Soil Mechanics
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Lecture – 57
Stability analysis of slopes – III

Welcome to lecture number three in stability analysis of slopes. In the previous lecture we have understood about types of slopes and failure types and causes of slope failures and then we did understand about infinite slopes, analysis and then finite slope analysis by using circular arc method but we discussed that the demerit of this method is in finding the weight of the entire portion of soil which is subjected to failure and its cg at its location.

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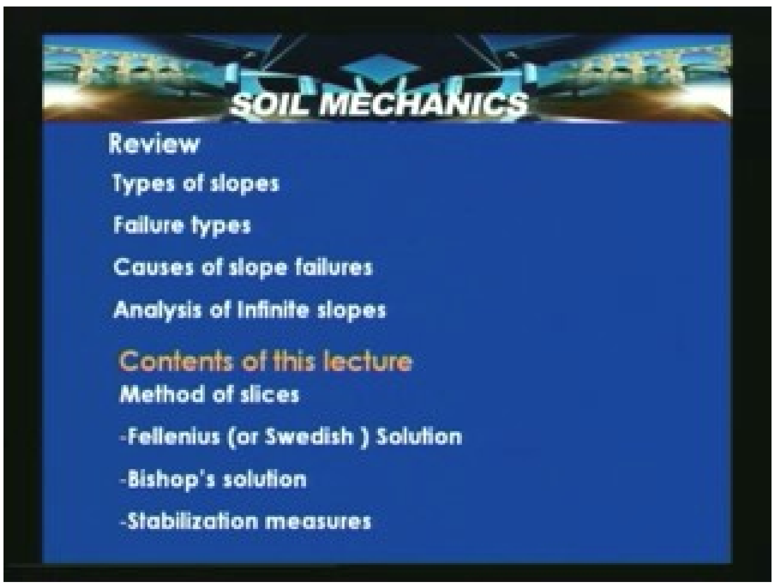

So in this lecture we look into the method of slices for which we specifically look Fellenius or Swedish solution and thereafter bishops solution. Then we discussed about some stabilization measures which are involved for improving the stability of a slope. So as we have discussed, a typical pattern of the rotational slides are shown. There are typical failures which can occur, sometimes a spoon shaped failure which is shown here can occur and these can have something like a spoon shaped failure where the entire portion will be subjected to a slipped in that localized zone or in some times, entire road mainly for this man made slopes this cylindrical shaped failure can occur. For the entire section of a slope there will be a slip surface can form.

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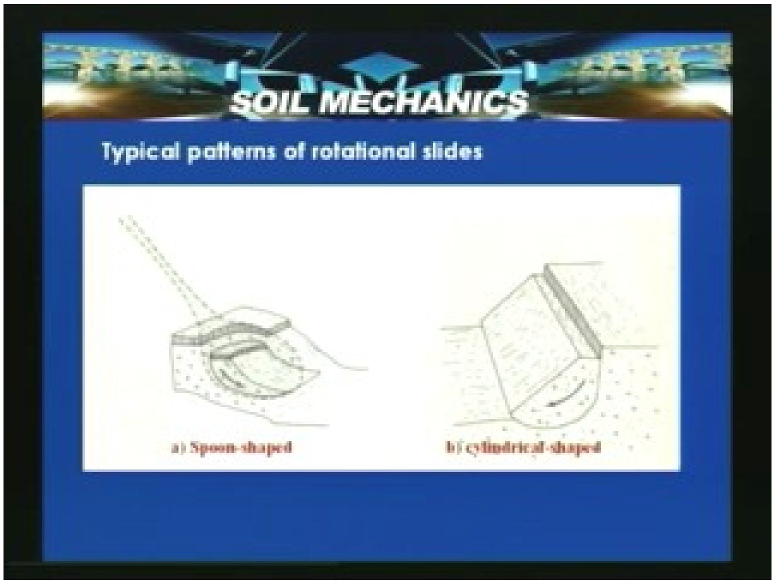

There is a settlement or a depression from this level and then down the movement of the slope takes place. In the method of slices the potential failure surfaces assumed to be circular arc with a centre of rotation O and its radius r and how to locate this critical failure surface that we look into it later.

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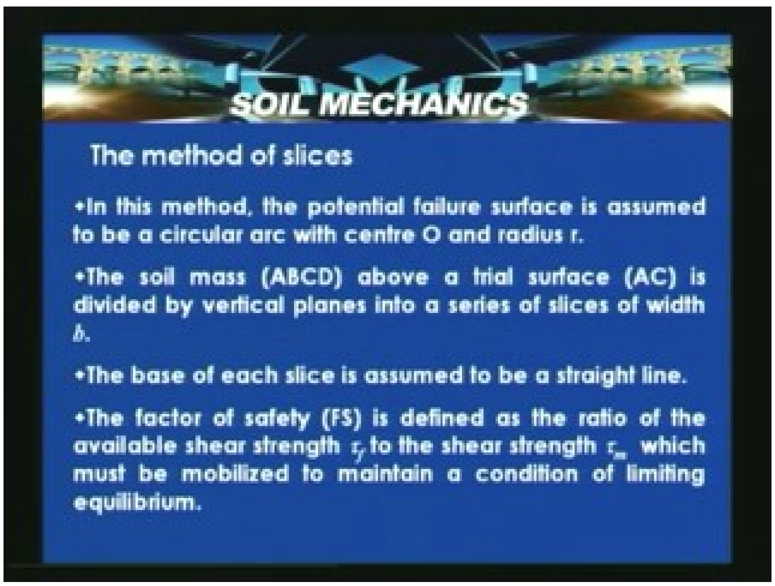

Now let us consider a slope cross section having certain slope inclination and ABCD is the portion of the soil which is subjected to say movement. So here ABCD is the slope portion, previously in the circular arc method what we did is that we try to find the weight area of the entire portion and then multiplied by its unit weight.

However it is difficult to find its weight and its location so one of the other alternatives which is available is to consider dividing into number of vertical slices. Nowadays even the method of slices is also coming in horizontal direction, it's called horizontal method of slices but currently we will be discussing only the method of slices that is cutting of the slope portion vertically.

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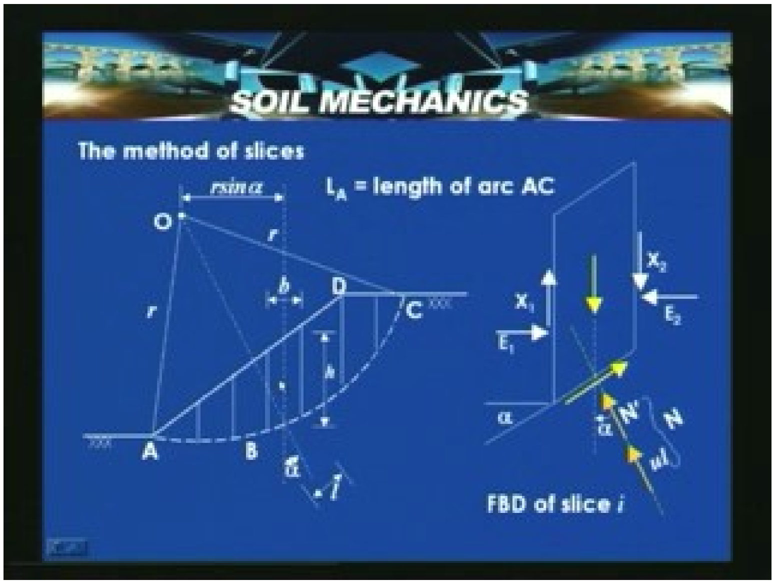

So here what we did is that this particular portion of soil ABCD is cut into equal widths of the slices. This is the width of the slice horizontally and then this is the width of the slice and this is the height of the slice. The assumption is that the weight of the slices is assumed to be at the center and at the base here. For this slide the weight will be acting at the central line of this particular slide. So h is the height of this slice and b is the width horizontally and l is the length along the slip surface, ABC is the slip surface so r is this radius. So this particular slice if you consider say if this slice happens to be i^{th} slice then its weight distance from the central line from the horizontal distance from the O is r sin alpha and L_A is the length of the arc AC.

Now if I take the free body diagram of i^{th} slice from here, let us consider this particular portion and then you represent here and this gives the various forces which can act on the slice are shown here. So here this is the slice and having w so if this w if it consists of say number of soils like soil 1, soil 2, soil 3, soil 4 the compound weight can be found out very easily in this particular method and x_1 and x_2 of the shear forces which are acting at the interface and E_1, E_2 are this normal forces which are acting on the slice and alpha is the inclined portion of the slice and N dash and ul they are nothing but the effective normal force and this is pore pressure due to water force. So now let us consider this method of slices and look into details of how we can analyze this to obtain factor of safety.

So what we did is that the soil mass ABCD above a trial surface AC is divided by vertical planes into a series of slices of width b. So what we did is that the entire portion of ABCD is divided into a series of slices of width b, the base of each slice is assumed to be a straight line say approximated as a straight line. The factor of safety f is defined as the ratio of the available shear strength tow_f to the shear strength tow_m which must be mobilized to maintain a condition of limiting equilibrium. So the factor safety is indicated as FS is defined as the ratio of the available shear strength tow_f to the shear strength tow_m which must be mobilized to maintain a condition of limiting equilibrium.

Now considering this the factor of safety, the definition what we had is tow_f by tow_m. In these the factor of safety is taken to be the same for each slice implying that there must be the mutual support between slides, forces must act between the slices. Factor of safety is taken to be the same for each slice implying that there must be mutual support between slices. Now from the free body diagram if you look, the total weight of the slice w can be determined by b is the horizontal distance and h is the slice height. So if gamma happens to be the unit weight of the soil material, suppose if there are say 5 different types of soils with different unit weights say $gamma_1$, $gamma_2$, $gamma_3$, $gamma_4$ and $gamma_5$. We can determine its composite weight by considering the portions of the soils which are involved in a particular slice.

