Advanced Soil Mechanics
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Lecture – 39
Stress Path-Field Cases - I

Okay, welcome back all of you. In the last few lectures, we were discussing about stress path, we have seen some common cases of stress path and we have understood how to plot stress path for laboratory cases. We have discussed it for drained and un-drained cases. Now, in this lecture onwards, we will see how these stress paths can be applied for actual field problems and we will see how to interpret distress path for a given field situation.

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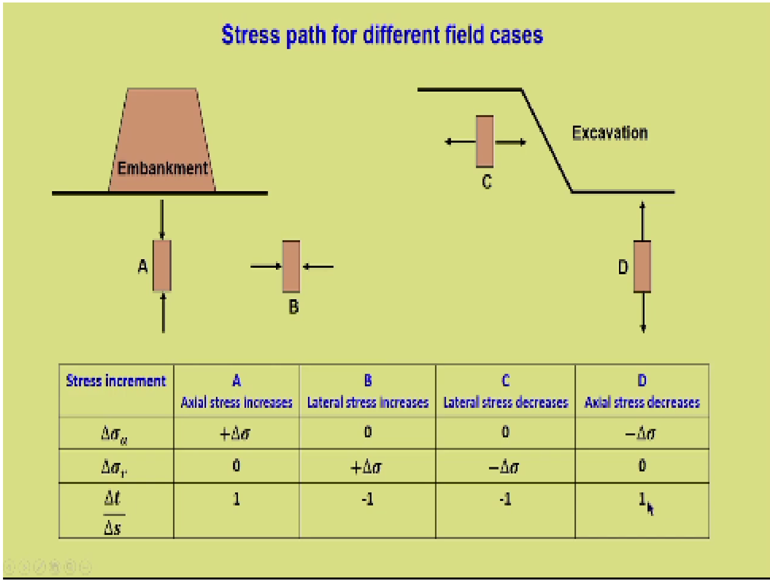

So, let us first take the case of an embankment. So, here, it is a manmade embankment and hence, what is the consequence of the construction of this embankment is that the stress acting on the soil increases. So, immediately below the embankment, if we consider a cylindrical soil mass, then what happens is because of this embankment there is an increase in the stress acting on this.

Now, this is very much similar to a typical compression of this particular element. Now, what is the consequence of this? On a cylindrical soil element which is away from the embankment, let us say the case B wherein, there is a stress increase that because of the stress acting here that will be delegated in the horizontal direction, because of which the radial stress increases in the case of sample B that is a cylindrical sample B.

So, these 2 are very much similar to the cases that we discussed. Let us take the case of typical compression to actual compression. And in the case of the sample B, we are increasing the radial stress. So, when we are increasing the radial stress, it is a typical case of extension. So, these 2 cases are very much similar to what we discussed. Now, let us take another case where we talk about excavation and there is a slope formation. Because of this excavation, there is a release of stress.

Now, if you consider a soil mass on the slope, what happens is the lateral stresses are released, whereas the actual stress remains more or less same. Now, actual stress is same and the radial stresses getting released means, it is a typical compression that we discussed in the lecture that we dealt with laboratory triaxial testing. Now, case D is a case where lateral stress remains same, but then the actual stress gets released.

So, that is also a typical case that we have discussed and that creates a kind of extension. So, let us summarise these cases A, B, C, D into a table. So, here, what is the stress increment, whether it is $\Delta\sigma_a$ or $\Delta\sigma_r$ is stated and once we know $\Delta\sigma_a$, $\Delta\sigma_r$, we can find out what is $\Delta t/ \Delta s$. And now, we will be typically using t-s, s' plot.

So, for case A, what is happening is actual stress increases and hence, it is + $\Delta\sigma$ and that is what $\Delta\sigma_a$ and $\Delta\sigma_r$ is 0. And this is a case where the stress path $\Delta t/ \Delta s$ will have + 1 that is around 45 degrees in the positive direction. Now, in the case of case B, where $\Delta\sigma_a$ is zero, there is no change but the lateral stress is increasing. So, $\Delta\sigma_r$ is equal to + $\Delta\sigma$.

Now, when you substitute this in $\Delta t/ \Delta s$, we will get minus 1 as the slope. Now, case C is the case of excavation, where $\Delta\sigma_a$ here is 0. $\Delta\sigma_r$ is released. So, it is - $\Delta\sigma$ and the slope will be again minus 1 and in the case of D, the actual stress is getting released. So, $\Delta\sigma_a$ is equal to - $\Delta\sigma$. $\Delta\sigma_r$ equal to 0. There is no change and hence, $\Delta t/ \Delta s$ is equal to 1.

Please try to work it out whether $\Delta t/ \Delta s$ is correct or not that will give you an experience of the determination of slope and what we need for plotting this stress path is the slope of the stress path.

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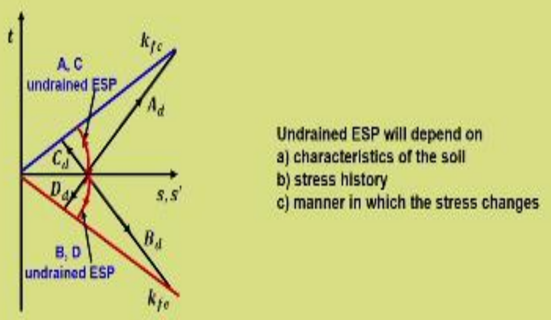
Stress increment	A Axial stress increases	B Lateral stress increases	C Lateral stress decreases	D Axial stress decreases
$\Delta\sigma_a$	$+\Delta\sigma$	0	0	$-\Delta\sigma$
$\Delta\sigma_r$	0	$+\Delta\sigma$	$-\Delta\sigma$	0
$\frac{\Delta t}{\Delta s}$	1	-1	-1	1



So, let us try to understand this on t-s, s' plot. This t-s, s' plot and let the starting point be same, let us assume. So, the first stress path that is corresponding to case A is typical drained stress path. So, let us first talk about drained stress path and those that an inclination of 45 degrees and A_d the presence the case A. Now, case B that is lateral stress increase. It is towards extension now, when the stress path moves towards the blue line, that means it fails in compression.

And when it moves towards red line, it means that it fails in extension and we know that the case B is a case of extension and hence, with the slope 1, it fails at extension failure line and that is given by B_d that is B drained condition. And for C, it will be negative one, but the cases compression and hence, it moves towards the compression failure line and the last case D is towards extension.

