Rock Engineering
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Lecture - 53
Rock Slope Stability: Toppling Failure - 2

Hello, everyone. In the previous class, we discussed about the types of the toppling failure and I mentioned to you that in which type of rocks, a particular type of toppling failure is going to occur. So, today, we will start the analysis of the rock slopes experiencing toppling failure mode. Before we go ahead with the limit equilibrium analysis, first let us try to understand the kinematic analysis of the rock slope undergoing toppling type of field. So, the potential of toppling is being assessed from the 2 kinematic tests.

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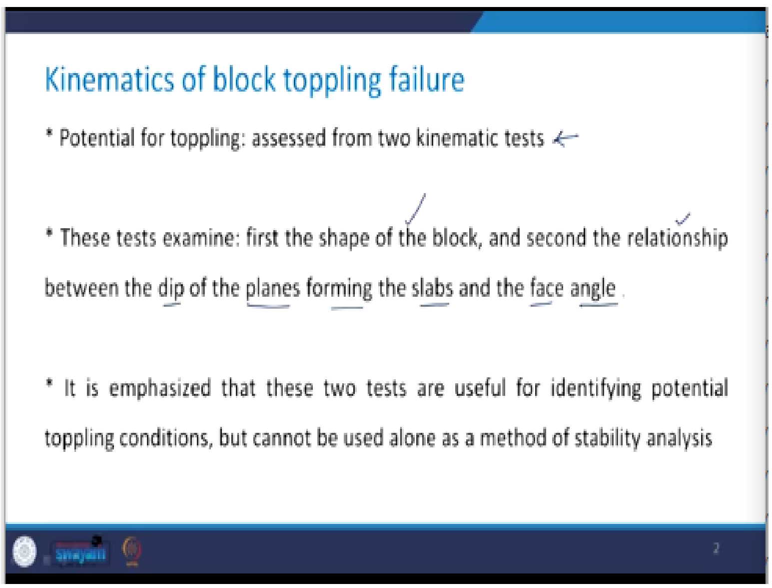

These tests examine first, the shape of the block and second, the relationship between dip of the planes forming the slabs and the face angle. If you recall, we had discussed these kinematic analysis for the plane as well as the wedge failure when we were discussing about the graphical representation of the geological data and its application. At that time, we did not discuss the kinematics of the block toppling failure.

So, in this case, there are 2 things which are to be tested. The first one is the shape of the block and the second one is the relationship between the dip of the planes forming the slab and the face angle. It is emphasize that these 2 tests are useful for identifying the potential toppling conditions, but these should not be used alone as the method of stability analysis. We need to be careful about it.

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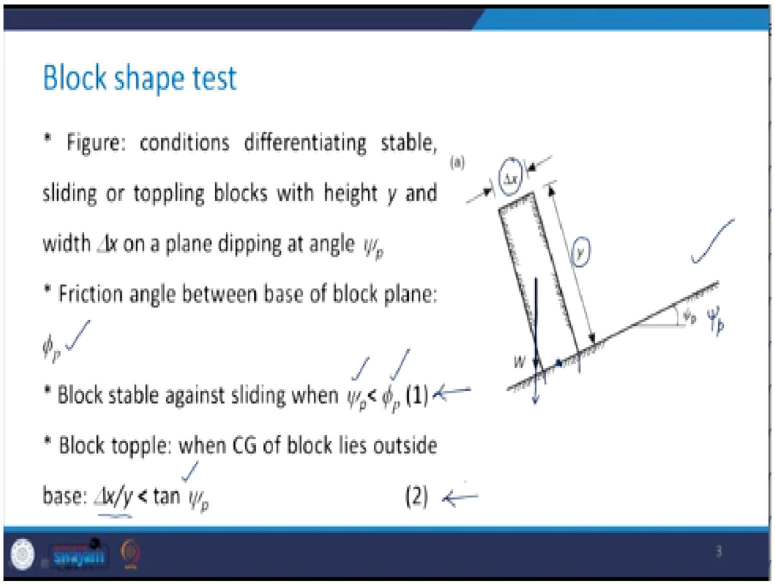

First, coming to the block shape test. So, you see here figure. This figure gives us the conditions which are differentiating between stable, sliding or the toppling blocks with the height of the block s y and width as Δx on a plane, which is dipping at an angle of ψ_p. The friction angle between the base of the block plane here is ϕ_p. So, blog is going to be stable against sliding when ψ_p is less than phi p that I am marking as equation number 1.

This block will topple when the CG of the block lies outside the base. As you can see in this figure, it has been shown that this is what is the CG and if I just drop here, see this is lying outside this base area and this condition would be satisfied when $\Delta x / y < \tan \psi_p$ and I mark this equation as equation number 2.

