Applied Seismology for Engineers

Dr. Abhishek Kumar

Department of Civil Engineering

Indian Institute of Technology Guwahati

Week – 09 Lecture - 02

Lecture – 22

Hello everyone, welcome to the 22nd lecture of the course Applied Seismology for Engineers. In lecture 21, we discussed a phenomenon known as liquefaction. In liquefaction, the soil will lose all of its in-situ shear strength and will almost behave like a liquid. It primarily happens because of external loading conditions, which may happen primarily because of earthquakes, blasting, or other construction activities, which induce forces resulting in the formation of excess pore pressure, which will push the particles away from each other. As a result, a particular soil medium, primarily we are discussing about cohesionless soil, will lose its strength in a static condition where it was offering significant bearing capacity to any external overcoming load. Now, because of the transition from almost closely packed material to another state where the particles are moved away from each other and the inter-particular space is occupied by water, which is also subjected to excess pressure, as a result, whatever load is coming on the surface, it will not, the surface will not be able to withstand that particular load, and the load will start sinking. This particular process is called liquefaction. If we take into account the seismic waves which are generated during a particular earthquake, there will be particle motion as the wave passes through a particular medium, particularly the shear waves, that will result in the development of excess pore pressure, and other waves related to particle oscillation will also contribute to this. As a result, understanding the phenomenon of liquefaction, starting with its initial state, that means the state at which the soil was in its in-situ condition before it was subjected to an increase in additional load, which is coming maybe because of cyclic conditions or static conditions, such that collectively both of these, whether it is static condition or dynamic condition, resulted in the increase in the confinement, reduction in the confinement, subjected to an increase in axial stresses, or there is a change in void ratio condition. All these phenomena again depend upon whether, in its in-situ condition, drainage is permitted to the soil or it is not.

So accordingly, one can assess whether we are talking about drained conditions. Then there will be dissipation of pore water pressure, and then significantly, we can see a change in void ratio. If it is dense soil, referring to lecture number 21, if it is a dense medium, initially, it will show contractive behaviour, followed by strain softening, and then dilation will be there. When such phenomena are happening in a dense medium, there will be an increase in void ratio, that we have seen already, referring to the critical state of the soil. We also discussed in lecture 21 that whether the soil is initially dense or loose, one soil which is dense will be subjected to initial contractive behaviour, followed by strain softening and dilation. On the other hand, the soil which is loose will be subjected to contractive behaviour. There will be continuous reduction in the void ratio, and the stage will come where dense material as well as loose material will reach more or less the same level of void ratio. That particular void ratio is called the critical void ratio, and the state was defined as the critical state. Such a state, which is defined as the critical state, can be obtained at a known value of confining pressure. Repeating the same set of strain control tests, a locus of critical states, which are corresponding to different values of confining pressure, can be obtained, and subsequently, one will be able to develop the critical state of the soil or critical void ratio line, which is the locus of how the critical state corresponding to void ratio is a function of confining pressure.

Accordingly, based on the initial state of the soil, it was found that some of the soils, which are located below the CVR line or critical void ratio line, are not susceptible to liquefaction. On the other hand, soils which are above the CVR line are basically subjected to liquefaction. So, depending upon the initial state of the soil, one can understand whether the soil with respect to the CVR line will undergo liquefaction or it will not undergo liquefaction. So, all those lines which are lying under the CVR line will not undergo liquefaction. So, in today's discussion, that is lecture number 22, referring to the end part of lecture 21, where we discussed that even though based on the critical void ratio line, we were able to find out whether the soils were dense or considered loose as far as reaching the critical state is concerned, but at the same time, it was realized that when we are discussing with respect to flow, when we are discussing with respect to the dissipation of pore water pressure, there were limitations in the strain control test that were performed earlier. As a result, most of the attributes which were happening in dense medium or in loose medium because of external loading conditions were not able to be reflected in their stress-strain behaviour.

So later on in 1969, Castro performed stress control tests. Remember, before this, when we were discussing about the critical void ratio line, most of the tests were strain control tests. That is why we were able to understand the drained behaviour, undrained behaviour of dense as well as loose material. But the limitation with those was that these strain control tests were not able to contribute or not able to help us understand how the flow of the soil medium is initiated with respect to the initial state of the soil. And that is how many of the samples, though identified as dense samples, actually underwent liquefaction in exoside conditions. So, Castro in 1969 performed a lot of stress control tests, both on isotropic as well as anisotropic materials. Remember, these were stress control tests, earlier ones were strain control tests, and based on these, based on the nature of these tests, it was observed primarily related to strain control tests on anisotropic material. Now, whenever I am referring to anisotropic samples, I am looking at all the samples to be tested under stress control tests on anisotropic materials, independent of whether the initial state is referring to dense soil or loose soil. So, it was observed primarily based on anisotropic conditions.

