Rock Engineering

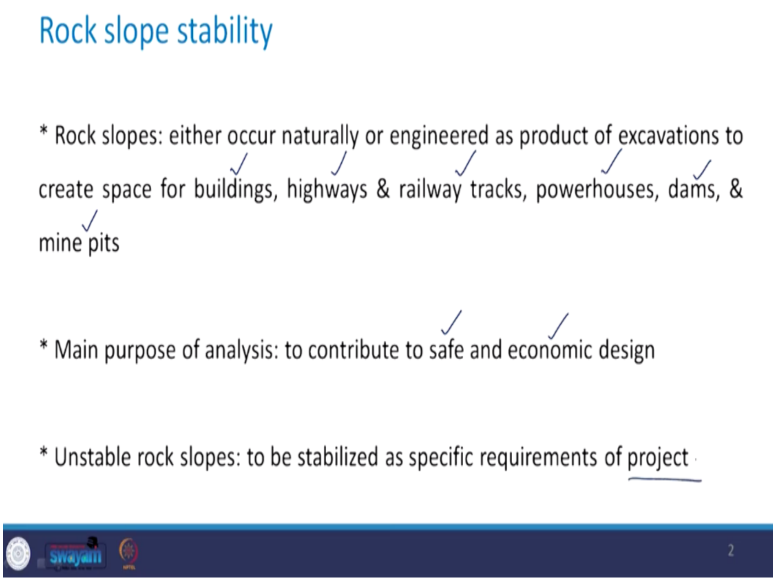
Prof. Priti Maheshwari
Department of Civil Engineering
Indian Institute of Technology – Roorkee

Lecture - 48
Rock Slope Stability

Hello everyone, in the previous class, we finished our discussion on one of the application of rock engineering that is tunneling. So, today, we will start another application area of rock engineering related to rock slope stability. I have discussed some of the aspects related to this rock slope stability, when we were discussing about the spherical projection or spherical representation of the geological data.

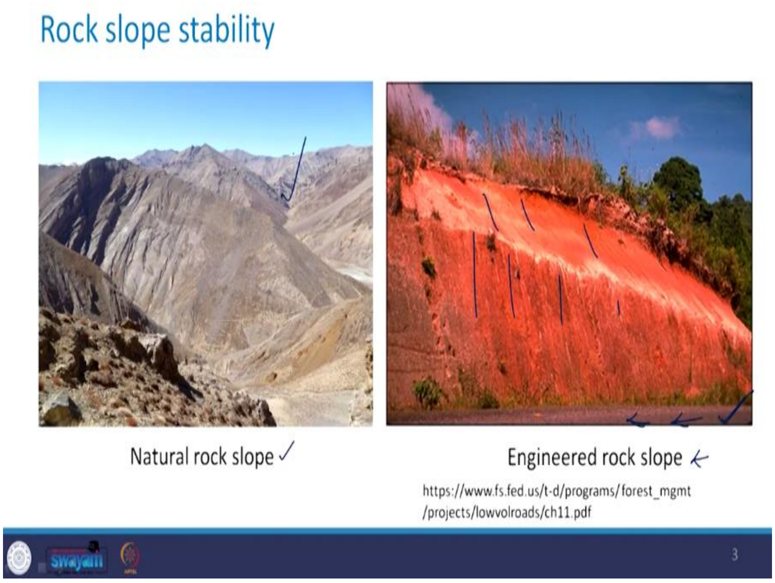
So, in this class, we will first discuss about the possible modes of failure in case of the rock slopes. And then we will discuss some aspects related to the one of these failure modes. We will try to see that using the limit equilibrium analysis, how we can analyze these rock slopes under different modes of failure?

(Refer Slide Time: 01:38)



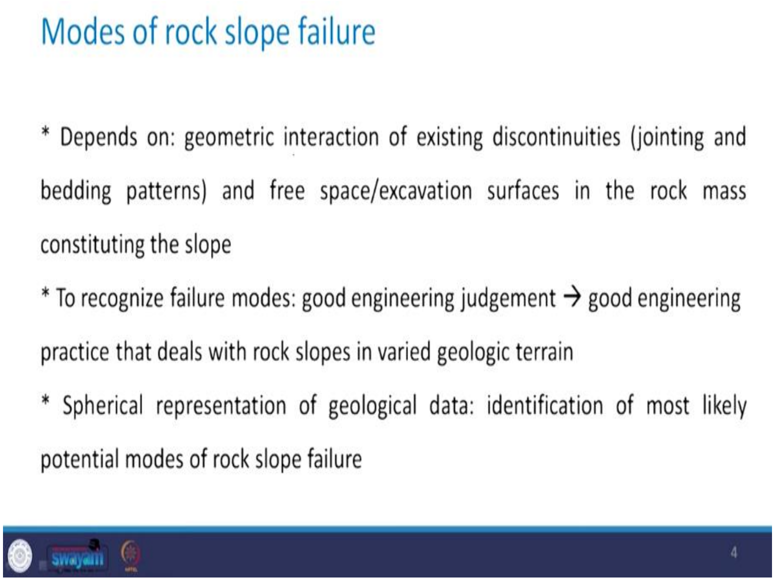
So, these rock slopes either occur naturally or they are engineered as the product of excavations to create space for buildings, highways and railway tracks, powerhouses, dams and mine pits. Main purpose of the rock slope stability analysis would be to contribute to the safe and economical design. Unstable rock slopes, they need to be stabilized as the specific requirement of the projects.

(Refer Slide Time: 02:30)



So, here you can see two pictures, the first one is showing the natural rock slope. This has been taken somewhere on the way from Manali to Leh. And this one is engineered rock slope, where you can see that a road is there in this particular portion and this slope has been cut in order to create the space for this. So, this is what that we call as the engineered rock slope. And this is the natural rock slope.

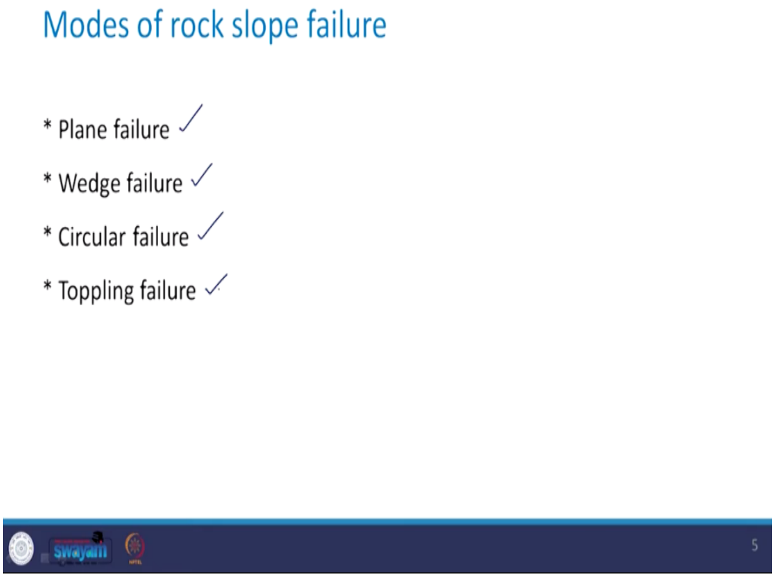
(Refer Slide Time: 03:20)



Coming to the modes of rock slope failure, these modes depends on geometric interaction of existing discontinuities. These discontinuities may be jointing or the bedding patterns and the free space or the excavation surfaces in the rock mass constituting the slope. In order to recognize the failure modes, one needs to have good engineering judgement. And this engineering judgement comes from good engineering practice.

