Rock Engineering

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Lecture - 52
Rock Slope Stability: Toppling Failure - 1

Hello everyone. In the previous class, we discussed about the circular failure mode of the rock slope and how the analysis is carried out using limit equilibrium approach. So, today, we will take up the next failure mode, which is the toppling failure mode. And before we go for the analysis of the toppling failure mode of the rock slopes, first we will learn about the types of the toppling failure and we will also learn that for which type of rocks such type of failure mode would be more likely to occur.

So, let us start our discussion. First with some introductory slides on toppling failure. So, all the earlier failure modes that is plane, wedge and circular, they all relate to the sliding of a rock or the soil mass along and existing or induced sliding surface. In case of the plane failure, there was one single plane of sliding. In case of the wedge failure, we discussed the analysis related to the sliding of a wedge which is being formed in between 2 discontinuity planes.

And in case of the circular failure, we saw that it is a kind of circular failure surface which will be formed along which the sliding of the rock or the soil mass is going to take place. But, what happens in case of the toppling?

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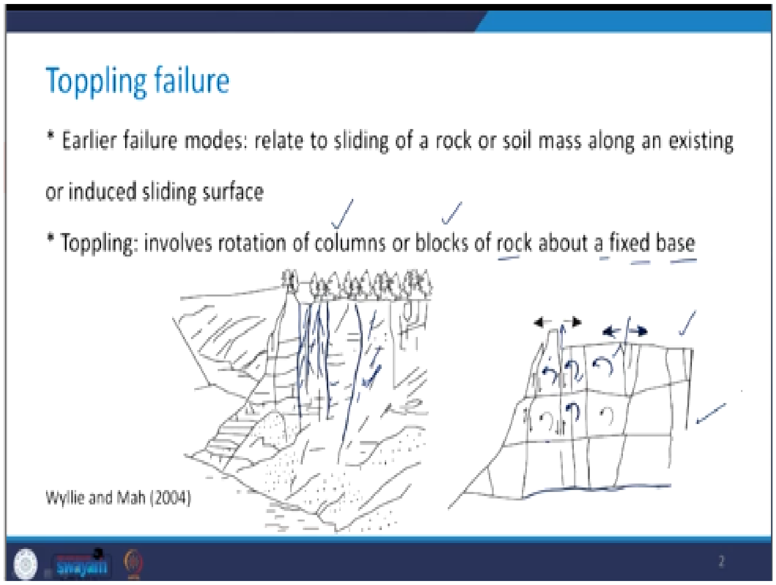

It involves the rotation of the columns or blocks of rock about a fixed base. Take a look at these pictures. And you can see that the rock mass which is here, it has very steeply dipping joints and therefore, it is kind of creating such type of columns in the rock mass and come here and see what it looks like that there is going to be the kind of rotation as shown by these curved arrows of these rock blocks. And this is what is going to happen about a fixed base.

So, you see that this is what is fixed and the rotation is taking place. So, what it is happening is what you are going to get here is that this kind of an opening, here also and here also, which is visible in this particular figure. So, toppling failure mode is therefore different than the earlier 3 failure modes in which sliding was taking place. However, in this case, it is the rotation of the columns or blocks of rock about a fixed base. So, the fixed solid blocks and open blocks which are free to move has been shown in this figure, which has 4 components.

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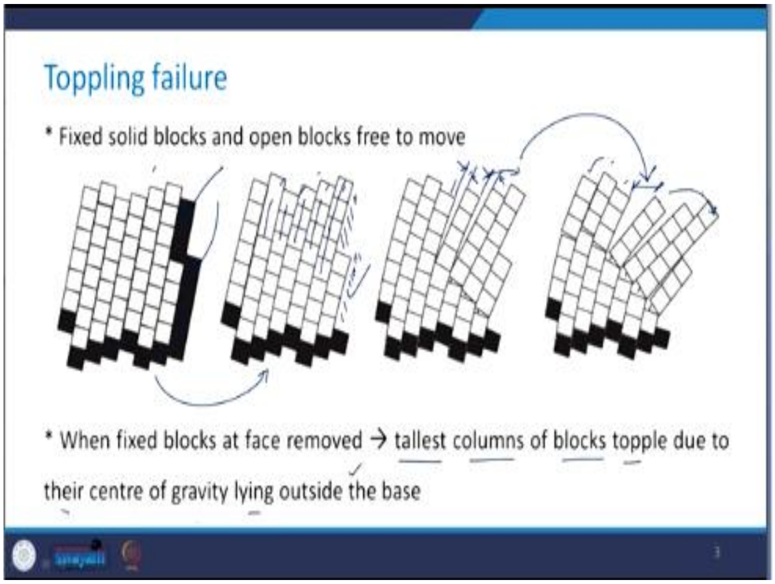

So, these solid lines, they are the fixed blocks and these are all open blocks and these are free to move. Open blocks are free to move. Now, let us say when these fixed blocks at the face, they are removed. So, come from the first figure to the second figure and you will realize that this portion and this portion has been removed in this particular figure. So, you see that what happens is that the tallest columns of the blocks topple due to their center of gravity lying outside the base.

So, you can see that the slide bending has started taking place. Here, the moment you remove the fixed blocks from this face, which was here. Now, if we leave it like that, slowly what will happen? There is going to be this toppling or the rotation and you can see that the gap here at the base is observed and you can see that there is the occurrence of these separation in between these 2 blocks here also.