Why? Because is that case of degrees in actual stress. So, that represents D_d and all the 4 cases were discussed in detail when we discussed about the triaxial testing. Now, we have drawn drained stress path. What about un-drained stress path? Now, we have already seen this that un-drained stress path is basically governed by A value and whatever be the condition the expression remains the same.

So, this is a typical un-drained stress path and depending upon A value, the effective stress path would either shift towards left or towards a right. So, this is the un-drained stress path for A and C Why it is written A and C? Because that represents the compression. And the effective stress path for cases B and D which represents extension is given by this. Now, where does it go and fail that is governed by the A value.

Now, if the A value after substitution that is 1 /1 – 2 A is the slope of effective stress path. So, when you substitute a value depending upon the A value, if you can decide effective stress path is in which direction. So, un-drained stress path will depend on the characteristics of the soil, stress history and the manner in which the stress changes is all these governs the A value and hence, that gives you an appropriate effective stress path.

So, we need to understand that it depends upon the soil behaviour, it is very much dependent on the stress history. And it also depends on the sequence and the manner in which the loading is happening. So that is all about brief introduction on how the effective stress path and the total stress path is dependent on the various field situations. Now, let us take some common examples in the field and see how the stress path changes.

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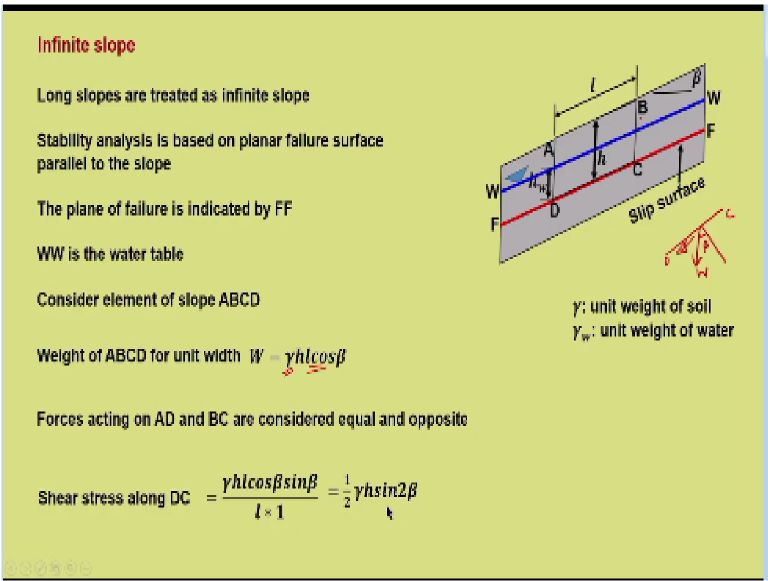

So, let us first take the case of infinite slope. And what is an infinite slope? Long slopes that are treated which are long are treated as infinite slope. For example, a mountain and the planar area gets extended over a long distance. That can be treated as an infinite slope. Whereas the smaller slopes for example in the case of embankment, these are finite slope. So in long, huge hills and big mountains, the slope can be treated as planar and it can be treated as infinite slope.

The stability analysis is based on planar failure surface parallel to the slope. I hope you remember about how we understand the stability of infinite slope. So, it fails, basically a longer planar surface which is parallel to the slope. So, let us take a representative infinite slope, the plane of failure is indicated by FF. This is the plane along which the failure happens. So, let us presume that this is the failure surface.

Now, let us incorporate water table into the slope condition where WW is the water table within this slope. Now, let us consider element of slope A, B, C, D and let us try to analyse this. So, the length of AB is l along the slope. Angle of the infinite slope is β. h_w is the height of water table that is this particular distance is h_w from the failure surface. γ is the unit weight of soil. γ_w is the unit weight of water.

Now, if you want to find out the weight of ABCD, this particular element ABCD; ABCD is nothing but a parallelogram. And hence, this ABCD area multiplied by one that is perpendicular to this particular plane. So, that will give you the volume. So, weight of ABCD for unit width. So, that is what I told it is unit width in the direction perpendicular to this plane.

So, the weight of ABCD is equal to γhl cos β. Now, what is hl cos β? Now, this is the distance h into this perpendicular distance is lcos β. So, that gives you the area of parallelogram. So, hl cos β multiplied by γ that is what is given here, into hl cos β gives the area; into one gives volume; into γ gives the weight of ABCD.

So, forces acting on AD and BC are considered equal and opposite. So, it cancels off and that does not come into the analysis. Shear stress along DC. Now, let us resolve the forces on this failure surface. When I say forces, all these stresses acting on any failure surface or plane, we understand that it is normal and shear stresses. So, we have understood this in our earlier lectures.

So, let us try to understand what is the normal stress and shear stress acting on the plain, so, plain DC. So, shear stress along DC is that is the component of weight acting along DC. So, we know this how to resolve. So, if you have DC, this is weight acting and this will be β. So, this will be w sin β. So, w sin β will be along the C direction. So, that is what is written here.

So, w is gamma γhl cos β sin β/ l * 1. Now, why it is l * 1? Because we have we are discussing about stress. So, the force component in sin β is in DC direction divided by l * 1 is the area So, that gives shear stress along DC that will give 0.5γhsin2β. l and l gets cancelled off; cos β sin β is 0.5 sin2β. So, substituting that we get what is the shear stress.

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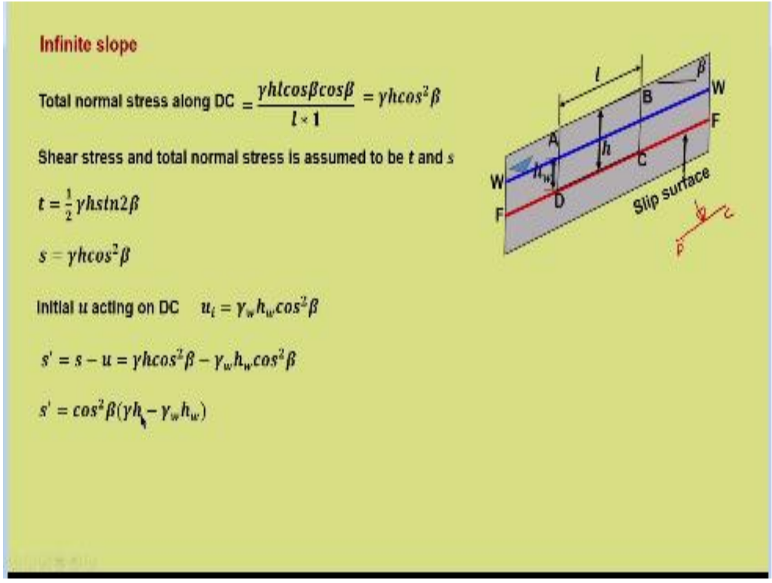

Now, total normal stress along DC that is what is the normal stress acting that is this is DC, so, this stress. So, we know that DC the component has been taken, so, it will be weight component in cos β direction. So, (γh l cos β * cos β) / l into 1 that gives γh $\cos^2$ β. All these exercise we have already seen during our undergraduate. So, we are just brushing it up and see how we will understand this in the context of stress path.