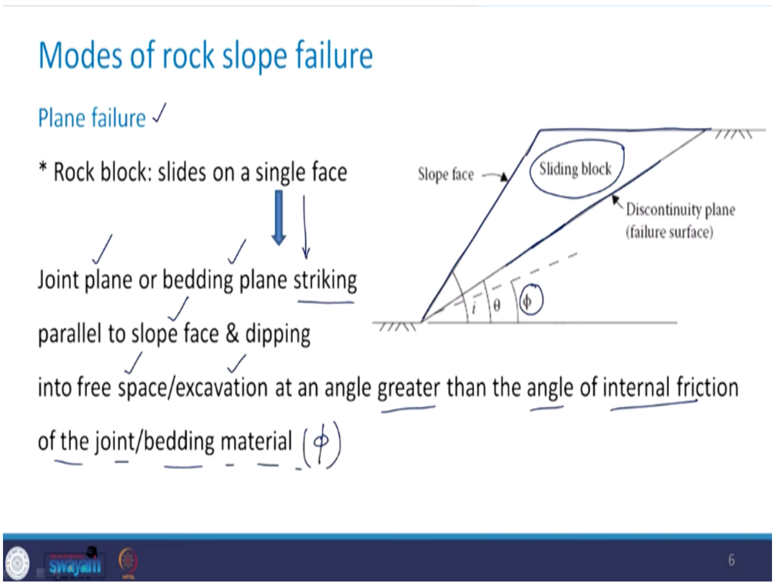
That deals with rock slopes in varied geological terrains. We have seen the spherical representation of the graphical data. This helps in identification of most likely potential modes of rock slope failure. If you recall our discussion of one of the earlier chapters, I mentioned to you with reference to this spherical representation of the geological data that in which case which mode of rock failure will be occurring.

(Refer Slide Time: 04:53)



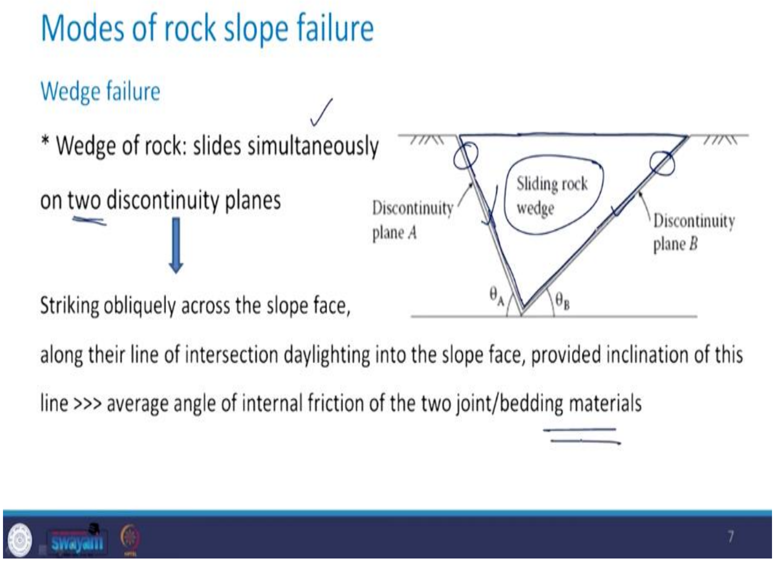
There are 4 modes of rock slope failure. First one is plane failure, then wedge failure, circular failure and the toppling failure. Plane and wedge failure, they occur commonly. However, the circular failure occurs in the rock mass where it is highly fractured. And for the toppling failure again when you have the steeply dipping jointed beds, then in that case there are chances that the toppling failure will occur. Let us start our discussion with plane failure.

(Refer Slide Time: 05:46)



So, here it is the slope face. And there is this discontinuity plane. So, in the case of plane failure, this rock block which is this is the sliding block it slides on a single face. Now, this single face can be a joint plane or a bedding plane which is striking parallel to the slope face and dipping into free space or excavation at an angle greater than the angle of internal friction of the joint or the bedding material which has been shown here as angle phi (ϕ).

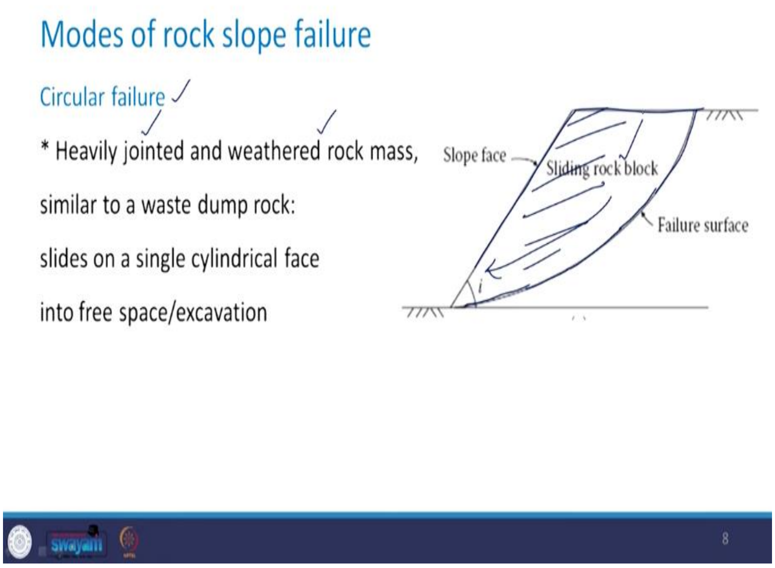
(Refer Slide Time: 06:48)



The second mode is the wedge failure. In this case, the wedge of the rock is formed in between 2 discontinuity planes. Take a look at this figure. Discontinuity plane A and discontinuity plane B and a wedge is formed like this in between these two continuity planes. And this wedge is going to be sliding rock wedge. So, this wedge slides simultaneously on two discontinuity planes which are being shown here as plane A and plane B.

These planes strike obliquely across the slope face, along their line of intersection daylighting into the slope face, provided the inclination of this line is much larger than the average angle of internal friction of the two joint or the bedding material.