With that total weight W can be determined as gamma b into h, the total normal force N which is nothing but the normal stress sigma into l includes N dash is equal to sigma dash l and u is equal to ul, u is the pore water pressure at the center of the base and l is the length of the base. The shear force on the base T is equal to tow_m into l and total normal forces on sides E_1 and E_2, the shear forces on the sides are x_1 and x_2.

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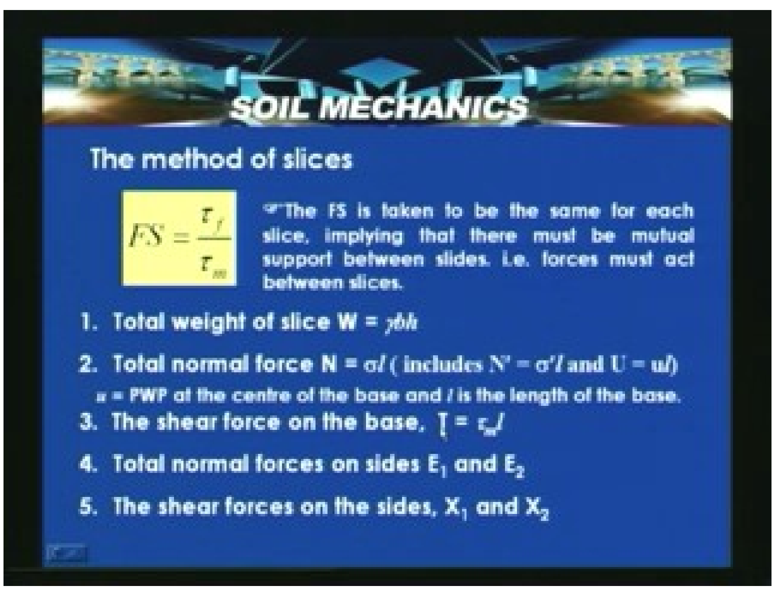

Once again let us look into the free body diagram E_1 and E_2 which are shown here and x_1 and x_2 which are shown here and this alpha is that inclination which makes with the line passing through the weight of the slice. So the weight of the slice is assumed to be center line and this is located at a distance r sin alpha from point of rotation O horizontally, so this is that l length along the base of the slice.

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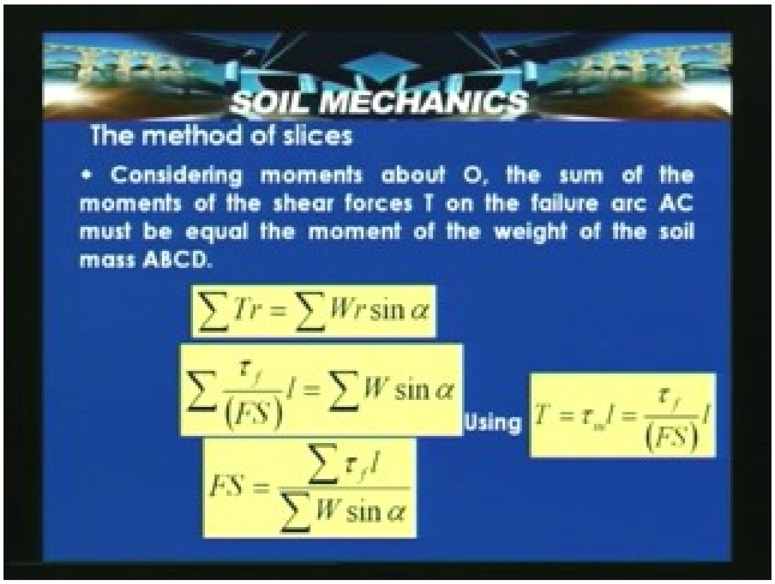

So now what we do is that having obtained, so considering the moments of all these forces about O, the sum of the moments of the shear forces T on the failure arc AC must be equal to the moment of the weight of the soil mass ABCD. That means considering the moments about O the sum of the moments of the shear forces T on the failure arc AC must be equal to the moments of the weight of the soil mass ABCD. So here sigma Tr so that means this T which is acting at this point, this is tangential force T which is shown and the T then into this radial distance r that is the sum of this moment due to the tangential forces and if w happens to be weight, w into r sin alpha that is for the i^{th} slice the moment is w r sin alpha.

Similarly for all number of slices if you consider, it will become sigma wr sin alpha so that's what is indicated here, this has to be equal. Now from the deliberations in the previous slide, we can write summation tow_f divided by factor of safety into l so this is written by using t is equal to tow_m into l which is nothing but mobilized shear strength to maintain equilibrium. The shear strength required to maintain equilibrium into l which is nothing but tow_f that is shear strength available that is the shear strength of the material divided by the factor of safety into l. So using this we can write tow_f by factor of safety into l is equal to the summation W sin alpha, here r and r will get cancelled. So now the summation tow_f by factor of safety into l is equal to tow summation W sin alpha. By rewriting this we can write factor of safety is equal to summation of tow_f l divided by summation of W sin alpha. So we are left with this expression, factor of safety equal to summation of tow_f into l divided by summation of W sin alpha.

Now for an analysis in terms of effective stresses that means under what conditions we need to consider total stress conditions and effective stresses, we look into these details later but for an analysis in terms of effective stresses; now we can write factor of safety is equal to summation of c dash plus sigma dash tan phi dash into l divided by sigma summation of W sin alpha.

So here what we did is that this tow$_f$ we have written as c dash plus sigma dash tan phi dash into l where c dash and phi dash are the effective cohesion and effective internal friction of a soil. Now this can be written as factor of safety is equal to c dash into L_a where L_a is the length of the arc AC which is shown in the previous slide, plus tan phi dash into summation of N dash divided by summation of W sin alpha.

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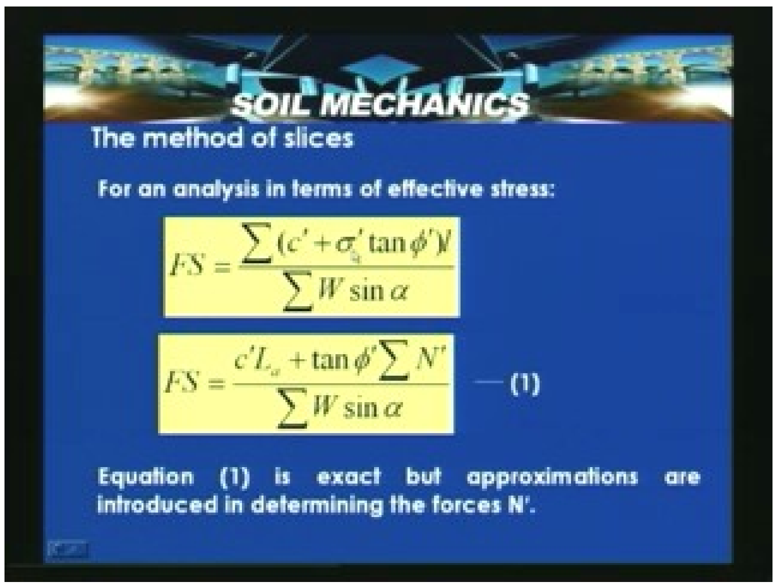

So this is nothing but this is the resisting moment and this is the driving moment, so equation 1 is exact but approximations are introduced in determining the forces N dash. Here factor of safety in the method of slices c dash L_a plus tan phi dash summation N dash divided by summation of W sin alpha. So this is equation 1 is exact but approximations are introduced in determining the forces N dash. So what we did is that we considered dividing the entire slope portion into for considering a trial slope surface.

We need to consider a trial failure surface and divide the portion into equal width of slices vertically and considering the equilibrium of a single slice and what we did is that we took the moments about O and based on that we have derived this expression factor of safety is equal to summation tow$_f$ into l divided by summation W sin alpha and substituting for tow$_f$ is equal to c dash plus sigma dash tan phi dash. What we did is that we got factor of safety is equal to c dash L_a plus tan phi dash summation N dash divided by summation W sin alpha. Now for this method of slices is extended further by the Fellenius or Swedish solution. In this it is assumed that for each slice the resultant of the inter slice forces is zero.

So here what Fellenius assumed is that for each slice the resultant of the inter slice forces is assumed to be zero. So the solution involves resolving the forces on each slice normal to the base that is N dash is equal to W cos alpha minus ul.