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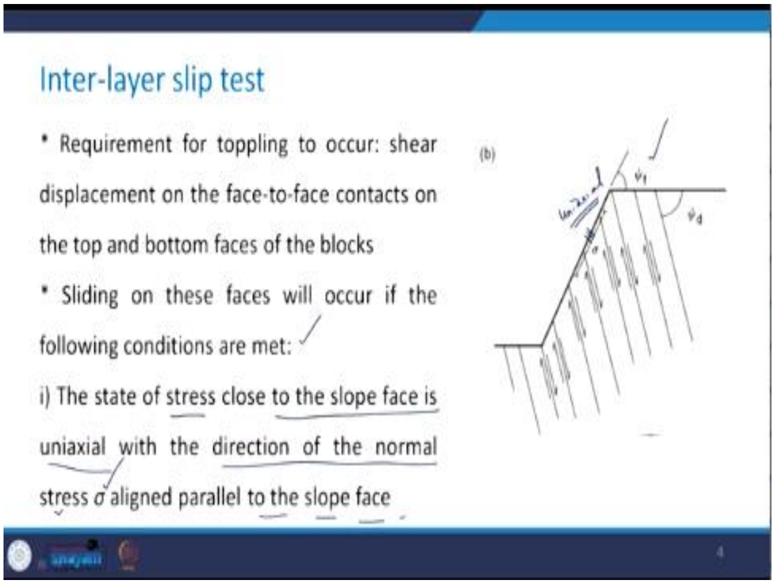

There is going to be the second test. Once the block test has been conducted, then this inter layer slip test is conducted. This is the requirement for the toppling to occur that the shear displacement on the face to face contacts on the top and bottom faces of the blocks. First is that the sliding on these faces will occur if the following conditions are met. What are those conditions?

The first condition is the state of stress close to the slope phase is uniaxial with the direction of the normal stress sigma aligned parallel to the slope face. Take a look at this figure. Here, the state of stress near this slope face is uniaxial. And this direction of the normal stress which is sigma here has been shown. This is parallel to the slow phase that mean this is parallel to this slope face.

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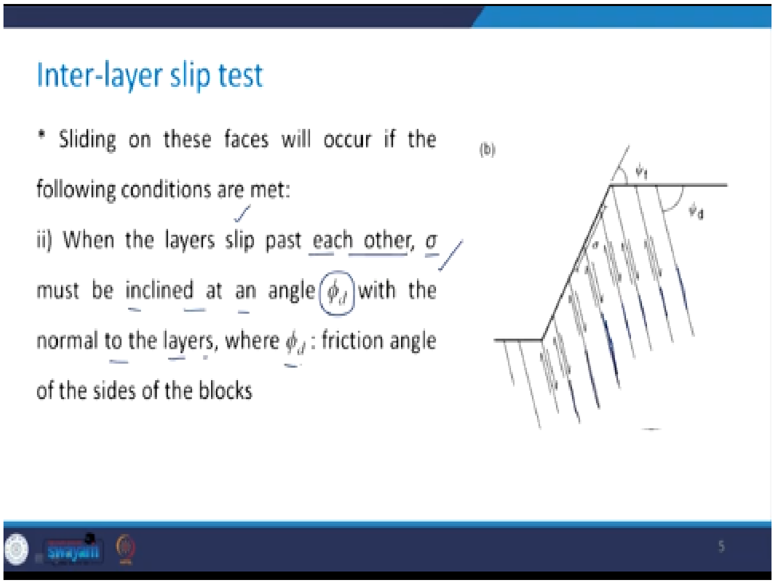

Now, sliding on these faces will occur if the earlier condition is met along with this particular condition also that when the layers slip past each other, sigma must be inclined at an angle ϕ_d with the normal to the layer. So, this is what the layers are. Where these ϕ_d is the friction angle of the sides of the blocks that is friction angle here.

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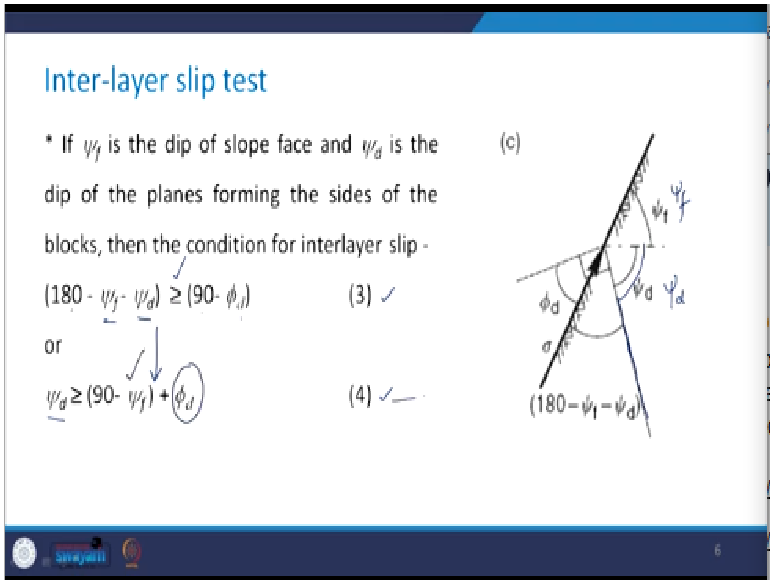

If ψ_f is the dip of the slope phase as has been shown in this figure. This is what is your ψ_f and ψ_d is the dip of the plane forming the sides of the block. So, you have seen that there were blocks. So, this is what the side of the block is and this angle is ψ_d. Then the condition for the interlayer slip is given by these equations 3 and 4 that is $(180 - \psi_f - \psi_d) \geq (90 - \phi_d)$or if you just shift that terms here and there.