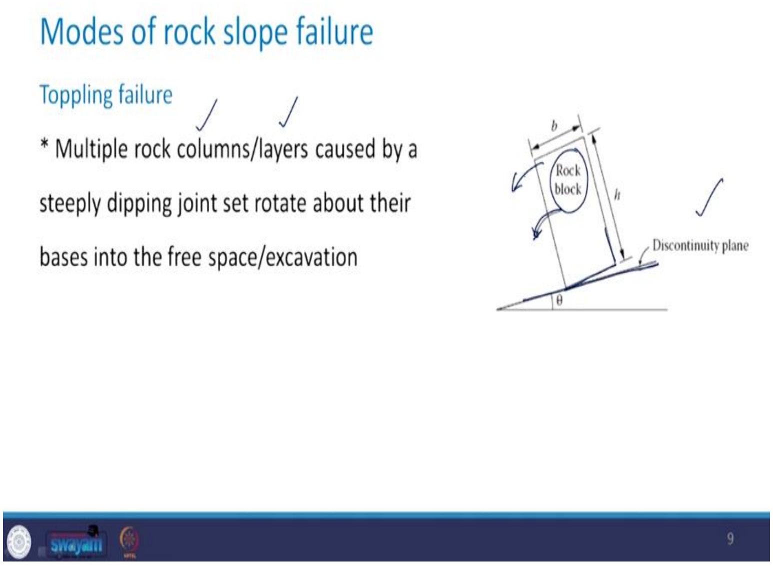
(Refer Slide Time: 08:10)



Coming to the third category, which is the circular failure. This occurs in case of heavily jointed and weathered rock mass, very much similar to a waste dump rock. And the sliding takes place on a single cylindrical face into the free space or excavation. So, you can take a look here that this is the slope face and there is going to be the formation of the failure surface of this type.

And the rock which is lying here it will have a tendency to slide. So, this is what is the sliding rock block.

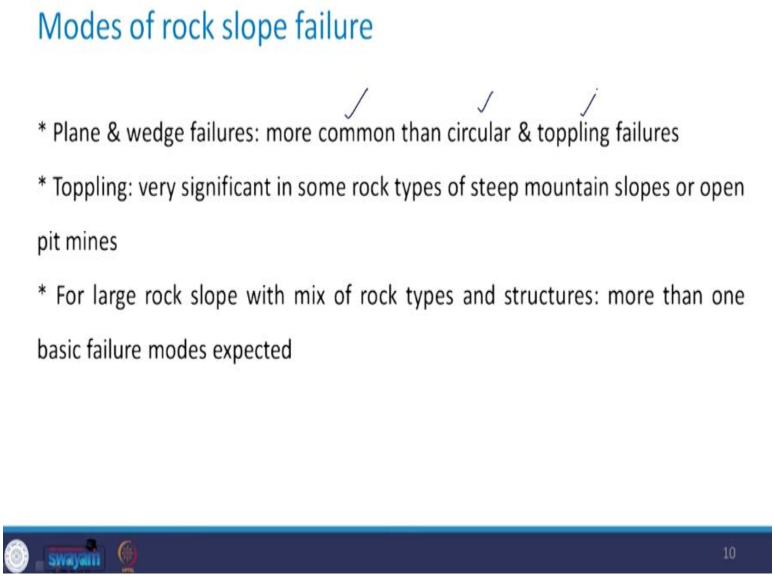
(Refer Slide Time: 09:04)



The next mode of rock slope failure is the toppling failure. And this occurs where we have multiple rock columns or layers caused by steeply dipping joint set and when they rotate about their basis into the free space or excavation. Take a look at this figure that you have a discontinuity plane. And this is a rock block which is steeply dipping. And if this rotates about its base see this is its base.

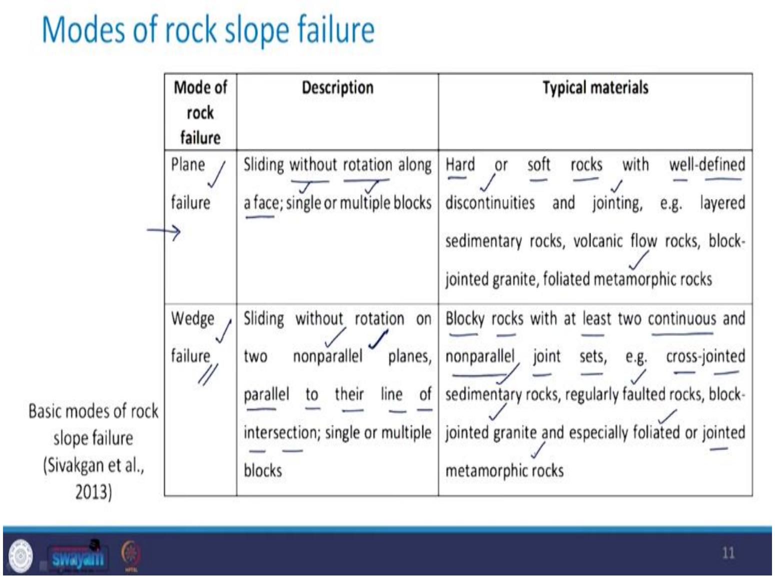
And when it rotates about this base, there is a chance the toppling of this block will take place. So, such type of failure falls under the category of toppling failure.

(Refer Slide Time: 10:10)



Plane and wedge failures, they are more common than circular and toppling failures. Toppling failure is very significant in some rock types of steep mountain slopes or in case of open pit mines. For large rock slope with mix of rock types and structure, one can observe more than one of these four basic failure modes. So, in that case, the analysis becomes even more critical.

(Refer Slide Time: 10:50)

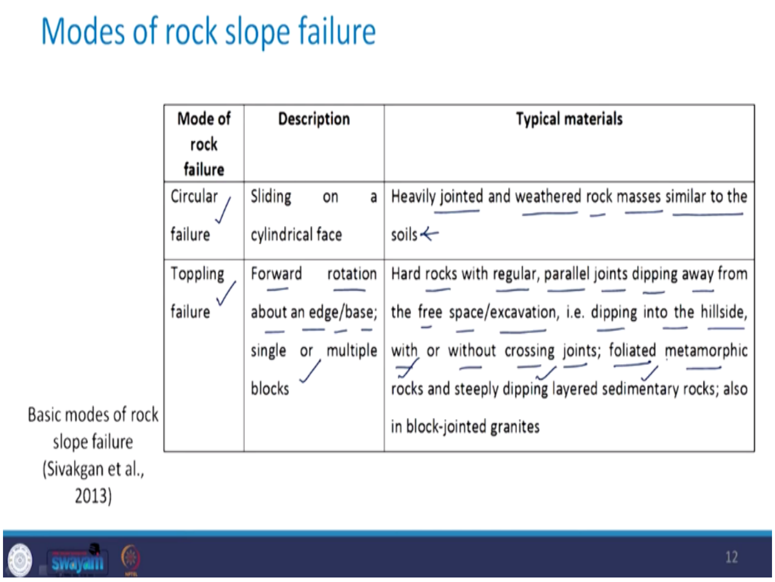


Here some description and the typical material have been given corresponding to each mode of rock failure. So, first let us take a look at the second row, which is the plane failure. There the sliding without the rotation takes place along a face. There can be single or multiple blocks, which will be siding along this face, hard or soft rocks with well-defined discontinuities and jointing.

