Earthquake Geotechnical Engineering

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Lecture 34

Initiation of Liquefaction

I welcome you again for this NPTEL online course on earthquake geotechnical engineering. And we are in the module 4th, and this is 34th lecture. So, in this module as we discussed we do have the four chapters introduction with one lecture which is already over the second chapter was on liquefaction susceptibility. So, liquefaction susceptibility was also with the two lectures over. Now, today we are going to talk the third chapter initiation of liquefaction and the third chapter initiation of liquefaction will consist of these topics. Flow liquefaction surface which we are going to cover in today's lecture and then influence of excess pore pressure EPP will be covered in the next lecture, lecture number 35.

Then probably we have that biggest topic under liquefaction, evaluation of initiation of liquefaction which will be 4 to 5 lectures and it will consist of cyclic stress approach and cyclic strain approach. So, let us start from the first one initiation of liquefaction, flow liquefaction surface and the second will be the influence of excess pore pressure. So, in the flow liquefaction surface is a concept which will be whatever we have learned earlier that is CVR line and then SSL they will be used in the flow liquefaction surface FLS. So, under the FLS let us first the introductory part and then we are going to talk monotonic loading, cyclic loading and then also development of flow liquefaction one by one.

Let us start from the introduction part and most of the stuff in this lecture is coming from the Kramer's book, but I will explain you each and everything. The fact that a soil deposit is susceptible to liquefaction does not mean that liquefaction will necessarily occur in the given earthquake why? The soil may be susceptible, but it does not mean the liquefaction will always occur because it requires some triggering action and a trigger, or a disturbance is required, and this disturbance should be strong enough to cause the liquefaction. Evaluation of the nature of that disturbance is one of the most critical parts of a liquefaction hazard evaluation and that we need to understand whether this disturbance is enough or not that we are going to discuss. Any discussion of the initiation of liquefaction must specify which liquefaction related phenomena are being considered, which phenomena means whether it is flow liquefaction or cyclic mobility because they are from mechanism point of view both work differently and we are going to talk in detail about flow liquefaction and cyclic mobility. Although cyclic mobility is an earthquake related phenomena, flow liquefaction can be initiated in a varieties of views.

Cyclic mobility because for cyclic mobility you require the cyclic shear stresses while the flow liquefaction may occur even without cyclic that is due to monotonic loading also. So, it is important to understand that for cyclic loading you require cyclic loading. During the initiation of liquefaction require identification of the state of the soil when liquefaction is triggered and what we are going to cover in this chapter. These conditions will be presented in a framework that will allow them that mechanics of both flow liquefaction and cyclic mobility to be clearly understood. So, we are going to discuss again in this detail flow liquefaction and cyclic mobility.

While some practical difficulties in the measurement of the flow liquefaction surface that is if we say ensured that is FLS flow liquefaction surface for general stress path remain, still it will provide with steady state concept a very useful framework for understanding the relationship between the various liquefaction phenomena that is particularly the difference between flow liquefaction and cyclic mobility. And the constitutional understanding is vital for evaluation of the behavior of liquefiable soils both during and after the earthquake shaking. So, now, we come to the flow liquefaction surface, and it will be discussed using in two part one is monotonic loading and another is cyclic loading. So, let us discuss first with the monotonic loading. The condition at the initiation of flow liquefaction can be seen most easily when the soil is subjected to monotonically increasing stresses.

That means, it is kind of a static, but it is increasing it is not a constant. So, it is increasing, but not in terms of cycles rather it is continuously the values of the like the loading that magnitude is increased like and, but there is no change as such frequency or because there is no frequency it is monotonically. So, response of isotopically consolidated displacement for very loose saturated sand in undrained conditions are given here. So, let us discuss this figure in detail and this figure consists of four parts. In the first part what you have flow liquefaction surface for monotonic loading it is like here.

So, it is isotopically consolidated specimen of loose saturated sand is subjected to straining here and this has been done under strain control testing. So, what you have here in the figure a you have deviatoric stress sigma d by 2 which is half of the deviatoric stress and this is normally represented by what we say the small factor q, q is equal to sigma d by 2. So, the point a is the initiation point where you have the deviatoric stress 0 strain is also 0. So, the point a is origin you move from point a to b, b is the point where you get the maximum value of deviatoric stress for a strain.

