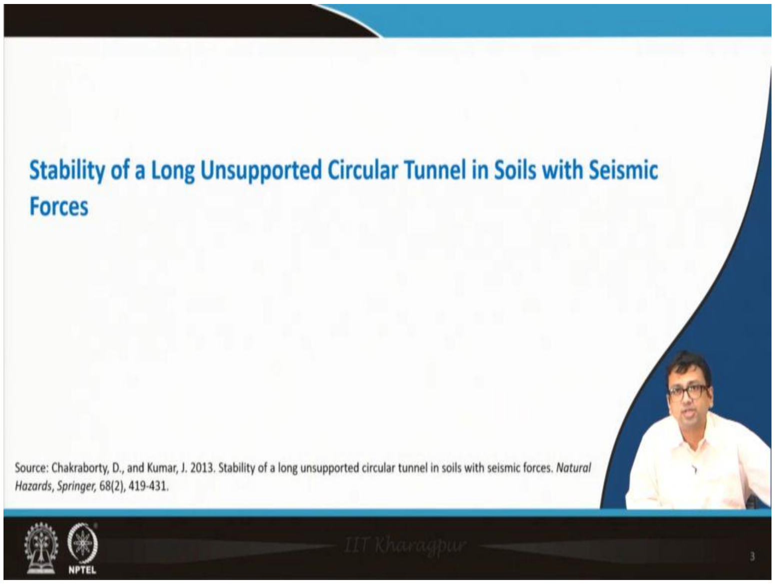
Rock Mechanics and Tunneling
Professor Debarghya Chakraborty
Department of Civil Engineering
Indian Institute of Technology, Kharagpur
Lecture – 56
Basic Concepts for Lined, Unlined and Pressure Tunnels (Continued)

Hello everyone, I welcome all of you to the fifth and last lecture of the module-11. So, in module-11 we are discussing about the analysis of stresses in tunneling. In addition, today we will continue our discussion related to the basic concept of lined, unlined and pressure tunnels. So, already I have discussed the basic things about these tunnels.

(Refer Slide Time: 00:51)

But today we will discuss about some of the recent research papers, research articles on this lined, unlined and pressure tunnels. Several researchers are working on this topic throughout the world. Here I will show you some of the work that I have done with my PhD supervisor and with my masters students and published in the International Journal; from this you will get better idea regarding the numerical modeling of the tunneling part.

(Refer Slide Time: 01:47)

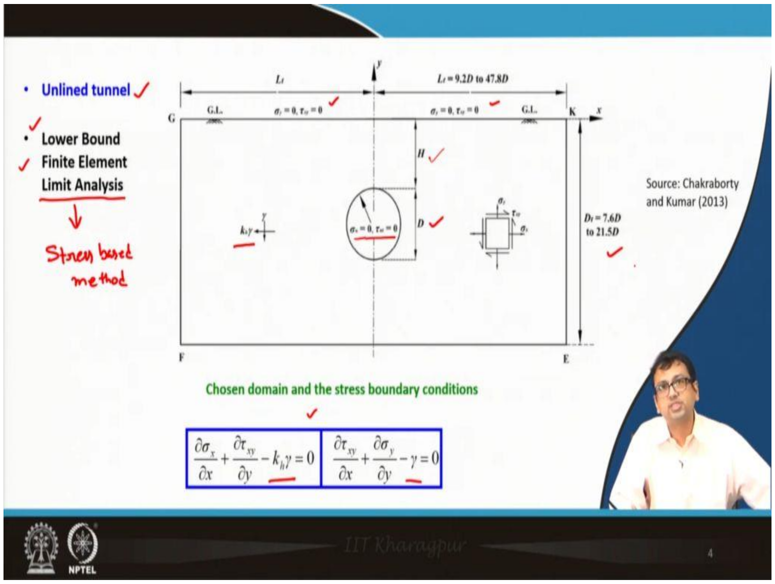


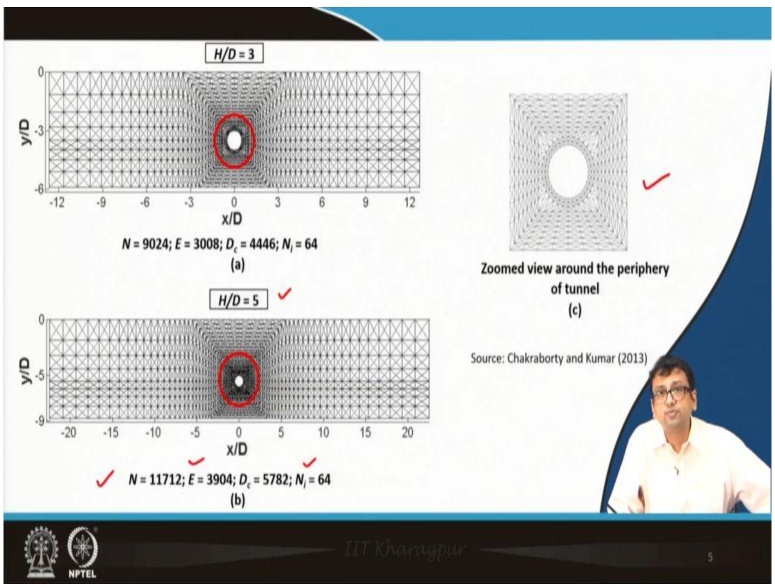
Although the analytical model of Kirsch’s is very useful and you get closed form solution but, there are several assumptions that are associated with it. Such as considering the material as linearly elastic, homogeneous, isotropic etc. and it may not be correct always; it can be taken into account in numerical modeling. Much more accurate model can be achieved for analyzing the tunnel stability. So, first I will discuss on the stability of long unsupported circular tunnel in soils with seismic forces.

We have till now discussed about analysis of tunnel under static condition. However, nowadays, the seismic design is take into consideration for the buildings; we go for the seismic design of the building depending on the zone in which the structure is to be constructed. Before designing, we go for the analysis. For regions with high chance of earthquakes, seismic analysis of the structure is performed instead of conventional static analysis.

In this lecture I have given a brief peek into numerical modeling and that technique.

(Refer Slide Time: 04:23)





You can explore few more international journal papers for recent research trends on the topic.