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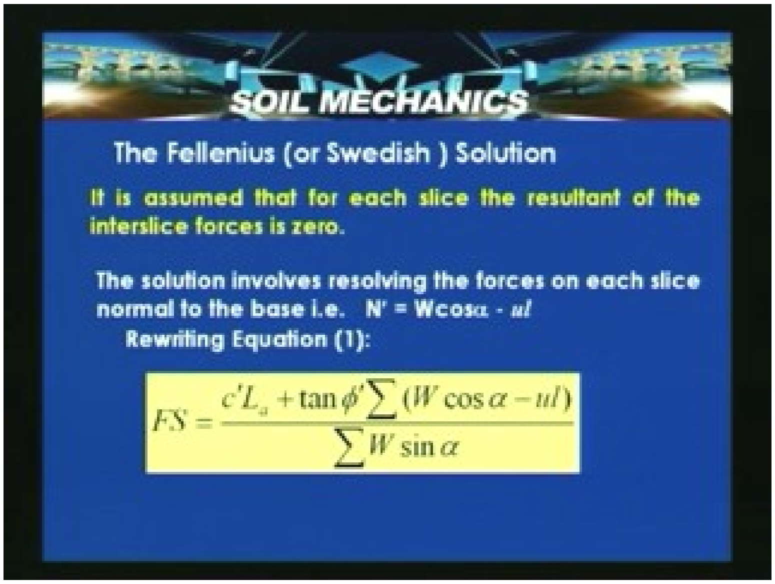

Now substituting for N dash as W cos alpha minus ul, in the previous equation which we derived; rewriting the equation one factor of safety can be written as c dash L_a plus tan phi dash summation of W cos alpha minus ul divided by W sin alpha summation. So further we look into this in the form of a figure so here the Fellenius or Swedish method of slices which involves, so here a particular slope portion which is shown and is assumed that is divided into 7 number of slices vertically; the entire portion ABCD is divided into 7 number of forces vertically and what we did is that this particular portion of slice at its cg assumed that its weight is acted. So two third distance from here, the cg of this weight of this slice is assumed to be acted then for all these analysis as we discussed earlier per meter or per unit length is considered.

So here the weight is nothing but area of this portion into 1 unit that is 1 meter into the unit weight if happens to be gamma then you will get weight of this particular slice per meter length. Similarly this slice 2, slice 3 like that so you get w_1, w_2, w_3, w_4, w_5, w_6 and w_7. After having obtained, when this is marked to a scale then by drawing lines to the assumed center of rotation, we can measure $alpha_1$, $alpha_2$, $alpha_3$, $alpha_4$, $alpha_5$ with vertical. So this vertical is nothing but the line of direction of this weight force for a particular slice. Here the $alpha_1$ is shown here, $alpha_3$ is shown, $alpha_4$ minus $alpha_5$ here observe that it changes it sign. So the components of W cos alpha and W sin alpha can be determined graphically for each slice. So for an analysis in terms of total stresses the parameter c_u and phi_u are used and the value of u is equal to zero that means assuming c_u and phi_u are considered for the total stress condition that indicates un drained condition.

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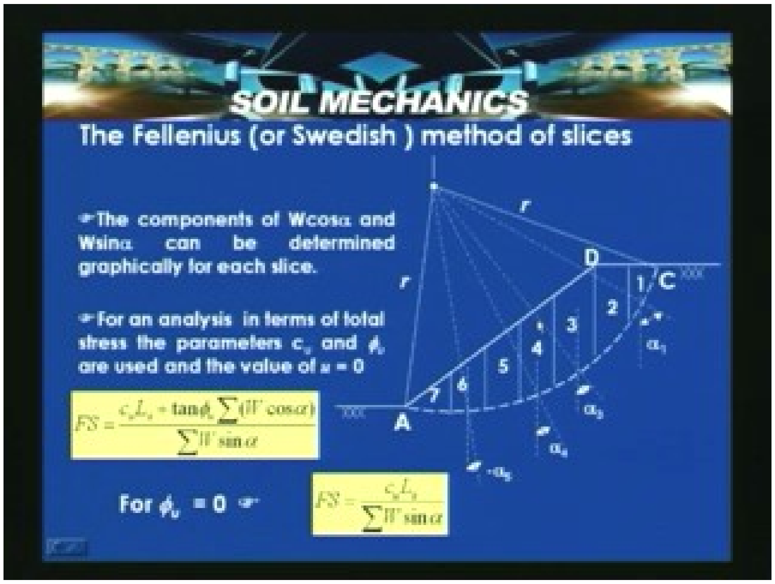

So for the case of un drained condition we can write factor of safety as c_u into L_a that is nothing but we can use this for L_a is the length of this portion, total length of this portion c_u and L_a otherwise when you have got each slice when you assume that this is the length then the L_1, L_2, L_3, L_4, L_5, L_6, L_7 forms this L_a. So c_u into L_a plus tan phi_u summation of W cos alpha divided by summation of W sin alpha; for phi_u is equal to zero that is for purely cohesive soil slopes or saturated clayey slope, in that situation for phi_u is equal to zero condition when this term gets cancelled what we have the factor of safety term is nothing but c_u into L_a divided by summation W sin alpha. This will be nothing but whatever we have discussed in the previous lecture about circular arc of analysis.

The only difference is that the soil which is same but under un drained conditions but we divide this entire portion of the slope into number of vertical slices and it will determine the factor of safety. In such situation the factor of safety is nothing but c_u into L_a divided by summation of W sin alpha. Now this was further extended by bishop and this bishops method of slices, it is known as the bishops method of slices. The previous method which we discussed is known as Fellenius method of slices or Swedish slip circle method or Swedish method of slices.

So in this solution it is assumed that the resultant forces on the sides of the slices are horizontal. So in this bishops method primarily, it is assumed that the resultant forces on the sides of the slices are horizontal that is x_1 minus x_2 is equal to zero. So for equilibrium the shear force on the base of any slice is we can write T is equal to 1 by FS into c dash l plus N dash tan phi dash.

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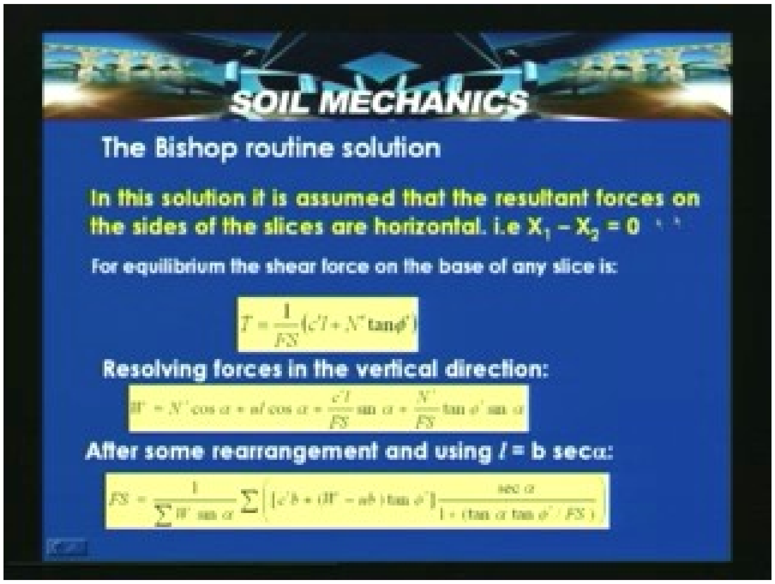

So resolving the forces in the vertical direction that means considering again the forces, with this equilibrium of this particular expression, this particular free body diagram of this slice i we get w is equal to the weight of the slice N dash cos alpha plus ul cos alpha plus c dash into l divided by factor of safety sin alpha plus N dash by factor of safety tan phi dash sin alpha. After some rearrangement and using l is equal to b sec alpha, we can write factor of safety is equal to that is after putting here, factor of safety is equal to 1 by summation of W sin alpha summation c dash b plus W minus ub tan phi dash sec alpha divided by 1 plus tan alpha tan phi dash by factor of safety.

If you look in to it the factor of safety term involved in both left hand side and right hand side indicates that it requires iterations. So for this manual calculation will be difficult but the manual calculations are possible for Fellenius method of slices, even manual calculations are possible if the soil strata is having say up to 5 number of soil layers but for the bishops routine solution considering the involvement of the iterations the computer program is recommended but this bishops routine solution can be calculated, first estimating the factor of safety by using Swedish method of slices or Fellenius method of slices and iterating that with a convergence to get a factor of safety by using bishops routine solution.

So the expression for the bishops routine solution is factor of safety is equal to 1 by summation W sin alpha summation of c dash b plus W minus ub tan phi dash sec alpha divided by 1 plus tan alpha tan phi dash by factor of safety. In the bishops routine solution, bishop 1955 also showed how non zero values of the resultant forces x_1 minus x_2 could be introduced into the analysis but refinement as only a marginal effect on the factor of safety. So bishop 1955 also showed how non zero values of the resultant forces x_1 minus x_2 could be introduced in to the analysis but refinement as only a marginal effect on the factor of safety.

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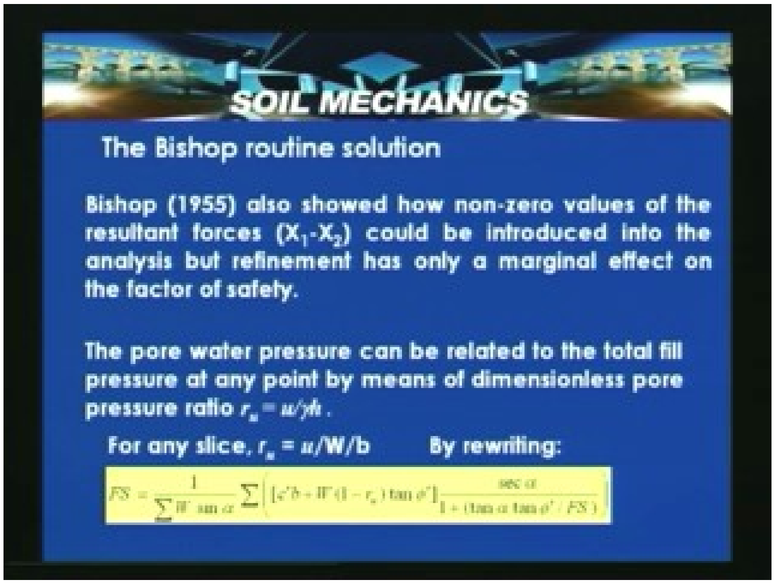

The pore water pressure can be related to the total fill pressures at any point by means of dimensionless pore pressure ratio. So which is also known as pore water pressure coefficient or pore pressure ratio. Here the pore water pressures can be related to the total fill pressure at any point by means of dimensionless pore pressure ratio or pore water pressure coefficient which is given by gamma$_u$ is equal to u by gamma h where h is the fill height, gamma is the unit weight of soil and u is the pore water pressure at a particular point.

