Applied Seismology for Engineers

Dr. Abhishek Kumar

Department of Civil Engineering

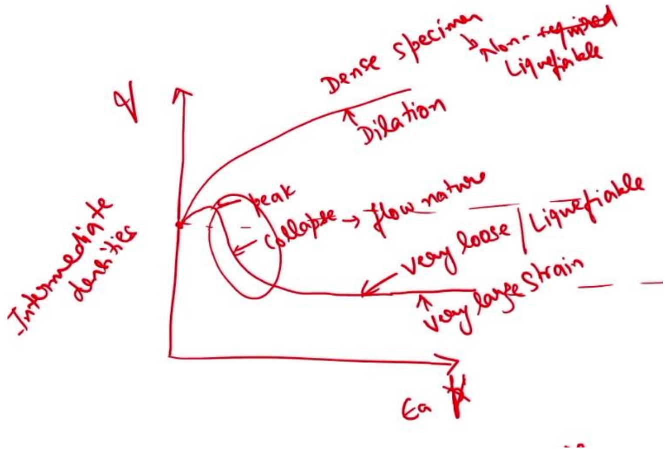
Indian Institute of Technology Guwahati

Week – 09 Lecture - 03

Lecture – 23

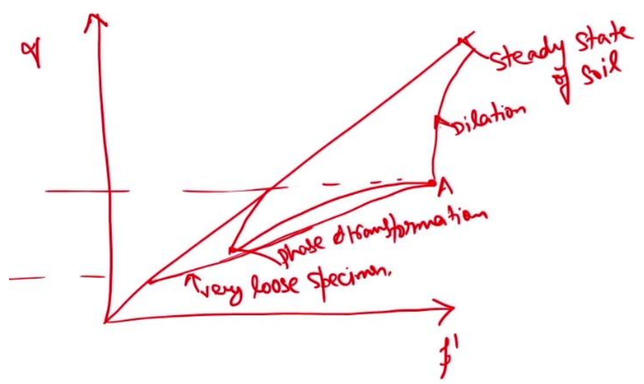
Hello everyone, welcome to lecture 23 of the course Applied Seismology for Engineers. In the earlier two lectures, which were also related to critical state identification followed by the steady state of the soil in terms of deformation, which is primarily related to large axial strain as far as the initiation of flow liquefaction and subsequently other loading conditions were concerned. Accordingly, in lecture 21, we discussed that independent of the initial state of the soil, taking different stress paths—one dense soil is there, one very loose soil is there—will undergo finally to the same state of deformation that is called the critical state of deformation, and corresponding to that, we developed the critical void ratio line in terms of e log sigma c or e versus the logarithmic confining pressure line. Then later on, we identified that despite based on the critical void ratio line, one can identify a particular soil medium whether it is susceptible to liquefaction or not. Many of the samples from the sites, which based on the critical void ratio line, were identified as non-liquefiable, but in actual site conditions, had actually undergone liquefaction. So, with that input, in lecture 22, we discussed another parameter, another state of the soil, rather, which is called the steady state of soil, which is more realistic as far as the process of initiation of liquefaction, primarily in terms of flow of the material, is concerned.

As a part of lecture 22, we discussed how to come up with the steady state line, primarily taking into account the stress control behavior of three types of samples. One was a very loose sample, which initially had undergone an increase in the stresses of peak strength had reached at very low values of axial strain; after that, the sample had undergone collapse and then subjected to a reduction in the stresses, and the same was continued to a very large value of axial strain. This was primarily related to the very loose sample. As the samples were very loose, so if we recall whatever has been discussed in the earlier class—that is, lecture 22—we tried understanding in terms of mean confining pressure and mean effective stress.

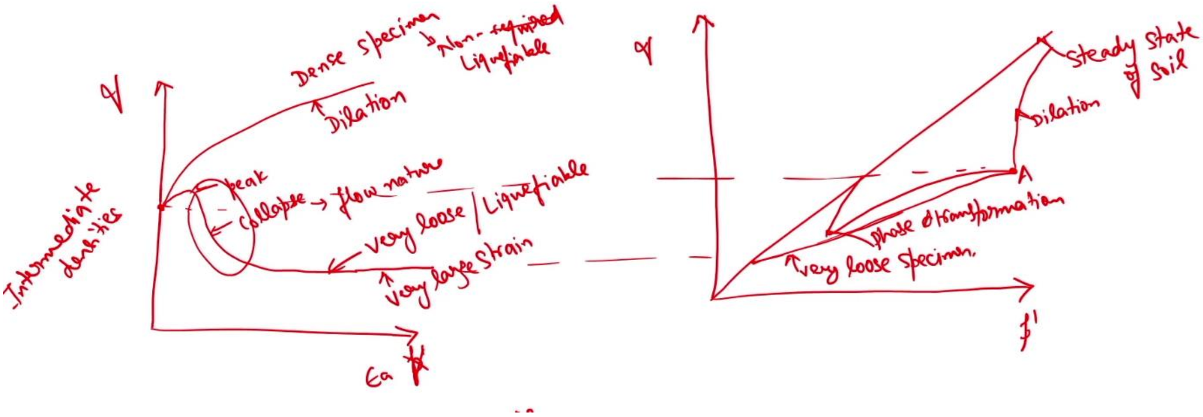


The three behaviors, which were permanently visible, were dilation, which was related to the very dense specimen of the soil medium. Remember, all these behaviors we are discussing are related to stress control tests. When we were discussing about the critical void ratio line, those were related to strain control tests. So, here, actually, we are able to understand the nature of change in excess pore pressure and subject it also to how the behavior is varying as far as low strain value is concerned or as far as high strain values are concerned. As a result of which, when we performed these tests, we got—so one was related to dilation behavior, which was primarily related to dense specimens. We can see initially the sample was subjected to very, I mean, initially there was gaining in terms of positive pore water pressure, that means subsequently the rate at which the effective stress was supposed to decrease. It initially started increasing; subsequently, there was a reduction in excess pore pressure followed by a negative pore pressure development. So, we can see the rate at which the effective stress was increasing subsequently reduced. Then we had also, in terms of the very loose specimen, initially had shown contractive behavior, followed by which there was—so this was peak value, followed by which there was collapse, and then, as part of the reduction in the confining pressure, we can also see in this particular portion there is an increase in the pore water pressure. So, because of this, there is a reduction in the confining pressure or effective stress. As a result, the sample was subjected to collapse, followed by this, there was a flow nature. That means the physical characteristics of the sample were resembling the loss of confinement and subjected to deformation, which is again a classical nature of very large deformation or very large strain. So, this collapse followed by steady state corresponding deformation that continued for a large value of strain.