So, when you go from the third step to the fourth figure, you see that how these gaps are increasing and here also. And how as these blocks rotate, these blocks which are they are behind these rotating blocks, they also have the tendency to rotate slowly in the same direction. So, this is what the mechanics behind the toppling failure.

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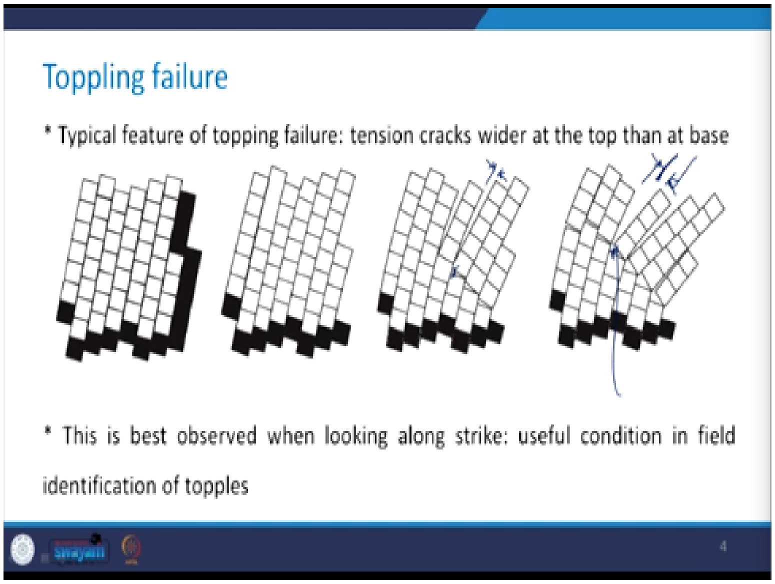

The typical feature of the toppling failure is the occurrence of tension cracks, which are wider at the top than at the base. So, you can see that here the width is only this much. However, here the width is larger as compared to what it was at the base and this is more evident. If you look at this figure, you see here this separation is this much and at the base, it is only this much separation which is there. So, these tension cracks are wider at the top as compared to at the base.

Now, this can be observed in the best possible manner, when you look along the strike direction and this can be a useful condition for the field identification of topples. So, these blocks which are toppling, they are called as topples. So, if we need to identify these in the field, we can observe while looking along the strike to that slope and we will be able to identify these topples.

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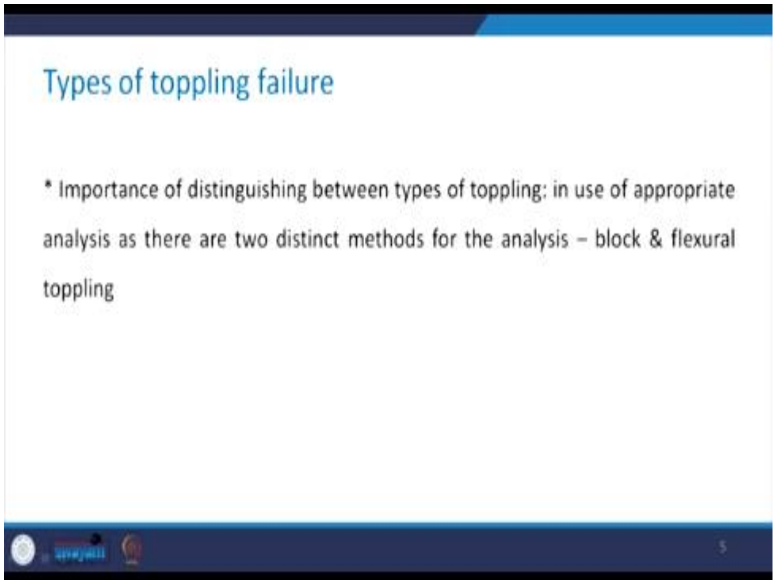

The importance of distinguishing between different types of toppling is helpful in the use of appropriate analysis as there are 2 distinct methods for the analysis of the toppling failure. So, before we go for the analysis, we need to first identify that which type of toppling failure is going to occur whether it is the block toppling or if it is the flexural toppling. So, in view of the decision to be taken related to the application of the appropriate method for the analysis, it is extremely important for us to distinguish between different types of toppling.

So, we will now discuss these types of toppling failure and the first one in this category is the block toppling.

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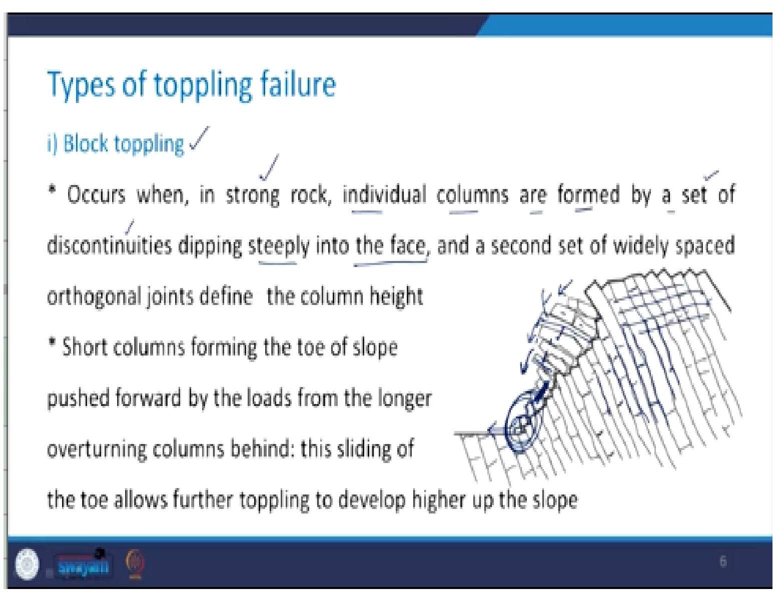

Now, it occurs when in strong rock, individual columns are formed by a set of discontinuities which are dipping steeply into the face and there occurs a second set of widely spaced orthogonal joints, which define the column height. Take a look at this figure. So, we have a set of discontinuities which are dipping in this direction. This is one set of discontinuity. So, these are steeply dipping into the face and then we have the second set of widely spaced orthogonal joints, these are these.