So, we considered an unlined tunnel and here for the analysis we have used lower bound finite element limit analysis. To learn this technique lot of time is needed and also it is beyond the scope of this course. This limit analysis is based on two limit theorems-lower bound theorem and upper bound theorem. Lower bound gives the conservative results. Generally, for foundation design also, if you try to find out the bearing capacity of the foundation, lower bound will always give you the conservative value. Upper bound will give you little bit more higher value than the actual one. So, anyway, it is always preferable to use this both this theorem together, to get a solution in bounded form. But, if you have to use only one equation, you should go for a lower bound, as it will give you the safe estimate.

Now, why I am using this method? Number one is finite element method; we have used the concept of finite element discretization. As well as the most important thing is you can a get a very good lower bound solution that can be very close to actually the actual or accurate solution, maybe within 1 or 2 percent lesser than the actual solution. It can happen that the collapse load maybe maybe 1 or 2 percent higher than the what estimated through this method.

Not only lower bound finite element limit analysis; you can go for normal displacement finite element modeling or different softwares are there like Flac which is based on the finite difference method. They are also used for the numerical modeling; and for finite element modeling, there are several softwares like, Abaqus, Ansys etc. is there.

Different software are there like Lexus that is also there.

I did the lower bound solution analysis by writing the code in my own in MATLAB only; mesh was generated as shown in the slide. H is the crown depth from the ground surface; D is the diameter of the tunnel. Limit analysis is stress-based method and here, one of the important requirement is to satisfy the equilibrium equation. So, we know the basic equilibrium equation from solid mechanics. So, in the horizontal direction, if earthquake is occurring then by using pseudostatic method, the effect of earthquake can be taken into account by considering a body force in the x direction as k_h into γ; where k_h is nothing but the horizontal earthquake acceleration coefficient and γ is the unit weight of the soil or rock, whatever you consider.

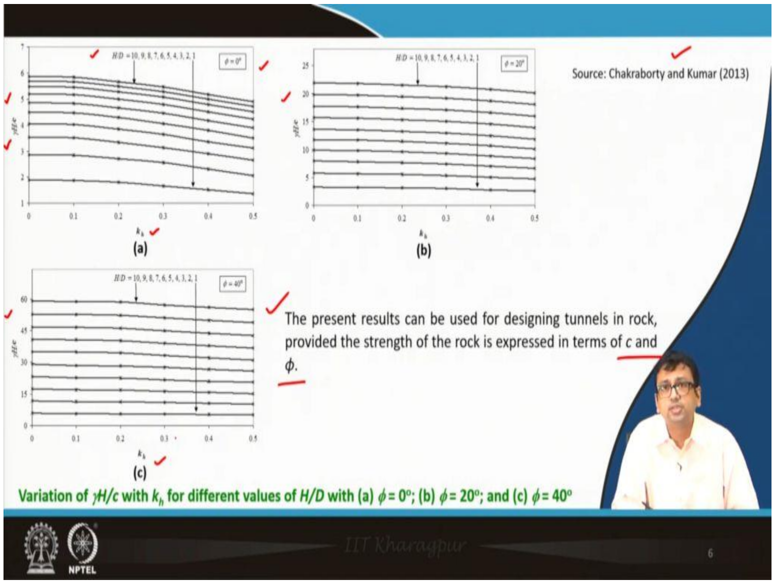
In lower bound limit analysis we present the problem as an optimization problem and we go for the solution. So, that is why the yield criteria, what we should be a convex one. So, here for the analysis, since it is in soil, the Mohr Coulomb yield criteria was utilized which is convex in nature.

In case of analytical modeling, we have to assume a failure surface in limit equilibrium method if you have to assume a failure surface. Whereas in finite element modelling, you do not have to assume any pre-assumed failure surface; that will come as the end product of your analysis. As failure surface is not predefined in case of numerical analysis; that is one of the biggest advantage.

Also you can incorporate heterogeneity in your model. Though in this study, we have not considered heterogeneity. I will show you the how failure surface is developing. So, the zoom view of the periphery of the tunnel is shown for different H/D ratio, corresponding number of nodes, elements, then nodes around at the tunnel boundary. Now, it is since it is an unlined tunnel, so along the periphery, normal and shear stresses are zero.

The domain is fixed based on boundary effects study; based on mesh convergence study, number of elements needed for finite element study is fixed.

(Refer Slide Time: 12:13)



Now, the end product plots are given in the paper if you follow it; you Here only three plots are shown by phi value of 0-degree, 20-degrees, 40 degrees. It is the variation of γH/c versus k_h. k_h is horizontal seismic coefficient; and γH/c is nothing but the stability number. γ is the unit weight of the material, and H is the crown depth from the ground surface and c is nothing but the cohesion of the soil.

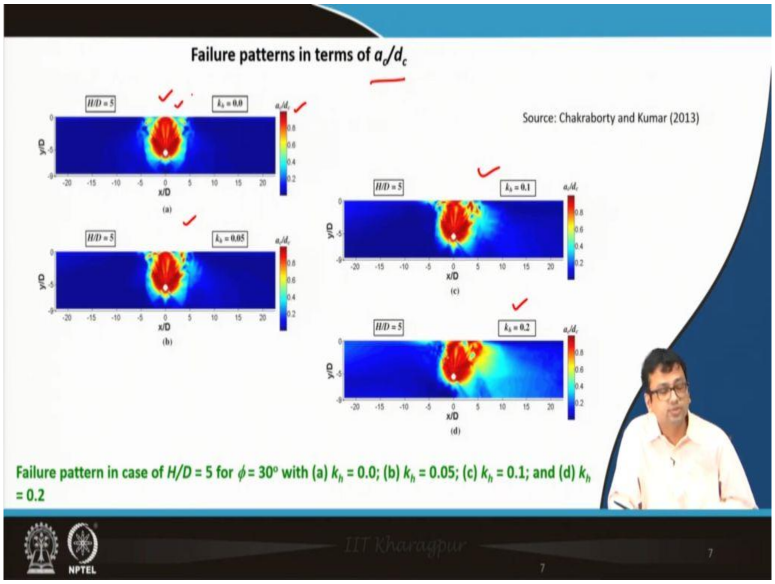
Now, for different phi, for different H/D ratio, the stability numbers are obtained. Stability number is in non-dimensional form it; so, for 0-degree, 20 degree and 40 degree plots are given. Since it is a non-dimensional form, so you can apply the results for any c and phi values.