And after that when you reach to the maximum deviatoric stress then even when you increase. So, this will be point of kind where the yielding occurs and after this point deviatoric stress reach maximum and then strain increases without any increase in deviatoric stress rather deviatoric stress decreases. So, you reach to the point c and after point c it is almost constant. So, if we plot the same on the stress path then stress path these points transfer because stress path q sigma d by 2 is the same as the here while p dash is here p dash is as we discussed earlier nothing but p minus u it will be linked with the pore water pressure. And when it is linked with the pore water pressure.

So, you will have in this case in this case the pore water pressure versus strain is given in the figure c and in the figure c it can be sealed because it is a loose specimen of course, it is saturated and once you have the loose specimen in the last lecture, we have seen that it will be subjected to contraction and when it is subjected to contraction what will happen positive pore water pressure will be developed. So, when you move from a to b positive excess pore water pressure EPP is developed, and it continue to develop up to point c where it increase the positive excess pore water pressure increase after point c the value of EPP remain constant. So, as a result because the pore water pressure is increasing a to b, b to c your effective stress p dash which is p minus u will decrease. So, when you move a to b the this point is moving. So, the value of this on x axis will decrease a, b, c like this while sigma d remains same as before.

So, this is how the b the relation between figure a, b and c is there. Now coming to the last figure d which is on SSL steady state line. So, once we have this steady state line on this case you will see that you have 3 points a, b, c and when you move from point a to b. So, and a, b to c the and E is keeping E constant means there is no change in void ratio and this condition will occur in undrained condition. So, this condition is reflecting nothing, but undrained condition.

So, undrained condition where no change in the void ratio, but the pore water pressure is increasing. So, under E remains same and a point will come at the same void ratio sigma 3 will decrease. Why sigma 3 is decreasing? Because u is increasing pore water pressure is increasing when you move from a to b to c and ultimately c comes to the point where you reach to the SSL that is steady state line. So, steady state line now this c point cannot cross this and then it need to follow this path. So, these things has been discussed in detailed out here prior to the specimen is under drained equilibrium under an initial effective confining pressure sigma 3 with 0 shear stress and 0 excess pore pressure.

Since its initial state that is which is well above the SSL, the sand will exhibit contractive behavior. So, this is we already discussed. When undrained shearing begins the contractive specimen generates positive excess pore pressure and as a result peak value point v that is occurs at a relatively small strain. Then from the point b the pore pressure ratio is at point b is also the because EPP at point b is relatively small of course, the deviatoric stress is large the pore pressure ratio is still less than 1. That means, the pore pressure ratio is defined Ru is defined u excess that is where u excess is nothing, but excess pore water pressure.

So, you can say u excess is nothing, but EPP excess pore water pressure. Sigma 3 CE is called effective confining pressure, or it is typically called in the fraction effective cell pressure also. The ratio of excess pore water pressure and effective confining pressure will be your Ru pore water pressure ratio. At point b the specimen becomes unstable and a result under stress controlled condition it collapses and what will happen the strain increases without the axial strain may increase from less than 1 percent to more than 20 percent in a fraction of seconds. So, this is happening here. At the point b where your specimen becomes unstable and after this the strain is increasing and this increase from b to c in the strain happens very quickly in a fraction of second. As the specimen strain from point b to point c the EPP increasing dramatically and at point c the excess pore pressure becomes maximum, and it becomes constant. After point c the specimen is the steady state of the deformation, and the effective confining pressure is only a small fraction of the initial effective confining pressure. This specimen has exhibited flow liquefaction behavior. The static shear stresses required for equilibrium that is at point b were greater than the than available shear strength at point c of the liquefied soil.

This is the case here. Here flow liquefaction behavior is exhibited. Why? Because flow liquefaction behavior one of the condition is that static shear stress should be greater than the available shear strength and that is happening for this liquefied soil. So, flow liquefaction was initiated at the instant it become irreversible. Once flow liquefaction start that is at point b at point b flow liquefaction starts then it is an irreversible condition that means you cannot go and the pore pressure will keep increasing and the strain will increase. EPP so this is the case the irreversible unstable that is at point b. Considering the response of series of triaxial specimen initially consolidated at the same void ratio that is void ratio keeps constant with different effective confining pressures. So, since all of the specimen have the same void ratio so this has been done in the next case. Another case we are considering here the another case where we are considering triaxial specimens which are consolidated at same void ratio at different effective confining pressures.