And then this same relationship can be written as in this particular fashion that is $\psi_d \geq (90 - \psi_f) + \phi_d$. So, the equation 4 if this is satisfied, we would say that the interlayer slip will occur.

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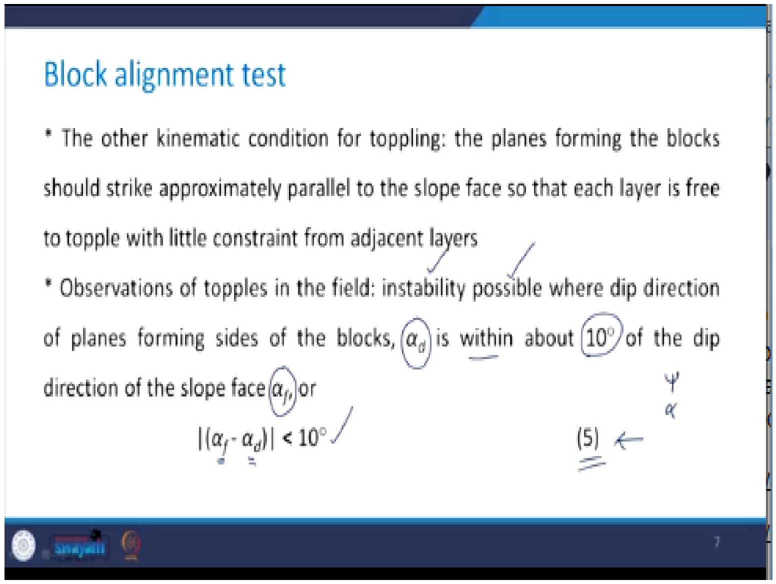

The other kinematic condition for toppling includes that the plane forming the blocks should strike approximately parallel to the slope face. So, that each layer is free to topple with little constraint from the adjacent layers. The observations of the topples in the field is used to identify whether the instability is possible or not. And this instability will be possible when the dip direction of the planes forming sides of the blocks which is represented by alpha d is within about 10 degrees of the dip direction of the slope face which is given by α_f.

You remember, we represent the dip by chi and dip direction by alpha. So, the same convention of the notation, we are following here. So, this condition can be written in the mathematical expression form by this equation number 5 that

$$|(\alpha_f - \alpha_d)| < 10^{\circ}$$

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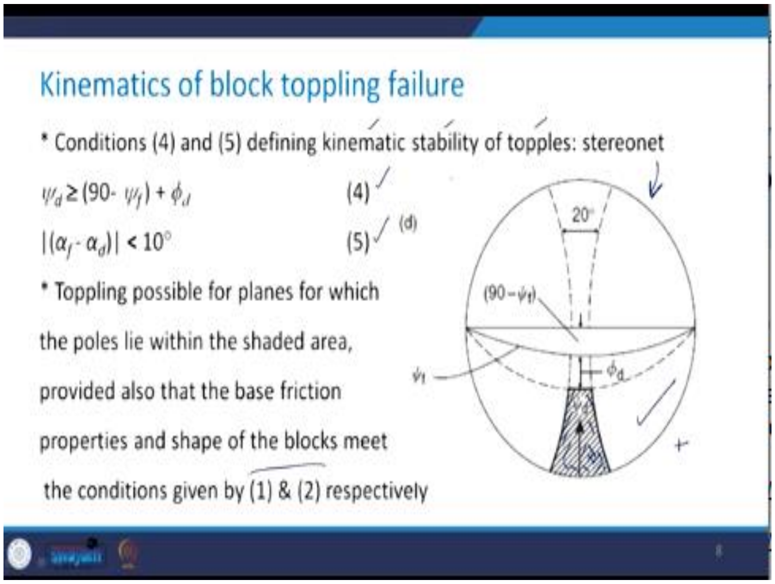

Now, these conditions 4 and 5, which I have again written here in this slide, these define the kinematic stability of the topples and this has also been shown in this stereonet. So, the toppling would be possible for the planes for which the poles lie within the shaded area that is this shaded portion. So, you know that the planes can either be represented by great circles or the poles. So, we have different planes along which the toppling may or may not occur.

So, we have to test whether the toppling will occur or not. So, if we draw the pole of those planes on this stereonet and if that pole falls within this shaded area, then the toppling would be possible for such planes plus the additional conditions which we already have defined with respect to equation number 1 and equation number 2 that should be satisfied as far as the shape of the block is concerned.

So, this condition plus the conditions given by equation number 1 and 2, all these should be satisfied for the toppling to occur along any plane.