See, these are so widely spaced another set of joints and these define the column height. So, you can take a look here that the joint which is there, it defines this column height. So, in this case, it is this, the column height and you can see that in this particular column, there will not be any orthogonal joint. The short columns forming the toe of slope that is here at this location. So, you see that here the columns are pretty short near the toe of the slope.

These short columns which are be part of the toe of the slope. They are pushed forward by the load from the longer overturning columns behind. So, you see, here this figure is the self explanatory figure. The moment this column tries to overturn whatever are these columns, which are ahead of this column, which is overturning. These columns are pushed forward by the load from these overturning columns, which are longer columns.

So, this sliding of toe allows further toppling to develop higher up to the slope. See, what will happen? The moment this block starts toppling, it exerts the force on to the small columns which are near the toe because of this force, this material try to slide. The moment it tries to slide, the upper column also starts experiencing the overturning and this is how this phenomena transfers from one column to the others till the last state comes beyond which these columns come in the stable state.

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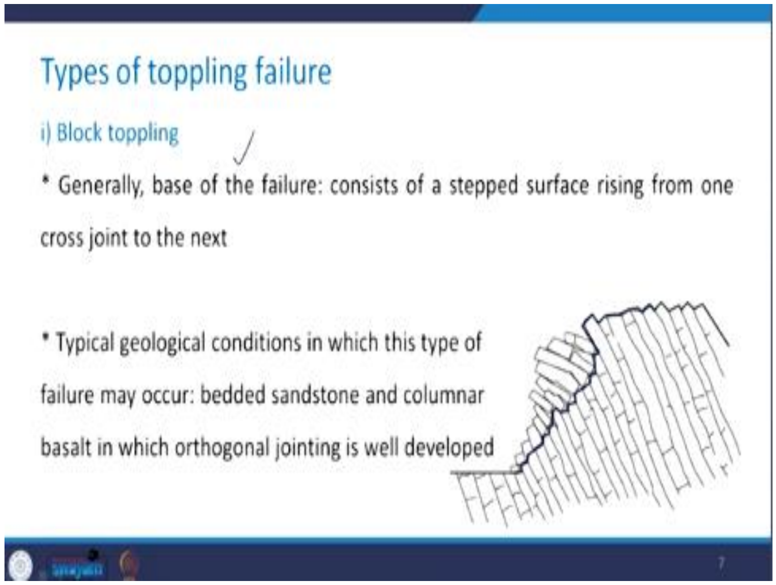

Generally, the base of the failure is consisting of a step surface rising from one cross join to the next. Take a look here, what I mean to say here is that this step portion which is formed by these orthogonal joins of these columns, this is what is going to define the base of the failure surface. Typical geological conditions in which this type of failure may occur involve bedded sandstone and columnar basalt in which orthogonal jointing is well developed.

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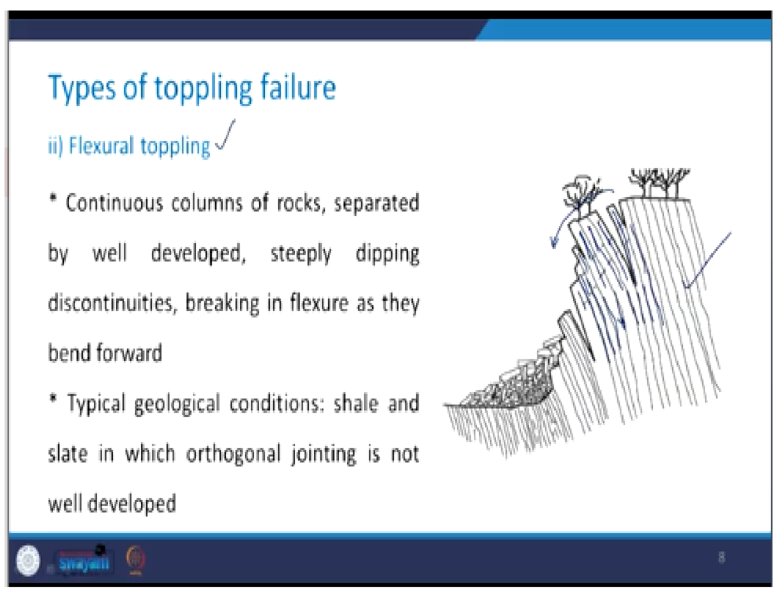

The second type of toppling failure includes flexural toppling. In this case, there are continuous columns of rocks, which are separated by well developed steeply dipping discontinuities. They break in flexure as they bend forward. Take a look at this picture, you have steeply dipping joints in this particular fashion. And these are the continuous columns and rather than sliding and then toppling, they fail in flexure.