Now, shear stress and normal stress is assumed to be t and s for the time being. So, let us assume that the shear stress what we have determined and the normal stress what we have just found out, this can be considered as t and s, s, s, s' respectively. So, t is equal to that is equivalent to shear stress 0.5 γh sin 2 β and S is equal to γh $\cos^2$ β.

So, initial u, we also have a static pore water pressure now, that is initial u acting on DC will be same as normal stress. So, always the pore water pressure is influenced in the normal stress. So, we take the normal component that is $u_i = \gamma_w h_w \cos^2 \beta$. Same as this only change is height and the unit weight corresponds to that of water. So, we can find out what is s' for effective stress.

But we need s' = s- u that is $\gamma h \cos^2 \beta - \gamma_w h_w \cos^2 \beta$ that gives $s' = \cos^2 \beta (\gamma h - \gamma_w h_w)$.

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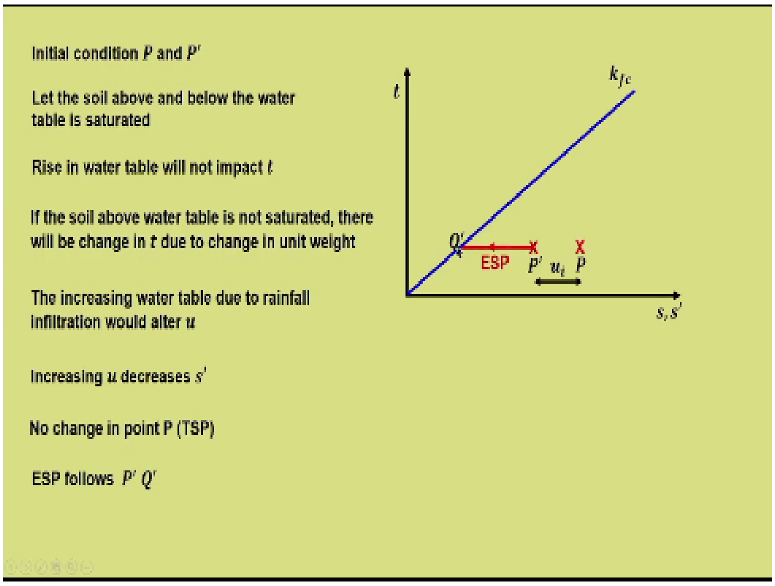

So, initial condition P, P', so, let us try to plot these conditions on t-s, s' plot. So, let us say P is the initial condition and there is an initial pore water pressure of u_i. So, this difference will be u_i, so, P and P' is separated by u_i. Let the soil above and below the water table is saturated. Let us presume that it is because of capillary rise or whatever the soil sample above the water table is also saturated.

We are just trying to simplify it because this means that when there is any change in the unit weight that is going to change the t component as well, I mean t component. So, in this case, if we presume that soil is more or less saturated, then there is nothing much that is going to change in t. So, that is the reason why it is assumed that the soil above and below the water table is saturated.

Therefore, rise in water table will not impact t because t is not influenced by pore water pressure. So, whether it fluctuates up and down, it is not going to get influenced. What will get influenced? s component will get influenced. Other s' will get influenced by variation in pore water pressure. But, if the soil sample is not considered to be saturated, then t can also vary because change in unit weight.

When you are calculating t, you know that it is governed by unit weights. So, if it is not assumed to be saturated, then it will change. If the soil above water table is not saturated, there will be change in P due to change in unit weight as the soil starts saturating because of the infiltrating rainwater. The increase in water table due to rainfall infiltration would alter u. So, what is the effect of infiltrating rainwater?

Infiltrating rainwater means, it will rise the water table. And when the water table rise, hw changes and when hw changes, u will change. So, increasing u will decrease s dash because of the assumption P remains same, but increasing u will decrease s', so, no change in point P that is total stress point is not going to change. ESP follows P'Q'. Now, there is no change in t but s' decreases which means that the stress path will be in this direction and that P'Q' gives the respective effective stress path.

Now, there is no requirement that Q' has to be always on k. So, it is a progressive failure condition. From P' as in when there is change in pore water pressure, it moves towards Q'. At some point of time, it fails.

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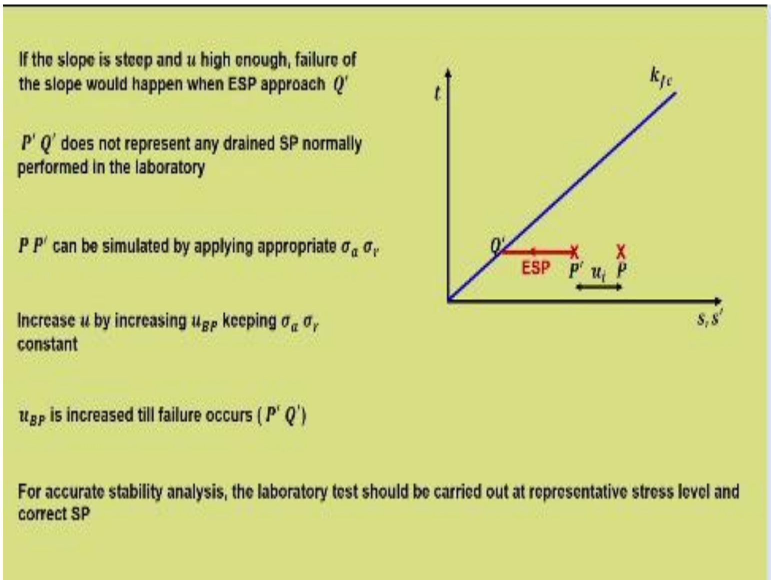

So, if the slope is steep and pore water pressure generated due to infiltrating rainwater is high enough, failure of the slope would happen when ESP approach Q'. Now, when it is steep, it will influence the weight and when rainwater infiltrates, u will increase. These 2 components together would alter the effective stress path and it will proceed towards Q' to fail. P' Q' does not represent any drained stress path normally performed in the laboratory. This is why we are discussing this in that much detail.