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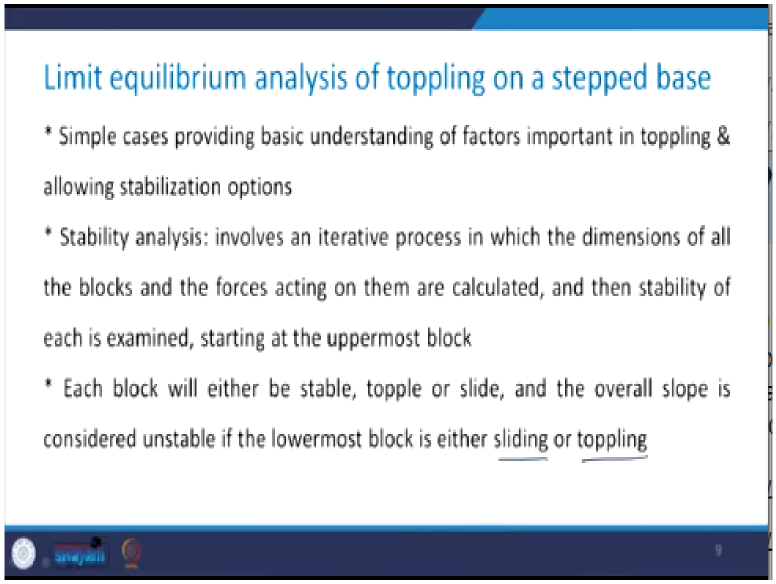

Coming to the limit equilibrium analysis of toppling on a stepped base, we are going to consider some simple cases in order to provide you the basic understanding of the factors which are important in the toppling failure and also in allowing the stabilization options because, if the factor of safety works out to be less than 1, then we need to adopt some stabilization measure for the slope stability.

The stability analysis in case of the toppling failure involves an iterative process in which the dimensions of all the blocks and forces which are acting on each of them, they are calculated, then the stability of each block is examined and this sequence is done from the uppermost block and then we come towards the toe of the slope. Now, this each block can either be stable, it can topple or it can slide.

And the overall slope would be considered unstable, if the lowermost block is either sliding or it is toppling. So, we need to be careful about it that in case if the lowermost block is either sliding or toppling, the overall slope is to be considered as unstable. The basic requirement is going to be the friction angle on the base of each block should be greater than the dip angle of the base. So, that sliding on the bass plane does not occur in the absence of any external force which is acting on the block.

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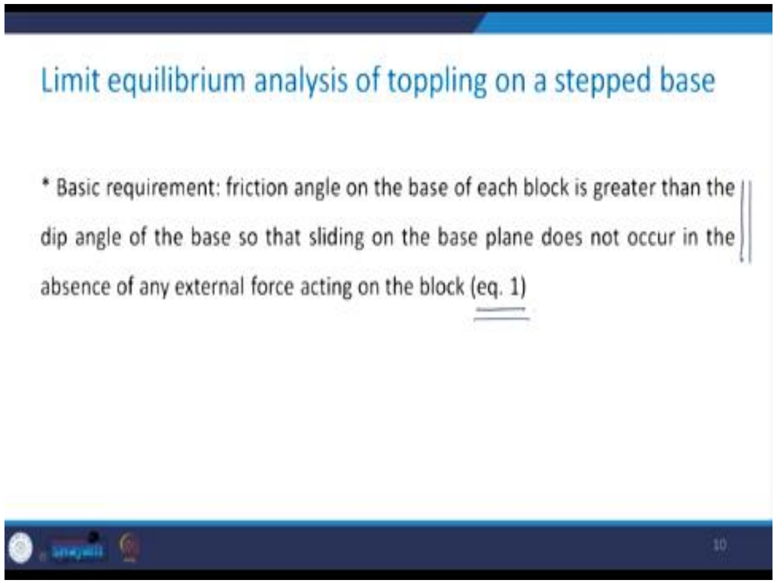

And how this condition can be ascertain mathematically by using equation number 1, which I have already discussed with you. Keep in mind that we are talking about the toppling failure.

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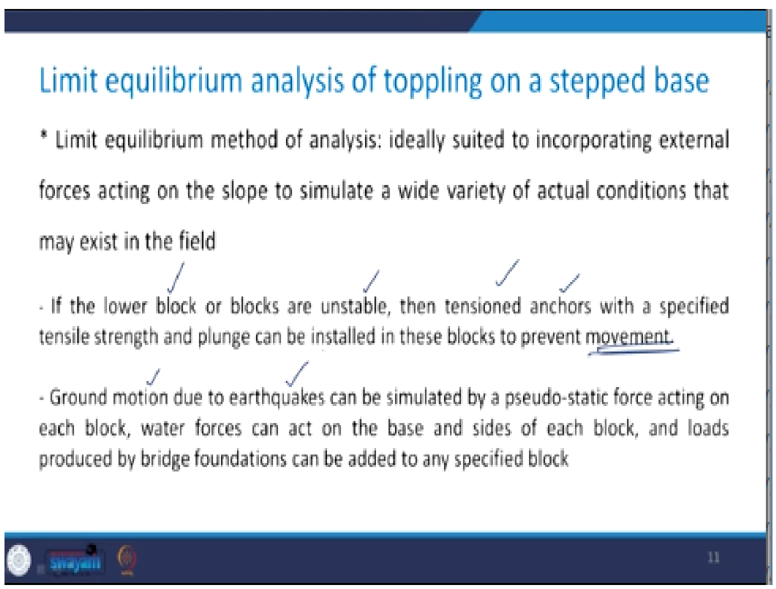

The limit equilibrium method of analysis is ideally suited to incorporate external forces which are acting on the slope to simulate wide variety of actual conditions that may exist in the field. We may not be able to take up all those actual cases here in the class, but this limit equilibrium method is capable of considering all those factors. What we are going to discuss is a simple case in order to make you understand that what exactly the basics behind this toppling failure of the rock slopes.