So, it is this kind of rotation is going to take place and these columns, they are going to experience the flexure. The typical geological condition in which such type of toppling failure can occur is the shale and slate in which the orthogonal jointing is not very well developed. So, you can see the difference between this figure and the figure which I showed you in the earlier slide that in this case, these orthogonal joints which were present.

In the previous case, they are not there. So, no orthogonal joints in this case and therefore, they break in flexure as they bent forward in this particular manner.

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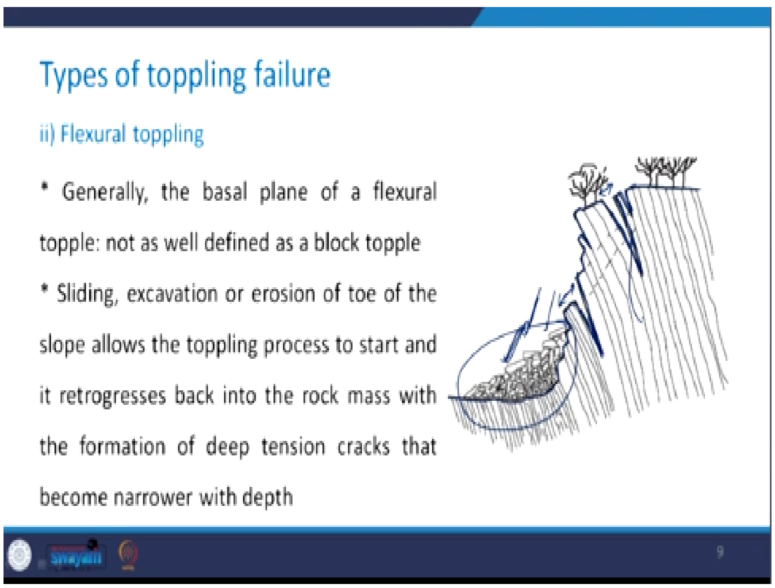

Generally, in this case, the basal plane of a flexural topple is not as well defined as it was there in case of the block topple. You can see here this dark line, this is the basal plane and you can see that it is not very well defined, sometimes there is a separation and then sometimes it is like this. So, it is not very well defined. However, in the earlier case, it was kind of a stepped manner that the base plane verse.

Now, in this case, the sliding excavation or erosion of toe of the slope allows the toppling process to start and it retrogressive back into the rock mass with the formation of deep tension cracks that become narrower with depth. Take a look here. Near the toe of this slope, there is either the sliding or the excavation or erosion of the toe of this slope. And this triggers the bending of the long columns which are behind this.

So, the moment, this toe portion of the slope experiences either sliding or excavation or erosion, this phenomena starts happening and what happens is there occurs a tension crack which goes deep into the rock mass. So, you can see here it is this deep and here also it is quite deep and the width of this tension crack is more at the surface as compared to when it goes deeper in the rock mass here.

So, the tension crack gets lesser or the tension cracks becomes narrower with the depth in the rock mass.

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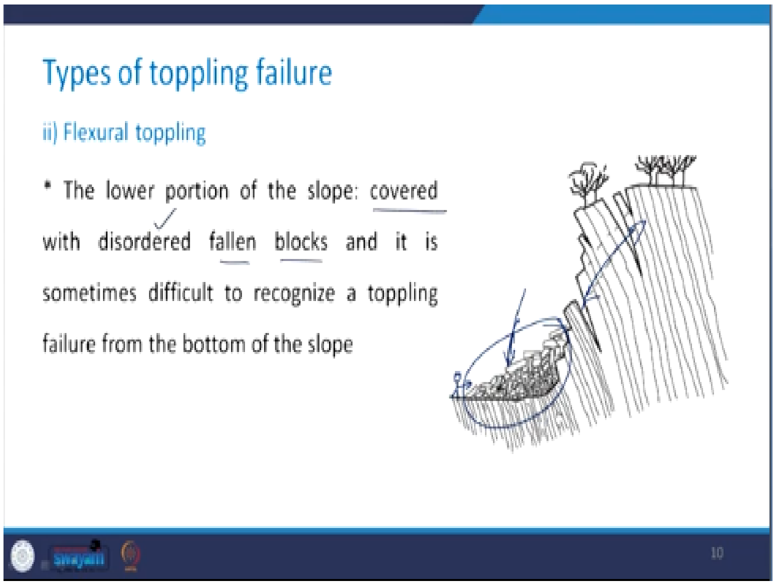

The lower portion of the slope gets covered with disordered fallen blocks and sometimes it becomes difficult to recognize a toppling failure from the bottom of the slope. Now, let us say that you stand here and you try to observe. So, what you are going to see is this material and if you look it from this point that is at the base of the slope, you may not be able to recognize that it is the toppling failure here in this portion of the rock slope just because that the lower portion of this slope is covered with the disordered fallen blocks.

And what you will see is only this much portion and you will not be able to recognize this. So, we need to be careful about such type of the toppling failure.