So, this is corresponding to the very loose specimen, and in between the dense specimen and very loose specimen, there were mixed characteristics of dense specimen as well as characteristics of very loose specimen, which were shown by intermediate samples or samples corresponding to intermediate densities. So, intermediate density samples were there, which were showing initially the characteristics of peak stresses, followed by which there was even strain softening. So, that was corresponding to intermediate samples. So, these loose samples can also be identified as liquefiable, and then there were samples which were identified as non-liquefiable. And remember, these were based on stress control tests. So, non-liquefiable. So, this is epsilon a. We can see the sample was subjected to a reduction in the confinement, and this particular nature continued to a very large value of axial strain. Same thing if you are seeing on p prime—that is, effective confining pressure versus mean effective stress.



So, here, we can see the sample is going up to—this was the state which was identified as the steady state of the soil. Steady state of soil. That means, samples considering the initial state of the soil, which was identified over here also, we continue with this particular part. If the samples are there, which are corresponding to the initial state, so dilation will again go to an increase in confining pressure, and then, so this is related to dilation. And remember, the steady state line, which has been identified over here on the e log p curve or e log sigma c curve, this is parallel to the critical void ratio line, but it will be lower than the critical void ratio line. Again, if we are talking about limited liquefaction. So, as I mentioned, there will be phase transformation in limited liquefaction or the samples which are corresponding to phase transformation. So, this is corresponding to phase transformation, and then there were samples which were corresponding to very loose soil. If we go over here, those continued directly to collapse, and that continued for a very large value of axial strain. So, this is corresponding to the very loose specimen.



So, we were able to identify, firstly, the steady state of the soil, where even the samples which had undergone liquefaction, but as per the critical void ratio line, were falling in the boundary of non-liquefiable soil. Now, based on the steady state of the soil, which is helping us understand how, in terms of the change in the state of the soil, the sample with respect to the initial state—whether it is subjected to strain softening, whether there will be a peak value—if we remember here, with respect to the critical void ratio line, there was contractive behavior. But in this particular case, whenever we are discussing about the stress control test, there is continuous, initially at very low values of effective axial strain, the sample has reached to a peak value. After that, the sample has undergone collapse, and followed by which this behavior continued for a very large value of axial strain. So, accordingly, the steady state of deformation has been identified. Now, here this is related to how the initiation of liquefaction happens at a particular site.

That means, at a particular site, there is some soil sample corresponding to what is the value of effective stress there, how much is the confinement available to the sample. One can get an idea about what is the initial state of the soil. Now, in addition to this particular state of the soil, there will be additional loads which are coming onto the sample, which can be because of maybe pile driving activities, it can be because of explosions, it can be because of other manmade activities, it can be because of earthquakes, it can be because of mining activities, which can again prove to be a source of vibrations or additional loading. Collectively, based on this, there will be additional stresses which are coming onto the sample. So, the sample, which was initially subjected to some state of stress by virtue of its position, now will be subjected to additional stresses which are coming from all the activities listed over here. As a result, there might be a state developed in the sample where the sample's in-situ strength will be exceeded by the stresses which are generated because of the following sources of vibration. There can be many sources of vibration.

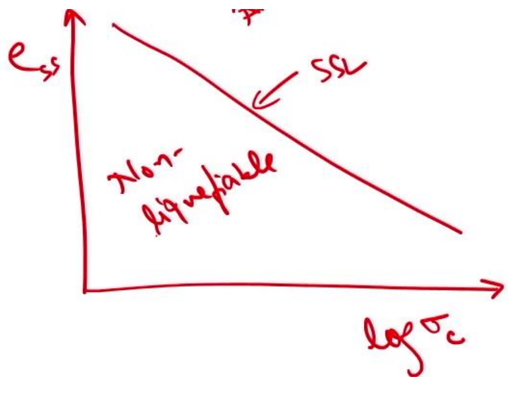
As a result, what will happen is the sample will be subjected to loss of strength. Subsequently, there will be an increase in pore water pressure, which we can see over here in terms of very loose specimen. Also, there is an increase in pore water pressure, which can be identified as a reduction in the effective stress. So, whenever we are interested in finding out whether a particular site sample is susceptible to liquefaction or not, based on a steady state line, we can find out. But what is the nature in which the sample will reach from the initial state of the soil to steady state deformation? That will be described by means of understanding what triggered or initiated the liquefaction in a particular sample, and that can be identified by means of stress path. So, stress path will give an indication about how the state of the soil is changing with respect to the initial state, where it was more or less stable whenever it is subjected to maybe monotonic loading or subjected to any kind of dynamic loading. It is like, though the soil is susceptible to liquefaction, considering the failure that has happened in actual site conditions, one has to also understand whether the favorable condition in terms of external loading has actually been reached at a particular site such that liquefaction can be triggered at that site. So, based on this understanding, we can say the state in which, if we look into the in situ stresses and in situ strength of the soil available at a particular site, and the stresses which are going to be mobilized in the soil sample by virtue of external loading conditions, that will give a fair idea about what sort of phenomena is going to get triggered in terms of liquefaction.

So, if we see about liquefaction, there will be a comparison of two parameters: one is how much the external loading condition, meaning the stresses mobilized in the sample which is primarily available at a particular site, and how much is the in-situ strength of soil undergone liquefaction or soil in its liquefiable position. So, based on that, the phenomenon of liquefaction can further be bifurcated into two further nomenclatures: flow liquefaction and cyclic mobility.

Now, we look into flow liquefaction. The definition says it generally occurs when the shear stress required for static equilibrium. So, there is a sample, and the minimum shear stress required by means of confining pressure such that the sample can retain in its original position or in its in-situ stress state. So, shear stresses which are actually required for static equilibrium of a sample are actually higher than the in-situ shear strength of the soil in its liquefied state. So, there is a soil which has undergone a liquefied state, and at that particular moment, the stresses coming from external loading conditions—whether from earthquake loading, construction activity, explosion, or other anthropogenic activities—are generating a state of stresses which are higher than the in-situ shear strength of liquefied soil. In such a case, what will happen is there will be a loss of confinement because there will be failure in the material, as the stresses are much higher than the strength of liquefied soil available at a particular site. And this process will result in larger deformation. So, there will be a soil sample which will try to come into equilibrium. The stresses required for static equilibrium will be much higher than the in-situ shear strength of the soil sample at the liquefied site. So, what will happen is the sample will try to come to equilibrium, but how much stress will be applied to that particular sample will be much higher than its in-situ strength. The sample will collapse, and again there will be larger deformation because it is primarily related to some phenomena prominent in larger axial strains. The process will continue, meaning the deformation will continue until the state of stresses, which are actually applied to the sample, becomes lesser than the in-situ strength of the sample. Or we can say whatever buildup of pore water pressure is there, corresponding to which there is a building up of in-situ stresses, so all those excess pore pressures developed due to external loading conditions have actually dissipated. As a result, what will happen is the effective stresses will reach a state where the in-situ strength characteristics are more than the stresses applied to the soil sample.