So, this is the case here. So, you have E D C so here A B C D E are there. So, let us say we start from E we go in the reverse way E D C B and E. And for these specimens the void ratio is same so you have the horizontal line on E axis. So, this is the horizontal line so the void ratio is not changing so there is void ratio is kept constant. However, there will be change in the pore pressure as a result pore pressure when the pore pressure is higher from when you move E to D then pore pressure increases.

As a result p dash as we discussed earlier p dash is nothing but p minus u when the pore water pressure increases or excess pore pressure increases then you will move from E to D D to C and B or this. So, this has been explained here. Response of series of triaxial specimens which was initially consolidated to the same void ratio at different effective confining pressure. Since all of the specimens have the same void ratio they will reach the same effective stress condition at the steady state but they will get there by different stress pass. So, this is important they are reaching to the same void ratio but they are coming using the different pass and this is response of 5 specimen again isotropic will consolidate to the same initial void ratio at different effective confining pressures.

The effective confining pressure is different for E D C B A the void ratio they reach to the same void ratio. Flow liquefaction in a specimen C D and E C D and E are flow liquefaction and they are and these where the liquefaction starts. Liquefaction start at the points where the cross has been marked in this stress path. So, these are the points where the liquefaction is starting and this is our point where the liquefaction starting the where you becomes this specimens become unstable. The dotted line passing through these points is a line of constant principal effective stress ratio.

If we get a line which is passing through from these points, then that will have a constant principal effective stress ratio which is denoted from k L. So, continue with this discussion here you have a steady state point this point and you have this like line SSL steady state line. So, the initial state of specimen A and B are below the SSL. So, they exhibit dilative behavior upon shearing. So, A and B if we talk about a specimen A and B. The initial condition that is shown here at this point is below the SSL you could see the because your SSL is here SSL is lying here and you can see in this the second figure they are below while C and D are above this SSL line. So, that is there. As a result because they are falling below this SSL. So, they will exhibit dilating behavior that means, when they go undergone they will dilate, but C and D and E will have different behavior they will contract. So, contraction so that means, when they will dilate what will happen negative pore pressure will develop.

Specimen C and D all exhibit contracting behavior, each reaches a peak under after which they strain rapidly. For a specimen C D and E flow liquefaction is initiated at the peak of each stress path at the points marked with is n x which we already discussed. The locus of points of describing the effective stress condition at the initiation flow liquefaction is a straight line which is shown using the dotted line here this is a straight line and that project through the origin of the stress path. Graphically these points may be used to define what we call the flow liquefaction surface. So, the flow liquefaction surface is defined using the joining these points in a stress path space.

Since flow liquefaction cannot occur if the stress path is below the steady state point, the FLS is truncated at that level. So, if FLS is touching this line then it need to be truncated which is done here. So, what is happening in this figure? This is connected by three points here. Now, after this point it cannot continue here because this value have at this reach is the same as a steady state point. So, that means you cannot reach the value of q less than a steady state point.

So, rather than going downward it need to be going in the horizontal direction. So, as a result your flow liquefaction surface if I say in the short then the FLS. So, FLS is here two part one is from here to here and then it moves from here to here. So, this line will be denoted as a FLS. So, the FLS marks now what is the use of FLS? This FLS which is flow liquefaction surface it marks a boundary between stable and unstable states in undrained shear.

When you do not allow the drainage then in that case and shearing is done then between stability and unstable case. If the stress conditions in an element of soil reach the FLS under undrained condition whether it could be by monotonic loading or cyclic loading flow liquefaction will be triggered and the shearing resistance will be reduced to the steady state strength. So, that will happen. So, the flow liquefaction the reason could be either monotonic loading or could be the cyclic loading, but in both monotonic or cyclic loading or combination of these two flow liquefaction will start in that case that if this reach to this. Therefore, the FLS describe the condition of which flow liquefaction is initiated.

So, this FLS line is used to describe the condition how the flow liquefaction. So, far we have discussed about monotonic loading, but what happens to cyclic loading if I change to loading the cyclic. Researchers have shown that FLS applied to both cyclic and monotonic loading. It is not only for a monotonic loading and a considerable amount of independent experimental evidence is also support this and some experimental evidence suggest that effective stress path can move somewhat beyond FLS before liquefaction is initiated by cyclic loading.