If you know the c, phi parameters; then using the plots shown you can find out the stability number; so, that was the one objective of this study. So now, not only these results are given for soil but also can be used for designing tunnels in rock, provided the strength of the rock is expressed in terms of c and phi.

So, already I have explained how to find the equivalent c and phi values when we discussed about the failure criteria, Hoek brown yield criteria which is suitable for rock mass modeling.

Now, by using equivalent c and phi parameters value, you can use these plots; and you can obtain the stability number for different seismic acceleration coefficient as given from 0 to 0.5. 0 mean, it is static case.

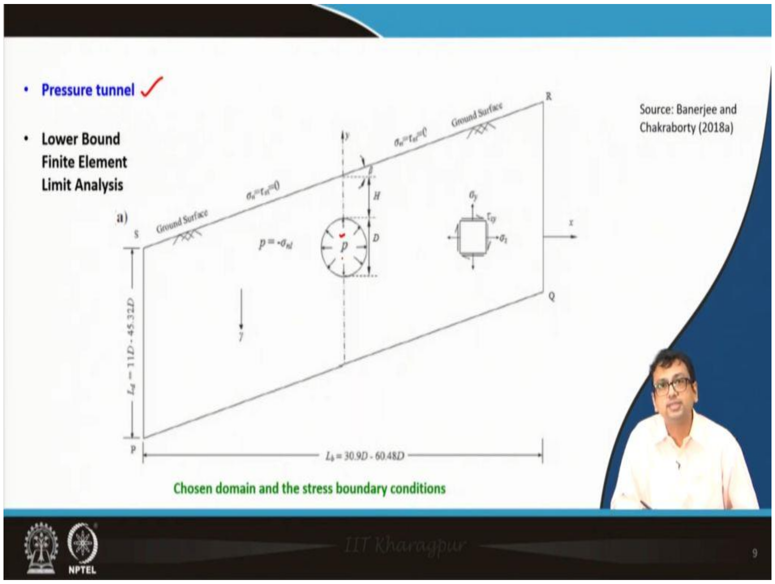
(Refer Slide Time: 15:34)

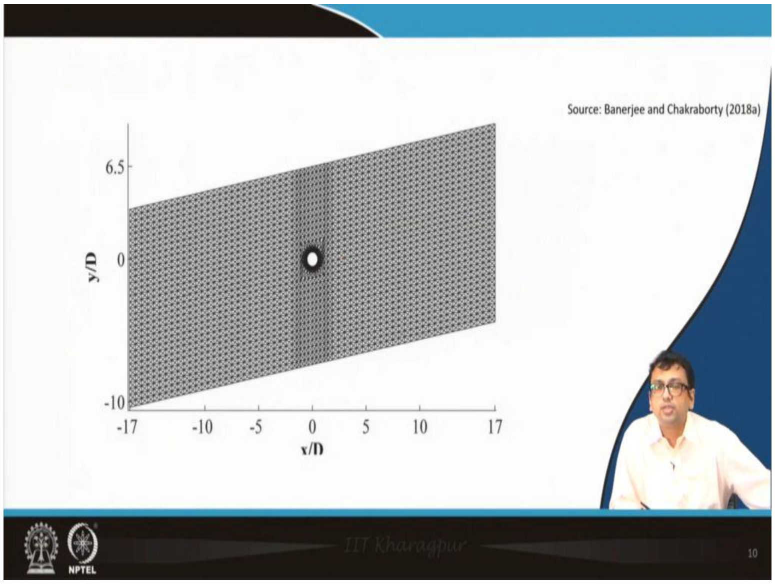


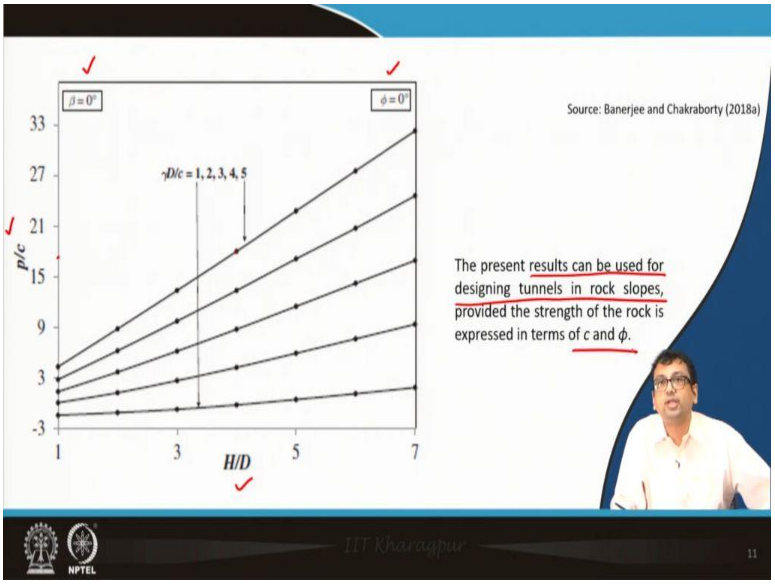
So, now we can see how the failure patterns look like. Now, here ac/dc is ratio that indicates plastic failure when it becomes one. Therefore, you can see deep red if it became 1. With k_H is 0, the failure pattern is very much symmetric.

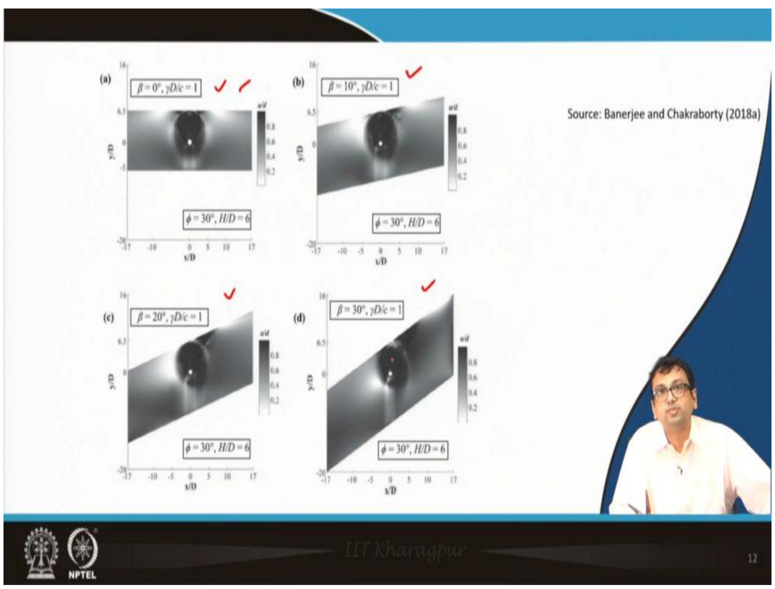
Now, with increasing k_H, it is gradually becoming asymmetric as expected. This diagram also indicates about how the stress distribution is occurring. So, you can identify where high stress zones are present.