So, three principal natures were observed, more specifically we can tell about two, because one, which is referring to the intermediate state, there is though the behaviour is there, but sudden change is not there. So, that is a mixed component of dense and corresponding to loose as well. So, three specimens primarily were focused on, and corresponding to these three principal natures, were observed. The first one, which was corresponding to loose specimens, now if you remember, with respect to the critical state or the samples which were observed for the critical void ratio line with respect to loose, those were initially subjected to, those indicated contractive behaviour. But in this case, here, which I am also referring to specimen number one, that is one specimen I am observing in a strain-stress control test on anisotropic material. So, specimen one, when we recollect whatever we have discussed in terms of the critical void ratio line, loose specimen, since the beginning or with an increase in confining pressure, deviatic stress, these were subjected to continuous contractive behaviour.

However, in this particular case, loose specimens (we can write also over here) loose specimens showed initial peak undrained strength, so there is no continuous contractive behaviour since the beginning of the sample, but there was an indication that loose, or we can say very specifically about very loose sample. So, very loose specimens, when they were subjected to stress control tests, they showed actually initial, there was a gain of the strength at very low corresponding axial strain, at small axial strain and then the sample collapsed. So, whatever peak value it had attained, again, it is undergoing collapse or there is reduction in the confinement of the material, resulting in, now, when we say it reached the peak confining pressure, and then there is collapse in the material subjected to reduction in the confinement. So, when the confinement is reduced to a very low value, what will happen? The material will start flowing because there is no confinement around to retain the material in its in-situ condition. The material will start flowing. So, the material started flowing rapidly, and the same procedure continued to larger strain. Remember, initiation of peak undrained strength was achieved corresponding to a very low value of shear strain, and then after which the material collapsed and subsequently there was a loss in the confinement. When the loss in the confinement happens, the material undergoes flow, and this continued to larger shear strain corresponding to low confining pressure. So, confining pressure had reduced to a very low value. At the same time, because there has been an initiation of flow liquefaction, the material is undergoing continuous movement. This is corresponding to very loose material, more specifically, we are discussing about cohesionless soil. So, these were the samples identified, or the samples which were corresponding to very loose specimens, one can refer to the classification of very loose specimens with respect to the relative density.

So, these samples, which initially showed corresponding to very low value of shear strain, there is peak undrained strength, followed by loss of confinement, reduction in the confinement, and that continued to a very large value of axial strain. So, axial strain is becoming larger, meaning the material is undergoing continuous flow. So, the material was there, undergoing continuous flow. So, it is very high axial strain, and there is loss of confinement. As a result, collectively, the samples were identified as liquefiable. These are the samples which are actually identified as liquefiable because these critically resemble a state of the soil that is favorable with respect to flowing consistency. The confining pressure is very low, the shear strain is very high, resembling possibly that there has been flow in the material.

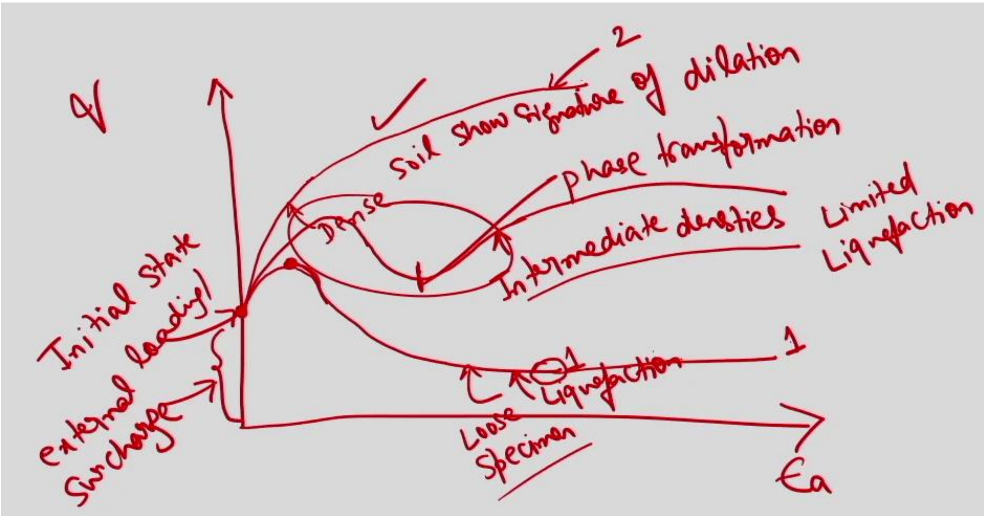
On the other hand, there is another material which is corresponding to dense soil. Now, if you remember again in case of loose soil, whenever we discuss about critical void ratio line, dense soil, since the beginning, was showing continuous contractive behavior. However, in terms of loss of confinement, that was not clearly resembling with respect to the critical void ratio line. However, in this particular case, whenever discussing about the steady-state line that will come later, we are also trying to understand what the change in the state with respect to the initial state is, which is justifying or giving the attribute related to flow characteristics of the medium. So, when we are discussing about dense specimens again, we can call it as another specimen corresponding to dense soil classified based on the relative density of the medium. So, such specimens initially contracted, which was also shown in, if we recollect the discussion in the critical void ratio line. So, initially, the sample showed some kind of contractive behavior. The sample was initially taking load, reached its critical value, and then underwent strain softening.

