Earthquake Geotechnical Engineering

Prof. B. K. Maheshwari

Department of Earthquake Engineering

Indian Institute of Technology Roorkee

Lecture 41

Slope Stability Analysis

I welcome you again in this NPTEL online course. Today we are at the 41st lecture of this course. What we are going to talk in this series of next 10 lectures are very important issue which is particularly in the hilly areas. You know in our country Himalayan area is mostly hills and that is seismically active area also. Most of the Himalayan region falls in seismic zone 5 or some parts even in zone 4, but all in zone 4 and 5 there is no zone 3rd in Himalayan region. So, when we talk about our Himalayan here particularly the hills, then slope stability is one of the major issues and other things to make the slopes stables and you making the roads in the hilly area, there is retaining walls also constructed. So, what we are going to talk in the next module that is module number 5 for this course, two topics one is slope stability and retaining walls. Today we are going to start with the slope stability analysis and how in the slope stability analysis which is in module number 5 and retaining walls will also be coming here. So, what we are going to cover in this module and this list only related to slope stability not related to retaining walls.

So, in the slope stability we will have three chapters in this module 5. So, these three chapters first chapter is introduction to earthquake induced landslides that landslide occurs due to two reasons. One reason for the landslide is that this is because this rain or precipitation and the second reason of creation of earthquake landslide that means due to this shaking the landslide are triggered. So, we are going to talk about how the landslides are triggered due to earthquake. Then we are going to talk about the strictly slope stability analysis which is many of you would have already gone through your under-result studies. And finally, during earthquake what the effect of on the slope stability due to earthquake seismic slope stability we will discuss. So, the first part of this module that is on slope stability will be covered in these three chapters and today in this lecture of 41st we are going to talk about the we are going to complete the first part introduction to earthquake induced landslides and we will cover the static slope stability analysis partly. Coming to what we are going to talk in this lecture today this is the list seismic slope stability introduction to that, types of earthquake induced landslides, earthquake induced landslide activities and then so these first three topics are related to mostly related to landslide introduction. Then we are going to talk about slope stability how to evaluate the slope stability and this in this case static slope stability analysis will be covered which is in two-part limit equilibrium analysis and stress deformation analysis. We are going to start limit equilibrium analysis and stress deformation analysis will be covered in the next lecture.

So, coming to the introduction to earthquake induced landslides, first of all before I go ahead most of the material is from the Kramer's book. The seismic slope stability analysis you know as we already discussed it is crucial issue in hilly areas to mitigate landslides and for civil engineering construction because whatever construction you do in the hilly areas if that construction is not protected from the landslide, then there is no meaning and then it is not going to survive. So, and many landslides occurs on natural slopes but there could be some landslides which is man-made slope because from and you know that in fact many of the landslides are occurring due to man-made slope. Man-made slope is in the sense even the slope is there in the hilly areas but because due to the widening of the roads and other issues this organizations are cutting the hills and they are creating the man-made slopes or maybe disturbing the already existed slopes. Slopes are unstable when shear stress required to maintain equilibrium exceed the available shearing resistance on some potential failure surface.

So, this is similar. One side you have the strength of the slope, on another side the stresses generated inside the slope which may be due to the loading, which may be due to the shaking or maybe another many reasons. So, if the shear stresses due to external loading increases exceed the shear strength then the failure will occur. So, as part of the introduction when an earthquake occurs the effect of earthquake induced ground shaking is often sufficient to cause failure of slopes that were marginally to moderately stable before the earthquake. So, the condition of the slope before the earthquake if it is marginally stable, it was not very much stable or moderately stable then earthquake may act like a triggering action where after the earthquake or due to shaking the stability of the slope may be disturbed and once it is disturbed then there may be slope failure. And when the slope failure occurs then there is a damage, the resulting damage which can range from it could be insignificant or it could be catastrophe depending on geometric and material characteristics of the slope which we will discuss in detail. Like when we talk about landslides or like you know the liquefaction, the 1964 Alaska earthquake and 1964 Niigata earthquake both the earthquakes are known in geotechnical earthquake engineering community for widespread liquefaction as well as landslides. So, in the 1964 Alaska earthquake which was a magnitude 9.2 as we discussed when we discussed about liquefaction, an estimated 56 percent of the total cost of damage was caused by earthquake induced landslides. So, this is the issue.