We are going to discuss now how the cyclic loading effect this. Whether liquefaction initiated precisely at the FLS under cyclic as well as monotonic loading is not whether now the issue is this one if you have combination of monitoring cyclic loading which one initiate the liquefaction whether due to monitoring load or cyclic load that is currently cannot be said with the certainty. But considering the response of two identical anisotropically consolidated triaxial specimen of loose saturated sand we shown in the next figure. So, two identical specimen and what these two identical specimen we will discuss that. Initially the specimens are in drained equilibrium that is point A, both specimen start at point A.

So, point A there are two specimen. So, I let me tell you before I discuss further the first specimen take path ABC which is monotonic loading. So, this will be treated as a monotonic loading while another specimen go through A to D and C. So, this is cyclic. So, one specimen is subjected to monotonic loading another is subjected to cyclic loading. But their initiation point is at the start thus from the same point.

So, initially are in drained equilibrium point A under a static shear stress, toe static that is greater than the steady state strength. So, let us we consider the toe static that is the static shear strength is greater than the steady state strength that is SSU. So, in this case we said that the toe static is greater than the SSU. The first specimen is loaded monotonically under end condition the shearing resistance built up to a peak value when the stress path reaches the FLS point B. So, up to point B ABC is the similar which we already discussed.

At point B is a point where your specimen become unstable because you are getting the maximum value of stress and after then strain will start reach there. So, if I go on this side FLS. So, the A to B is like this and then B to C is the CV is a point which lies on this steady SSU which is denoting here. So, in this case toe static you could see the toe static is denoted by this SSU is this value.

So, in this case toe static is greater than SSU. So, this is the condition here that is steady state strength. So, initiation so, this was about monotonic loading. Now, we will come in that how the cyclic loading does from when you move from A to D. At the point the specimen becomes unstable and strain rapidly towards the so, this is the same we already discussed. The second specimen is loaded cyclically, and this is also under under end condition the effector stress path moves to the left as a positive excess power pore pressure develops and permanent strain accumulates.

Here when you apply the load cyclically because their pore water pressure will develop positive, as a result the p will be decreased, and the cyclic loading difference is there it will oscillate the value of q is not constant rather in cyclic loading it will go up and down and this is us like you know that the double amplitude of the cyclic loading which is applied. So, and permanent distance develops when the effector stress path reaches the FLS at point D which is have reached this is FLS, FLS is here which is shown here by this. So, from when applying the cyclic loading it reaches at point D. The specimen become unstable and in that case strain towards the steady state of deformation point C. So, the in monotonic loading at it become unstable at point B while in cyclic loading it become at point D and ultimately, they come from B to C or D to C.

So, the stress condition and initiation of liquidation point B and D were different they will fail both in cases on the FLS. So, ultimately they will like whether it is monotonic loading or cyclic loading they will final termination will be at FLS. The FLS therefore, mark the onset of the instability and product so flow liquefaction. Now, continue with this one development the last topic for this development of flow liquefaction and the this flow liquefaction occur in two stage. The first stage which makes which takes place at a small strain level involves the generation of sufficient excess pore water pressure to move the stress path from its initial position to the FLS.

This excess pore pressure may be generated by undrained monotonic or cyclic loading. So, you have undrained loading undrained case both it could be either monotonic or cyclic loading. When the effective stress path reaches the FLS the soil become inherently unstable and the second stage begins. So, this is also we already discussed. The second stage involves strain softening and additional EPV generation that is driven by the shear stresses required for a static equilibrium.

So, additional pore water pressure generate excess pore pressure is generated and as a result the strain will be increase. The shear stresses are driving stress says they must be distinguished from the what we call the local stresses that may develop during deposition and consolidation of the soil. So, like here in the last local shear stresses which is those exist beneath level ground when k naught where k naught is the coefficient of earth pressure at rest is not equal to 1 cannot drive a flow liquefaction failure. So, this is important here. So, these stresses it can drive what we call the cyclic mobility, but it will not lead to liquefaction failure flow liquefaction failure.

Large strains develop in the second stage as the effective stress path moves from the FLS to the steady state. In the first stage take the soil to the FLS the first stage will take the soil to the FLS under undrained stress control condition. The second is so, once first stage take you to FLS then second stage in avoid table that means, it is going to be must. Issue is this one once you reach to the FLS whether you using monotonic loading or cyclic loading then you point have reach of a point of instability and after that within a fraction of seconds the level of strain increases without like increase in the value of a deviatoric stress or the shear stress. So, this was about this and we will continue in the next lecture the remaining part of this. Thank you very much for your kind attention. Thank you.