So, such a state where the in-situ stresses are more than the in-situ strength of liquefied soil is called flow liquefaction. The phenomenon is called flow liquefaction. On the other hand, another phenomenon is there, which is again related to liquefaction, called cyclic mobility. Cyclic mobility is defined as when the static shear stress required for equilibrium of the sample is actually lesser than the in-situ strength of the soil sample. So, in this case, primarily what we will encounter is the loss of confinement. So, static shear stress is less than the shear strength of the liquefied soil. In the first case, there was a sample which, once subjected to higher stresses compared to its in-situ strength at steady state deformation, will certainly be subjected to deformation. The process will continue. This is called flow liquefaction. In the second case, we have cyclic mobility, where the in-situ strength of the soil sample is higher, but due to the loss of confinement, the sample will still undergo liquefaction. Cyclic mobility can be triggered both during cyclic loading and during monotonic loading.

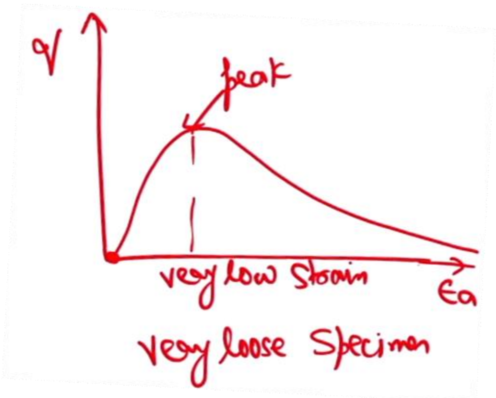
So, to discuss further about flow liquefaction and cyclic mobility, one thing is very clear: despite the initial state of the soil, whether the soil will undergo liquefaction will depend on the external loading. So, soil, being potentially liquefiable, will undergo liquefaction only when the stresses in its in-situ condition are much higher than the in-situ shear strength of the liquefied soil. So, whether the soil will undergo liquefaction or not will be decided by external loading. So, although the soil is capable of undergoing liquefaction, whether it will in its in-situ condition will depend on the characteristics of external loading conditions. Hence, in addition to the steady state line, knowledge about the stress path is equally important. So, the stress path, which the sample or soil will take, is crucial. It is important for both flow liquefaction and cyclic mobility. We have discussed that if we look into e log sigma c, which is confining pressure, and if you remember, this is a locus of void ratio at steady state of soil as a function of confining pressure. As we change the confining pressure for stress control tests, the soil reaches steady state, corresponding to which there is a void ratio, which can be mentioned as ESS.



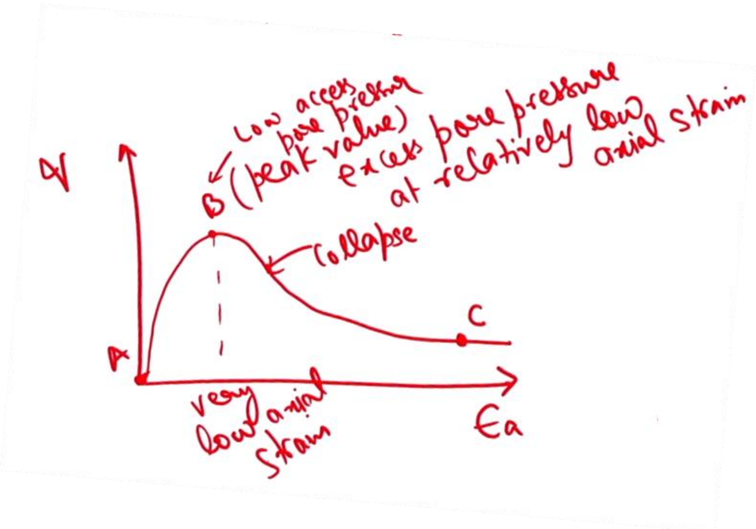
This plot corresponds to the steady state line, where liquefiable soil is on one side and non-liquefiable soil on the other. Whether the soil will undergo liquefaction depends not only on this but also on the stress path. The nature of the loading is also significant. As I mentioned, the nature of the loading helps understand the triggering mechanism, particularly the initiation of flow liquefaction. This can happen during monotonic loading, including in natural soil deposits, man-made fills, etc. Similarly, it can also be triggered during non-seismic events such as blasting or pile driving. These activities generate favorable conditions that result in the development of excess pore pressure. So, higher onward, we will primarily discuss loose specimens that are potential to undergo liquefaction and the development of excess pore pressure. So, we will be interested to find out what is important: how the liquefaction has been initiated with respect to the initial state of the soil. So, that actually is the objective here, which actually led to triggering or initiation of liquefaction. So, that is already mentioned; we can avoid it.

Now, flow liquefaction, as I mentioned, is related to the identification of the state where, considering the initial state of the soil and in-situ strength of liquefied soil, how much the stresses are actually applicable on a particular soil sample. So, in order to understand, primarily related to monotonic loading condition, what one can do again is discuss flow liquefaction. So, what is the condition here? The stresses required for equilibrium are much higher than the shear strength of soil in its liquefied state. Now, in order to understand the initiation of flow liquefaction in terms of stress path, primarily, as I mentioned, it can be done during monotonic loading or cyclic loading and even during seismic loading, more specifically cyclic loading. We can have other characteristics of loading as well. So, seismic loading also. So, flow liquefaction situation, or the favorable condition where the state of stress can be higher than the in-situ strength of liquefied soil, this particular condition can be met; it need not be every time related to cyclic loading or seismic loading, but even during monotonic loading condition.