If in any earthquake the landslide is not occurring that is okay, but if the landslide is occurring then this phenomena itself may be responsible for most of the damages sometime 90 percent of the total damage. For example, Kobayashi in 1981 found that more than half of the dust in large magnitude earthquake that is magnitude more than 6.9 in Japan between

1964 to 1980 were caused mostly by due to the landslides. So, evaluation of seismic slope stability is one of the most important activities of the earthquake geotechnical engineering. The reason being simply because due to the landslides lot of damage, lot of casualties have been already done particularly during the earthquakes.

According to the types of earthquakes induced landslides, stability of slopes and characterization of landslides is influenced by many factors. And what those many factors? It includes geology, hydrology conditions, topography that is and that means basically the slope characteristic and climate. And these landslides can be broadly classified into three groups. First one is called disrupted slides and falls. And it includes not only slides related to rock but also soil include rock falls, rock slides, rock avalanches, soil falls, disrupted soil slides and soil avalanches.

These types of falls are usually found in steep terrain and can produce extremely rapid movements. So, if you have a gentle slope then it will be the absent. But if your slope is steep then these like you know disrupted slides and falls will be present. Coming to the second one coherent slide such as rock and soil slumps or rock and soil block slides and slow earth flows.

It occurs relatively at lower velocity than disrupted slides and falls. So, the velocity is high in the first one, disrupted slides but in the coherent slide it is lower side. Third one is really little different which is lateral spreads and flows and you know the lateral spreading when we talk come the lateral spreading that is a liquefaction generated phenomena and it is linked with the cyclic mobility. Generally, involves liquefiable soils although sensitive clays can produce landslides with similar characteristics. Due to the lower residual strength sliding can occur on remarkably flat slopes and produce very high velocities.

So, here in this case even this slide the third category may occur on very gentle slope also and the reason is mostly lateral spreading that if liquefaction may occur then it is what we call the like weakening instability which we are going to discuss in detail later. So, this is a different case than the normal because in the liquefaction the soil loses its shear strength so that is why it occurs. Coming to different types of earthquakes induced landslides that will occur with different frequencies their frequency of occurrence will be different. Rock falls, disrupted soil slides and rock slides appear to be most common types of landslides observed in historical earthquakes. So, it has been observed that in the past most of the landslides was in the category of disrupted slides or rock falls.

Then another category where this landslide which is the opposite to slow earth flows rock block slides, they contribute very small to them like their contribution is small. So, here is a table which suggest types of earthquakes induced landslides during the past earthquake. The first column says what is the frequency abundance and the second column gives the description for example, very abundant slides mean like those happening in a like in last

40 earthquake more than 1 lakhs. So, this is rock falls, disturbed soil slides and rock slides. So, their frequency is very high while abundant will is categorized in last 40 earthquake it is between somewhere number is between 10,000 to 1 lakh and in this category soil lateral spreads soil slumps, soil block slides falls.

Third one which is moderately common which is not very common that is the frequency 1000 to 10,000 in number of 40 number of 40 earthquakes. So, it includes soil falls, rapid soil flows, rock slumps. The last one is very uncommon which is like the frequency is very low and this is sub-accused landslides, slow earth flows, rock block slides and rock avalanches. The this and here is the magnitude of earthquake which consider 40 earthquakes for this data is between 5.2 to 9.5 and the source of this data is paper published by Keefer 1984. So, continue with this earthquake induced, so this was about types of earthquake induced landslides. Now, what are the activities which earthquake induced landslides may create? For preliminary stability evaluation, no layers of the condition under which earthquake induced landslides have occurred in past earthquake is useful. Two major factors which influence occurrence of landslides are listed here. First factor is earthquake magnitude and there could be a minimum magnitude below which earthquake induced landslide would rarely occur.