So if gamma$_u$ is equal to 0.5 that indicates the slope is completely saturated, if it is approximately about 0.5 the slope is assumed to be saturated and so by putting this for any slice gamma$_u$ is equal to u by W by b and by rewriting the equation which we derived in the previous slide that is this particular equation, we get factor of safety is equal to 1 by summation W sin alpha summation c dash b plus W into 1 minus r_u tan phi dash sec alpha divided by 1 plus tan alpha tan phi dash by factor of safety.

So here this particular r_u considers the effect of the priotic line within the slope. If the priotic line is far away from the slope say for a road embankment constructed on a foundation soil, in such situation if the ground water table is far away form the slope section where we can assume r_u is equal to zero. If it is assumed that r_u is about partially submerged then r_u, a specific value for r_u can be given or the priotic line is estimated within the dam or any slope cross section. Then the priotic line can be dictated so with that given condition we can obtain what is the factor of safety of a given slope.

So what we looked into is that two methods of slices basically the development of method of slices and then for that Fellenius and bishops solutions were given so in all these things, it is very important to locate a critical failure surface. The critical failure surface is the one which gives the lowest factor of safety, so for which the slope is said to be stable.

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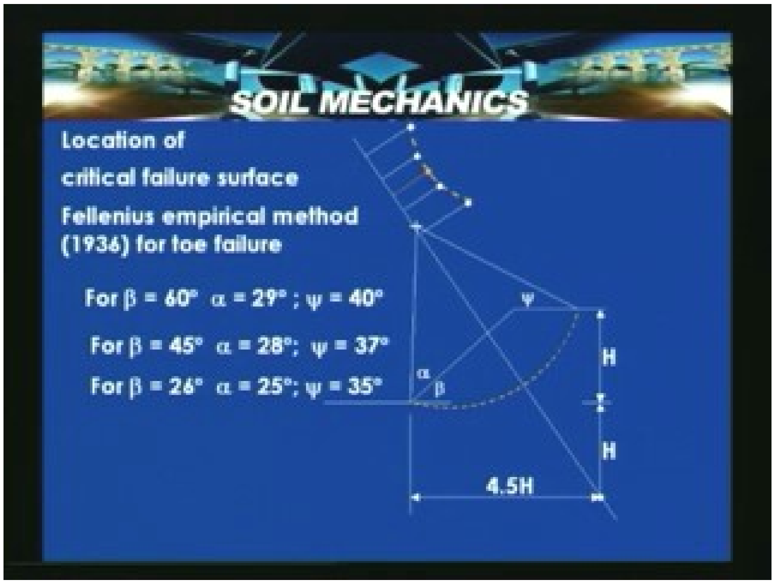

In the moderant advent of the computers and with availability of the programs, number of options available for locating a critical failure surface and options involved; the automatic generation of circles or failure surfaces based on the initial input values or one can specify the point where the circles have to be located physically. So based on that the number of failure surfaces can be generated. Once it calculates the factor of safety of all these failure surfaces and the efficiency of the program depends upon the one which actually gives the correctly the lowest factor of safety. That happens to be the possible failure surface which can actually occur and for a given section which is being analyzed but there are earlier methods which are put forwarded.

The one of the methods is that the Fellenius empirical method for a toe failure. For this method what is done is that for a given slope cross section say if a cross section is there and if the slope inclination is beta then what we do is that if h is the height and locate a point that is at a distance 2h from this particular point and from this point at a 4.5h, you locate a point here and join this point through this slope and along this slope if you draw number of circles, suppose this is center 1, center 2, center 3, center 4 what will happen is that the factor of safety decreases and then factor of safety increases.

So once that happens the one which actually gives the lowest factor of safety, so here what one can do is that one can generate grid of centers and number of slip surfaces can be tried; one can draw the contours which gives the factor of safety and the one which gives the lowest factor of safety is actually identified as a critical failure surface.
In this empirical method where for beta is equal to 60 degrees this alpha is equal to 29 degrees, psi is equal to 40 degrees, with that we can locate this particular point and then that is one of the critical failures with that we can draw a circle.

Similarly for beta is equal to 45 degrees, alpha is equal to 28 degrees along this line if you draw then we get alpha is equal to 28 degrees, psi is equal to 37 and beta is equal to 26 degrees that is almost flat slope one vertical, two horizontal that is alpha is equal to 25 and psi is equal to 35 degrees. So this is one of the methods, for example if this is a base failure like location of a critical failure surface for the base failure where a circle passing through the entire foundation soil as well as to the fill material. In this case this can occur because this failure surface cannot penetrate through the rigid stratum.

So it will be tangential to this so if this slope distance is marked and horizontal distance is say b by 2 and b by 2 what we can get is that at a distance b by 2 and b by 2 if you locate, that is along this line if you draw a line and set this points x_1 and x_2 such a way that the angle is around 133.5 degrees. With this process if you are able to construct a circle and that is assumed to be a critical failure surface which is actually a tangential to this, the condition is that tangential to this and then with that conditions once you draw the circle along this vertical line that one will give the critical failure surface. So we try to look into this very empirical procedure which are available for locating critical failure surface.

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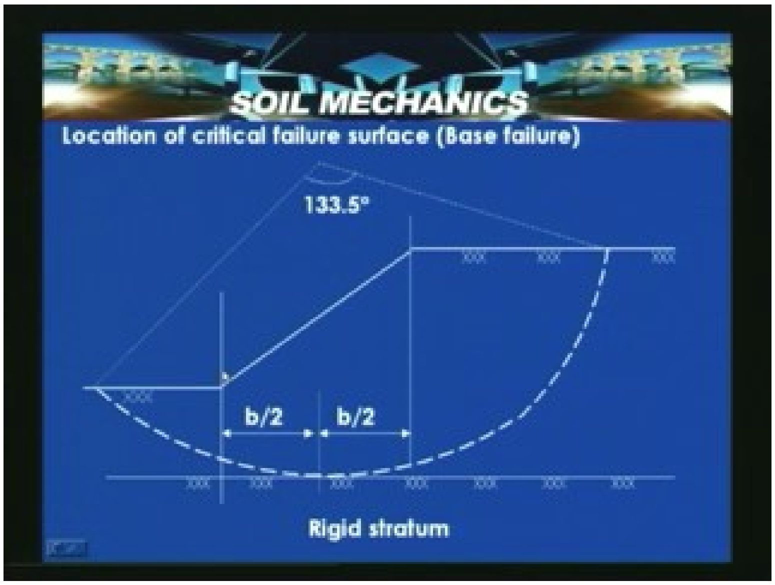

Now having looked into it, particularly this stability analysis which is required to be carried out for short term and long term conditions. So short term stability basically this is carried out for a low permeability soils where the drainage is not permitted and long term conditions where the fully drain stage can occur, in that case c dash and phi dash parameters are required to be used.

So effective or total stress parameters, the short term low permeability soil that is example clays; at the end of construction the soil is almost still un drained. Hence the total stress analysis making use of the un drained shear strength and a free draining materials like in case of sands and gravels, the drainage takes place immediately hence the effective stress parameter c dash and phi dash are used.

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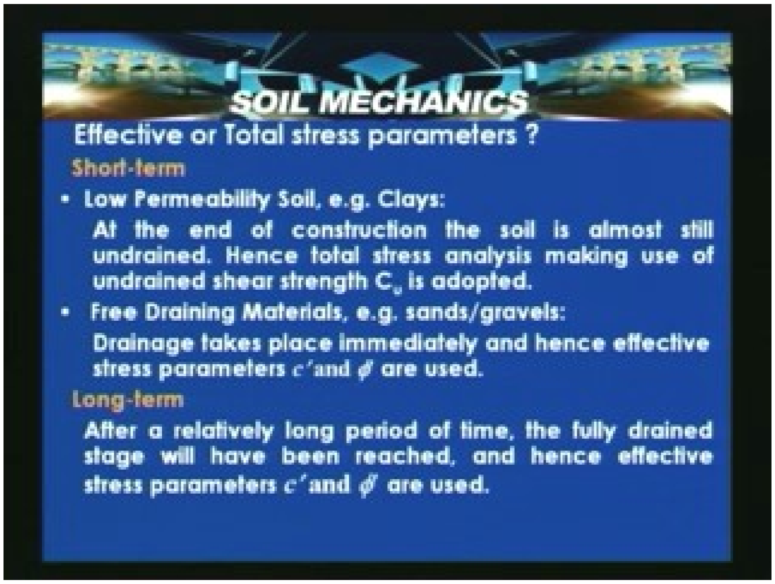

So in the long term after relatively long period of time, the fully drained stage would have been reached. Hence the effective stress parameter c dash and phi dash are used. So based on this judgment one can perform either effective stress analysis or total stress analysis for the stability of a particular slope under consideration. Now let us look an example based on whatever we are discussed about Fellenius methods of slices or bishops method or Swedish methods of slices. Here a slope with certain cross section is shown and with a pore water pressure data and this is the location of the tension crack that is zc is a tension crack which is based on this 2c by gamma which is estimated here. So with that this is the tip of the tension crack.