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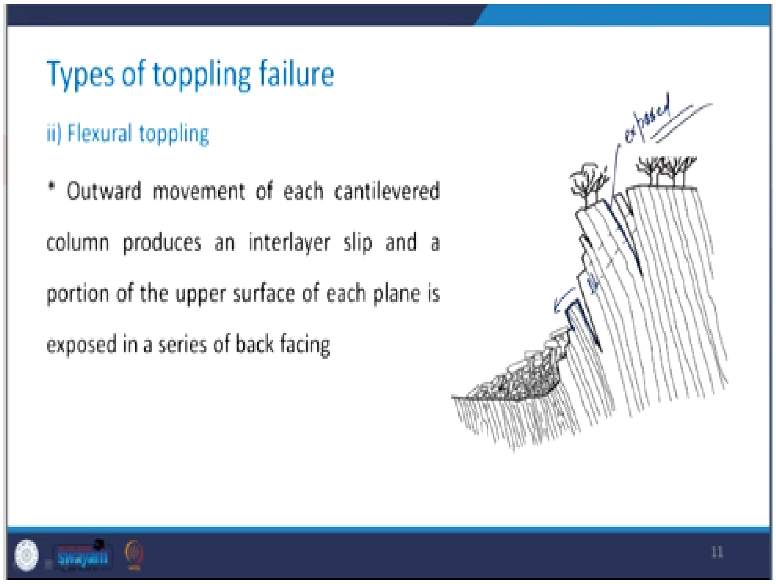

The outward movement of each cantilevered column produces an interlayer slip. So, the moment, there is the outer movement of each column; there is going to be the interlayer slip and the portion of the upper surface of each plane is exposed in a series of back facing. Like you see here, this portion that is the upper portion of this column is exposed in a series of back facing here.

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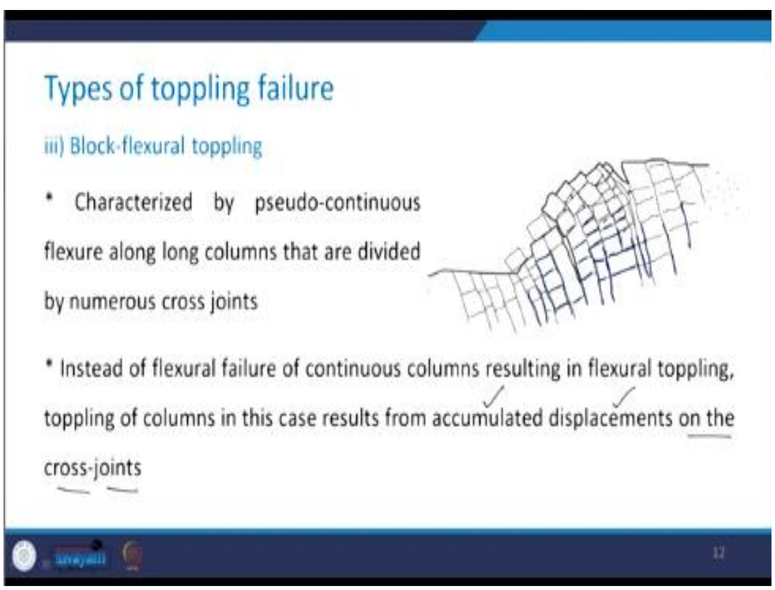

Coming to the next type of the toppling failure, which is block flexural toppling. This is characterized by pseudo continuous flexure along the long columns that are divided by numerous cross joints. So, that is a difference between the earlier 2 mode of failure and this toppling mode of failure. Again here, in this case, all these joints are steeply dipping in the rock mass. But, you can see that there are numerous cross joints, which are present in each column, which are formed because of the presence of these discontinuities, which are dipping steeping.

So, instead of the flexural failure of the continuous columns, which was there in case of the flexural toppling, in this case, toppling of the columns result from the accumulated displacements on the cross joints. So, take a look here at the cross joints. So, you can see the gap here in between these cross joints. So, basically, the toppling will take place from the accumulated displacements on the cross joints rather than having the flexural failure of the continuous columns, which was there in case of the flexural toppling.

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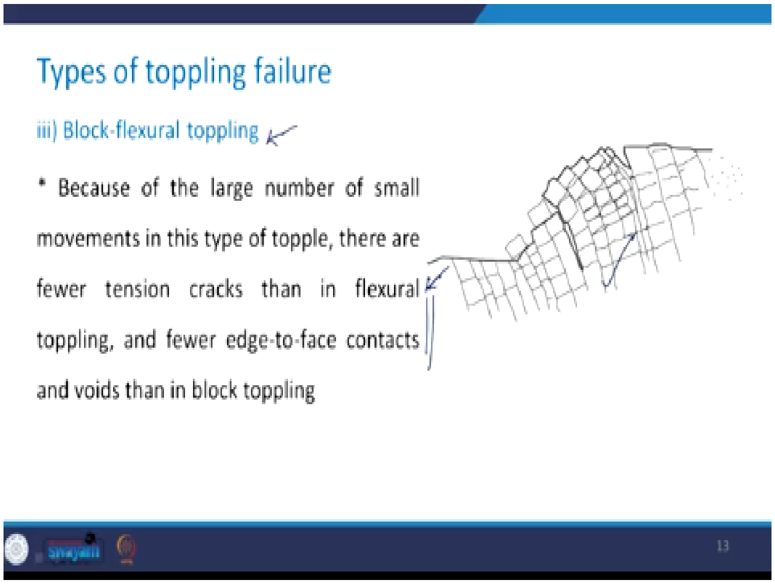

Now, because of the large number of small movements in this type of topple, there are fewer tension cracks than in case of the flexural toppling and fewer edge to face contacts and voids as compared to block toppling. So, the difference between block flexural and block flexural toppling has been given here. In case, if you have this block flexural toppling kind of behavior, there are going to be fewer tension cracks as compared to those which were present in case of the flexural toppling.

And there are going to be fewer edge to face contacts and voids as it was there in case of the block toppling and this figure itself is self explanatory as far as this concept is concerned.