So, in order to understand about the monotonic condition, and keeping the initiation of flow liquefaction condition in mind. So, we are interested to find out that one can understand the response of loose, if we recall, loose sample means loose sandy sample, saturated samples, remember, because we will be talking about liquefaction, which is mostly the development of excess pore pressure, subjected to undrained stress control test. So, we are discussing about stress control test, which one can correlate with respect to the steady state of the soil. So, we can, at this stage, at least distinguish between the critical state of the soil as well as the steady state of the soil, which is more related with respect to the stress control test. So, in order to understand how the initiation of flow liquefaction takes place in very loose specimen, we can write, maybe again, very loose, because this is the terminology we have been using with respect to the steady state of the soil. So, there is one very loose sample of sandy soil, which is saturated also and is subjected to monotonic loading. So, it is undrained condition. So, all these conditions, that means there is, because the sample is loose, and we have seen that when loose samples are there, subjected to external loading condition in stress control test, initially there was contractive behavior. It will reach to the peak, followed by which the sample will be – so, this is peak corresponding to very low value of strain, very low axial strain.



This one is q value; this is epsilon a value. So, this is corresponding to very loose sample, which we have seen when we were discussing about steady state of deformation. So, very loose specimen, and when we say about specimen, again, we are discussing about sandy specimen, because that is more specific related to initiation of liquefaction, as concerned. Now, here, so stress control triaxial test. So, triaxial tests are there, which are stress control triaxial tests are there, and the condition is these are undrained condition, and the sample is very loose specimen. So, what we have understood prior to undrained shearing, which actually has to start from this particular side, the sample might be having some state of the soil, which is an indication of its initial state in a particular site condition. So, we can see over here. So, let me draw it here to get an idea about.

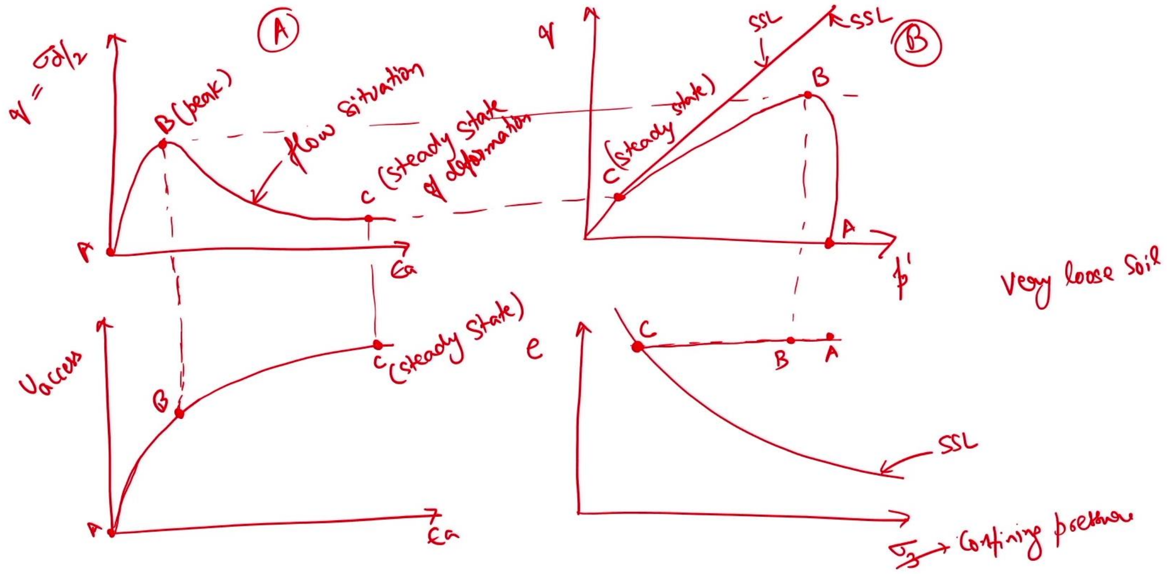


So, what will happen in terms of q vs epsilon a, which is shown over here also, representing that the undrained shearing in the sample for stress control test has actually started, taking into account some initial state of the soil in which the sample was there? Or we can say, because there was some initial state of the soil at which the sample was more or less in equilibrium, that is why the site was selected for a particular construction activity. So, when we started this particular thing, it is corresponding to some drained equilibrium, which is corresponding to some initial state of the soil, came into existence primarily at point A. Because of external loading condition, static condition, and corresponding to this, there was some value of effective stress, and there will not be shear stresses because now we will start applying shear stress in the sample, and accordingly, once we start loading the sample, whether it is because of any external loading condition, which is going to trigger liquefaction. So, there will be now development of pore water pressure. Again, we remember that we are talking about very loose specimen, very loose specimen. So, very loose specimen means we are talking about samples which are well above the steady state line. So, if we remember the steady state line, that is basically demarcating the sample which are not susceptible to liquefaction and which are susceptible to liquefaction. So, all the samples which can be plotted based on the initial state below the steady state line that we call it as not susceptible to liquefaction, and those that are plotted above, those are susceptible to liquefaction. So, those will be subjected to peak stresses at low strain, followed by collapse, and that will continue to reduction in the confinement, development in the excess pore pressure. Finally, that will turn the consistency of the sample to almost liquid form. So, this is the initial state of the soil, suggesting that such samples can be located well above the steady state line.

Again, if you remember, if we start loading this particular sample, there will be reduction in the effective stresses, there will be development in the excess pore pressure, because we are talking about undrained condition. So, there will be reduction in the effective stress condition, but there will not be any change in the void ratio condition. So, again, in this particular sample, which is point A, is corresponding to the initial state of the soil. When shearing happens in this particular sample, initially, there will be contractive behavior, followed by which – So, because this is contractive behavior corresponding to very low value of axial strain, we can say very low axial strain, because that is what plotted on x-axis, very low axial strain, and corresponding to which it reached to another state, which is we can define it as peak value. So, you started loading the sample, very loose sample subjected to stress control test. The sample was initially started to be loaded corresponding to whatever was the state of the soil in its in-situ condition, started loading the sample. It shows contractive behavior, reaching to the peak value, that is point B, and followed by which there will be collapse. Again, there will be development of pore water pressure, but that will be relatively low. So, we can call it as excess pore pressure at relatively low axial strain. So, epsilon a value will be very low.

What will happen after this? If we are able to recollect from lecture 22, the sample will be subjected to collapse, followed by which there will be reduction in the confinement, we remember the sample is subjected to collapse, there is development of excess pore pressure. So, we see, though in this particular section from A to B, there was contractive behavior, but after point B, there will be development of excess pore pressure. So, we can see over here, subjected to which the sample is subjected to very high value of axial strain, and this primarily we are correlating with respect to excess pore pressure. So, at this particular point, the excess pore pressure is relatively low, at point B, and after which the sample is undergoing collapse, and this will continue till very large value of axial strain till the sample reaches its steady state. So, point C is basically marking the steady state of the soil between point B and point C. We can say A is initial state of the soil before shearing started. Point B, corresponding to peak value at low axial strain, followed by collapse beyond point B. Collapse cannot happen at point B, but just immediately after point B.