So, there would be a minimum, if we go below that magnitude the chances are not there that landslide will occur and smallest earthquake to produce landslide in magnitude is considered to be magnitude 4 which will create some landslide very near to the epicenter. So, this is one thing that earthquake magnitude is one of the important factors. If magnitude is higher naturally the earthquake magnitude is higher than chances of landslide is more. So, there is a threshold value below you may not expect that there will be landslide. Then another parameter is source to the site distance which is basically epicentral distance and that there could be a distance beyond which landslide would not be expected in a given magnitude of earthquake.

The maximum source to site distance at which landslide have been produced in historical earthquakes are different for different types of landslides and this is shown in this figure. So, in this figure on x axis you have the magnitude of earthquake which is varying from 4 to 9.5. While on y axis you have maximum epicentral distance which is on the log scale and varying from 1, 10, 100, 1000 it is in kilometer and the result has been presented in the form of three curves. These three curves are like here. So, how you can say that dashed line is for disrupted falls and slides. So, if I categorize this one. So, this is 1, 2 and 3. So, the first one is the number 1 is here dashed line, then number 2 is the middle one and number 3 is the solid line. So, now you can like for a given magnitude of earthquake let us say if I select a magnitude earthquake of 5.5 or 6 then what happens you can see that for a given magnitude of earthquake this the first number dashed line will may occur even the larger epicentral distance. But the third one that is lateral spread will occur only near to the epicentral. So, the distance will increase. On another side for the same epicentral distance for example, if I draw a line at 10 kilometers then what will happen that the magnitude which is required will increase from first 2, 3. That means the solid line for the same distance for the same epicentral distance lateral spread and flows to generate will require more magnitude compared to the disrupted falls.

So, the magnitude required is increasing from 1, 2, 3 for the same epicentral distance or if we keep the magnitude same then this epicentral distance will decrease when you go from 1, 2, 1, 2 and 3. Now this chart need to be read again for let us say for the category 1 which is standing for dashed line for distributed falls and slides. In that case for one first curve what happens that when the magnitude increases the epicentral distance up to which you can expect the landslide may occur is exponentially increasing. But if you have less than 5 magnitudes if a magnitude is 5 magnitudes, then it will be at the most the landslide epicentral distance may occur up to 10 to 12 kilometer not beyond that. So, when the magnitude of earthquake is increasing then domain of the landslide where it will occur is increasing which is expected also.

Similarly, within the same domain the chances are there that the disrupted falls will occur more compared to lateral spreads and flows. So, this was also from the Keefer 1984. Then another chart which is also given by the source Keefer 1984 it is magnitude versus area affected by the landslides which is in kilometer square. Naturally as the magnitude increases the area which is affected by the landslides will also increase so it is kind of proportionate but not this proportionate is not linear. Rather than when magnitude increases at higher magnitude this area which is affected is tremendously increased and you need to mind it then on the y axis is in the log scale it is not a normal scale.

So, when you go from let us say from 4 to 6 magnitude it is jumped from 1 kilometer square to 500 kilometers. If I go to 8 magnitude then it will be around 100,000 that means 1 lakh kilometer square. So, even when you jump from 1 magnitude then the area which is like subjected to landslide is tremendously increased and which is expected also that is like common. So, this was. Now earthquake induced landslide activities here is there is a relation between magnitude and different types of slides. So, for example, if you have the magnitude 4 then you can expect rock falls, disreps of slides, rock slides but naturally the lateral spreading will not be there in magnitude 4. 4.5 if you increase the magnitude 4.5 you can expect that there could be this is the minimum value of the magnitude on the first column. This first column says it is the minimum value of the magnitude required for this activity. Soil slumps, soil block slides similarly if you have magnitude 5 there could be rock slumps, rock block slides. If you have 6 then it could be rock avalanches. If magnitude is 6.5 then it may generate 6.5 or above soil avalanches may be generated. So, the estimate of the smallest earthquake likely to cause landslides. So this table is least smallest magnitude of earthquake in this table and the source is same Keefer 1984. So this was all about the landslides. Now we come to the second part of this lecture and in fact like that is on evaluation of slope stability. So, that is the second chapter basically of this module to reliably perform and interpret the results of both static and seismic slope stability analysis.