Let us assume that the slope is divided into 7 number of slices 1, 2, 3, 4, 5, 6, 7 and these are the horizontal widths of the each slice and the circle is located like the procedure whatever we had discussed just now with 4 meters and 4 meters is the horizontal distance. So this is the central line so with that point and when this angle is about 133.5 degrees also this particular slip surface is located. Here what we have is that the soil which is within the embankment portion is having gamma about 18.5 kilo newton per meter cube, phi dash is equal to 20 degrees, c dash is equal to 15 kilo newton per meter square. And in this case foundation soil gamma is equal to 18.5 kilo newton per meter cube, phi dash is equal to 25 degrees, c is equal to 8 kilo newton per meter square.

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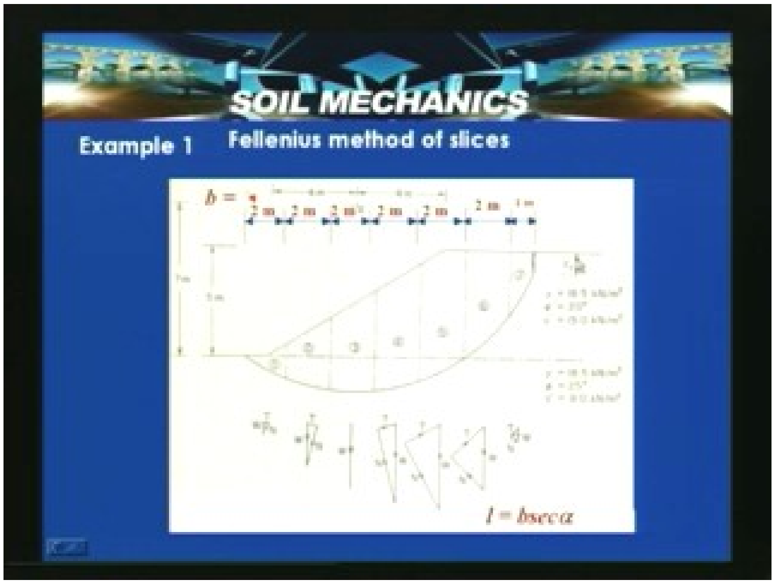

So this is the properties of the foundation soil and this is the properties of the soil within the bun. So two layers are there that means up to this portion, this base of this slice is exposed so this is the soil portion which is existing here as well as here. So we need to consider in this zone these properties and below this portion this is another soil which is having c is equal to 8 kilonetwon per meter square and phi dash is equal to 25 degrees and gamma is this much. These properties have to be considered. So by drawing each slice we can calculate weight W_1, W_2, W_3, W_4, W_5, W_6 and W_7 and in this $gamma_1$ and $gamma_2$ is considered for arriving at weight 3 in this portion.

Similarly weight 4 is considered by using this particular procedure. Here so happened that gamma is same for both the soils which is given here. This distance vertical distance is 7 meters for the center of rotation and phi meters is the height of slope. So when we plot this t and w, w is the weight of the slice so the force diagrams are shown here. This is for the first slice, sixth and seventh are the slice. So you can see that this is the portion where only the w is acting, the other portions remain that is the components are zero then l is equal to b sec alpha.

Now let us tabulate the results what we got from this particular analysis in this form of a table. So Fellenius method of slices here being the effective stress factor of safety is equal to summations c dash l plus tan phi dash summation N minus ul divided by summation T. So in the slice we have divided into 7 number and weight of the each slice is determined by measuring graphically the weights here this portion. This is considered as a trapezium, this is considered another trapezium and this weight is determined similarly this portion, this portion like this the other remaining slices also considered.

Having done, these are the properties that has been considered and this is the tan phi dash, these two slices have got different properties and these slices entirely lying on the second soil that is the foundation soil. Then these are the length of the base along the arc so this is given here which is nothing but b sec alpha and b is the horizontal distance of the slice, the horizontal distance have shown in the previous slide.

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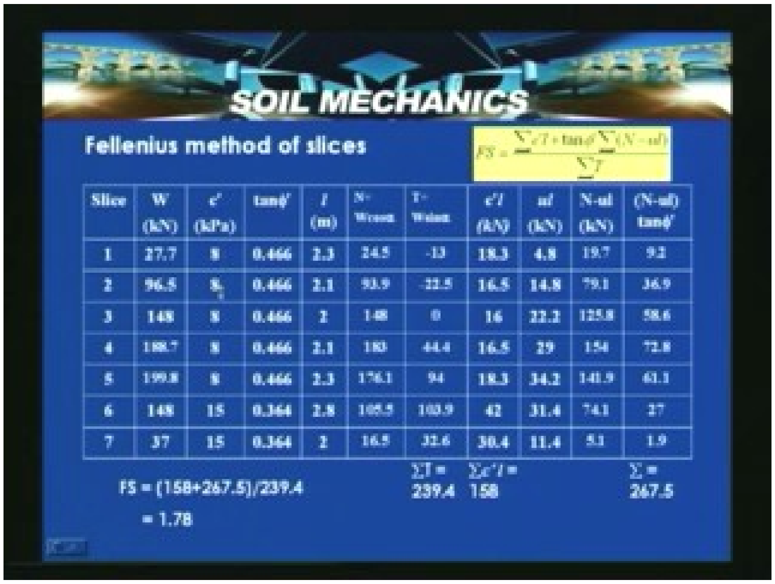

Slice	W (kN)	c' (kPa)	tanφ'	l (m)	N=Wcosα	T=Wsinα	c'l (kN)	ul (kN)	N-ul (kN)	(N-ul) tanφ'
1	27.7	8	0.466	2.3	24.5	-13	18.3	4.8	19.7	9.2
2	96.5	8	0.466	2.1	93.9	-22.5	16.5	14.8	79.1	36.9
3	148	8	0.466	2	148	0	16	22.2	125.8	58.6
4	188.7	8	0.466	2.1	180	44.4	16.5	29	154	72.8
5	199.8	8	0.466	2.3	176.1	94	18.3	34.2	141.9	61.1
6	148	15	0.364	2.8	105.5	103.9	42	31.4	74.1	27
7	37	15	0.364	2	16.5	32.6	30.4	11.4	5.1	1.9
						ΣT = 239.4	Σc'l = 158			Σ = 267.5

Now N is equal to W cos alpha, t is equal to W sin alpha these components which are shown here W cos alpha is this component and W sin alpha is this; this is the one which causes the driving moment. Now c dash l is obtained c dash and then multiplying that we get l and ul depending upon the priority client location, multiplying with the heights of the slices we get this ul in kilo newton. Then n minus ul we get this and n minus ul tan phi we get summation as 267.5. Similarly if summation t we get 239.4 and summation of the c dash l we get summation of c dash l as 158 kilo newton.

Now substituting in this equation c dash l that if you substitute that is 158 and summation of this particular this thing 267.5 into that summation of this into n minus ul tan phi is given here so that is nothing but 158 plus 267.5 divided by 239.4 that is summation of the W sin alpha. That is summation W sin alpha that is summation of t which is 239.4 which yields a factor of safety 1.78. So like the factor of safety is equal to one it indicates that the slope is under the wedge of failure but for the static loading conditions, the factor of safety which is adopted nominally for the working stress conditions is about 1.5. If you considered the three dimensional effect of the slope according to din core it is about 1.4 but there are different loading conditions like earthquake loading and other conditions demand different factor of safeties but conventionally a factor of safety of 1.5 is adopted and the working stress conditions but if the factor of safety is less than 1 that means the slope would already failed. The factor of safety is equal to one means it indicates that the slope is on the wedge of the failure.

Sometimes while analyzing the already failed slopes, one can also obtain by back calculating the shear strength parameters of a particular soil. So this particular method is called back analysis of a slope. So based on that one can perform the back analysis and by fitting a failure surface, passing through the tension crack which was observed on the wedge of the failure or so, with that we can obtain the factor of safety. For a given factor of safety of one, if that failure occurs on un drained conditions catastrophically then we can obtain under total stress conditions what is the un drained cohesion which is available.

So this can give some extent soil shear strength parameters so those parameters are called back analyzed parameters and can be comparable to the laboratory parameters. Now having looked into it, this is how the Fellenius method of slices can be adopted. So in case if the soil is having say more than 3 or 4 and if it is required to be adopted by using bishops method then computer programming is required and for this standard codes are available and based on that the analysis can be performed.

Now having discussed about the method of analysis of the slopes and causes of the failures of the slopes and we also required to consider, what are the avenues available for stabilizing a slope. There are many options which are available for stabilizing or reinforcing the slope, this slopes can be natural slopes or man-made slopes. Sometimes these slopes are natural slopes or hilly terrain slopes which requires elevation. So different types of techniques are available, sometimes for the sake of construction of a steep slopes in urban areas so the slopes are initially strengthened by using certain reinforcement layers. That is called reinforced earth slopes or so; in urban areas which are possible but if there is an existing slope which has been investigated and found out that is required to be stabilized then many methods are available.