Now, if the lower blocks or the lowermost block is unstable, then tensioned anchors with the specified tensile strength and plunge can be installed in these blocks in order to prevent its movement. So, this is a kind of stabilization measure which can be adopted. In case of the ground motion due to earthquake that also can be simulated by a pseudo static force acting on each block.

Then water forces can also act the base and the side of the each block and the loads, which are produced by bridge foundations can also be added to any specified blocks. So, in this particular manner, this limit equilibrium method of analysis can take care of many such external factors, which are more relevant in the field, but, we will first learn about the basics behind this limit equilibrium method of analysis in case of the slopes experiencing toppling kind of failure.

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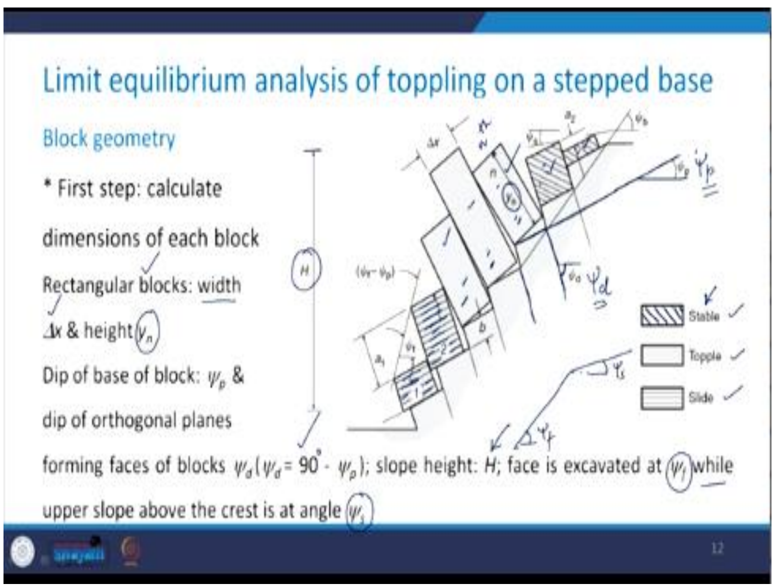

So, coming to first the block geometry, you can see here that there is a figure which is having the slope phase and these columns are there and the toppling failure has been shown here. There are three types of blocks which have been shown. First one is stable. So, this is like with the inclined hashed portion. So, this and this block, they are stable. Then these 3 blocks which are next to these stable blocks, they have the tendency to topple and the blocks which are even below these blocks which are undergoing or experiencing the toppling.

They will slide and it has been represented by the hatching in this particular manner. So, there can be 3 types of blocks stable, the block which is toppling, the block which is sliding. So, we need to find out the block geometry that is the first thing which we need to do as far as the limit equilibrium analysis is concerned. So, in case of the block geometry, the first step is going to be that we need to calculate the dimensions of each block.

Now, the assumption which is made here is that all these blocks are the rectangular blocks having width Δx and the height y_n. So, if I take the nth block, which is here, so, the height of this block that is from its base to its top that is what is y n. So, if it is first block, its height is going to be y_1, y_2, y_3 and so on, up to y_n. Now, the dip of the base of the block is given as ψ_p which you can see that it has been shown like this here.

This angle is chi p and the depth of the orthogonal planes which are forming the faces of the block that means these planes, this has been considered as ψ_d, which is this angle and there is a relationship between ψ_d and ψ_p which is given as ψ_d is equal to 90 degree minus the ψ_p. The slope height is represented by capital H, which has been shown here. The face is excavated at an angle of ψ_f, while the upper slope above the crest is at an angle of ψ_s. So, you see that it is something like this. So, this is ψ_f and this portion here is ψ_s.

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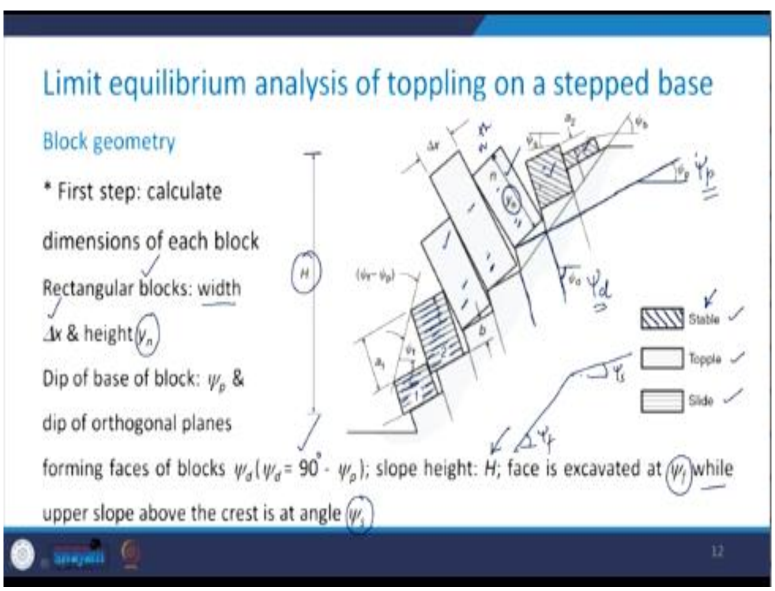

The angle of the base plane is represented by ψ_b. You can see here in this figure that the base of these toppling blocks is a stepped surface. You can follow the way, I am drawing and you can see that these is a stepped surface with an overall dip of ψ_b. You need to take a note that no explicit means are available to determine this ψ_b. But since, it is necessary to use an appropriate value for ψ_b in the analysis as it has a significant effect on the stability of the slope.