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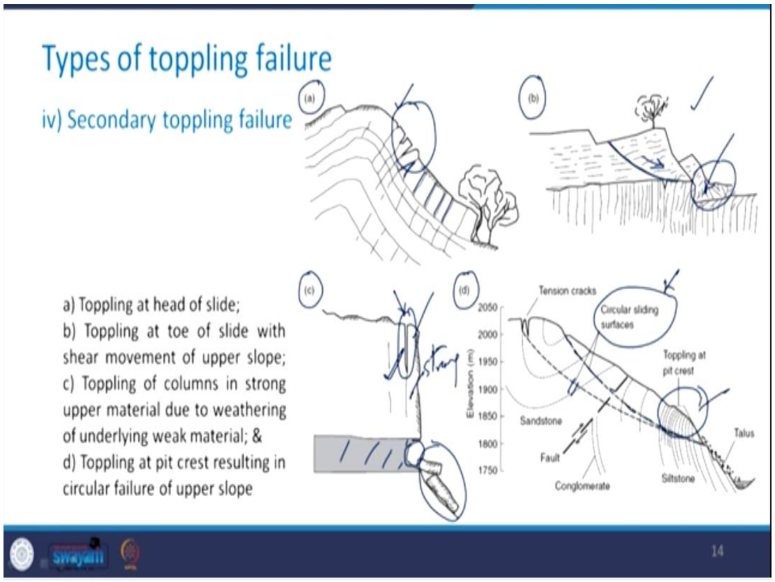

There are few secondary toppling failure which also take place. So, some of these have been mentioned in this figure. So, this portion of the figure which is figure part a, it shows the toppling at the head of the slide. So, you can take a look that here you have the steeply dipping joints and the toppling is taking place at this location. Then here, which is part b, there is the toppling near the toe of slide with the shear movement of the upper slope.

So, you can see here that in this portion, there is going to be the toppling and along with the shear movement of this upper slope. So, you can see, there is a surface which has been shown here. So, the shear moment is going to take place and also there is going to be the toppling here near the toe of the slope or the slide. Then the c part deals with the toppling of columns in strong upper material due to weathering of underlying weak material.

So, you see, this is what the weak material, which is underlying this strong material. And the moment, there is a weathering of this underlying weak material and its situation becomes like this. This strong material will experience the toppling of the columns and the occurrence of the crack in this particular manner as has been shown like this. Coming to the next one, which is the d part of this figure.

So, in this case, there is the toppling at the pit crest that means at this location and it results the circular failure of the upper slope. So, you can see that 2 dotted lines have been shown. This is the first one and this is the second one and these are representing circular sliding surfaces. And these triggers when there is a toppling at the pit crest in this particular manner. We will try to see these in detail now, one by one.

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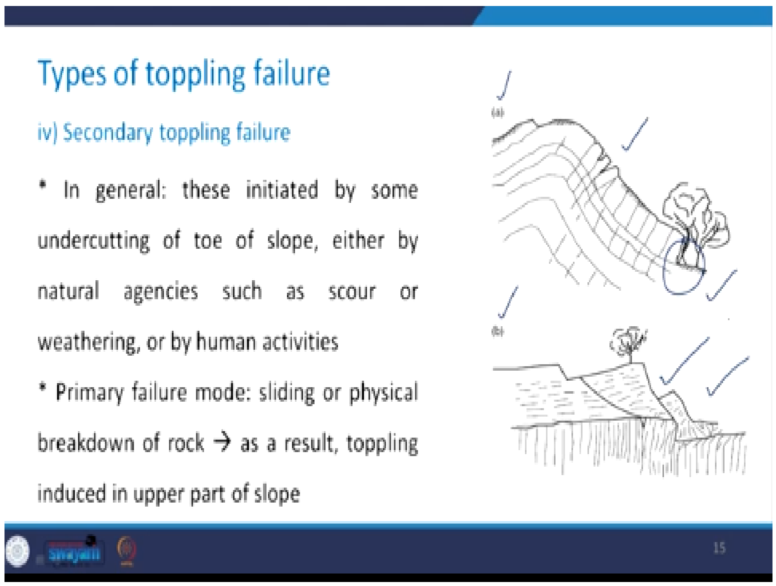

So, I have here a, and b which I explained you earlier. So, in general, these kind of toppling failure are initiated by some undercutting of the toe of the slope either by the natural agencies such as scour or weathering or by some human activities. So, wherever you have the undercutting of the toe of the slope, such type of secondary toppling failure mode can be expected.

The primary failure mode would be sliding or physical breakdown of the rock. And because of this sliding and physical breakdown of the rock, this toppling will be induced in the upper part of the slope. Like you can see here, the toppling is being induced in this case.