(Refer Slide Time: 16:46)









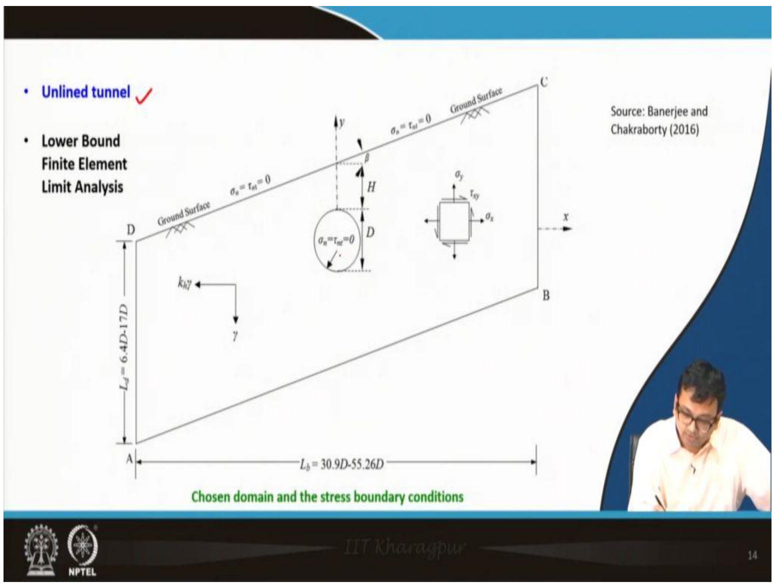
Now, stability of long circular tunnels in sloping grounds. This work is for a pressure tunnel. In our previous lecture only, we have discussed about pressure tunnel. So, a uniform pressure, P is applied; lower bound finite element limit analysis used for this problem also. Here also all the codes were written in MATLAB.

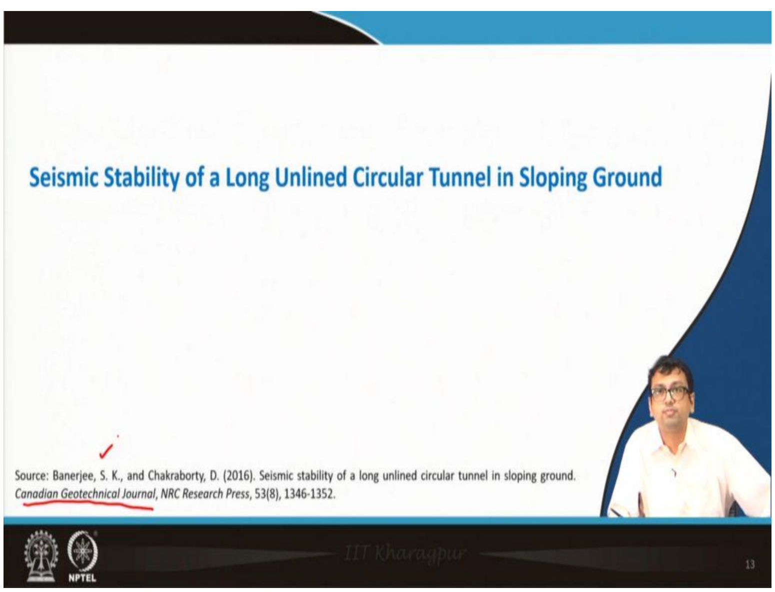
So, several types of design charts have been provided in this paper; but only one is presented here. phi is equal to 0 case, beta is equal to 0 case i.e. the horizontal ground; and now here H/D is 1 to 7. Now, for different γD/c, D is nothing but the diameter of the terminal, c is the cohesion. For different γD/c, what p/c, you should have to get the stability of the tunnel. For γD/c value, suppose 5 and H/D is equal to 4, what should be your p/c? You can get from design chart, which is around 16 or 17. Now, for a known c value for a particular site, you can obviously can find out the required p value i.e. the internal. Now, here also these results can be used for the designing tunnels and rock slopes, provided strength of the rock in terms of c and phi.

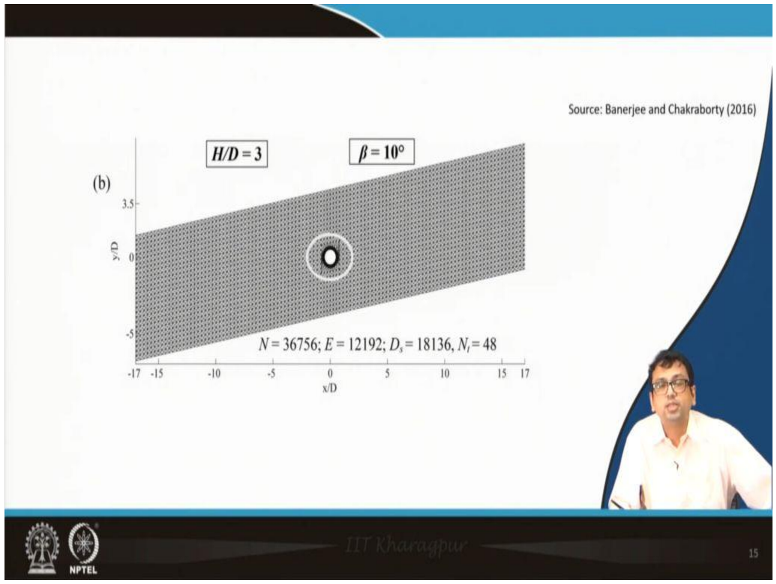
Various failure patterns are shown, beta=0, beta=10, 20, 30 etc. nad the change of pattern from symmetric to assymetric is observed.