Whenever we want to do a slope stability analysis, we need to have the shear strength parameters. Now, if the soil is brought to the lab, we normally do a triaxial compression test.

This stress path which is followed in triaxial compression test may not be same as that of the condition that is actually existing in the field. Now, this stress path P'Q' is not simulated in the lab for determining shear strength parameters.

So, that differences is what we have to appreciate in this lecture. So, P P', this points P and P', it can be simulated by applying appropriate σ_a and σ_r in the lab. So, the initial conditions can be mimicked in the laboratory. Now, for simulating this particular effective stress path, what we have to do? So, we need to increase the pore water pressure because that is what is happening in the present case.

The slope is not failing because it is getting loaded. It is failing because pore water pressure is getting altered. So, the same thing if we want to, the same condition has to be simulated in the lab, then we need to increase the pore water pressure. Now, we know that there is a way of increasing pore water pressure which we have known for saturation that is by increasing the back pressure.

At that point of time, it did not destabilise the soil because we increase both confinement and back pressure together, but in this case, if we do not disturb the stresses, that is axial and radial stresses and keep on increasing the pore water pressure in terms of back pressure, then that will simulate a situation which is very close to the infinite slope condition that we just discussed. So, increase u by increasing u_{BP}, keeping σ_a, σ_r constant. So, that will give us this appropriate effective stress path.

Now, whatever failure and the failures strength parameters that we get corresponding to that will be realistic condition very close to the field 1. So u_{BP} is increased till failure occurs that is till the stress path reaches Q'. For accurate stability analysis, the laboratory tests should be carried out at representative stress level and correct stress path. Representative stress level means simulating the initial condition P and P' and correct stress path means how the stress path moves towards the failure.

Now, unless we discuss this in this manner, that is discussion of P' Q', one will not be able to appreciate what actually is happening in the field. So, this gives a very good opportunity for us to understand better I mean to say the stress path plot gives us an opportunity to understand better what is realistic in the field. And if one really wants, we can try to simulate the same condition in the lab and then get the appropriate strength parameters.

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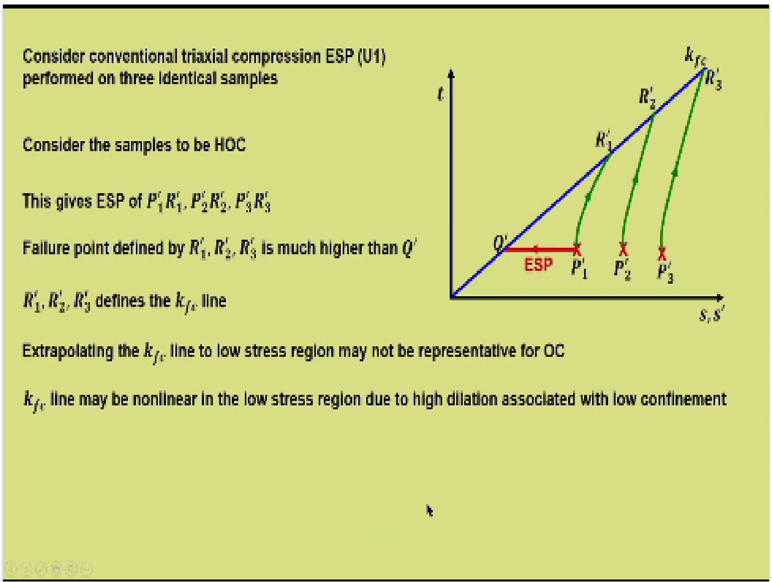

So, now consider the conventional triaxial compression ESP that is U1 performed on 3 identical samples. We are just going to see how things will be different if we perform a triaxial compression test. Now, U1 is familiar to you, because we have already discussed this, when we discuss un-drained triaxial stress path. So, please refer to U1 is a typical un-drained stress path.

Now, it is governed by the slope 1/ 1-2A in t-s, s' plot. Now, what we will do? For finding out the strength parameters, we consider 3 identical samples and we apply 3 cell pressure and then get the deviatoric stress at failure plot the Mohr circle or we plot it on t-s, s' and obtain the shear strength parameters that is what we generally do. So, let us see, if we do U1 test in the lab, how it will look like visa- versa this stress path, which is the actual stress path in the field which is P'Q'.

So, consider the samples to be highly heavily over consolidated, what is the implication of the statement? The only implication is, A value will be negative. Let us say that A value for a heavily over consolidated sample will be minus 0.5, it is an example. So, 1 /1 – 2 A 2 into – 0.5 – 2 into – 0.5 will be plus. So, this will be a positive slope. So, we need to understand now only that the effective stress path in t-s, s' will move in a positive direction.

So, this gives effective stress path of P'_1 R'_1, P'_2 R'_2, P'_3 R'_3. Let us say the first point simulated in the lab for U1. U1 case of compression is P'_1. So, the initial point is P'_1 and the stress path is in the positive direction effective stress path which is P'_1 R'_1. For P'_2 R'_2 that is at a higher confinement and P'_3 R'_3 at even higher confinement. So, this gives the effective stress path.

The failure points are defined by R'_1 R'_2 R'_3. So, these are the failure points, you can see that these points are much higher than Q', which means, this strength that we anticipate from laboratory test is much higher than the actual stress strength which is available in the field when an infinite slope fails due to infiltration of rainwater. So, that is what that difference is what we need to understand here.

So, R'_1 R'_2 R'_3defines the k_{fc} line. Now, if we try to extrapolate this for the present case, I am telling about this present case, if we tried to extrapolate R'_1 R'_2 R'_3 downwards, then in the lower stress region, it may not be representative for over consolidated soil. Why? We have seen that the failure lines are always non-linear in the case of over consolidated because of the variation in dilation.

A lower stress region, the dilation will be more or much more free because the confinement is less. As we increase the confinement, the dilation gets suppressed because of this, there is a non-linearity that creeps in. So, k_{fc} line may be non-linear in the lower stress region due to dilation associated with low confinement but I am not showing that in this particular plot because we know this much earlier.

