us say there is one tunnel, and you are going for the other one in the vicinity of that, and for that, you have to go for the blasting. So, once the blasting takes place, vibrations are going to be generated, and that will influence the adjacent existing tunnel.

So, during the construction of a new tunnel that was to run parallel to the side wall of the existing portal, cracks appeared in the lining, which was made of bricks of the existing tunnels. The cause behind this was the voids behind the existing tunnel loosened, and the lining was distorted due to the vibration of the blasting for the construction of the new tunnel. So, the remedial measures which were adopted were the provision of steel supports and temporary concrete lining to protect the existing tunnel.

Then backfill grouting was also carried out. Then the excavation was carried out by non-blasting rock-breaking method, and the limit for the chemical agent was set to mitigate the vibration.

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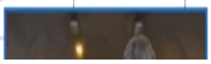
Quality aspects related to tunnel collapse

S. no.		Type	Phenomenon	Cause	Remedial measures
10	Adverse effects on the surrounding environment	Ground settlement due to the excavation for dual-tunnel directly beneath residential area	Considerable distortion of supports occurred in the embankment section; although additional bolts were driven into the ground and additional sprayed concrete was provided, ground surface settlement exceeded 100 mm	Since the soil characteristics in the embankment section were worse than expected, the ground settlement was considerably increased by the construction of tunnels following the dual-tunnel	- Pipe roofs were driven from inside the tunnel to reduce ground surface settlement



The second category under this type is the ground settlement due to the excavation for dual tunnel directly beneath the residential area. So, this is a very crucial and risky. This phenomenon took place as the considerable distortion of the support occurred in the embankment section. Although additional bolts were driven into the ground, and additional sprayed concrete was also provided.

But then still the ground surface settlement exceeded 100 mm, and just imagine that case if this high ground surface settlement is there and residential areas are there. What will happen? So, the cause behind this phenomenon was that the soil characteristic in the embankment section was worse than expected. The ground settlement was considerably increased by the construction of the tunnels following the dual tunnel.

So, in this case, the remedial measure which was adopted included the driving of pipe roofs from inside the tunnel to reduce the ground surface settlement.

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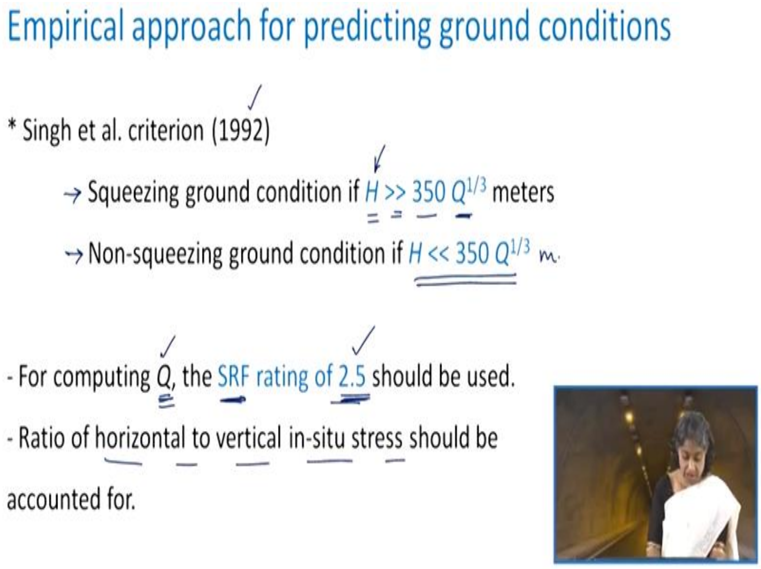

This was all about some of the tunnel hazard. Now I will connect some of these situations to the next rock mass classification system, which is the Q system. So, we have the empirical approaches first for the prediction of the ground condition. So, one of such criteria was given by Singh et al. in 1992. So, they mentioned that there is going to be the presence of the squeezing ground condition.

$$H \gg 350Q^{1/3}$$

Here, H is the depth of the overburden or height of the overburden and the depth of the tunnel top from the ground surface. Q is the rock mass quality. In case of the non-squeezing ground conditions, you will have this condition satisfied that H will be:

$$H \ll 350Q^{1/3}$$

Again, this is in meter. So, for computing the Q, the SRF rating of 2.5 should be used. Kindly recall our discussion on the computation of Q. If you look back to the some of the previous lectures, you will realize that you needed 6 parameters and the corresponding rating for computation of Q. So, there one factor was SRF stress reduction factor. So, its rating will be assigned as 2.5 for the computation of Q. Further, the ratio of horizontal to vertical in situ stress should also be accounted for.