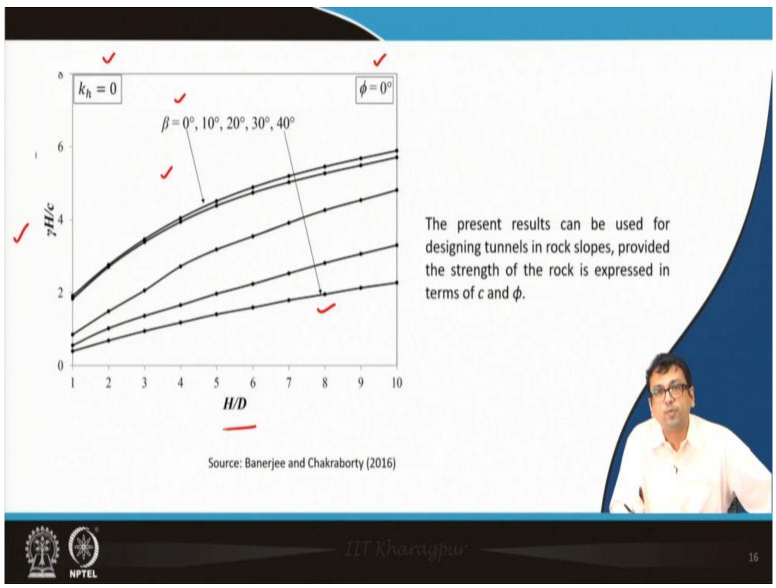
Now, seismic stability of long unlined tunnel. It is unlined tunnel in sloping ground.

(Refer Slide Time: 19:37)





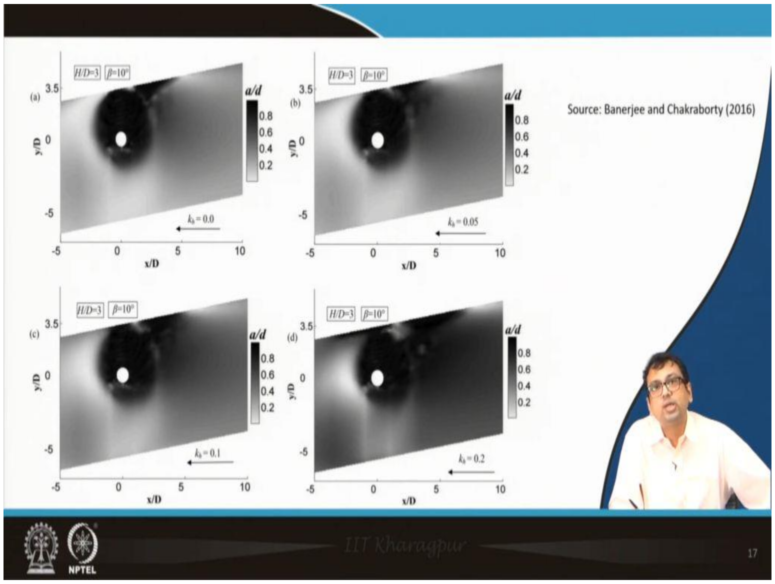




This is this was published in Canadian Geotechnical Journal; this is also one of my master's students. So, a typical finite element mesh was generated and here also I am showing you only one result. There we have provided results for different k_h values; but however, here it is only for k_h is 0 and phi is 0. I am showing for different beta; beta is the sloping angle. You see how with H/D, the stability number is changing for different beta values.

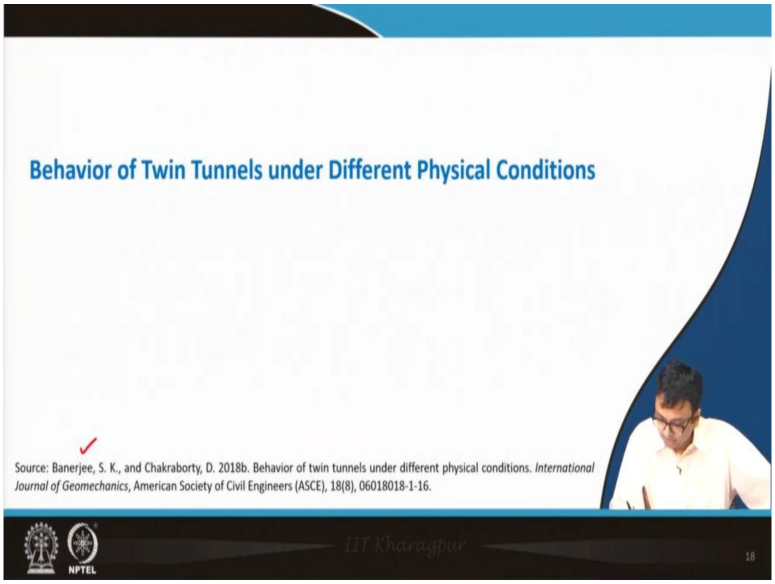
We can see, for beta=0 and beta=10; they are quite close to each other. But when the beta angle becomes 40 degree, the stability has reduced a lot; And here also these results though we have generated for soil; but for rock if you can find out the equivalent c-phi parameters using the expressions I have provided earlier you can utilize for tunnel analysis in rock also.

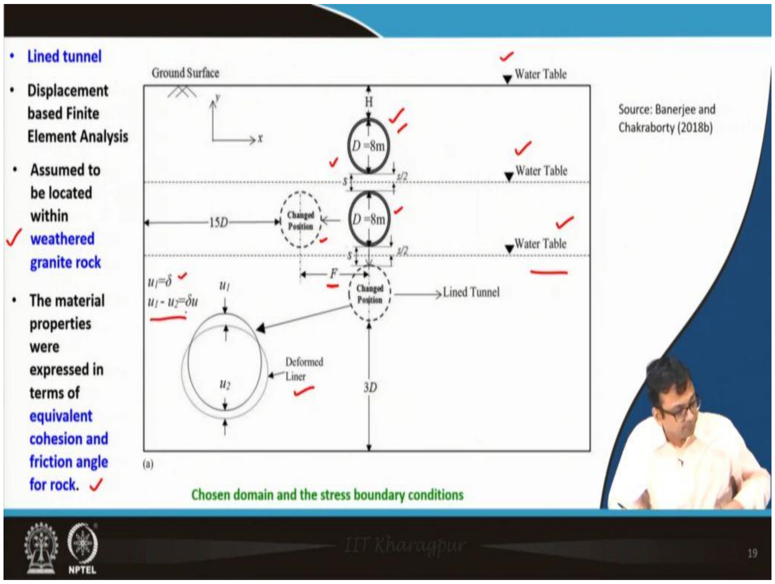
(Refer Slide Time: 21:09)



Again, there are some of that failure pattern, again the same thing a/d equal to 1 indicates failure.