So, we just want to understand here what is that a normal compression test in the lab may not simulate the actual field condition. So, you may naturally have a question that we are working with the highest strength, then how we get an appropriate result. Now, if any kind of work which we execute on a given slope, we always have a higher factor of safety. We take a factor of safety margin. So, it is mainly because of that.

And please understand, we are not dealing with a manmade slope when I say infinite slope, it is a natural slope. So, natural slope normally fails during rainfall or due to any other forces, but generally a lot of failures happens during rainfall. Now, this rainfall increases the pore water pressure. So, the actual cause of failure is P'Q', P'_1Q'.

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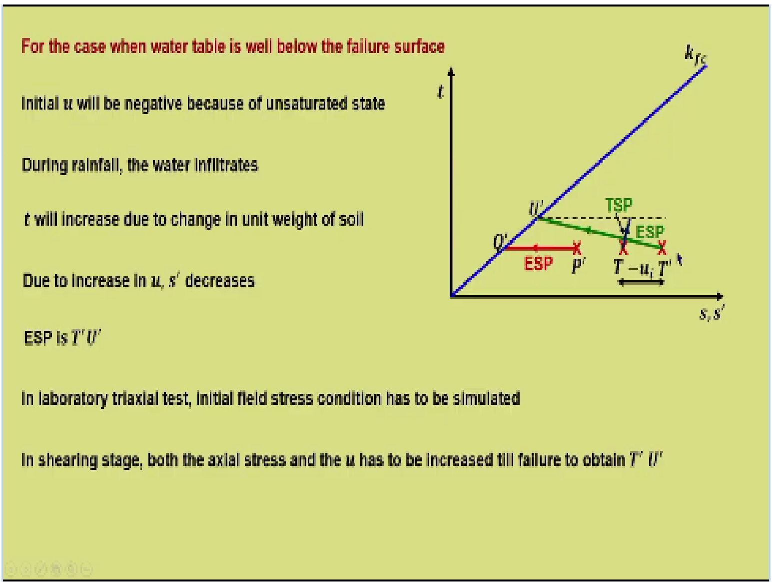

For the case when water table is well below the failure surface, now, we have considered the case where water table is above the failure surface. Now, here let us try to see what difference will it make from P'Q', if the water table is well below the failure surface. Now, what is the implication when water table is below? When the water table is below, the pore water pressure in the along the failure surface will be initially negative.

So, initial u will be negative because it is an unsaturated state. So, let us say t is the initial point, total stress point and there is a negative pore water pressure so, it will shift towards right; if it is positive, which shifts towards left. So, the effective stress point the initial point will be t'. So, during rainfall, the water infiltrates. Now, when the water infiltrates, t will increase due to change in unit weight of soil.

Now, in this particular case, the unit weight initially was bulk as it gets saturated, it becomes gamma set which is more and hence, t will increase. So, we know now the direction in which the stress path would move because of increase in t, it has to move towards in the upward direction. Now, due to increase in u, what happens to s'. As u increases, s' starts decreasing, so, the stress path should move towards left and towards upwards.

So, the total stress path remains same it is in this direction whereas, the effective stress path is T'U' that will be in this direction. So, this satisfies what we have told that is t is increasing and s' is decreasing, because of the increase in pore water pressure. So, T'U' represents the effective stress path. So, this total stress path is drawn only up to this because the soil sample fails here at U'.

So, that is why this dashed line shows the limit of total stress path. So, effective stress path is T'U'. In laboratory triaxial test, initial field stress condition has to be simulated which means to say it is T and T'. In shearing stage, how to simulate this particular condition? In shearing stage, we also need to increase the actual stress as well as we need to increase the pore water pressure.

Here, in the shearing stage, both the actual stress, actual stress increase means, we are increasing the deviatoric stress. This deviatoric stress increase is increase in t because t is same as $\sigma_1 - \sigma_3/ 2$. So, $\sigma_1 - \sigma_3$ has to increase because that is the case discussed here. t is also increasing and the s' component is reducing because of the increase in pore water pressure.

So, when we simulate this in the lab, we need to make sure that the actual stress is increased; at the same time the back pressure is also increased, so, that u increases that gives the effective stress path P'U' if we want to simulate that in the lab. So, that is all about infinite slope.

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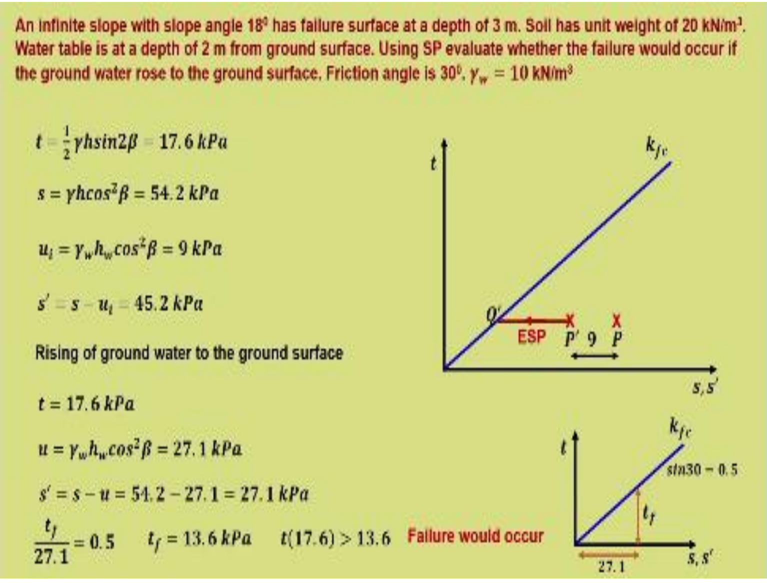

Now, let us see a small example related to this and related to how to use stress path for a given field condition. An infinite slope with slope angle 18 degrees has failure surface at a depth of 3 m. Soil has unit weight of 20 kN/m^3. Water table is that a depth of 2 m from the ground surface. Using stress path, evaluate whether the failure would occur if the ground water rose to the ground surface.

Friction angle is 30 degrees. γ_w is equal to 10 kN/m^3. These are this given condition in the field. We just need to understand by plotting the stress path whether the failure would occur or not, if there is a groundwater fluctuation from the given depth to ground surface. So, let us try to solve. It is on t-s, s'. t = 0.5γhsin 2β, substituting for β will get 17.6 kPa.