So, we take the average value of ψ_b. How to choose this? We will see it a little later. Now, once we need to know the block geometry, so, for that, first we need to know that how many number of blocks are going to be there in that geometry. So, let us try to obtain those number of blocks. The assumption here, which has been made is that the dimension be which you have seen in the previous slide is going to be same for all the blocks.

So, I am going to draw a simple figure in order to derive that how you can obtain these number of blocks.

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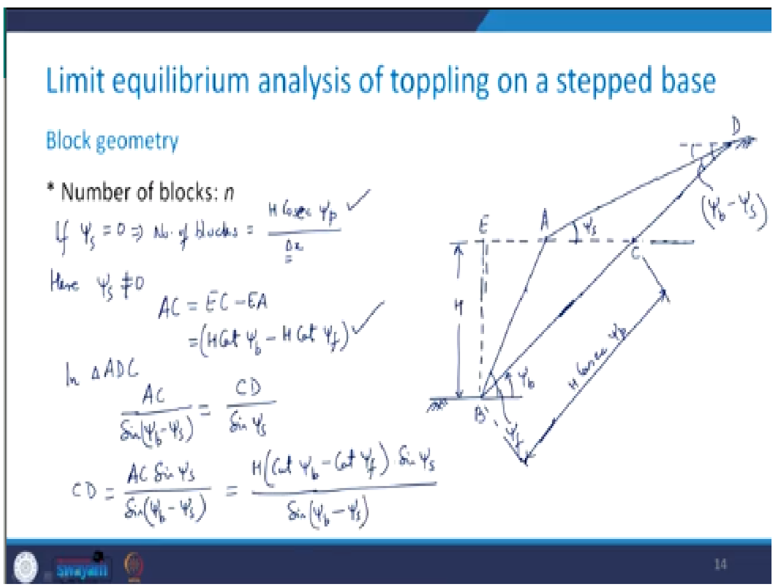

So, you see here that we have the simple figure. See, this is the lower portion of the slope. And this is what the upper portion of the slope is. And this is the failure surface. Now, this is what your base that is ψ_b is. Although it is stepped, but here I need to take the average angle, so that is what that I am considering. This angle here is ψ_f and this angle at the upper portion is ψ_s. Now, I mark this point as point A, this is as point B, this is C, this point is D here.

And so, basically it is this line. So, this point here is the point E and this is your height H. Now, just imagine that if your ψ_s is equal to 0. If this would have been equal to 0 that means that the slope would have been this face and then this horizontal line. Then in this case, the number of blocks would have been $(H \operatorname{cosec} \psi_p) / \Delta x$. And I am assuming that for each blocks, this delta x is going to be same, because you see that this distance would have been $(H \operatorname{cosec} \psi_p)$. And Δx was the dimension along this basal plane.

So if I divide that by the Δx, this whole distance, I am going to get the number of blocks, but in this case here, ψ_s is not equal to 0, it has some value. So, what we are going to get is, AC will be equal to EC minus EA and this is going to be $H(\cot \psi_b - \cot \psi_f)$. Now, you consider the triangle ADC that means, this triangle ADC, this triangle, what we will get is AC, this AC and in front of this side, this is the angle.

So, this angle, what this angle would be you see here? This angle is going to be $(\psi_b - \psi_s)$, because this total angle will be ψ_b and that sound that you will get here this angle is chi s and you will get $(\psi_b - \psi_s)$. So, this is going to be; I apply the sin rule; $\sin(\psi_b - \psi_s)$ that is going to be equal to CD. So, this is what your CD is and in front of this, you have this angle, so, this is going to be $\sin(\psi_s)$.

So, from here, I can get

$CD = \frac{AC \sin(\psi_s)}{\sin(\psi_b - \psi_s)}$

Now, AC, we have obtained here, so, just substitute it here, what you will get is $H(\cot \psi_b - \cot \psi_f)$ and there will be

$$CD = \frac{H(\cot \psi_b - \cot \psi_f) \sin(\psi_s)}{\sin(\psi_b - \psi_s)}$$

This is what that we are going to get.