(Refer Slide Time: 21:18)





So, now this is one work, which is on the behavior of twin tunnels under different physical conditions. So, this work is also with one of my master student. So, this work, we could publish in ASCE International Journal of Geomechanics. So, this is a case of lined tunnel.

We have used the conventional finite element method i.e. we did displacement finite element analysis using Abaqus. Here twin tunnels were assumed exactly located within weathered granite rock.

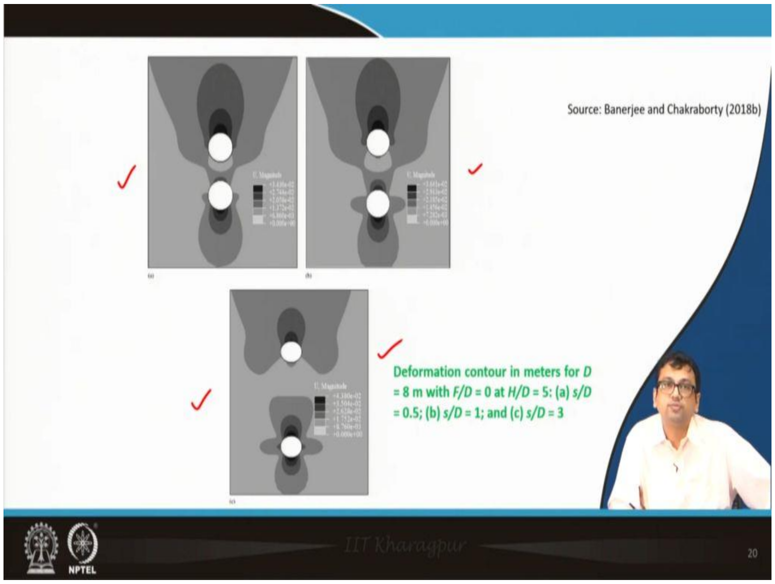
The material properties were expressed in terms of equivalent cohesion and friction angle of rock; and then, it was analyzed. Now, different physical conditions consideration that they are in the same line, and the spacing between the two tunnels is varying. It means that instead of keeping them in the same line it was shifted in left or right direction and also the vertical spacing was changed as well.

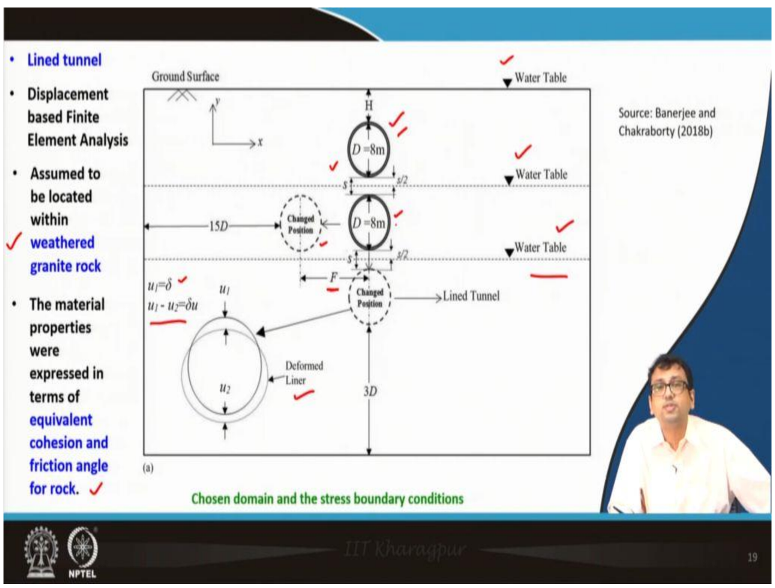
F is nothing but the lateral distance between the two tunnels. So, other than that, variation of water table has also been considered, at the ground level, in between the two tunnels, below the tunnel. We have considered the effect of stiffness of different liners. So, if under the developed stresses the liner will deform then

$$u_1 = \delta$$
$$u_1 - u_2 = \delta u$$

; so u1 is equal to delta and u1 minus u2 is convert delta u.

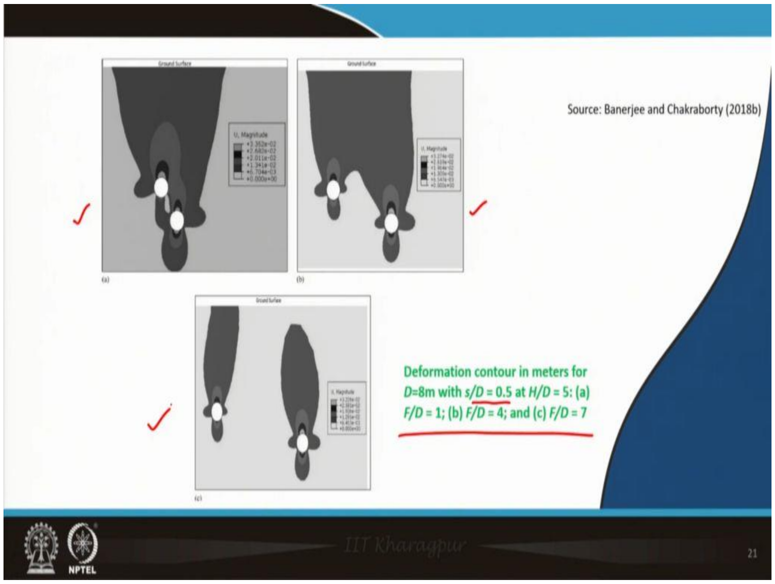
(Refer Slide Time: 24:03)