For example, layered sedimentary rocks, volcanic flow rocks, block jointed granites and foliated metamorphic rocks fall under this category. The second mode of failure is the wedge failure where there is the sliding without the rotation, but the sliding is on two non-parallel planes. This is important that it is non-parallel planes. These are parallel to their line of intersection.

That means that the sliding will take place parallel to the line of intersection of these two non-parallel planes. The block which is sliding, it may be single or multiple. Blocky rocks with at least two continuous and non-parallel joint sets. They usually have the wedge failure. For example, cross jointed sedimentary rocks, regularly faulted rocks, block jointed granite and especially foliated or jointed metamorphic rocks. They fall under this category.

(Refer Slide Time: 13:13)

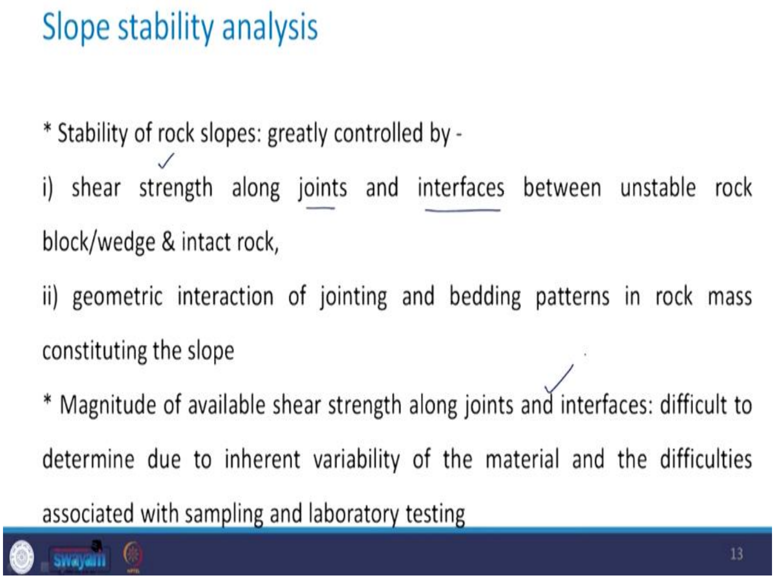


Mode of rock failure	Description	Typical materials
Circular failure	Sliding on a cylindrical face	Heavily jointed and weathered rock masses similar to the soils
Toppling failure	Forward rotation about an edge/base; single or multiple blocks	Hard rocks with regular, parallel joints dipping away from the free space/excavation, i.e. dipping into the hillside, with or without crossing joints; foliated metamorphic rocks and steeply dipping layered sedimentary rocks; also in block-jointed granites

The third one is the circular failure where the sliding occurs on a cylindrical face. And this type of failure is observed in case of heavily jointed and weathered rock masses which are quite similar to the soils. The fourth and the last category is toppling failure where there occurs a forward rotation about an edge or base. And this can happen to single or multiple blocks.

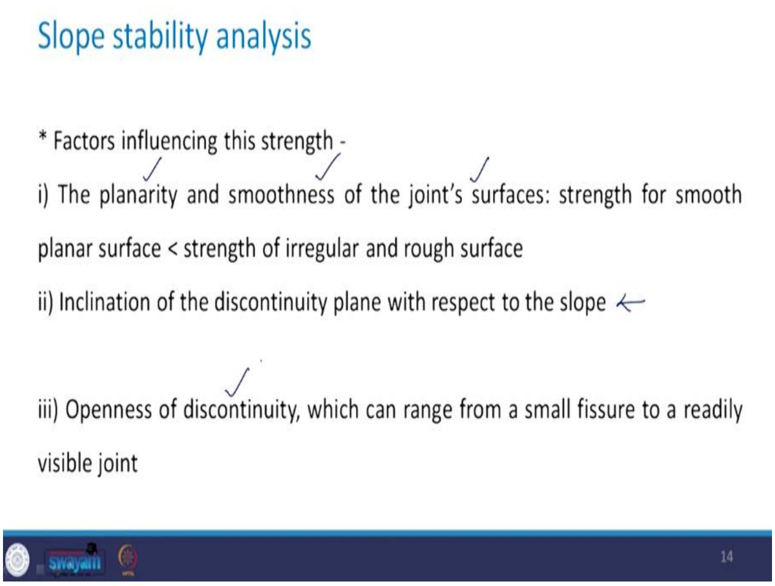
Hard rocks with regular, parallel joints dipping away from the free space or excavation that is these are dipping into the hillside with or without crossing joints. Foliated metamorphic rocks and steeply dipping layered sedimentary rocks and toppling behavior is also observed in block jointed granites. Coming to the slope stability analysis, the stability of rock slopes, these are greatly controlled by first is the shear strength along the joints and interfaces between unstable rock block or wedge and the intact rock.

(Refer Slide Time: 14:52)



The second parameter is the geometric interaction of jointing and bedding patterns in rock mass constituting the slope. The magnitude of available shear strength along these joints and interfaces, it is difficult to determine these because of the inherent variability of the material and the difficulties which are associated with sampling and the lab testing.

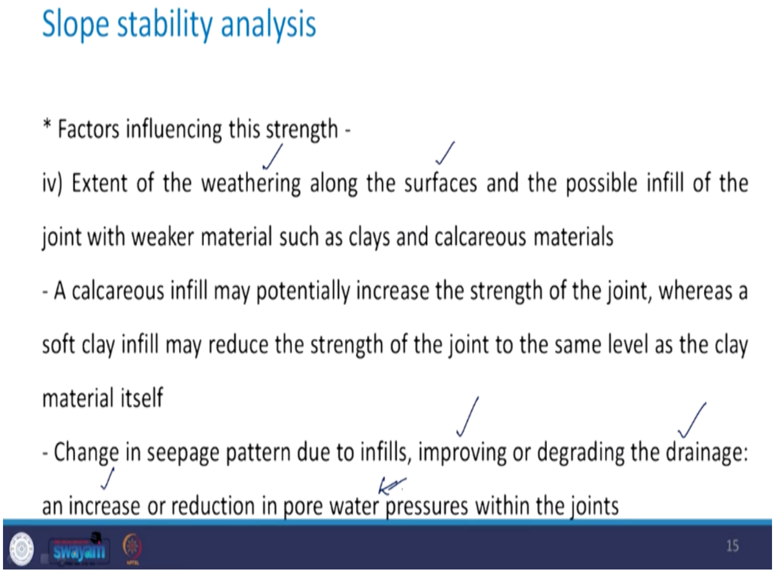
(Refer Slide Time: 15:40)



The factors which influence this strength characteristic of the joints or the bedding planes, these include the planarity and smoothness of the joint's surface. This we have seen when we were discussing about the characteristic of the joints and when we were discussing about the classification of the rocks and rock masses. We know that the strength for smooth planar surface will be less than the strength of irregular and rough surface.