And this total stress path point, initial point is γhcos ^{2}β which is equal to 54.2 kPa. So, the initial point, we can mark, let this be the initial point P. Now $u_i = \gamma_w h_w \cos^2\beta$, which is 9 kPa. Please substitute this and see for yourself. So, s' = s- u_i, which is equal to 54.2 – 9, which is 45.2 kPa. So, let us say that this is P', P remains same. Now, this is the u_i that is 9 kPa.

Now, let us assume that the stress path reaches Q' when there is groundwater fluctuation. Now, actually, whether it is touching the failure line or not that is what we need to evaluate in the given example. Now, if it is touching, then it means that the failure would occur. Now, this is a given ESP for this infinite slope condition which we have just seen. Rising of groundwater to the ground surface, let us try to understand this particular case.

t is equal to 17.6 kPa which is not changing. u changes to 27.1 kPa. So, s' = s- u which is equal to 54.2 minus 27.1 which gives 27.1 kPa that is if the groundwater table is rising, then the s' becomes even less that is 27.1 kPa. Now, let us try to understand whether this is a failure state or not. So, let us again re-plot t-s, s'. sin 30 which because the failure line is defined, we know that friction angle is 30 degrees and tan α for this is equal to sin φ' which we have already seen.

So, we know that it is sin 30 which is equal to 0.5. Now, let us say that this distance. Now, s' is 27.1. Where it is and what will be the strength available at this particular point? Let us try to see. So, t_f is the strength which is available at s' of 27.1. Here, it is 27.1 So, t_f divided by 27.1 equal to 0.5. So, t_f is equal to 13.6 kPa. Now, what is the strength available at s' of 27.1? The strength available is 13.6 kPa, but, what is the stress t at 27.1? The stress t is 17.6 kPa.

Now, the stress t 17.6 is greater than this strength. Hence, the failure would occur. So, that is how we try to analyse the given situation. So, the pore water pressure increase led to this failure which means that there is no scope for the pour the pressure to rise up to the ground surface before that the failure would happen for the given situation. So, this is a small example to show how to use the stress path for understanding and analysing the field situation.

We can anticipate when the failure is going to happen. So, all these exercises can be done using a stress path plot.

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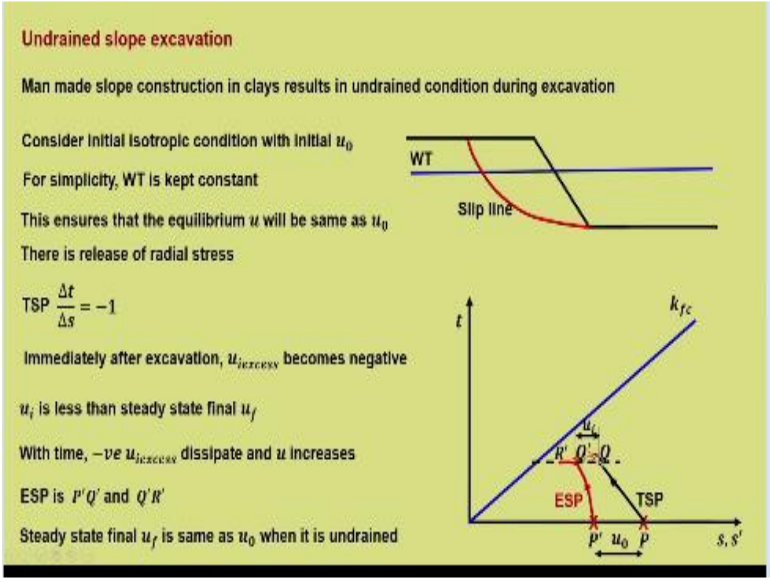

Now, let us deal with un-drained slope excavation. Manmade slope construction in place results in un-drained condition during excavation. So, here also we are dealing with slope but a finite slope instead of an in finites. Now, this is a given finite slope, this has been created because it got excavated from this end. So, consider initial isotropic condition with initial u_0. For simplicity, water table is kept constant and why we want to maintain this?

Normally, it is not maintained in this manner. First of all, the water table will be slightly lower and because of that the phreatic line changes and we do not want to complicate this problem with that. So, we are considering water table to be constant and hence the equilibrium pore water pressure after excavation, there will be change in pore water pressure and again the pore water pressure reaches to an equilibrium value.

Now, if you consider water table to be seen, then after equilibrium, whatever pore water pressure attains will be same as the initial pore water pressure because the height of the water table is not changing. So, let us try to understand. Since the initial condition is taken to be isotropic and with an initial u_0, let us say that the point will be on the isotopic line. So, P P' is drawn now. I hope you are familiar how to at least mark the initial points. So, P and P' at a difference of u_0.

There is a release of radial stress because of excavation. Here, a typical case of release which is happening. So, TSP that is the slope of total stress path Δt / Δs will be – 1. So, it will be in the reverse direction with a negative slope. Let it be PQ which is the TSP. Immediately after excavation, there will be change in pore water pressure. Now, this is a kind of loading in post, but here it is a release that is happening.

But whatever P it is one of the same, there is a stress change which is happening because of this there is a change in pore water pressure. This change in pore water pressure can be taken as excess pore water pressure change. So, that is why there is u_i excess becomes negative. Why? Because there is excavation, it is released and whenever there is release, there is a tendency for negative pore water pressure.

So, u_i excess becomes negative. So, u_i is less than steady state final u_f. Now, this u_i will whatever at the point of Q, when the excavation is made, that u_i will be generally less than the final pore water pressure. So, with time, negative u_i excess will dissipate and slowly u will increase. So, initially immediately after excavation, there will be negative pore water pressure generation, but with time, this negative pore water pressure will dissipate.

And slowly the pore water pressure will again regained and come to its original value of u_0. So, u_f which is the equilibrium pore water pressure in the final stage will be more or less equal to u_0. So, that is why it is told at the beginning the pore water pressure u_i will be less than the earlier pore water pressure that is u_0. Why? Because there is a negative pore water pressure and it gets reduced.

The positive pore water pressure gets reduced. So, this is what it means. So, when you have this, this is the point where there is an initial pore water pressure u_i. So, this pore water pressure which is marked as u_i, so, this is u_i, this u_i is generally less than u_0 or maybe it is this is the final point of effective stress path, this u_i will be less than the final u_f. Now, this P'Q' is the effective stress path and Q'R' is the point when it reaches equilibrium.