Again, point C is there, which is related to the steady state of deformation, which will continue and will correspond to a very large value of axial strain. The epsilon value is significantly large because the sample has collapsed. So, it was an undrained condition, remember, but it is like there is development of excess pore pressure, as a result of which the sample has almost become like liquid form. So, the specimen has reached the steady state of deformation at point C with effective confining pressure. Now, the sample at point C has reached the steady state with effective confining pressure, with effective confining pressure, only a small fraction of its initial values, means whatever was the initial value of effective confining pressure, once the sample reached, after collapse, to point C, there is almost a loss of confinement; the sample has a very low value of effective confining stress in comparison to how much stress was there, maybe corresponding to point number A.

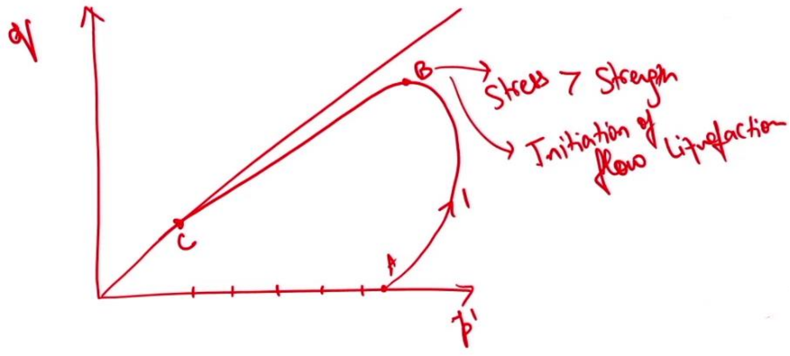


So, again, if we are trying to develop this with respect to, so, again, in terms of p prime versus q plot, in terms of deviatoric stress or average confining pressure with respect to p prime, average confining pressure, and average mean effective stress. So, this is the same plot we did in an earlier slide; we are getting more or less the same thing. So, initially, there will be contactive behavior, and at the same time, here we are also trying to understand the p versus q plot in terms of understanding the effective stress path. At the same time, we are also trying to understand excess pore pressure, which is continuously increasing because it is a very loose specimen. So, the u-axis shows how much excess pore pressure was generated when this sample was subjected to continuous shearing. And in addition, how much the confining pressure changed, but void ratio is not going to change because, again, it is an undrained condition. So, this was a sample that actually, this was the initial state of the sample. It was subjected to shearing, reached a peak value, and then, after reaching a peak value, the sample is subjected to shearing, which continued for a larger value of strain. So, you can see this is the peak value, point B, corresponding to the peak, point C, which is corresponding to the steady state of deformation. And then, at the same time, if you are seeing in terms of the p-q plot, we remember this was the steady state line, which was developed with respect to the p-q plot, which can also be shown in terms of the e versus sigma c plot, sigma 3 or sigma c plot, where sigma c is referring to confining pressure.

Now, here, as I mentioned, there will be contactive behavior, but the rate at which the excess pore pressure is generating with respect to the initial state, point A, between the initial state of the soil and the peak stresses. So, that rate will be relatively less. So, we can see the rate at which the convective strain is increasing is relatively less, but at the same time, there will be development in excess pore pressure between point A and point B. So, this is related to point B. You have continuously sheared the sample, or the shearing is going on. So, this is corresponding to point B, this is corresponding to point A, and after this, once the sample collapses, that means it has almost turned into liquid, which is only possible when the excess pore pressure, or the pore water, which was under very high stress, can push the soil particles, leading to flow conditions. So, this is like a flow situation. That means there is significant increase in excess pore pressure. So, we can see that particular part like this significant increase in the axial strain because that is what the flow means, continuous flow. So, that means there is significant increase in terms of axial strain. This is corresponding to the steady state. So, all those same states only in terms of different x and y axes. So, point A related to the initial state, point B corresponding to some state, which is resembling peak stresses we can say, which the soil sample has been exposed to, followed by which it collapsed and reached the steady state.

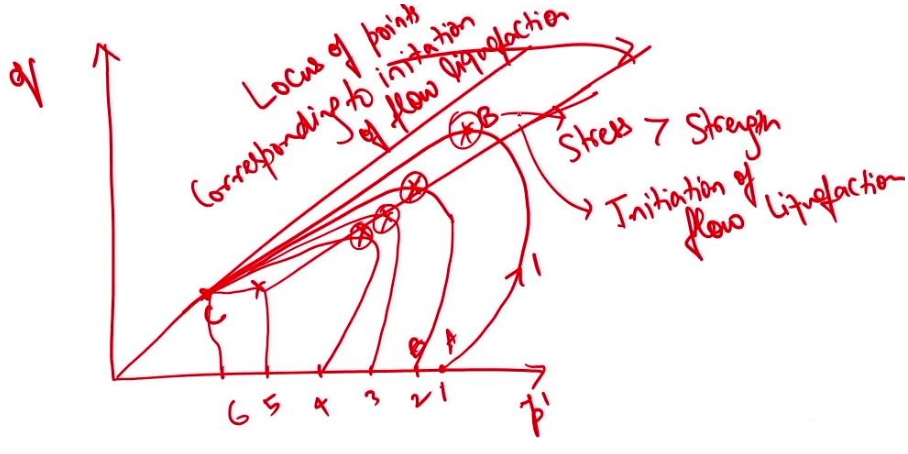
Now, again, this particular point A, because it is corresponding to some value of confining pressure resembling how much the initial state of the sample is in its in-situ condition. The sample, when subjected to – So, this is a state in which basically the sample is subjected to. We can see over here. Now, here it is three points which are clearly to be understood here. Point A resembles some value of confining pressure and corresponding to q value. We have taken... we have actually started our graph corresponding to confining pressure, which was there in its in-situ condition. Again, the sample was subjected to loading. So, there was some reduction in the confining pressure because the rate at which the axial stress is changing is relatively low. Reaching the peak value, which is again shown on the p-q plot over here. Finally, this is a very loose sample. So, this particular loose sample will be subjected to flow collapse. Finally, it will reach a particular state, which is called as steady state of deformation, which is marked by the SSL line. Now, here we can see, for a particular soil, the steady state of the soil is marked by the steady state of deformation, which is marked by this particular line on the p-q plot.