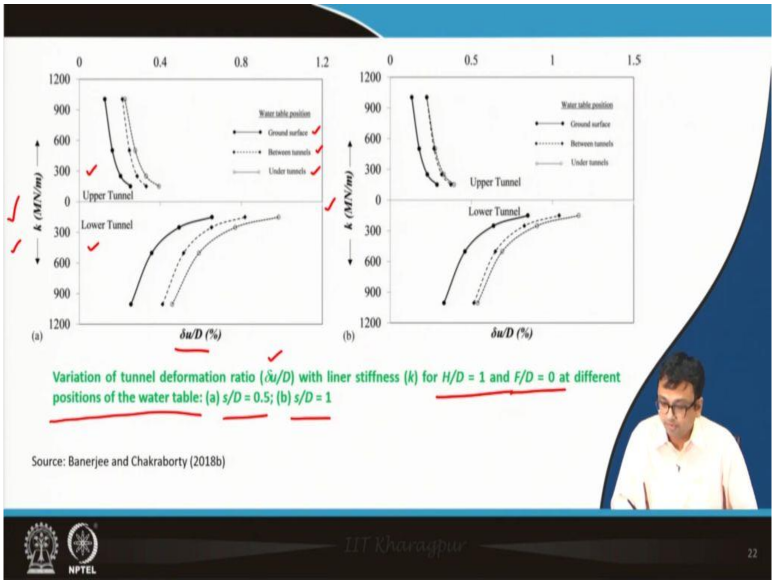
Now, let us discuss some of the results. The deformation contour in meter for D = 8 m, F/D = 0 which means both the tunnels are in the same line. At H/D = 5, and s/D = 0.5, 1, 3. So for s/D = 0.5 the deformation contours are overlapping with each other and for s/D = 3 they are separated from each other; so, influence is almost vanishing. So, if you place two tunnels at a reasonably good distance, it may vanish the effect of the presence of the two tunnel.

(Refer Slide Time: 25:11)



Now, for second set of results, s/D = 0.5; and F/D = 1, 4, 7. For F/D = 1, the deformation contour is very much overlapping, for higher values the overlap reduced and for F/D=7 it has completely separated from each other. So, that is one important observation.

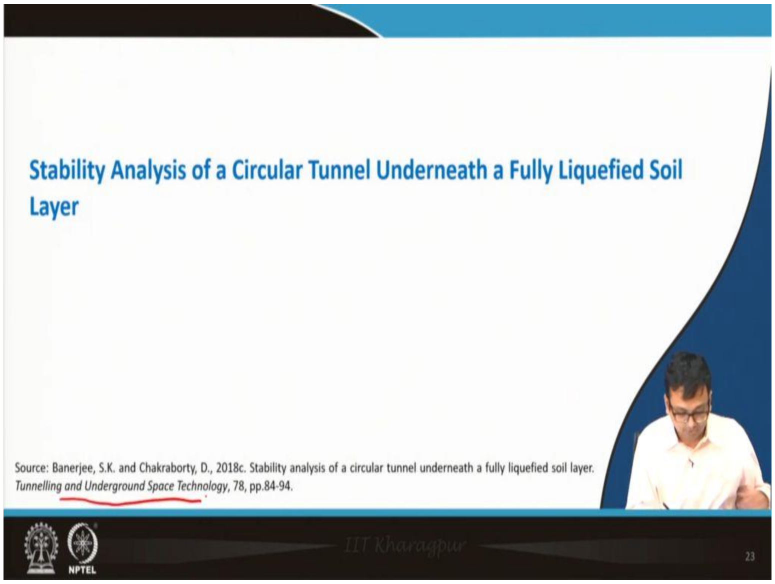
(Refer Slide Time: 25:41)

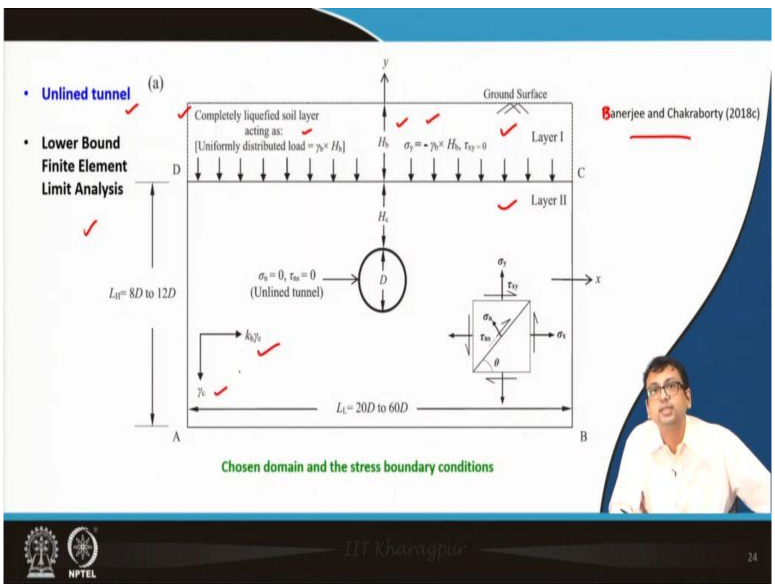


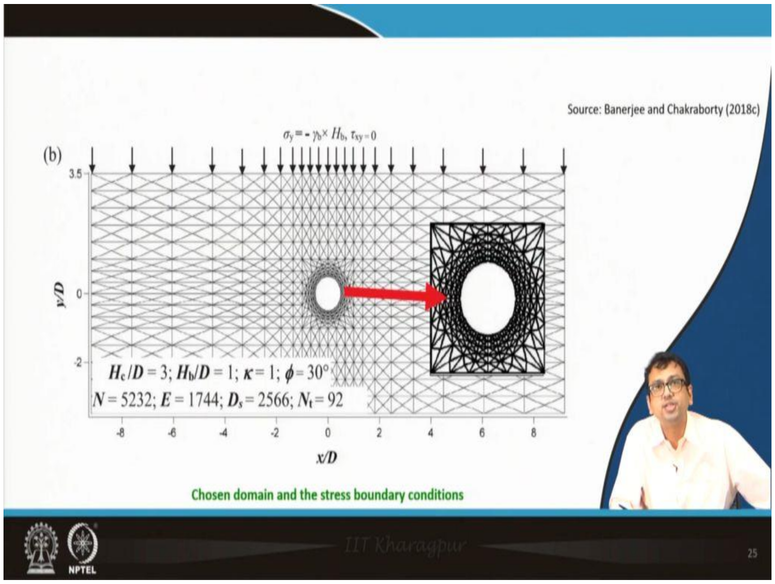
Then a representative plot for the variation of tunnel deformation ratio that you have present in terms of δu/D, with liner stiffness. Liner stiffness presented for H/D = 1, F/D = 0 at different positions of water table, for s/D = 0.5, 1. So, water table at ground surface, between tunnels, under tunnels is shown; and upper part of the plot is for upper tunnel, lower part is for lower tunnel.