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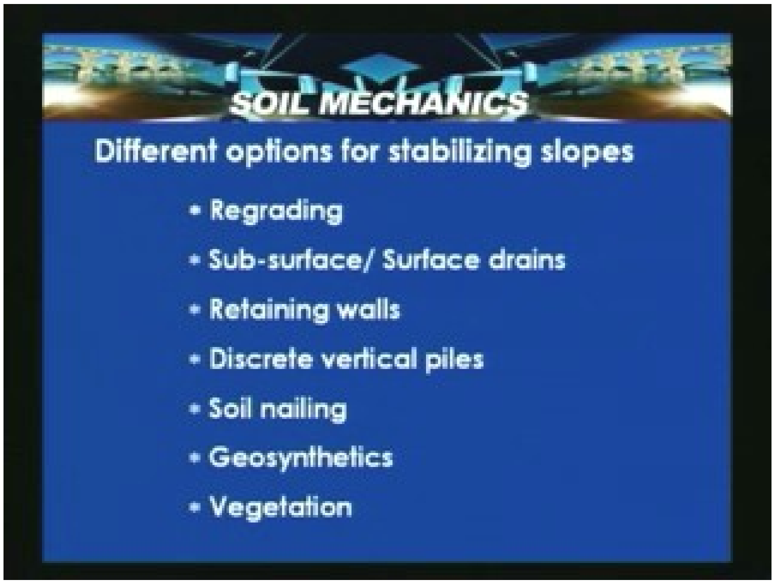

So one of the options which is available is that re grading that is removing the unstable portion and increasing the stability of a slope that is flattening of a slope or so or another revenue is that subsurface and surface drainage. The drainage is very important aspect in this slope stability so that is required to be considered and retaining walls that is particularly at the toe walls and they can be considered as a remedial measure for enhancing the stability of a slope but if the failure surface is passing beneath the slope then retaining the slope with a wall is also in danger. In such situations methods like pile stabilization that is discrete or vertical piles discrete or staggered piles with or without connections can be considered for stabilizing a slope.

So in this method what will happen is that the load is transferred, load which arised due to moving soil mass is transferred to the piles into the deeper stratum. That is this method which is discussed is a discrete vertical piles and this method can be adopted for new construction or to the existing, suppose if there is a predominantly soil slope so there it can be used in stabilizing the existing slope. Another technique which is gaining momentum in the recent past is soil nailing. so in this technique a certain steel bar or of certain diameter is drilled into a pre driven hole and then with spaces and then the portion is grouted and then once it is grouted the extended portion of the rod outside is connected and so with the friction interaction between the grouted portion and due to tension in nail and it will try to give the stabilizing effect to the slope.

Then another aspect is geo synthetics and recently the vegetation or bio technical stabilization is gaining momentum. So in this slide what we try to understand is that different options which are available for stabilizing slopes, one is re grading, second option is sub surface drainage or surface drainage; sub surface drainage to get rid of the pore water pressures within the slope and surface drains to prevent erosion failures on slopes and making flat slopes steeper and then can cause failure. So this surface drains will allow the erosion to be kept under control.

Similarly retaining walls, discrete vertical piles and soil nailing and geo synthetics and vegetation and some of the techniques which are there can be adopted to the existing slopes or intuitive slopes and some of the techniques can be adopted only for some slopes which are required to be constructed. Particularly the slopes like geo synthetics with horizontal orientation. So in the re grading, so here the slopes which are flatten this is the original slope so this is the revised slope cross section is shown that means here by removing this portion of the soil then what will happen is that the factor of safety of a particular slope cross section increases.

Here this is the removed portion and here by removing this particular portion of a soil that means this particular slope is like benching. So provision of a berm or a benching for slopes also is thought to be one of the remedial measures where for increasing the factor of safety.

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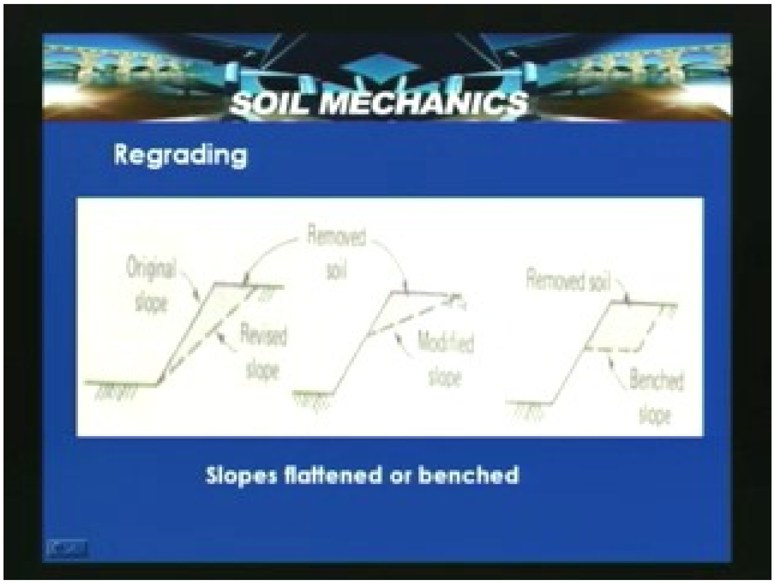

In this case what will happen, the slope will tend to behave like a two slopes one is here and one is here, this is the new slope surface after removing this particular portion of the soil. So benching technique which is also as a re grading or a flattening technique which actually increases the factor of safety of a particular slope which actually works out as the one of the simple option for considering or improving the performance of a slope or re grading a berm provided at the toe which increases the factor of safety and protection against the erosion at the toe.

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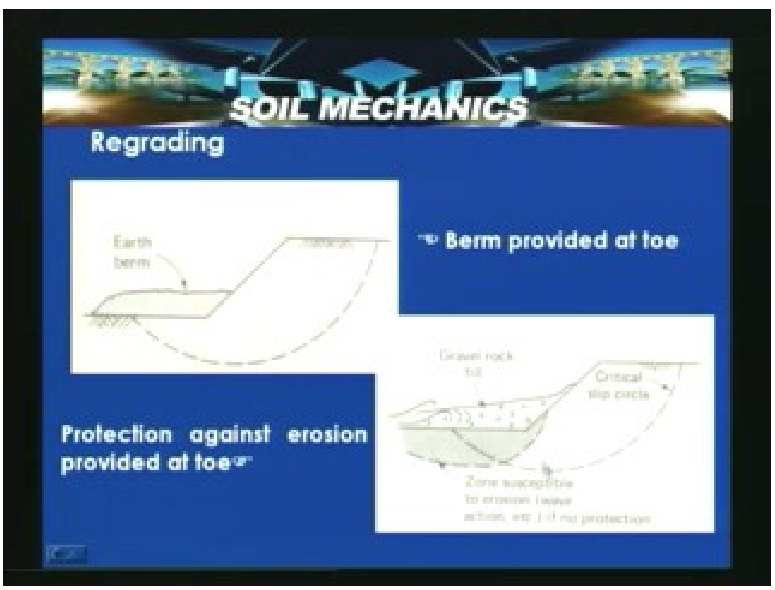

For example if this is the zone susceptible to erosion due to wave action or and if there is no protection then it can be subjected to a slip circle failure. This is the zone; in case of no protection a failure can occur. So if there is a gravel or rock fill is provided which actually increases the factor of safety and acts as a protection for the slope against instability. So re grading or unloading is a technique to reduce the driving forces within a sliding mass. The two methods for the re grading are excavation and light weight fill.

So the two methods what we discussed are that excavation and light weight fill. So re grading or unloading is a technique to reduce the driving forces within a slide mass and the two methods for re grading are excavation and light weight fill.

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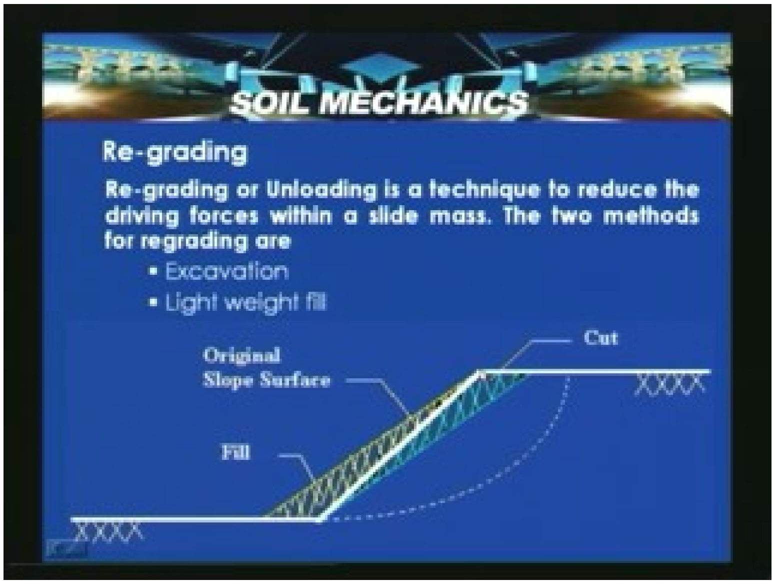

Now here which is shown, another option is that this portion of the slope was removed and then provided here which actually makes the slope flattened slightly. Lowering of ground water to reduce pore pressures in the slope. so that is nothing but the portion for drainage of a slope, here interceptor ditches for diverting the surface slopes that actually helps here and these are the collector drains with perforated pipe in gravel filter envelope.

So collected water can be discharged below the toe by utilizing the man holes connected to transverse drains. This is water table before draining and this is the lowered water table with the help of this, so when the water table which is kept under control, the pore water pressures within the slope under control so that effective stress or maintain. So with that what will happen is that the slope stability increases.