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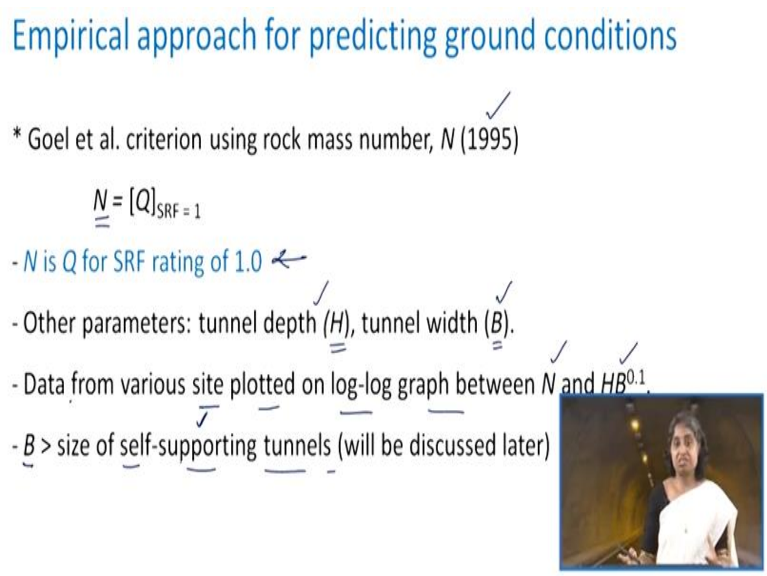

Further, Goel et al. gave the criterion using the rock mass number N, in 1995. Now, this rock mass number N is nothing but the value of Q when you have SRF to be equal to 1.

$$N = [Q]_{SRF=1}$$

So, N is nothing but Q for the SRF rating to be equal to 1. The other parameters which are coming into the picture include the tunnel depth H and the tunnel width B. Now, this data from the various sides were plotted on the log-log graph between N and H into B to the power 0.1, where B is more than the size of self-supporting tunnels.

Now, what are these self-supporting tunnels? We will discuss little later. But the name is self-explanatory, that the ground conditions are very good. So, you do not need a typically very good support system for such tunnels. So, just a nominal support system is needed.

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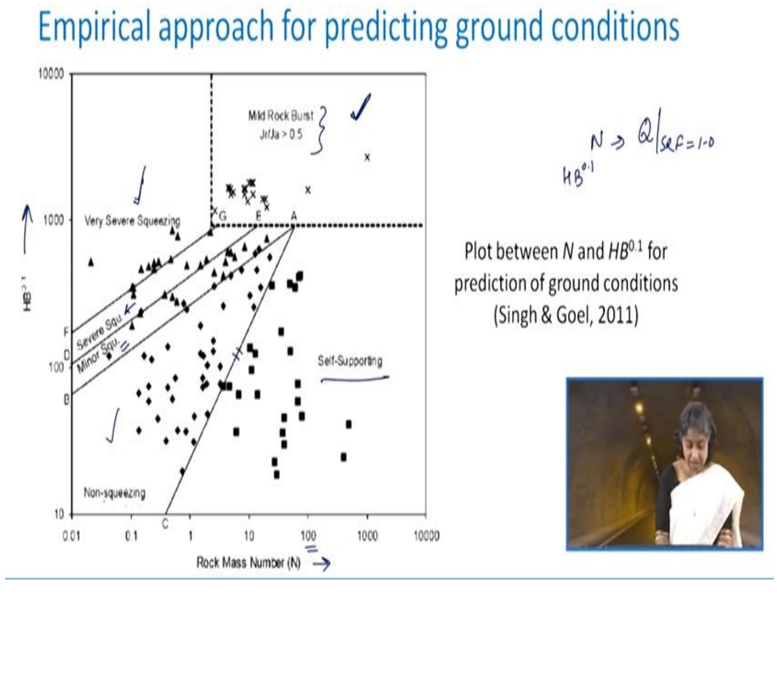

So, this was the plot that was given by these research workers. So, you can see that on the x-axis, we have the rock mass number. What is this rock mass number? It is Q when SRF = 1 or the rating for SRF is 1. So, this is plotted on the x-axis using the log scale, and another quantity that is H into b to the power 0.1 is plotted on the y-axis. Again, this is on log scale. So basically, it is the log-log plot. So, a lot of data related to the prediction of the ground conditions were plotted on to this, and then clear cut a few demarcations have been made.

For example, if the point or if the situation is lying below the line CA, then it is a self-supporting tunnel. In case it is between CA and BA, it is a non-squeezing ground condition. If it is between DE and BA, it is minor squeezing followed by severe squeezing. If the point falls between FG and DE and beyond FG it is very severe squeezing.