Information's on the characteristic of the factors and the factors which we already discussed geology, hydrology, topography, geometrical and geotechnical properties. They influence slope stability and these all the input is required. Review of available documents, field reconnaissance, field monitoring, subsurface investigation and material testing can all be used to obtain this information. Now what is done for the evaluation of slope stability? Previously published documents, what are the previously published document which can be used? Geologic maps, soil survey and or agriculture maps, topographic maps, natural hazard maps and geologic and geotechnical engineering reports. So, these are the, if these documents are already available from the literature or from the past data then they will help to decide the evaluation of slope stability.

So, this is based on the previously published document basically literature. The second category, if we have the data on the field reconnaissance for example, interviews from the locals that is also part of the field reconnaissance. So, careful observation and detailed mapping of variety of site characteristics associated with existing or potential slope instability. So, that may include the, so if this information are available this will be very helpful for evaluating slope stability. Then monitoring of slope movement, photographic methods, inclinometers for monitoring lateral deformation patterns below the ground surface. So, inclinometers are measured that what are the lateral deformations occurring. Then there are piezometers which may be helping to measure the pore water pressure measurements. Then you have the subsurface investigation that the investigation below the ground surface and this investigation may include expression and mapping of test pits and trenches, boring and sampling, there could be field testing, in-situ testing and geophysical testing. So, all these revealed the depth, thickness and density, strength and deformation characteristics.

Then there could be laboratories. In case of laboratories, physical characteristics of the various subsurface materials for input into numerical slope stability analysis, for example soil density, strength and stress system behavior are of very important curve. Once this information is obtained, stability analysis can be performed. It is important to note that the analysis itself is a single part of a complete slope stability evaluation. Once you collect this information and you do the analysis that does not mean that everything has been done. There are many other issues which need to be obtained and the accuracy of this analysis which you are single pointer that only one point, then it will depend on your input parameters.

If your input which you are inputting that is accurate, then you may expect that the result of this analysis will be accurate. Now coming to this like with this background, we will carry out the first static slope stability analysis and then the second seismic slope stability analysis. What is going to be covered in static slope stability analysis are discussed here. Stastic slope stability analysis, we already discussed that the slope becomes unstable when the shear stress which is required to maintain equilibrium reach or exceed the available shearing resistance or shearing strength on some potential failure surface. So, what we do inside the slope, you select a potential failure surface and along that for potential failure surface, if shear stresses exceed the shear strength, in that case, the slope stability issue may come.

Slopes could be marginally stable that means they are only just stable; their factor of safety and shear stability is not large. If shearing resistance is marginally greater than the shear stresses which is needed to produce instability, the most commonly used method of static slope stability analysis are limit equilibrium analysis and stress deformation analysis. You have two ways one is limiting equilibrium and another is stress deformation analysis. And we will be discussing both, but in this remaining part of this lecture, we will talk about partly limit equilibrium analysis and we will continue limit equilibrium analysis in the next lecture also.

So, let us discuss limit equilibrium analysis. In this case of analysis, which is limit equilibrium analysis, considered force or moment equilibrium, either you will have force equilibrium or you can have the moment equilibrium of a mass of soil above a potential failure surface, the soil above the potential failure surface is assumed to be reached. So, it is here like or let us say that it can be made like this one also in terms of slope. Let us say if I have a slope and I create a slope like this. Now in this slope, I create a potential failure surface, whatever this material is here. So, this material in this limit equilibrium analysis, the mass is assumed or reached, though in actual case it is not reached.

So, this is basically an assumption that this is assumed reached and what is the, because the problem gets simplified with this assumption. So, this analysis considers force or moment equilibrium of a mass of soil above a potential failure surface, the soil above the potential failure surface is assumed to be reached. The available shear strength is assumed to be mobilized at the same rate at all points on this potential failure surface. As a result, the factor of safety is constant over the entire failure surface. So, what you have here like and this may be, I think here. So, this is the potential failure surface, which is the potential failure surface, these ways. And along this potential failure surface, this could be like that may not be necessary that this is whole way, this could be like this one also partly, may not be for the full height. So, whatever you decide, so this is potential failure surface PFS, if I say in the short. So, potential failure surface, the material on above this is the reached. The factor of safety in this case, it is assumed that the available shear strength is mobilized at the same rate at all the points.