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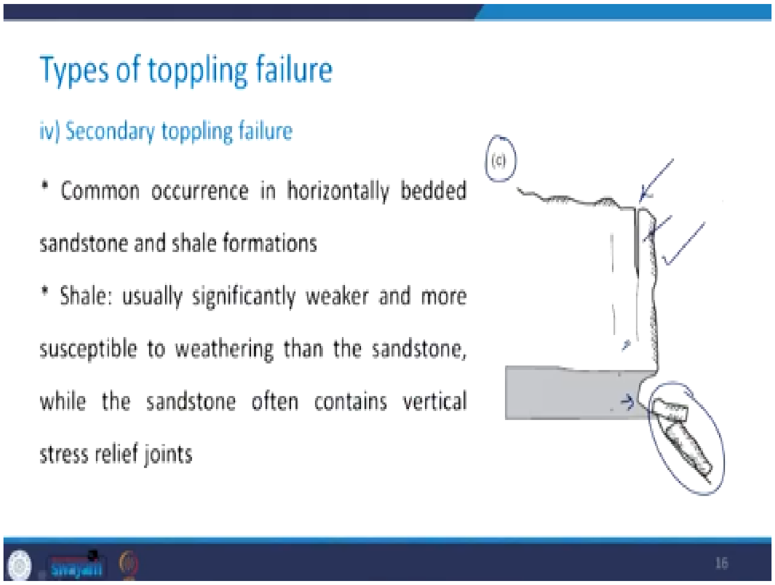

The part c which I explained that when the weaker material, which is underlying these stronger material, if this gets weathered, then there occurs the toppling in the upper portion. This is the common occurrence in horizontally bedded sandstone and shale formations. Shale usually are quite weaker and more susceptible to weathering as compared to the sandstone while the sandstone often contains vertical stress relief joints. So these two characteristics of shale and sandstone, they made them prone to experience this type of toppling failure.

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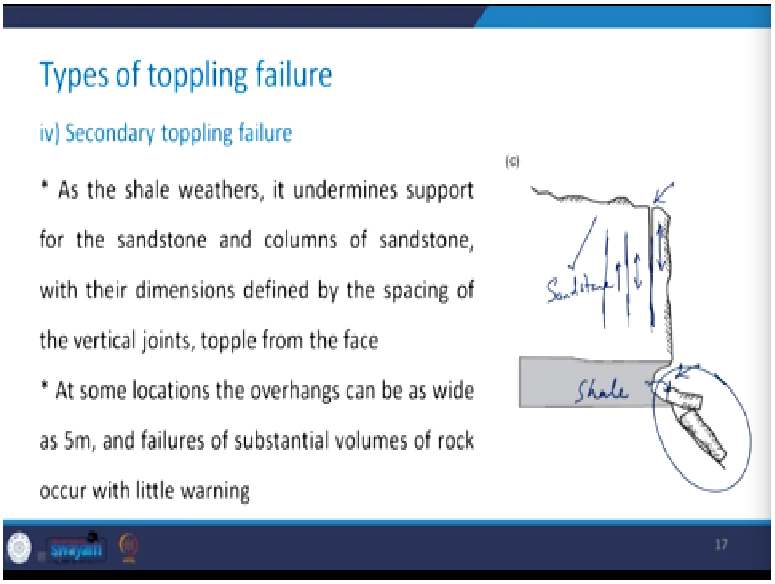

Now, in case of the shale, as it weathers, it undermines the support for the sandstone and the columns of the sandstone with their dimensions defined by the spacing of the vertical joints, they start toppling from the face. So, what this mean is, say, this is the shale and I mentioned to you that shale is quite prone to the weathering. So, in this particular part, when it starts weathering, and here, you have say, the sandstone in which vertical joints are present like it has been shown here.

The moment, there is a weathering here at this particular portion, there is going to be the formation of the column in this sandstone portion along these vertical joints, which are the characteristic of the sandstone and the moment, it weathers and or erodes the splitting of these columns start taking place in the sandstone portion. At some locations, the overhangs can be as wide as 5 meters and the failures of substantial volumes of rock occur with little warning.

So, such type of failure can be really fatal, because they do not give us enough time before the failure. So, we have very little time as the warning.

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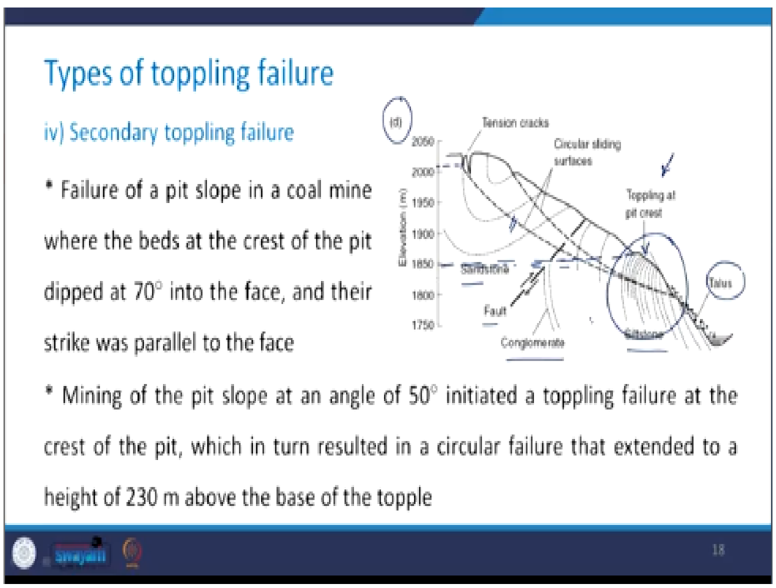

Coming to the last part, which is the type of the secondary toppling failure that is the toppling at pit crest. Now, here you can see that sandstone, fault, conglomerate and siltstones are present as a part of this slope and here you have talus. So, what happens that the failure of a pit slope in a coal mine, where the beds at the crest of the pit, they dipped at 70 degree into the face and the strike was parallel to the face here.