Again, if you remember, the sample is corresponding to a very loose soil. That means, with respect to the steady state line, which is also mentioned over here on the e-sigma c plot, the sample will be somewhere above the steady state line. And then, when it is subjected to loading conditions, there is significant development of excess pore water pressure, resulting in reduction in the confinement, which can also be seen. So, the sample is actually moving from point A, the left-hand side, towards point C, keeping the void ratio to be constant. So, void ratio is not changing because this is under undrained condition. So, this was the initial state B, and this is point C with respect to the initial state. Now, collectively looking at this particular part, what we can see between point B and point C, there is collapse, larger deformation, which is the characteristic of flow. At the same time, if you go with plot number B, what we can see, point C is resembling the steady state in which finally, the sample has reached. However, point B is resembling another state corresponding to external loading, which is the representation of a higher value of stresses, much higher than how much is the stress value available, how much is the in-situ strength corresponding to the steady state of the soil. So, at corresponding to point C, there might be some in-situ strength of the soil because finally, the sample in its liquefied state has reached the steady state, but at point B, there is some state of stresses which are significantly higher than point C. Since point B is a representation of peak value, it is quite distinct, it is quite clearly identified which is point B whenever these stress control tests are being subjected to very loose specimens.

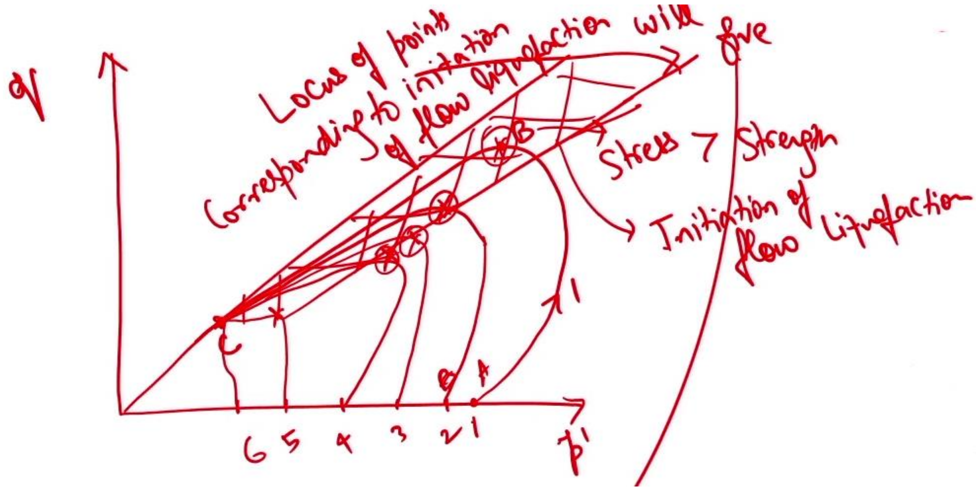


So, with this particular part, if we are interested to find out what is the state of stress related to flow liquefaction. That means, stresses due to external loading conditions required for static equilibrium are more than the strength of the liquefied state of the soil. Again, related to q versus p prime, what we have understood is there was a sample when it was subjected to external loading conditions. So, this was the peak value, this is corresponding to the initial state, and this is corresponding to point C. Now, as far as flow liquefaction is concerned, if I am interested to find out the initiation of flow liquefaction, that means, which is the state of stress where confidently one can say maybe this was a favorable condition at which the flow liquefaction was initiated, resulting in loss of confinement or the stresses due to external loading conditions were significantly higher.

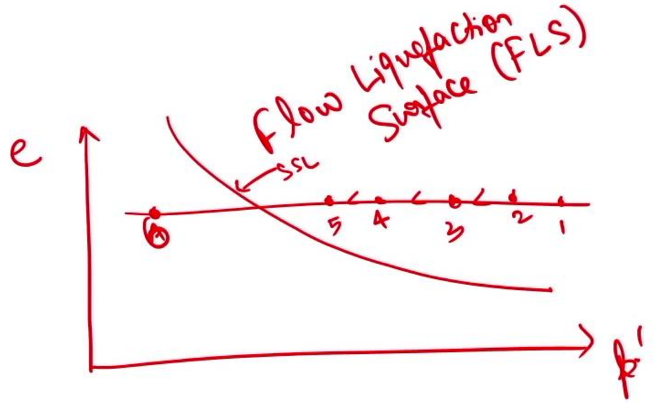
So, I am interested to find out the initiation of flow liquefaction. Now, with respect to the initial state of the soil, here I have taken the initial state of the soil somewhere minimal, which is almost touching the q equals 0 or there is no deviatoric stress. So, point B marks, in this particular case, point B marks the state in which the sample is reaching a condition where the stresses due to external loading are much higher than the strength of the soil. That means, point B for this particular loading condition is basically demarcating the initiation of flow liquefaction because it is meeting the criteria that the sample has just now been subjected to well-identified peak stresses, which are significantly higher than the stresses available corresponding to the steady state. So, initiation of flow liquefaction. So, repeat the same procedure we have just done by conducting a series of triaxial specimen tests, initially consolidated at the same void ratio to the same void ratio, but at different confining pressures, but at different confining pressures.



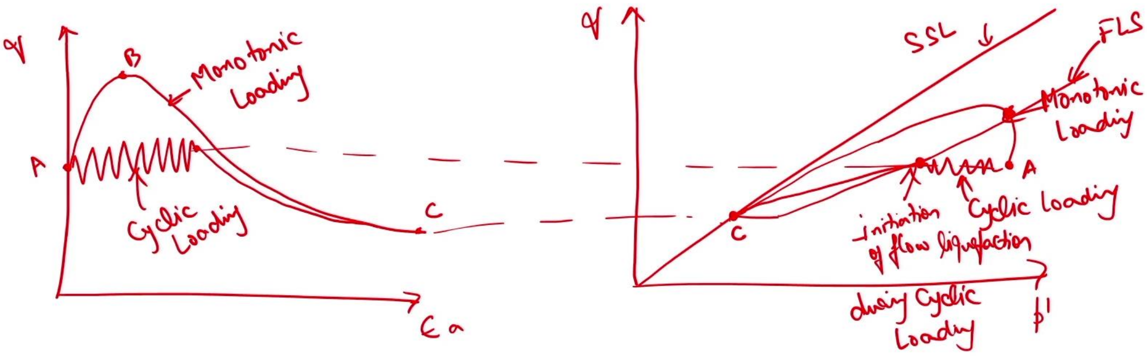
So, one example is shown over here. Similarly, we can repeat the same thing, and we will have what we will get each of these samples. That means, we are repeating the test on very loose specimens. Each sample is corresponding to the same void ratio, but to start with it was like corresponding to a different value of confining pressure. So, we can say maybe n number of confining pressures are there, and considering the sample is related to the same type of soil. That means, the sample will finally reach the same value of steady state—that is, point number C. So, point number A: sample 1 reached point number B related to the initiation of flow liquefaction; finally, there was collapse and it reached its steady state. Similarly, point number B, or maybe we can write it as point number sample number 1, 2, 3, 4, 5, 6. So, we can see almost all the samples will be reaching more or less the same state. Again, in sample B, sample 2 also reached some state where the peak stress is higher than the steady-state strength, the same way we can get n number of samples. So, if we join all those points, which are basically marking the initiation of the state at which flow liquefaction has just started, these are the locus of these points: this one, this one, this one. Same way, over here, all these points, which are basically marking the demarcation of flow liquefaction, will come like this, like this. So, this particular line, which is basically joining the locus of points corresponding to the initiation of flow liquefaction.