So, P' to Q' is immediately after excavation and Q' R' when the negative u_i excess start dissipating. So, when negative pressure start dissipating, the pore water pressure increases and Q Q' R' is the corresponding effective stress path. So, this is the point. So, that is why a horizontal line is drawn. So, TSP point is Q. So, steady state final u_f that is when it reaches equilibrium is same as u_0 when the condition is un-drained.

So, this is the final pore water pressure, which is the steady state or equilibrium pore water pressure u_f and you can see that u_i is less than u_f. Now, this u_f is equal to u_0 because of our assumption, but provided the condition is un-drained. When the water table start changing because of drain condition, then the final pore water pressure will not be same as that of the initial pore water pressure. So, this is the condition where it is un-drained condition and water table still is uniform.

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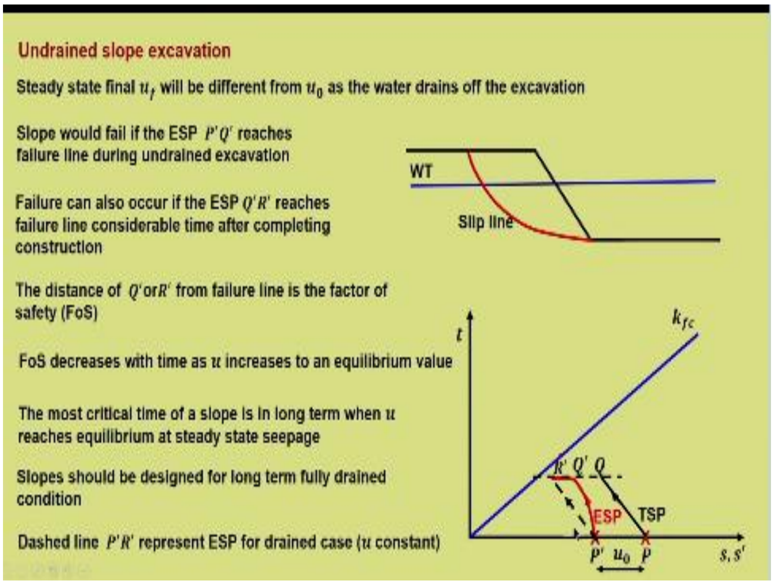

Now, we will see 2 different cases that is steady state final u_f will be different from u_0 as the water drains off the excavation. So, in the previous slide, we have assumed that there is no change, but now if it starts draining off, then the final pore water pressure u_f will not be same as that of the initial pore water pressure u_0. Slope would fail if the ESP that is P'Q' reaches failure during un-drained excavation.

Now, it can so happen that from P' to Q', it just extends and join the failure line. So, it can fail in that manner as well that is during the un-drained excavation itself, it can fail. P'Q', it represents the excavation. So, during excavation itself it can fail or it can also fail, because Q' R' can reach towards the failure line that is after some time completing the excavation.

So, here the excavation is over. So, Q’ R’ is the manner in which the pore water pressure increases and it can extend and it can fail at this point. Now, that is what it means. So, there are 2 ways the failure of this particular slope can happen. The distance of Q’ or R’ whichever be the case either this case or this case is the factor of safety of the slope. Now, if it is here, then this is the margin of safety.

If it is here, this is the margin of safety and factor of safety decreases with time. Why? Here the factor of safety is this much, but as the time progresses, u increases and Q’ R’ is the stress path. So, the factor of safety reduces and as the u increases to the equilibrium value. So, the most critical time of a slope is in long term when u reaches equilibrium at steady state seepage that is u is increasing. So, the critical path of a slope under excavation is in long term. Why?

We know that the pore water pressure keep on increasing with time. So, if the equilibrium value is less than the failure state, then the slope is safe or it may free. Slope should be designed for long term fully drained condition when it comes to the excavation. So, dashed line P’R’ represents the effective stress path for drain case that is when u is constant. So, if it is drained, we know that is the same slope and P’ R’ represents this condition.

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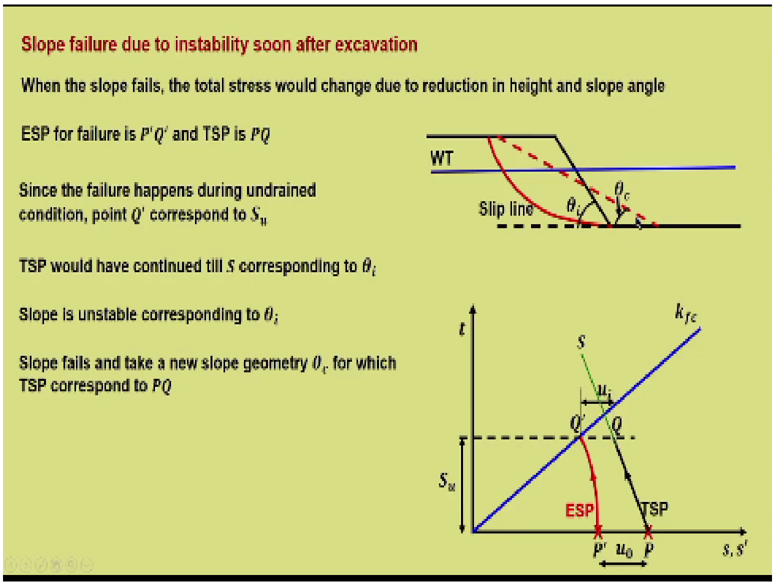

Now, slow failure due to instability soon after excavation. So, when the slow fails, the total stress would change due to reduction in height and slope angle. So, what is happening? When there is instability, there is a failure which happens to this slope and because of this failure, both the height and the slope angle changes and it tries to achieve an equilibrium condition. So, if θ_i is the initial angle, after failure the slope will look like this because it needs to shut off this much portion and that will give the new slope angle which is θ_c.

So, effective stress path for failures P'Q' and total stress path is PQ. So, we will see again what is happening. So, the initial condition is same and this is the total stress path and P'Q' is the effective stress path that is immediately after excavation, so, the excavation stops here. TSP and ESP and u_i is the initial pore water pressure at the point when the failure takes place due to excavation.

Since, a failure happens during un-drained condition, this strength can be considered equal to un-drained shear strength because it is completely under un-drained condition. TSP would have continued to s corresponding to θ_i. So, let us say that this total stress path would have continued to this point corresponding to this particular height of θ_i, but it is unstable due to excavation and hence, it falls to, it cannot sustain θ_i corresponding to the θ_i.