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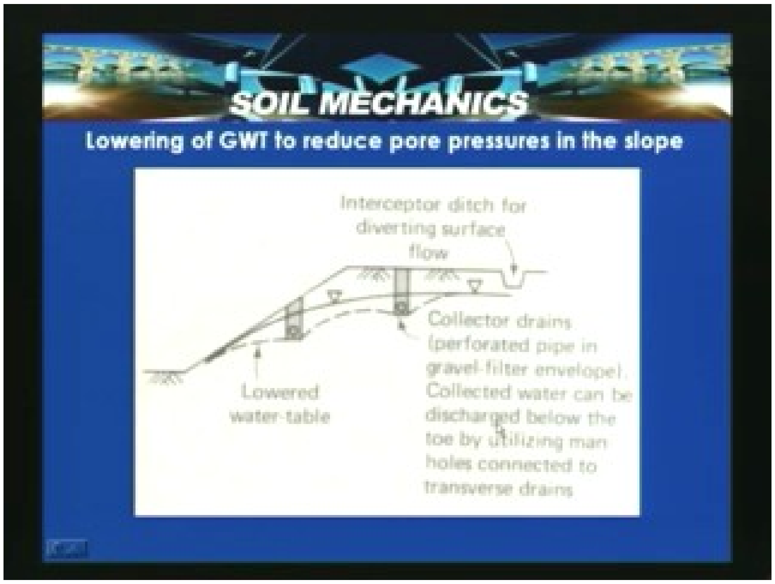

So the lowering of the ground water table to reduce the pore water pressure in this slope is another option which is actually done through surface interceptor ditches or collector drains within the slopes. So drainage reduces the destabilizing hydrostatic and seepage forces on a slope as well as the risk of erosion and piping. So it can be surface drainage and sub-surface drainage.

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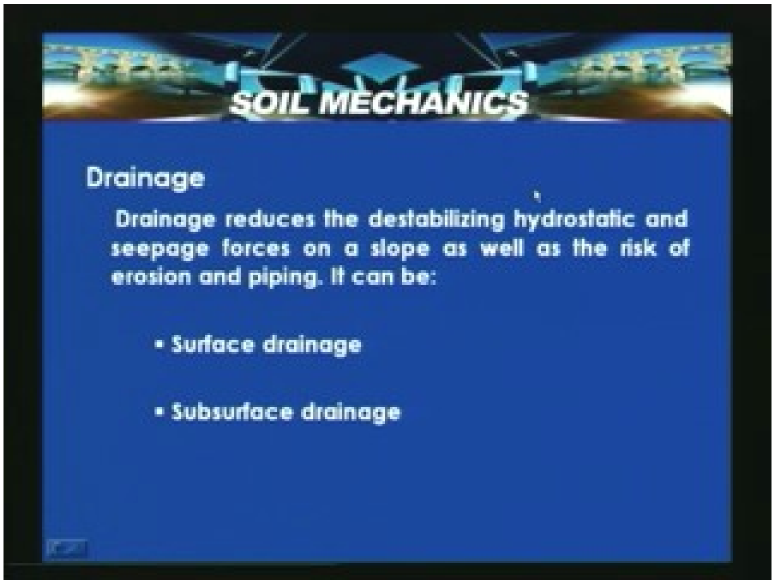

The drainage phenomenon which reduce the destabilizing hydrostatic and seepage forces on a slope as well as the risk of erosion and piping. Plan for building design to aid slope stability, suppose if the building design is made like this if at the crest of the slope a building is constructed and similarly at another building is constructed at the toe of the slope, the shallow foundations or basement for the building or below the toe and deep foundations or basement for the building on the top of the slope.

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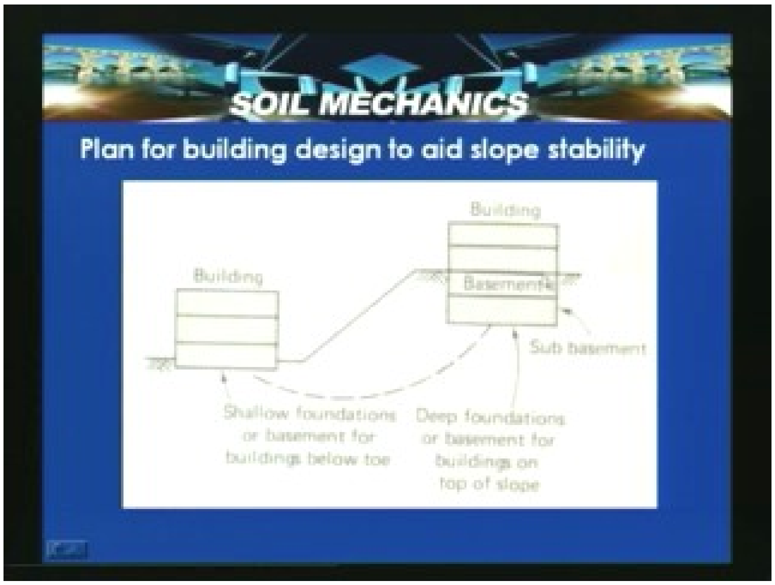

So if this occurs then what will happen is that if the planning is done like this by locating the building at this different elevations, this actually enhances the slope stability and here typical surfacial slope failure in highway embankment is shown after loher et al 2000. We can see that if a transportation embankment or highway embankment how that a typical slope is subjected to, this is the embankment where the slope is subjected to a surfacial slope failure. So here what they have adopted is that for improving the stability of the slope, recycled plastic pins were used and then it was stabilized by driving this into the slope.

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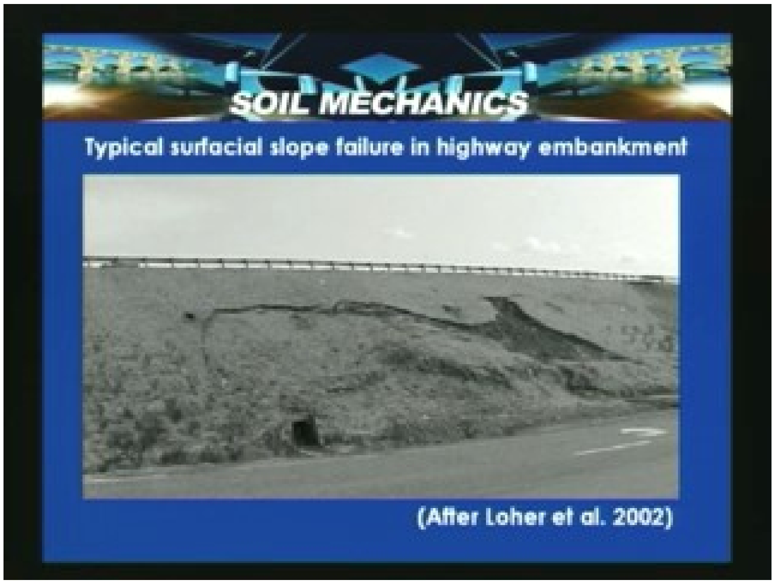

So what happened is that this unstable portion was detained by driving recycled plastic pins into the slope so the cross section is shown and the failed area so entire area is actually strengthened to prevent this slope.

So this one after installation of this, this slope was being stabilized you can see in this portion. So you can see that the improvement which actually reflected in this particular slide.

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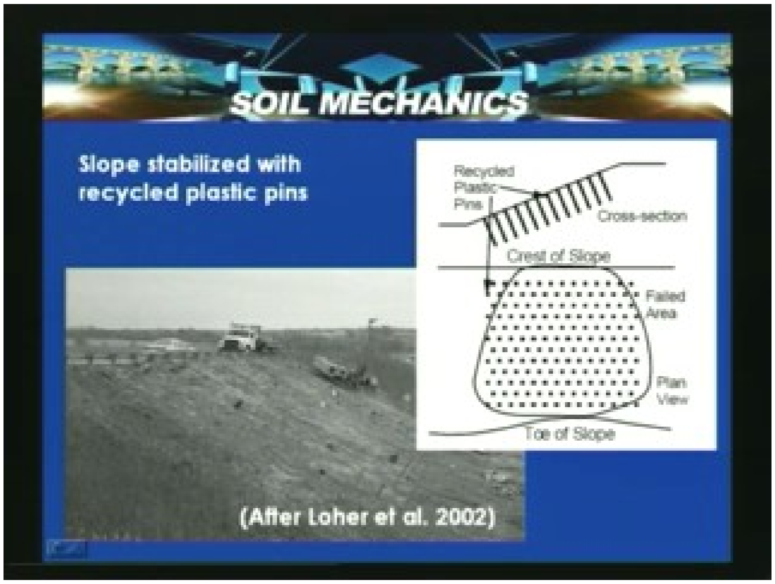

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Another method is the gabion walls for slope stabilization. In this technique what is done is that this gabion walls are nothing but is wide measures which are pre dominantly made with mild steel which are coated with anti-corrosive elements. So in this if the area is actually having abundant availability of stone, the stone is actually filled in this cases and placed one above the other and with that actually these types of walls can come.

So advantage and merit of this gabion wall is that being free freely draining materials the water can see through this one and also because of the gravity or the self weight they also ensure the stability and behave like and because of this iron cases we can have steepness as close to 90 degrees so the gabion walls applications is actually even catching its momentum in India also.

Now another technique which is conventionally used but we never looked into details but this technique which is picking up in the recent past it's called the bio technical slop slope stabilization or this is the part of bio engineering where here live brush layers were used for stabilizing the slope. so the cross section is shown and this is the plan view so the presence of these, when this brush layers are planted with a planned layout and all and with that what will happen is that the stability of this particular structure…(Refer Slide Time: 49:38). So these elements which are penetrating or embedded into this soil act like reinforcement elements and enhance the stability.