So, what finally we are getting is this particular plot. If you join all those points, it will give the flow liquefaction surface. That means, whatever points are there between the steady-state line and the flow liquefaction surface, that means, all those points are actually in a state of flow liquefaction or under continuous flow. So, this is related to flow liquefaction, only this particular line. Flow liquefaction surface, or FLS, flow liquefaction surface. So, this particular surface is basically an indication of the triggering of flow liquefaction. After that, whenever samples are there between steady state—because no sample can go beyond steady state—whatever samples or whatever stress path is located between steady state and flow liquefaction surface, that means, all are resembling the initiation of flow liquefaction or the state of the soil after the initiation of flow liquefaction and finally reaching the flow liquefaction surface.



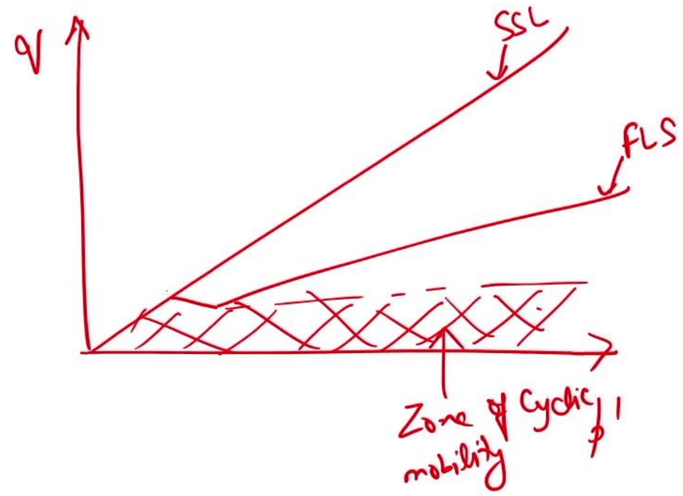
Then, if you are interested to find out here in terms of e vs p prime. So, again, over here, because this was the initial state of the soil, we can see over here maybe 1, 2, 3, 4, 5, and this is maybe sample 6. As far as samples 1 to 5 are concerned, corresponding to very loose specimens, they will be subjected to loss of confinement, subjected to an increase in pore water pressure. Subsequently, they will move towards the left-hand side to reach the steady-state line. Sample 6, which is maybe an indication of non-liquefiable soil, which is shown over here, will directly reach the state of steady-state condition without undergoing any kind of initiation of flow liquefaction. So, this particular line, which we have mentioned over here, is basically an indication of the flow liquefaction surface.



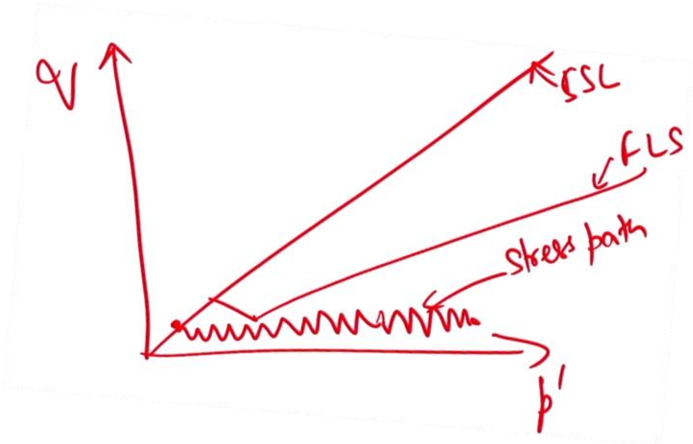
Now, whenever we are interested to find out flow liquefaction initiation with respect to q and epsilon a. Maybe we can discuss right now with respect to firstly epsilon a, and then correspondingly we will also have q versus p prime plot. Now here, we will be interested to find out the initiation of liquefaction, but we will not take the initial state of the soil corresponding to 0. So, there will be some minimum value of deviatoric stress or confinement from which we are actually starting the initial state. We have just seen with respect to monotonic loading; here we will also be discussing with respect to cyclic loading. So, here we see it reached some state, and then followed by which there was continuous deformation. So, this was corresponding to point number C. This was corresponding to point number B when the sample was subjected to monotonic loading, initiation of flow liquefaction. At the same time, the sample can also be subjected to cyclic loading.

So, cyclic means there will be to-and-fro motion, followed by which the sample has actually reached a very high value of axial strain, and then the sample will collapse, subjected to a very high value of strain. So, more or less, the sample will follow the same stress path. So, this is corresponding to cyclic loading. Same thing, we are interested to find out on the p-q plot. We have just seen with respect to the steady state of the soil. So, this is corresponding to the initial state of the soil when the sample was subjected to loading condition; this was the state in which the sample has reached. However, if the sample is subjected to monotonic loading condition, this was the state, followed by which the sample has reached. So, this is corresponding to monotonic condition or monotonic loading, and this is corresponding to cyclic loading in both cases. So, in monotonic loading, the sample was subjected to peak stresses because of external loading condition. However, in cyclic loading condition, there the loading itself has subjected to an increase in axis pore pressure because this is the nature of loading, subjected to which finally the sample, in both cases, will be reaching to its steady state of deformation.