So, it is mobilized at this point if I select a number of points on that and as a result the factor of safety is constant on the entire failure surface. So, on this entire failure surface, the value of F s will be constant, it is not varying from point to point. In the case of limit equilibrium analysis, a soil on the potential failure surface is assumed to be reached perfectly plastic as we discussed earlier. Limited provide no information of slope deformations. So, limit equilibrium analysis though it will give you a factor of safety, but that is the disadvantage of the limit equilibrium analysis, you do not get what is the displacement or deformations on the slopes.

So, that is the limitation, but we will discuss this again further. So, what is shown in this slide, stress strain curve for rigid perfectly plastic material, no shear strain occurs until the strength of the material is reached. So here, shear stress is there and thus quickly without no strain, it reaches to this value. So, it reaches to shear stress, then after that and this is without almost at 0 shear strain. After this, the strength of the material is reached, after this we see the material strain at constant shear stress.

So, after this point, you see the shear stress is constant and your shear strain increase without there is increase in shear stress. So, basically this type of material which is reached perfectly plastic, so this material basically what we will say this is reached perfectly plastic material. So, the stress strain curve is a straight line and like it is like you know it is starting from 0. So, basically it starts from here, then goes here and then move along this path.

So, this is the characteristic of reached perfectly plastic material. Assuming this assumption, slope stability is usually expressed in terms of an index most commonly which is called the factor of safety which is usually defined factor of safety in the slope stability defined as available shear strength divided by the shear stress which is required to maintain equilibrium. It is basically ratio of capacity that is the shear strength of the soil to demand that the shear stress which is induced on the potential failure surface. So, the factor of safety is basically ratio, so shear strength versus shear stress. And on the top you have capacity and the numerator it is capacity, so this is basically capacity here on the numerator, capacity versus demand. So, if capacity is more than the demand then factor of safety more than one otherwise it will be less.

Now, in the static slope stability analysis in the limit equilibrium, a variety of limit equilibrium processes have been developed to analyze the static stability of slopes and this depends on many like four types of like planar used in one common failure surface geometries are discussed here. So, failure surface geometries first was in planar, then multi-planar, circular and non-circular. In case of planar, culmann methods which is based on slope that fail by translation on a planar surface. So, culmann use the planar method such as bedding plane, rock joints etc. Then there was a Wedge method, in the case of Wedge method there are two or three planes multi-planar for example, here you have three planes, one, two, three planes.

Third one is circular which is used normally for homogeneous slopes. Critical failure surface usually has a circular which is shown in figure c or log is parallel shape. Homogeneous slopes are usually analyzed by method of such as the ordinary method of slices or Bishops modified method. So, this ordinary method of slices is very popular, later on the Bishops have modified it. So, ordinary method of slices is used for slope stability. In homogeneous subsurface conditions, when layers with significantly different strength, highly anisotropic strength or discontinuities exist.

So, in that case, you use what we call the non-circular surface. For example, in the D case when you use non-circular, there are many methods. These methods like Morgenstern and Price, Spencer method, Jambu's method. So, Morgenstern and Price, Spencer and Jambu's method, these are the different methods which are used for this limit equilibrium analysis method for non-circular surface. Coming to these limitations of the limit equilibrium analysis, nearly all limit equilibrium methods are susceptible to numerical problems under certain conditions. These conditions will vary from different methods, but most commonly encountered where soil with high cohesive strength is present at the top of the slope or when failure surface emerge steeply at the base of slopes in soil and high frictional strength.

So, if you have clay, it contains more high cohesive strength, that is could be the one case, another case could be on the top of a slope, you have failure surface which is at the base of the slope with high frictional strength and the top of this. So, in that case, the errors will be large. So, this is the limitations of seismic slope stability analysis. So, with this, I conclude this lecture number 41 and we will continue with the limit equilibrium analysis in the next lecture. Thank you very much for your kind attention. Thank you.