So, it cannot achieve this particular state s rather slope fails and take a new slope geometry of θ_c for which total stress path correspond to PQ. So, due to failure, it brings down and hence Q is the point which corresponds to the new slope geometry of θ_c.

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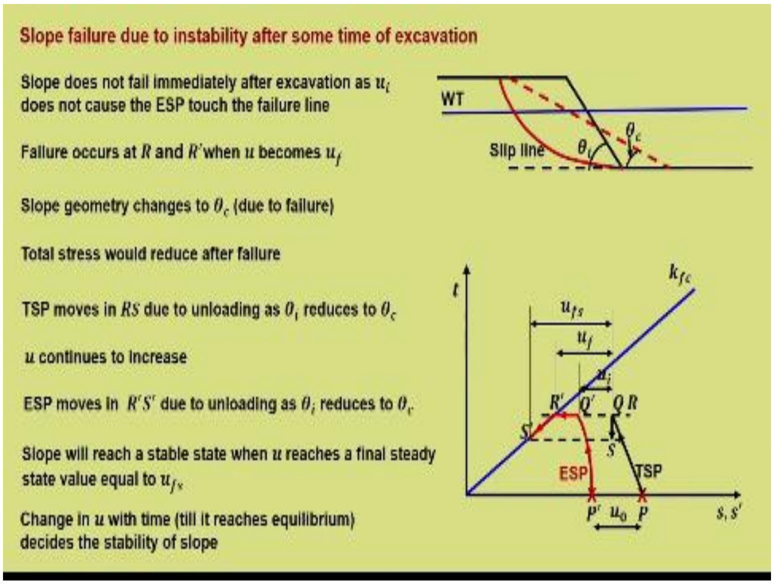

Now, if the slope fails after some time of excavation, so, what will happen? Slope does not fail immediately after excavation as u_i does not cause the ESP to test the failure line. So, this case is different, but the failure happens after some time of excavation. So, the initial condition is same; total stress path is same; effective stress path you can see that the point Q' is not touching the failure line. So, it is not failing immediately after excavation.

Now, u_i has not caused the failure. A failure occurs R and R'. When u becomes the stable value of u_f, this is the point R and this is the point as the pore water pressure start increasing that is the final equilibrium value, it reaches at this particular point. This is not final equilibrium value as the pore water pressure increases, it touches the point failure line at R' which corresponds to the value u_f.

So, u_f is the value which causes the failure at R' and then the slope changes its geometry from θ_i to θ_c due to failure. Total stress now would reduce after failure. Why the total stress now has to reduce? Because the slope height is reduced and the failure has occurred, so, the slope angle got changed. So, definitely the total stress path also would change because the total stress is reducing.

Earlier cases, total stress did not change. So, TSP moves in RS. So, it moves downwards due to unloading as θ_i reduces to θ_c. But, u continues to increase because it is a gaining of the pore water pressure till it reaches a steady state equilibrium value which is denoted as maybe u_{fc}. So, ESP moves in R' and S'. Now, what is the effect that happens to effective stress path?

So, it is not terminating here, now, it has achieved a new geometry. Now, due to unloading because of the θ_i reducing to θ_c, what is happening to ESP? ESP moves towards S', so, R'S' corresponding to a reduction in total stress path. So, slope will reach a stable state. Now, θ_c will become a stable state when u reach a final steady state value which is equal to u_{fs}.

So, u_{fs} is the stable final value of pore water pressure. So, where S which means that S' So, R'S' at this point, this slope will be stable corresponding to θ_c and u_{fs} is the final equilibrium pore water pressure. Change in u with time till it reaches equilibrium decides the stability of slope under excavation. So, 2 cases we have discussed. One is immediately after construction it fails; after some time it fails.

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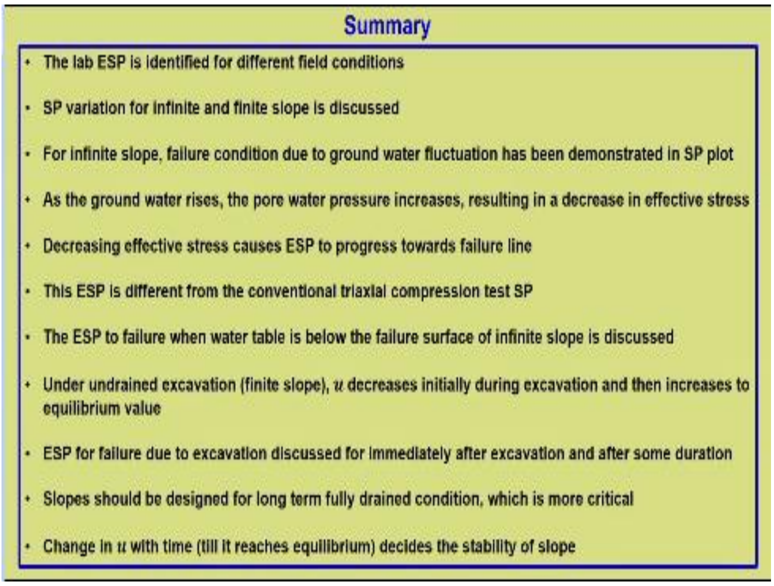

So, let us summarise today's lecture. The lab ESP is identified for different field conditions in the very first slide what we have discussed. Stress path variation for infinite and finite slope is discussed. For infinite slope failure condition due to groundwater fluctuation has been demonstrated in stress path plot. We have seen that as the groundwater rises the pore water pressure increases resulting in a decrease in effective stress and that causes the ESP to progress towards the failure line.

This ESP is different from the conventional triaxial compression test stress path and that we have already seen in this lecture. The ESP to failure when water table is below the failure surface of infinite slope is discussed. Under un-drained excavation that is for a finite slope, u decreases initially during excavation because of release and then it increased when equilibrium value. It gains the pore water pressure again.

And ESP for failure due to excavation, it is discussed for immediately after excavation and after some duration. Slopes should be generally designed for long term fully drained condition, which is a more critical condition because generally it fails because of the change in pore water pressure. So, once the equilibrium pore water pressure is achieved that determines whether the slope is stable or not. And this is particularly applicable for excavation.

Change in u with time till it reaches the equilibrium decides the stability of slope. So, that is all for today's lecture. We will see a few more cases of stress path under field condition in the next lecture. Thank you.