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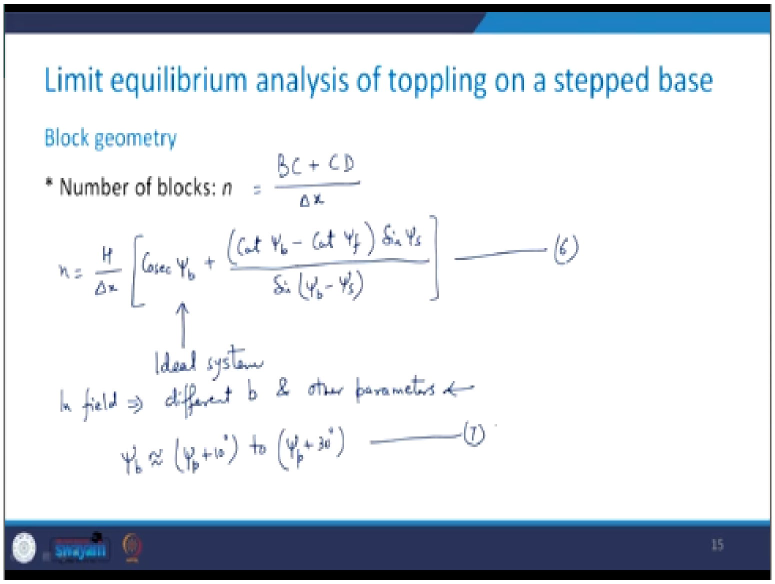

So, let us see how can we get the number of blocks in this case. This is going to be equal to

$$n = \frac{BC + CD}{\Delta x}$$

and therefore, this n is going to be

$$n = \frac{H}{\Delta x}\left[\operatorname{cosec}\psi_b + \frac{(\cot\psi_b - \cot\psi_f)\sin(\psi_s)}{\sin(\psi_b - \psi_s)}\right]$$

this is what I will write here as equation number 6. Now, this is what is going to be an ideal system because we considered that all the blocks have same Δx and same b.

But, what happens in the field? You will have different b and other parameters. So, we have to be careful about it. Now, this chi b can be taken

$$\psi_b \approx (\psi_b + 10^{\circ})\text{to}(\psi_b + 30^{\circ})$$

I am marking this equation as equation number 7. So, this is how one can consider as far as the deal system is concerned the number of blocks, but in case of the field situation, different conditions can be there and which also can be accounted for, but for the time being, we are restricting ourselves to this simple case only.

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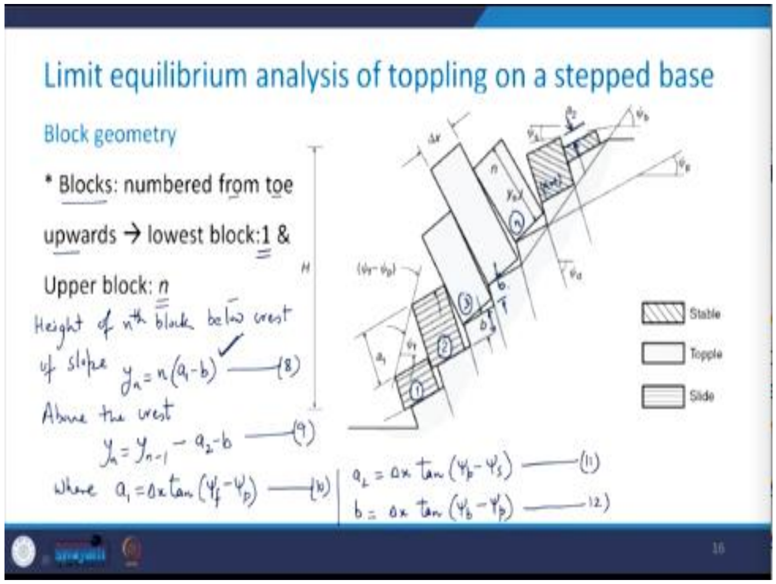

Now, when we go for the numbering of the blocks, these are numbered from toe upwards that means the block bottommost block at the toe will be numbered as 1, then go upwards 2, 3 and so on. Say, this is the nth block and this will be your (n+1) and so on. Say, n number of blocks are there. So, lowest block, I will write as block 1 and the upper block for which the analysis is being carried out is going to be block *n*.

So, here, height of n^{th} block below the crest of the slope. Now, that is going to be $y_n = n(a_1 - 1)$. This is equation number 8. See here you need to keep in mind that I am considering this *b* same for all the blocks. Otherwise, I will not be able to arrive at this expression. This highest block can be below the crest or it can be at the crest or it can be above the crest. So, in case, if it is above the crest, what will happen?

I will have$y_n = y_{n-1} - a_2 - b$. This will be equation number 9. See, here, this is what is the a_2 dimension. Where this a_1, a_2 and *b*, they can be determined in terms of Δx and these dip angles. How? See, a_1 will be written as

$$a_1 = \Delta x \tan(\psi_f - \psi_p)$$

I will make it as equation number 10. Then a_2 will be equal to

$$a_2 = \Delta x \tan(\psi_p - \psi_s)$$

that is equation number 11.

And b is going to be equal to

$$b = \Delta x \tan(\psi_b - \psi_p)$$

This is equation number 12. So, this is how the block geometry for each of the block can be determined.