Mining of the pit slope at an angle of 50 degree initiated a toppling failure at the crest of the pit, which is at this location and this in turn resulted in a circular failure that extended to a height of 230 meter above the base of the topple. So, you see, this is the base of topple, where the toppling is taking place. So, somewhere here it is say about 1850 or so and this triggered the kind of the circular failure surface and see it goes up to here. So, it is about let us say, 2000. So, you see that what the height difference here.

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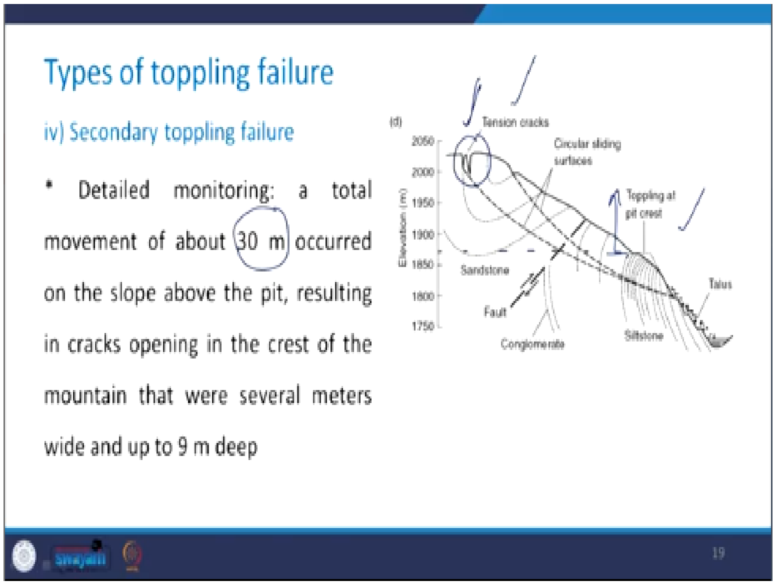

The detailed monitoring of the slope was carried out at the site and the total movement of about 30 meters occurred on the slope above the pit. See here, 30 meter on the slope above the pit that means here above the pit and this resulted in the crack opening at the crest of the mountain which is here; these cracks were several meters wide and up to 9 meters deep these cracks. So, you can see that how one particular phenomena, it triggers the other phenomena.

And therefore, there occurs the tension cracks in the slopes, which are not desirable because the moment tension crack occurs; it reduces the factor of safety.

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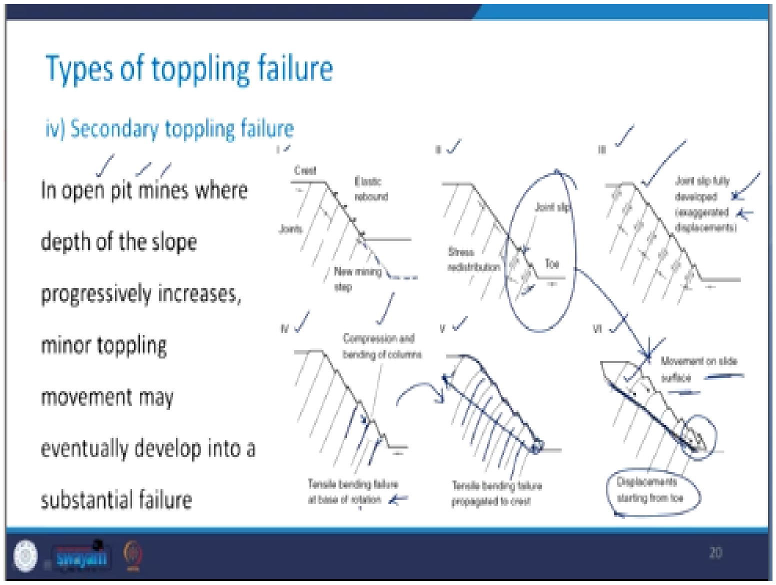

So, these are some of the typical pictures for the open pit mine activities. So, in case, you have the open pit mines, where the depth of the slope increases progressively, minor toppling movement may eventually develop into a substantial failure. So, as we saw in the previous case, there was some failure at the crest of the pit and that ultimately caused the occurrence of detention crack in the mountain.

Likewise, here in case of the open pit mines, you can see that different stages are given 1, 2, 3, 4, 5 and 6, go in this order. So, first you see that this is the new mining step which has been shown like this. Now, when this is removed, see how the joint slip is created here and slowly as you keep on going towards the top towards the mining activities and see how the joint slip gets fully developed in this case and it is shown by the exaggerated displacements.

Then what happens is that the tensile bending failure takes place at the base of the rotation and you see compression and bending of these columns. So, you see in this particular manner bending and the compression is taking place. Then slowly in the next step, when you come from 4 to 5, there is a tensile bending failure which is propagated to the crest. So, it is started from this point and it got propagated and you can see that this kind of tensile bending failure takes place.

Now, what happens? Ultimately, there is going to be the movement on the slide surface of this particular portion which is formed by the surface as has been shown in this part. So, there is the displacements which are starting from the toe. This is the toe and the displacement which is starting from here and it triggers the movement on this slide surface. So, you see that it was very small event here in this case, but how it led to the sliding of this whole mass along this particular surface.

So, we need to be extremely careful as far as the identification of these toppling modes are concerned before we start the analysis of the slope, which may undergo the toppling failure. So, we learned about different types of the toppling failure. So, in the next class, we will take up the limit equilibrium analysis of the toppling failure. First, we will learn about the kinematic analysis and then we will see that how the factor of safety can be determined for the slope, which is likely to experience this toppling failure mode. Thank you very much.