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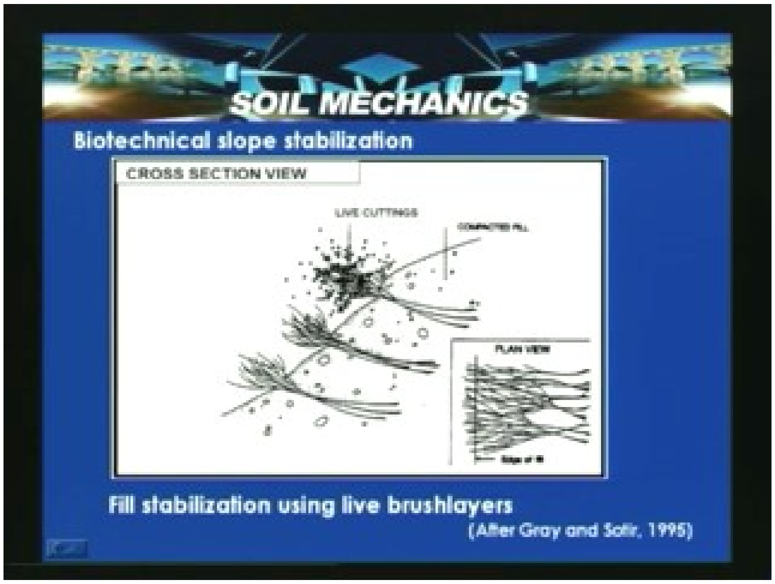

Several laboratories which are involved in investigating and developing techniques for bio technical slope stabilization and the detail is beyond the scope of our lectures but this is a technique which has got also in asterisk look as well as the technical advantage with the biotechnical stabilization and also environmental friendly technique. Another application for stabilizing slopes is that wrap around geo textile or reinforces slopes or we can also have geo synthetic wall with geo synthetic slope with a facing.

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So in this case a wrap around geo textile info slope is shown and after about certain time you can see how that green esthetic view of the look. So this type of techniques can mingle well with environment. So this is another type of slope stabilization technique which can be used for retaining this and which also is gaining momentum in its application.

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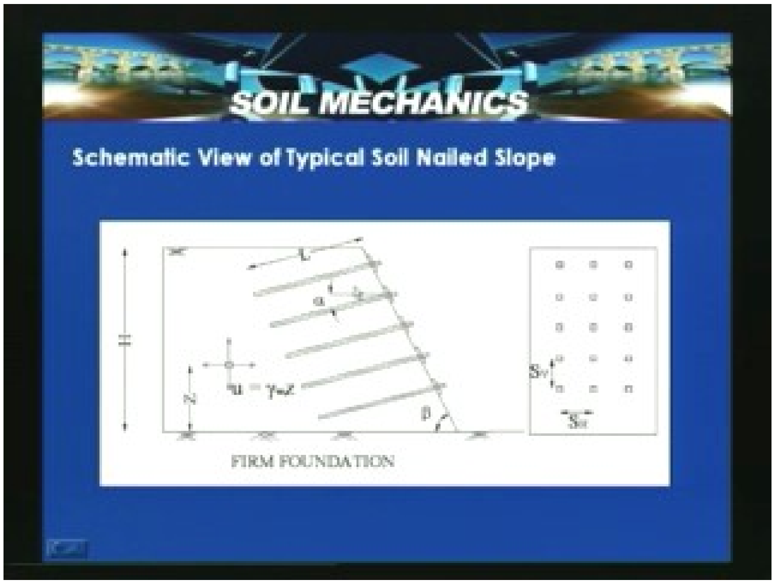

Another technique which is being discussed is the schematic, a nailing technique so in which what is done is that nails of certain diameter with certain layout horizontal spacing and vertical spacing driven into the soil with certain inclination alpha. Generally it is driven between 10 to 20 degrees inclination and u is this pore water pressure. So if this value is u is equal to gamma$_w$z, if this u by gamma z is equal to 0.5 then the slope is actually is said to be completely exaggerated.

So l is the length so for the stability point of u a minimum requirement of about 0.8 to 0.9 times l is required. So the mechanism here is that if this is the active zone and this is the resisting zone, what you can see is that nail with certain inclination. The friction interaction between the nail and the soil and the soil structure interaction between the facing and wall contributes to this stability.

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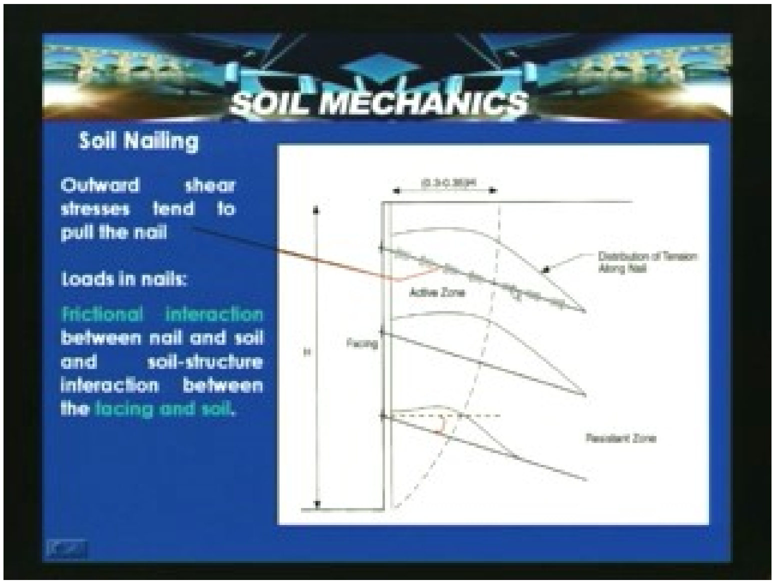

So you can see that in the active zone this portion is trying to be pulled out and this portion is trying to pull inside. So because of this outwards shear stress tend to pull the nail but this is being resisted by this embedded depth. So it requires a certain length so that it can actually generate this particular forces in the resistant zone. So what we did in this particular this in particular topic, we have reviewed type of slopes and failure types, causes of slope failures and we also looked into analysis of infinite slopes and method of slices and we used circular arc method of analysis and Taylor's method we have discussed based on un drained conditions and Fellenius method and extension of bishops and stabilization measures we have discussed.

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So with this we come to the end of the stability of the slopes and where we have discussed the analysis methods as well as some example problems and also different avenues available for stabilizing slopes.

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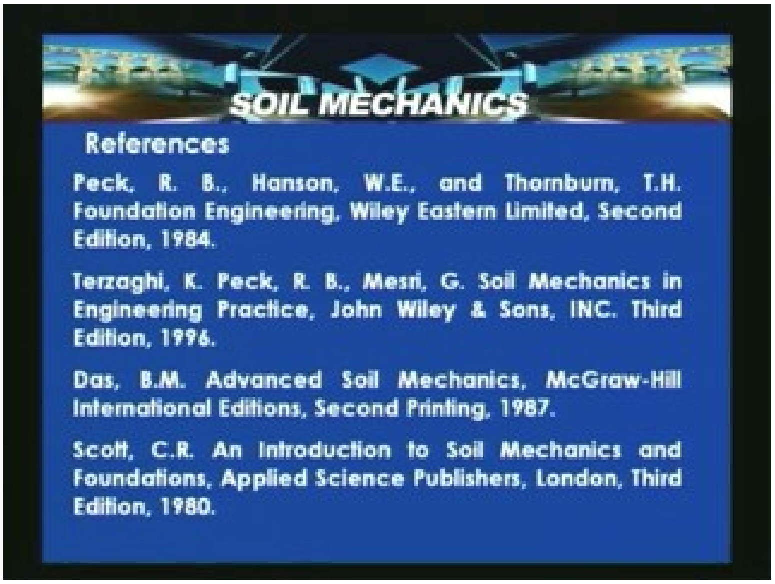

In this slide some of the references which are used in the development of this course material are given. This is Peck Hanson Thorn burn foundation engineering and Terzaghi Peck and Mesri, this is soil mechanics in engineering practice and Das advanced soil mechanics 1987, Scott introduction to soil mechanics and foundations 1980 and Dunn Anderson and keifer fund fundamentals of geo technical analysis 1980.

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McCarthy essentials of soil mechanics and foundations basic geo techniques 1982, the Barnes soil mechanics principles and practice 2000, Craig soil mechanics 1992 and Gulati and Datta geo technical engineering two thousand and five Budhu soil mechanics and foundation 2000, Holtz and Kovacs introduction to geotechnical engineering and these books which are recommended for further knowledge in this particular subject area.

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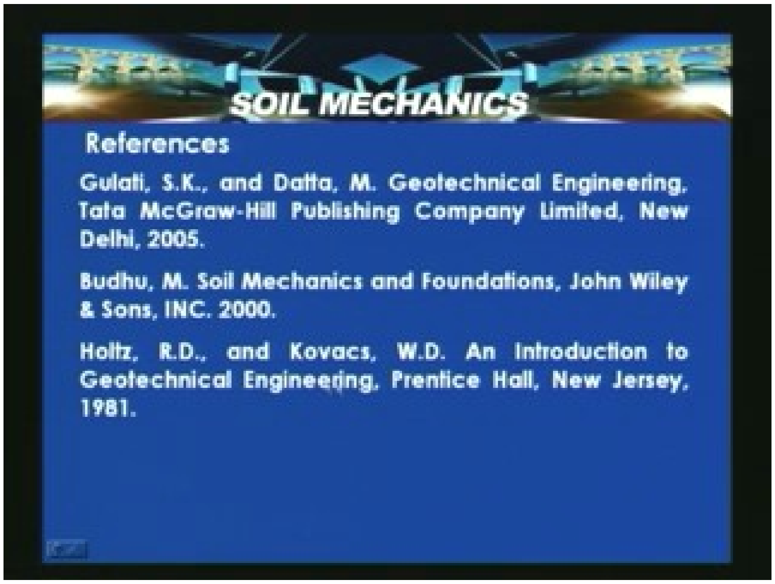

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So these references are once again shown which is in this first slide and these references are not arranged in alphabetical order. These are the references which are given in the first slide and second slide and in the third slide. so as you see in this slide, the soil mechanics learning is a continuous learning process so which involves the commitment and interest in this particular subject.