The second factor that affect the strength includes inclination of the discontinuity plane with respect to the slope. Openness of the discontinuity is another factor. And this can range from a small fissure to a readily visible joint.

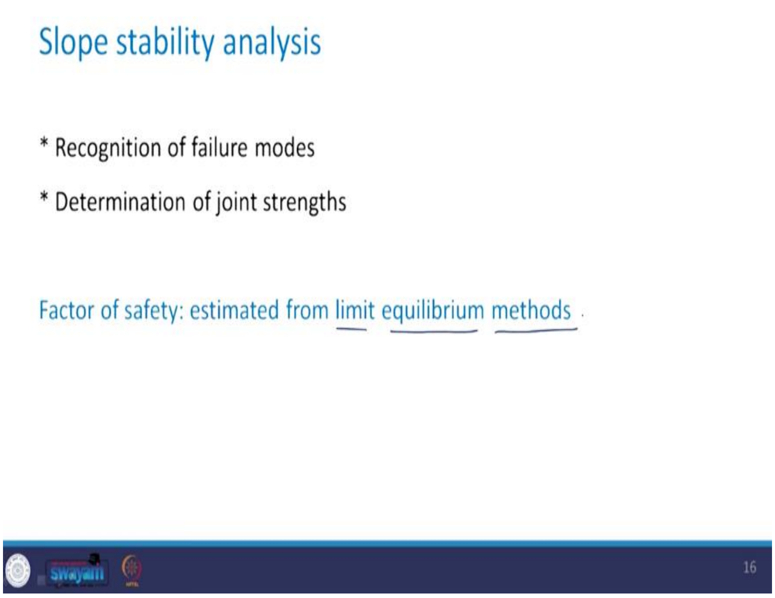
(Refer Slide Time: 16:51)



The fourth factor is the extent of the weathering along the surfaces and the possible infill of the joint with weaker material such as clays and calcareous materials. In case if the infill is a calcareous one, it may potentially increase the strength of the joint whereas in case of the soft clay as infill the strength will be reduced for the joint to the same level as the clay material itself because it will be the soft clay infill which will govern the strength characteristic of the joint.

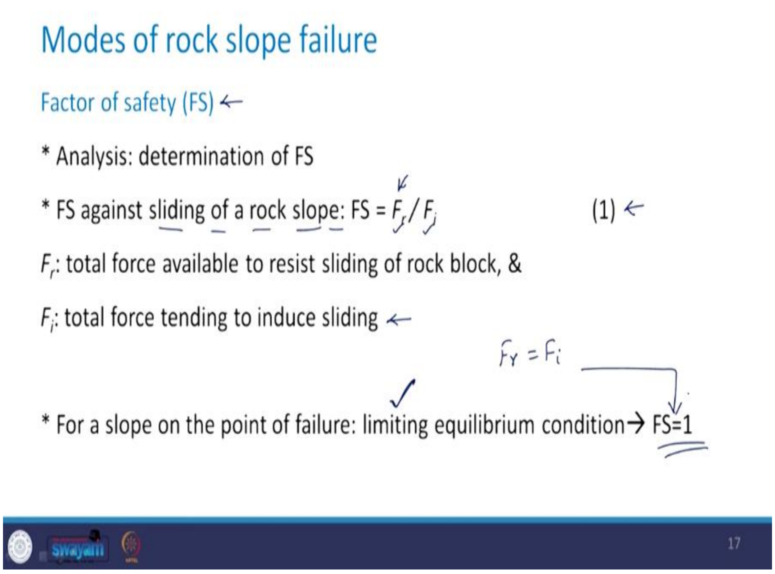
Change in the seepage pattern due to the infills may improve or degrade the drainage. And in case if the drainage characteristics they are improved then in that case one would observe an increase in the pore water pressure within the joints. And in case of the degradation of the drainage characteristic, there is going to be the reduction in the pore water pressure within the joints. And accordingly the strength characteristic of the joints shall be altered.

(Refer Slide Time: 18:24)



So, it is important for us to recognize the failure modes and determine these joint strength properly. Then, in this analysis of the rock slope stability, this factor of safety is estimated from the limit equilibrium approaches.

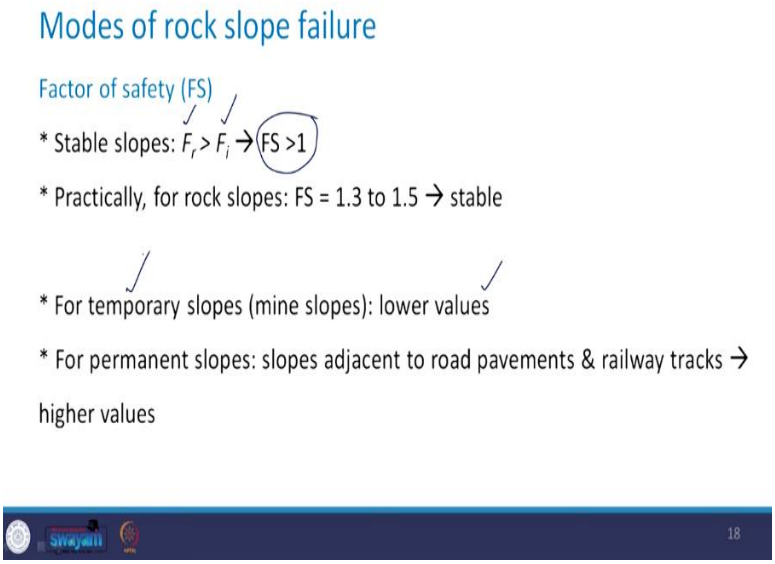
(Refer Slide Time: 18:53)



Where we try to find out the factor of safety which is against these sliding of a rock slope? And it is defined as this expression 1 that is F_r/F_i where F_r is the total force available to resist the sliding of the rock block and F_i is the total force which tends to induce the sliding of the rock block. So, for a slope on the point of failure or for a slope which is on the verge of the failure, what is going to be the limiting equilibrium condition?

In terms of the value of this factor of safety which will be equal to 1. Because just in that limiting situation this F_r that is which is the resisting force will become equal to F_i which is the force that is inducing the sliding and thereby making this factor of safety to be equal to 1. So, this is what the approach that we are going to adopt in order to analyze these rock slopes using limit equilibrium methods.