The variation of tunnel deformation with liner stiffness is can be seen from the plot. It can be useful for the designing engineers.

(Refer Slide Time: 26:52)





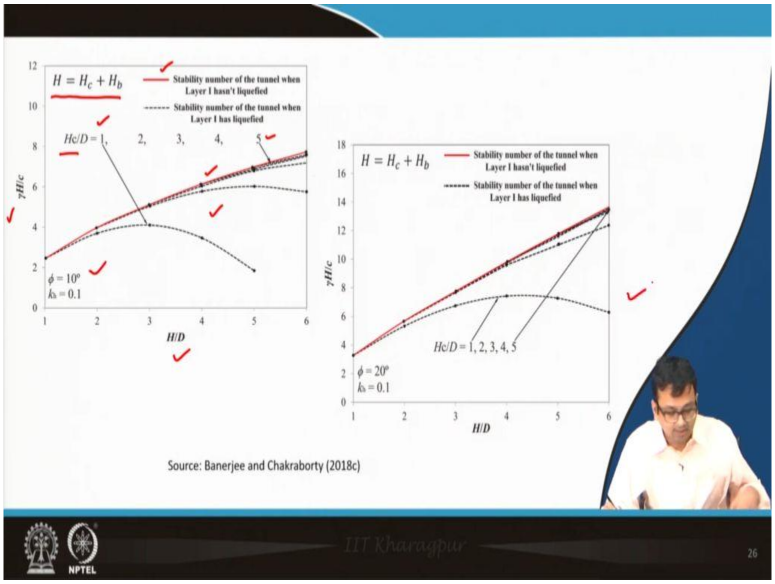


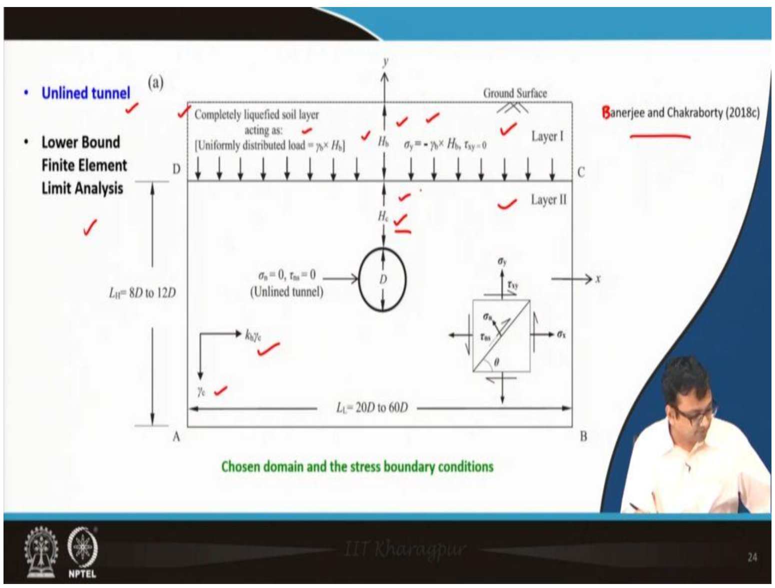
So, another work is the stability analysis of circular tunnel underneath fully liquefied soil layer. So, here also unlined tunnel has been considered and lower bound limit analysis is used. So, Banerjee and Chakraborty, this paper is published in Tunneling and Underground Space Technology.

So, here it is assume that the zone of the soil has liquefied; during earthquake or if some other sudden blast occur, soil may lose its entire strength and it may behave like liquid; its shear strength will be lost. It is called liquefaction. So, since soil will behave as a liquefied layer, so a completely liquefied soil layer, acts as uniformly distributed loads.

Layer 1 was considered liquefied so was take as overburden load but layer 2 wasn't liquefied. The similar type of analysis and the earthquake effect was taken into consideration as shown; typical finite mesh is also shown in the slides.

(Refer Slide Time: 29:05)





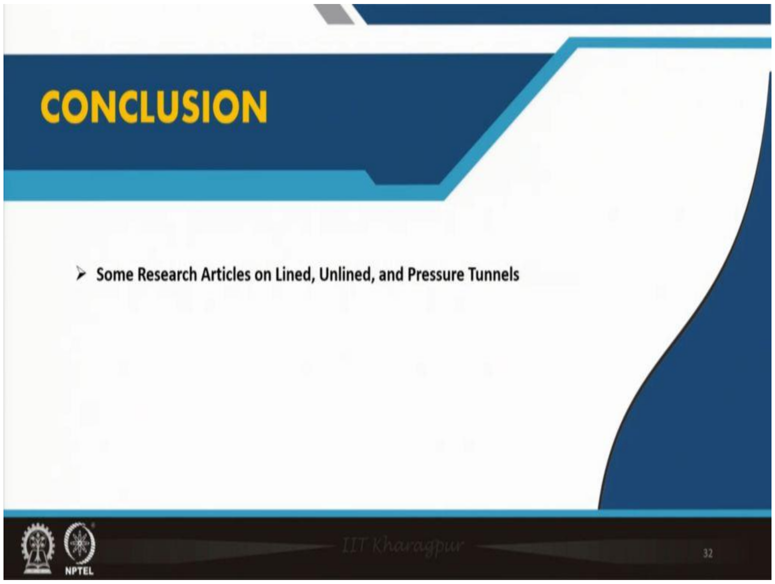
A plot of variation of stability number with H/D.

$H = H_c + H_b$ (refer to the figure in slide)

We can notice when H_c/D is becoming very high then we are getting the stability number almost similar to the case where layer-1 is not liquefied. So, if my H_c/D is quite high like 5, then effect of liquefaction will not be that much prominent.

Whereas, if H_c/D is 1, the deviation from the red line; what you can see red line is for the stability number of the tunnel, when layer-1 has not liquefied and dotted is stability number of tunnel when layer-1 has liquefied. So, the effect when the H_c/D is 1, then the difference is high. These results are for phi 10 degree and 20 degrees.

(Refer Slide Time: 30:31)



So, today we have discussed about some of the research articles on lined, unlined and pressure tunnels. Many good research works are going on throughout the world on this topic. So, those who are interested should definitely read the latest literature related to this topic and can follow. I wanted to give you some idea through the work that I have done related to tunnel. Thank you.