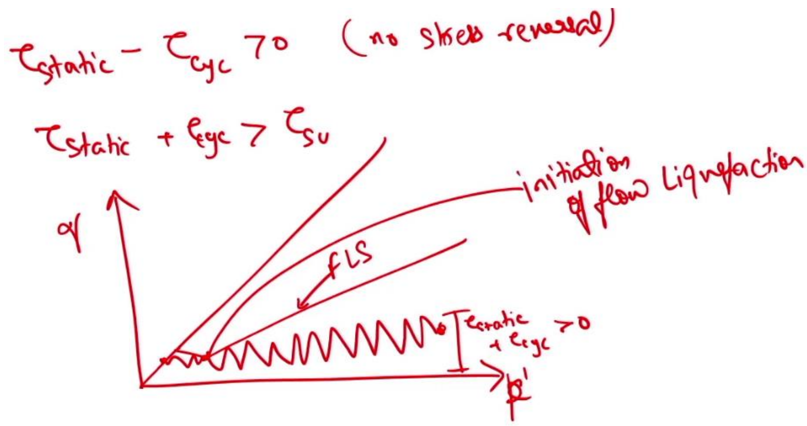
So, in this part, if we are able to locate with respect to the critical state of the soil, we can actually locate the flow liquefaction surface over here. So, in this particular case, this was the point; in this particular case, this was the point, which is also located over here, which is basically the initiation of flow liquefaction during cyclic loading. So, this is related to cyclic loading, and this is the initiation of flow liquefaction in cyclic loading condition, and this particular line is the flow liquefaction surface. This particular line is the steady-state line. Now, as far as flow liquefaction is concerned, based on this, we can understand when monotonic loading is there, the moment when peak stresses state reach, we can say the initiation of flow liquefaction has happened. Same way, in terms of flow liquefaction in terms of cyclic loading, there will be a reduction in the confinement because external loading condition will cause an increase in the pore water pressure; this is the characteristic of seismic waves once reaching a particular soil medium. Subsequently, there will be a reduction in the confinement because of this. Again, in this particular case of cyclic loading, there will be a stage reaching, leading to the initiation of flow liquefaction, and this will continue in the form of flow till the sample reaches its steady state of deformation.



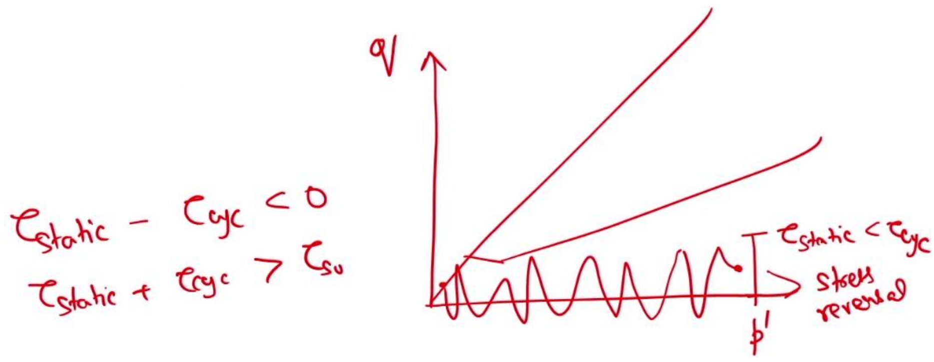
Now, as far as cyclic mobility is concerned, we can discuss in the next slide. In cyclic mobility, we can primarily encounter. So, the sample which may or may not undergo flow liquefaction but can experience cyclic mobility. So, in the first case, if we see over here this in terms of Q p prime, this was the steady state of the soil, and then this is the flow liquefaction surface. So, if you look into this, these particular zones which are located here, this is a potential zone for cyclic mobility. All the samples which are described by means of the state of stress in these particular zones, this can undergo cyclic mobility. So, three possible combinations—three possible combinations again—in the case of cyclic mobility, the initiation, the moment at which cyclic mobility is going to initiate, will not be well identified. Still, there can be three possibilities. So, one is when the static stress minus cyclic stress—that means the amplitude of cyclic stress—is still lesser than the amplitude of static stress. In such a case, there will be no shear stress reversal. There is no reversal in the stresses even though the sample is subjected to cyclic loading condition. At the same time, tau static plus cyclic—that means in addition to whatever static load was there—both are less than the steady-state shear strength. That means no exceedance of steady-state strength. So, in such a case, what will happen?



The sample, which was initially over here, maybe we can mark over here also with respect to q vs p prime. This was the initial state, and this was the flow liquefaction surface. This is the initial state of the soil or the steady state of the soil. So, the sample in this particular case was taken with respect to the initial state. When the sample was subjected to reversal in the stresses, remember, the value of tau cyclic plus tau static is lesser than the steady-state shear strength. So, it will not touch this particular path. This is the stress path. Finally, the sample will reach steady state, but it will not touch the flow liquefaction surface. So, this is potential. In the first case, the effective stress path will move towards the left till it reaches the steady-state condition, but there will not be any reversal of stress. There will not be any initiation of the flow liquefaction surface.



Similarly, another case can be there where tau static minus tau cyclic is still greater than 0. So, that means no stress reversal, but tau static plus tau cyclic is more than the steady-state shear strength. So, what will happen in this particular case? The initial state of the sample was like this, but when it is subjected to cyclic loading, the sample reaches the flow liquefaction surface. In addition, this particular point will again be called the initiation of flow liquefaction. So, in addition to cyclic mobility, where the sample was reaching steady state, there will be initiation of flow liquefaction in this particular case, and the sample will finally reach its steady state. So, here, this will be tau static plus cyclic, which is still greater than 0. So, there is no reversal of stresses. So, this is p prime, and this is q.



The third one is again when tau static minus tau cyclic has now become lesser than 0. That means the cyclic stresses are basically dominating, and tau static plus tau cyclic is greater than tau. In this particular case, in addition to flow liquefaction, there will be a reversal of stresses. That means, here, we can say tau static is lesser than tau cyclic. As a result, there is stress reversal. In this particular case, the sample, rather than reaching the flow liquefaction surface, will not reach the flow liquefaction surface, but there will be reversal in the stresses, and then the sample will reach the steady state. So, this is again the q value, and this is again the p prime value. So, potentially three cases can be there with respect to how much is the static stress, how much is the cyclic stress, and whether the combination of cyclic plus static stress is leading to stress reversal. That is how the state is. But certainly, all these three cases which are mentioned over here will be triggered only in the zone which is identified over here, which is below the flow liquefaction surface. So, that is how the cyclic mobility can be understood in terms of its initiation. But the point of initiation of cyclic mobility has not been well identified, as was the case with flow liquefaction.

So, thank you, everyone. This was all related to the initiation of liquefaction. Thank you.