(Refer Slide Time: 20:30)

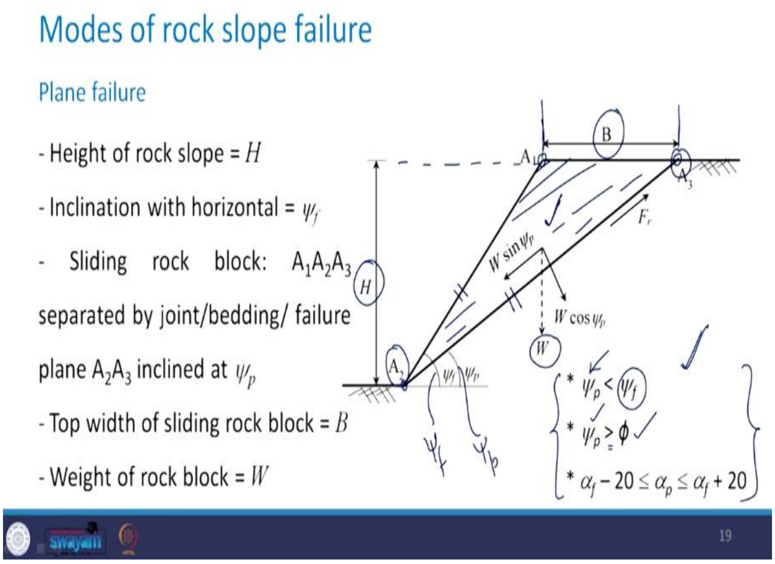


For the stable slopes, obviously, the resisting force has to be more than the force that is inducing the sliding. This results into the factors of safety greater than 1. So, practically for rock slopes, when this factor of safety works out to be say 1.3 to 1.5. We say that the rock slope is stable. For temporary slopes, as an example, mine slopes, they can be taken or they can have the lower values of the factor of safety in view of their temporary nature.

In case of the permanent slopes, the slopes which are adjacent to road pavements and the railway tracks, one needs to go for the higher values of the factor of safety. So, basically these factors of safety also take into consideration some of the uncertainty factors. Coming to the analysis, as far as the plane failure mode is concerned, before we go to the analysis, recall our discussion when we were discussing about the spherical representation of the geological data.

I mentioned to you as a part of its application that we can find out whether there is a possibility of the plane failure or not from that geological data. And that was called as the kinematic analysis. And what were the conditions for those kinematic analysis has been mentioned here.

(Refer Slide Time: 22:34)

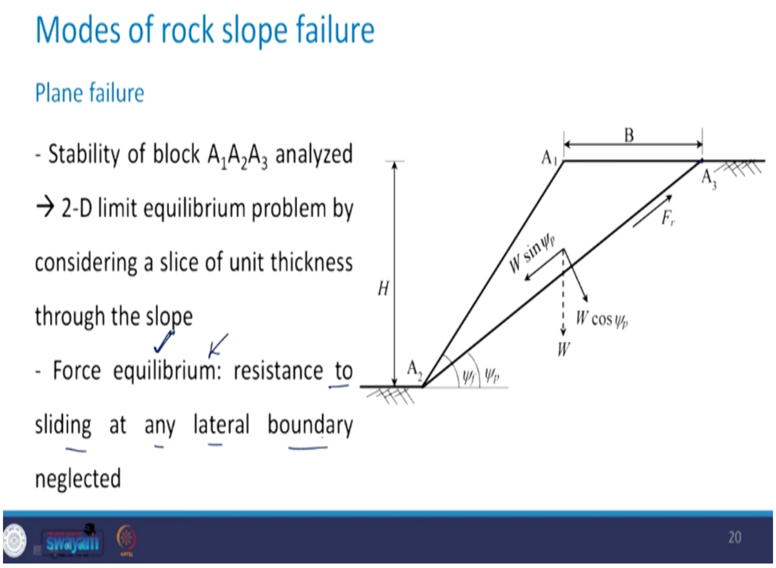


That is dip of the slope should be more than the dip of the failure plane. Dip of the failure plane should be more than the friction angle. And then the dip direction should be within plus minus 20 degree. So, this we have already discussed earlier. In case if these conditions are satisfied, that means, we know that the plane failure is going to occur. Now, come to the analysis part.

Here, our slope has been shown which has a height of *H*. And the inclination of this slope face with the horizontal is ψ_f. The sliding rock block here has been represented by A_1 A_2 and A_3. So, that means whatever is this wedge that is being formed this block is going to slide. And this is separated by a joint or the bedding or the failure plane A_2 A_3 which is this one. And the inclination of this with the horizontal is ψ_p.

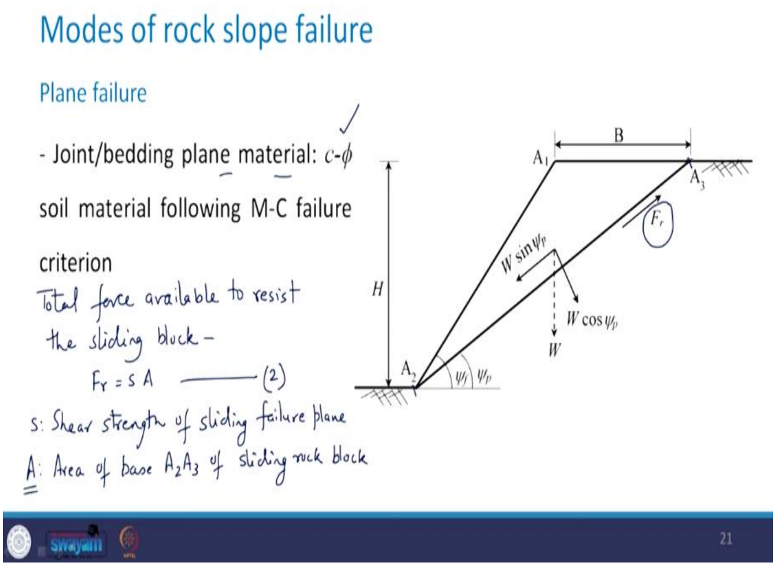
The top width that is this much width of the sliding block is represented by *B*. And the weight of this sliding rock block is *W*.

(Refer Slide Time: 24:27)



So, the stability of the block A_1 A_2 A_3 is analyzed using two-dimensional limit equilibrium problem by considering a slice of unit thickness through the slope. What does this mean is that we take the unit dimension in the plane perpendicular to the plane of this screen. The force equilibrium condition is considered and when we consider this force equilibrium, the resistance to sliding at any lateral boundary is neglected.