Plus, they also came out with the situation where the point lies in this rectangular zone on the top right portion of this plot. Then there is the prediction of a mild rock burst with J_r upon J greater than 0.5. So, let us understand these things in more detail.

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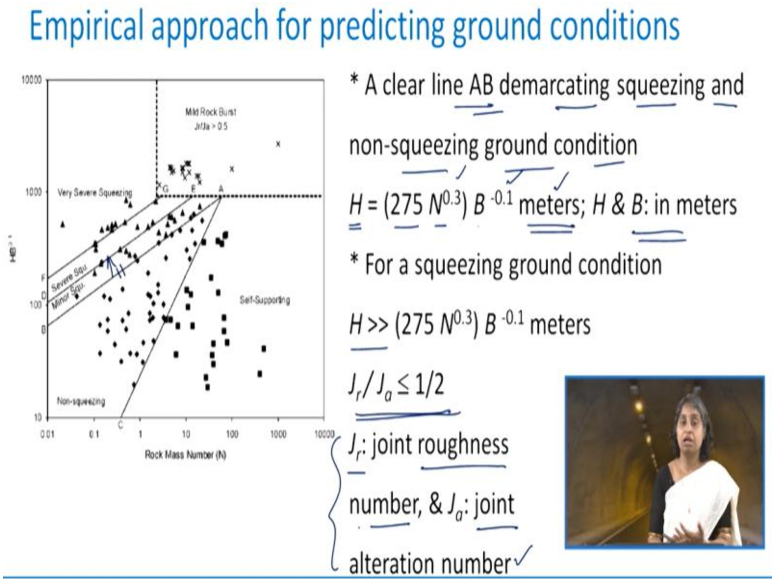

So, a clear line AB is there. See, this is AB is there which is demarcating squeezing and non-squeezing ground condition. The equation of this is:

$$H = (275N^{0.3})B^{-0.1}$$

Please remember we are dealing with the empirical approaches, and so the units are going to be extremely important. So, both H and B will be in meters. For the squeezing ground condition, H should be greater than this, obviously.

$$H \gg (275N^{0.3})B^{-0.1}$$

$$J_r/J_a \leq 1/2$$

See here, beyond this it is the squeezing ground condition and J_r upon J must be less than or equal to 0.5 where J_r is the joint roughness number and J_a be the joint alteration number. If you want to know the definition of these and how these are assigned the values based upon the field situation? Maybe you can refer back to our discussion of the classification system of rock mass Q system.

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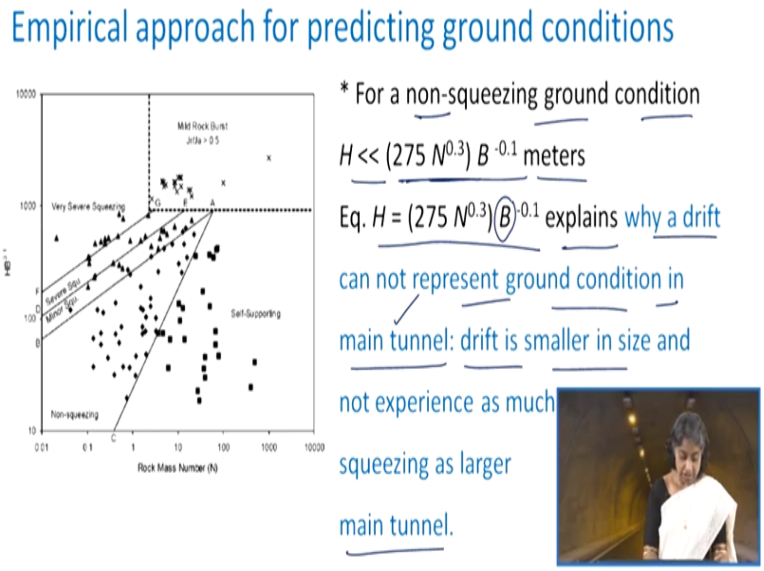

For the non-squeezing ground condition, H should be less than this expression again in meter.

$$H \ll (275N^{0.3})B^{-0.1}$$

$$H = (275N^{0.3})B^{-0.1}$$

So, this equation explains why a drift cannot represent the ground condition in the main tunnel. You know that the drift is the small tunnel that is driven to a certain some of the geological conditions. So, drift is basically smaller in size, and it will not experience as much squeezing as the larger main tunnel.

Because you see that here the size of the excavation comes into picture. So, therefore we cannot say that drift will represent the typical and proper ground condition for the main tunnel. So, you need to be extremely careful about it. So, this was all about the squeezing and the non-squeezing ground condition and how using these empirical approaches, you can demarcate between these ground conditions. So, in the next class, we will continue with the discussion, and we will study some aspects related to squeezing ground condition. Thank you very much.