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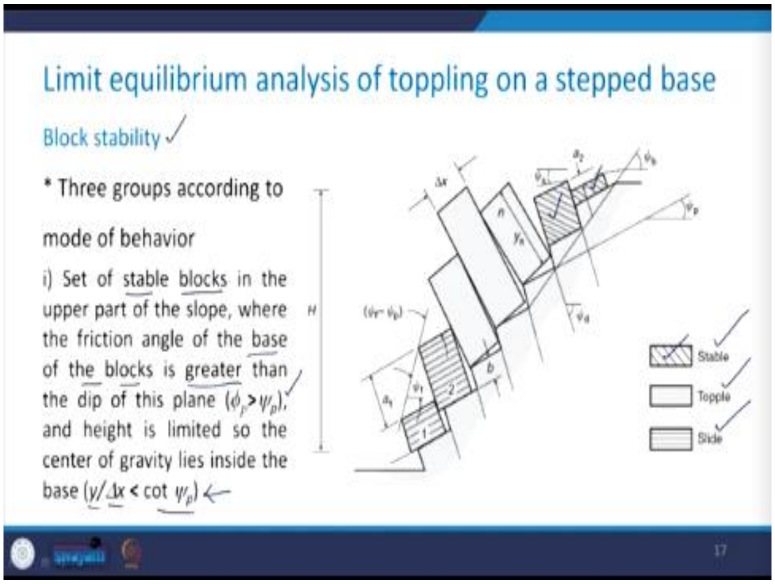

Now, the second step is going to be the block stability. So, there are 3 groups according to the mode of behavior. I already explained this to you that there can be stable blocks; there can be toppling blocks and there can be sliding blocks. So, the first set comprises of the stable blocks and this will be in the upper part of the slope as you can see this block and this block, they are the stable blocks.

In this case, the friction angle of the base of the block is greater than the dip of the plane that means,$\phi_p > \psi_p$ and the height is limited such that the center of gravity of these blocks, it lies inside the base that means that this condition is satisfied that is $y/_{\Delta x} < \cot \psi_p$.

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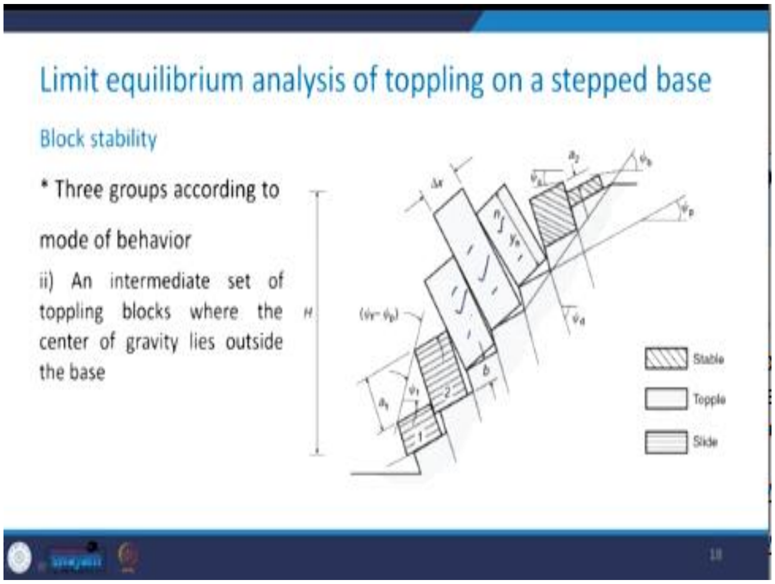

The second set has the intermediate set of the toppling blocks as given by these 3 blocks in this particular figure. And in this case, the CG lies outside the base that means that these blocks will topple.

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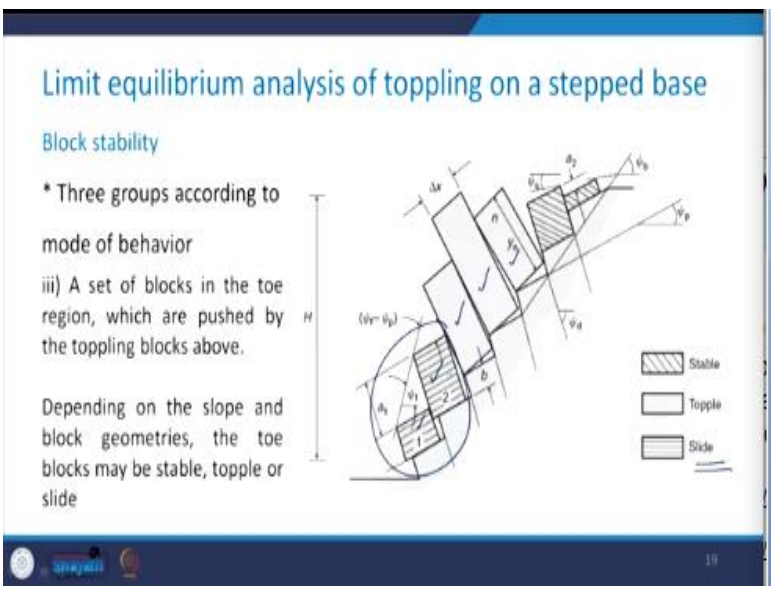

And the third set of block which is in the toe region, these are pushed by these toppling blocks. So, let us say that these 3 blocks are the toppling blocks in this figure. So, these will push, these 2 blocks which are lying in the toe region. And therefore, these will experience the sliding. Depending upon the slope and the block geometries, the toe blocks may be stable, they may topple or they may slide.

So, this was all about the block stability, how the mathematical expression for this limit equilibrium analysis of the rock slopes undergoing toppling type of failure mode is carried out that we will take up in the next class. Thank you very much.