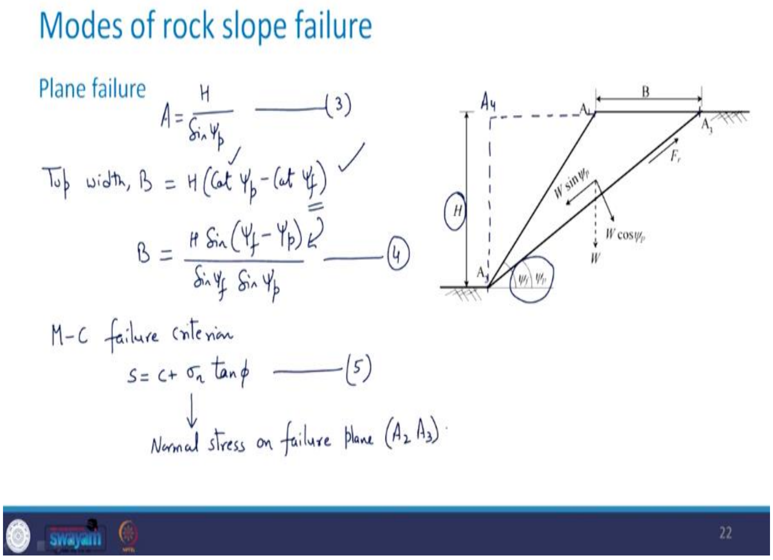
(Refer Slide Time: 25:16)



It is assumed that the joint or the bedding plane material follows the Mohr Coulomb failure criterion. And it can be considered as the c-ϕ soil material. Now, let us try to take a look at some of the mathematical expression here. So, the total force available to resist this sliding block, see, this has been shown here with this force F_r. So, that is going to be F_r is equal to S into A. Make it equation number 2.

Here, this S is the shear strength of sliding failure plane and A is the area of base A_2 A_3 of sliding rock block. Now, since we are taking a unit dimension in the direction perpendicular to this screen, this area would be equal to the length A_2 A_3 multiplied by 1.

(Refer Slide Time: 27:14)



So, this can be calculated as

$$A = \frac{H}{\sin \psi_p}$$

This equation is equation number 3. Now, the top width which is *B* here this will be

$$B = H(\cot \psi_p - \cot \psi_f)$$

See here, I can extend this line and drop a vertical line from the point A_2. So, this top width will be what? Let us say this point is some point A_4. So, this will be A_4A_3 minus A_4A_1. And this A_4A_3 and A_4A_1 can be determined in terms of this *H* and these 2 angles.

And, what you will get is in this particular form. Or, this can also be written as

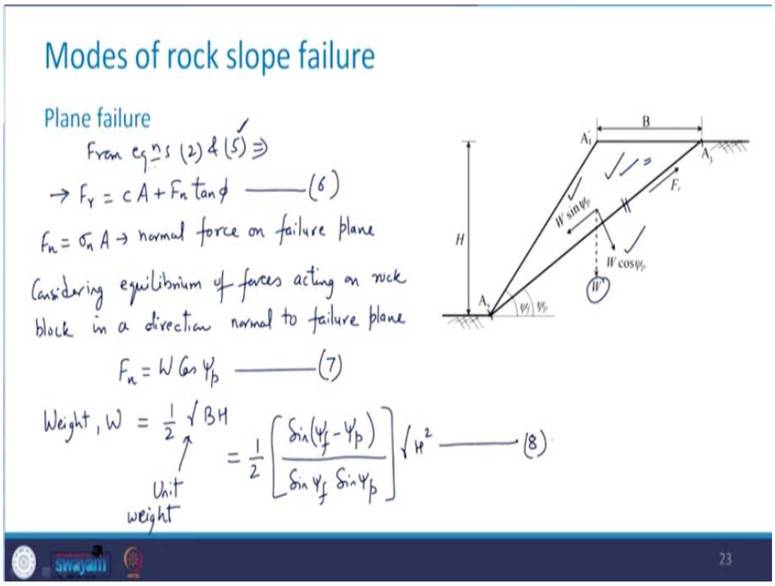
$$B = \frac{H \sin(\psi_f - \psi_p)}{\sin \psi_f \sin \psi_p}$$

This is equation number 4. I have not done anything just I have written cot as cos upon sin and then made this form into this particular form. Now, since this is following Mohr Coulomb failure criterion as per our assumption. So, what we have here is

$s = c + \sigma_n \tan \phi$ This we have already learnt.

This equation is going to be equation number 5 where this σ_n is the normal stress on the failure plane. What is the failure plane here? It is A_2A_3.

(Refer Slide Time: 29:53)



Now, from these equations 2 and 5, what we will get is this F r will be equal

$$F_r = cA + F_n \tan\phi$$

Make this equation as equation 6. Take a look at equation number 5, and you will realize that that was in terms of the stresses. So, I have multiplied it with the area on which those stresses are acting. So, we will get this equation in the form of forces where this $Fn = \sigma n. A$.

That is the normal force on the failure plane. Now, we consider the equilibrium of forces which are acting on the rock block. That means, this rock block in a direction normal to this failure plane. So, what we are going to get is $F_n = W \cos\varphi_p$. See, we can get the component of this weight W in the 2 direction. That is one is the direction perpendicular to the failure plane and second is the parallel to the failure plane.

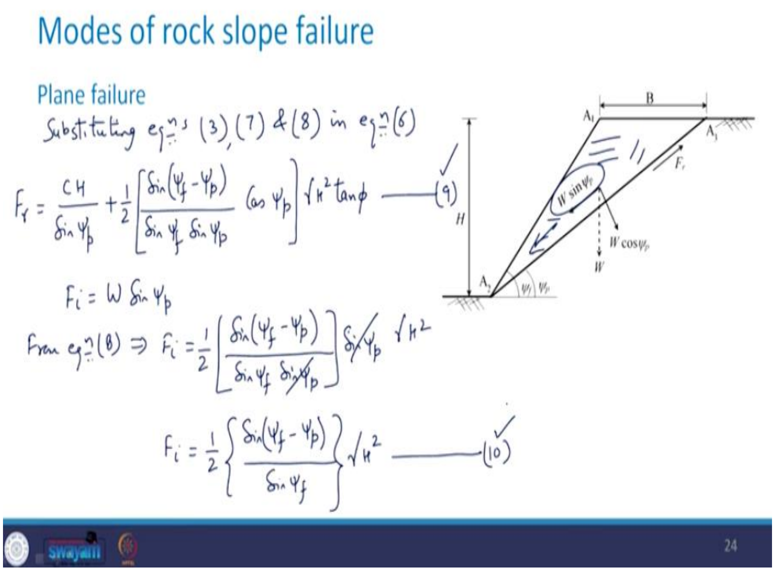
So, this equation I will write as equation number 7. Now, this weight W of the wedge is defined as$W = \frac{1}{2}\gamma BH$. See, this is the triangle A_1 A_2 A_3 which is making this block which is sliding. I need to find out it is weight. So, gamma is the unit weight of the rock material that is there in this block. So, from equation number 4 you just substitute the expression for B.

And see, this is what that you will get as

$$W = \frac{1}{2}\left[\frac{\sin(\psi_f - \psi_p)}{\sin\psi_f \sin\psi_p}\right]\gamma H^2$$

This is equation number 8.

(Refer Slide Time: 33:15)



Now, we carry out the further analysis. And we substitute equations 3, 7 and 8 in equation number 6. This is what that we are going to get Fr

$$F_r = \frac{cH}{\sin\psi_f} + \frac{1}{2}\left[\frac{\sin(\psi_f - \psi_p)}{\sin\psi_f \sin\psi_p}\cos\psi_p\right]\gamma H^2 \tan\phi$$

This is equation number 9.

Now, from the figure you can see that this $F_i = W \sin\psi_p$ because F_i is what is the force which is tending to induce the sliding in this block. And that is this component of W will cause the sliding of this block like this. So, $F_i = W \sin\psi_p$. Now, from the equation number 8, substitute the value of W here. What you will get?

And then you have here $\sin\psi_p$ already.

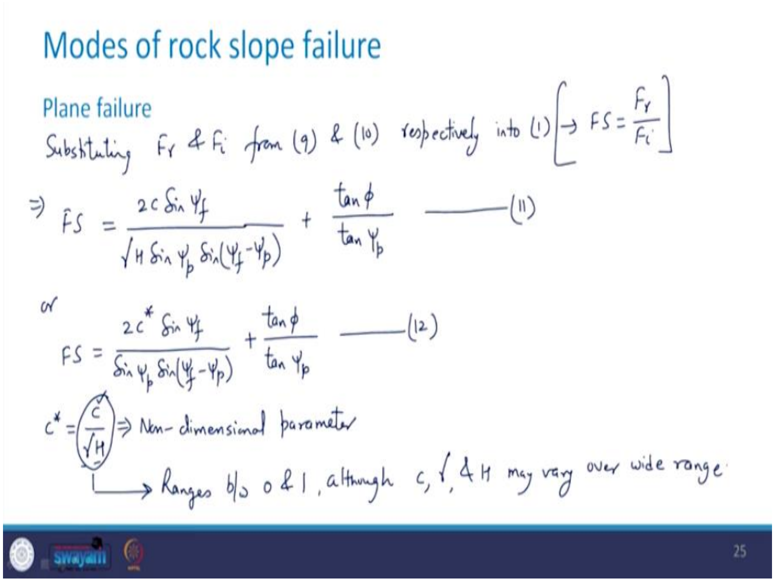
$$F_i = \frac{1}{2}\left[\frac{\sin(\psi_f - \psi_p)}{\sin\psi_f \sin\psi_p}\right]\sin\psi_p \gamma H^2$$

And this will get cancel out.

$$F_i = \frac{1}{2}\left[\frac{\sin(\psi_f - \psi_p)}{\sin\psi_f}\right]\gamma H^2$$

This is going to be our equation number 10. Now, we substitute this F r from equation 9 and F i from equation 10 to equation 1 and try to get the expression for the factor of safety.

(Refer Slide Time: 36:09)



So, we substitute F r and F i from 9 and 10 respectively into equation number 1. What was this equation number 1? That is $FS = F_r/F_i$. So, we can get

$$FS = \frac{2c \sin\psi_f}{\gamma H \sin\psi_f \sin(\psi_f - \psi_p)} + \frac{\tan\phi}{\tan\psi_f}$$

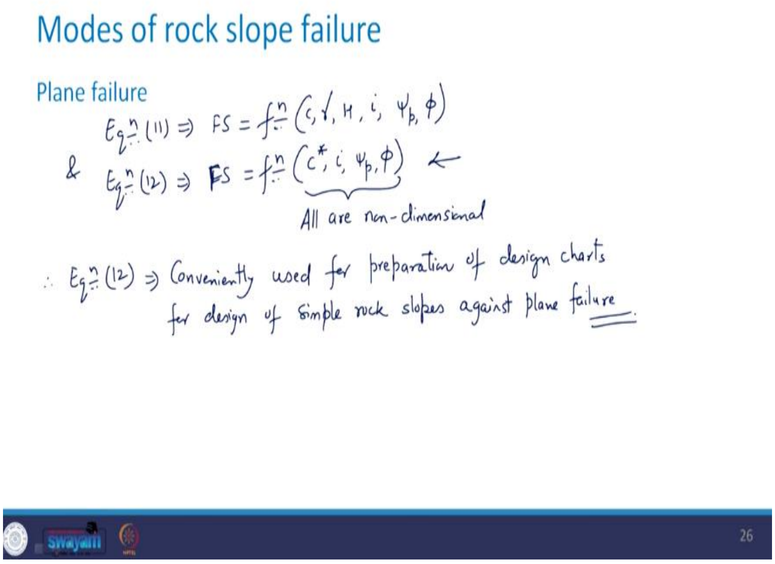
This equation will be equation number 11. Or, I can write down this factor of safety in this manner.

$$FS = \frac{2c^* \sin\psi_f}{\gamma H \sin\psi_f \sin(\psi_f - \psi_p)} + \frac{\tan\phi}{\tan\psi_f}$$

equation number 12. Now, see this term c^*. That is equal to c/H. This is the non-dimensional parameter. Why? Because the unit of c is the unit of the stress that is kN/m^2 and gamma H is again kN/m^2. So, this whole quantity will become a non-dimensional parameter.

And this quantity range between 0 and 1 although all these 3 parameter that is c, γ and H may vary over wide range. So, this helps in representation of the results.

(Refer Slide Time: 39:07)



So, we can see that these equation 11 where the factor of safety is

$$FS = f(c, \gamma, H, i, \psi_p, \phi)$$

And your equation number 12, again factor of safety that is a function of

$$FS = f(c^*, i, \psi_p, \phi)$$

And all these 4 quantities, they are non-dimensional. So, we do not need to worry about that what is the value of γ, H, once we represent the equation for factor of safety in this manner.

So, therefore, these equation number 12 can be conveniently used for preparation of the design charts for the design of simple rock slopes against the plane failure. So, rather than writing this factor of safety in terms of the dimensional parameters, we prefer to use equation number 12 because it is easy for us to make various design charts for the design of simple rock slopes against the plane failure.

Now, this was all about the simple analysis as far as the plane failure is concerned. Now, when the slope is excavated, and when the lateral confinement is removed, there can be the occurrence of the tension crack either on the slope face or on the part of the slope which is above its crest. In that case also the plane failure may occur and how to do the analysis because, till now, we have not talked about the occurrence of the tension crack.

So, in the next class, we will carry out the analysis of this plane failure mode only, but with due consideration to the tension crack. Thank you very much.