In this particular case, initially, the sample was contracted. Remember, we are discussing primarily in terms of how there is change in confinement, how there is change in deviatoric stress. So, initially contracted, and then subjected to dilation. So, there is strain softening followed by dilation. There will be orientation of the particles with respect to along the plane of movement, and the same procedure continues until a relatively larger axial strain, relatively high confining pressure.

Remember the first case, that is with respect to the very loose specimen. Initially, there was an increase in the confinement. Once it reached the peak value, there was a loss in the confinement. The sample collapsed, and the loss in the confinement followed by very large axial strain. In the case of the dense sample, initially, the sample contracted, started taking a load, followed by dilation, resulting in an increase in void ratio, subsequent reduction in the pore water pressure, and then increase in confining pressure. The same procedure continued with very high confining pressure and very large axial strain. So, this entire process, we have still not reached to a very low value of axial strain, which was the state reached in the very loose specimen. So here, whether we are talking in terms of dilation, or in terms of confining pressure, or in terms of axial strain, all these things are related to very large values in comparison to the loose specimen. So, we have one specimen which initially showed peak, followed by collapse, and then very low confining pressure and very large axial strain, another sample which is corresponding to dense specimen. Initially, it showed contractive behavior followed by dilation, resulting in an increase in void ratio, subsequent reduction in the pore water pressure, and then increase in confining pressure. The same procedure continued to a very large value of axial strain.

Now, in between the two samples, that means based on the initial state of the soil and based on the relative density, it is very difficult to clearly demarcate whether the sample is corresponding to very loose sample or dense sample. That means we are talking about samples which are having intermediate relative density. So, such samples, which are having intermediate relative density, will represent the mixed characteristics of both loose specimens as well as dense specimens. Similarly, there will be contractive behavior followed by that there will be collapse and then corresponding to a very low value of confining pressure, the sample will continue for larger axial strain. So, at intermediate densities or relative densities, we are again talking about sample number 3, or specimen number 3. This is the sample which is not corresponding to loose specimen, it is also not corresponding to dense specimen, but relative to the intermediate stage of the sample. So, there will be initial exceedence of peak strength, which is a resemblance of loose sample, followed by that this is happening corresponding to a low value of shear strain at low axial strain and low confining pressure. So, this is happening, that means it is reaching peak value after that, followed by collapse or strain softening in even intermediate density. Because it has reached peak value, after that there is collapse, followed by strain softening behavior, and this strain softening behavior will only continue for a short duration. After that, again the sample may start taking load, and we can see some increase in the confining pressure, followed with the onset of dilation at intermediate strain.

So initially, the sample took peak value, followed by which there is strain softening in the material. The material again subjected to reduction in the confinement. After that, again it is showing dilated behavior and this is happening only up to intermediate strain. So, though it is showing the behavior of dilation, it is only restricting to intermediate strain. So if you further continue loading of the sample produces continuous dilation, produces continuous dilation in the material at high effective stress, higher confining pressure. Now, again the material has started taking a load, or we can see there is an increase in the confining pressure corresponding to the sample, and the same procedure will continue to higher strain. Again, when we are talking about strain, we are referring to axial strain. So, higher strain, it is referring to. Now here, if we compare with respect to loose and dense specimens, initially, there was peak value, which was an indication of loose specimen. After reaching a peak value (when I say peak for loose specimen, it is referring to point number one mentioned over here), the sample underwent collapse or strain softening in the particular material, followed by which there is dilation. The material started rolling, and subsequently, continuous dilation will be there. In addition, there will be gain in the confining pressure, and this particular nature will continue to higher strain values.

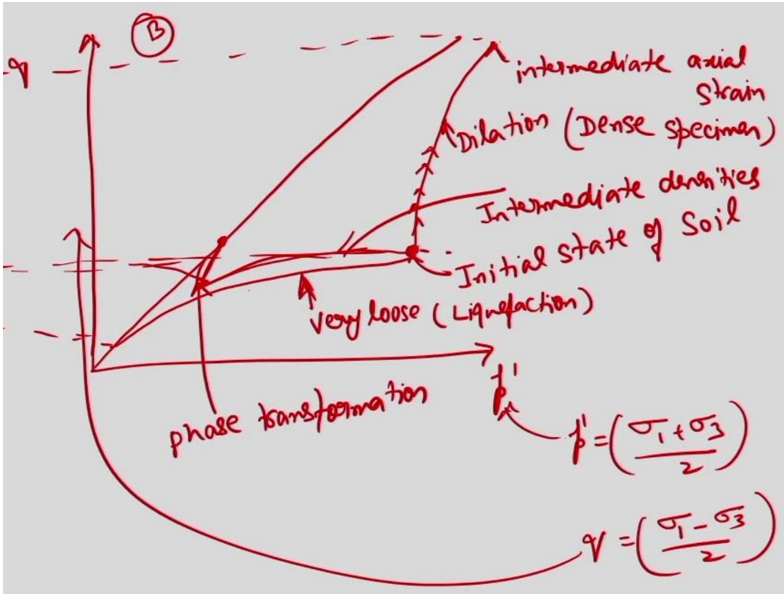


So, we are interested in one can even develop these plots with respect to two parameters: one is Q value on the Y-axis, and epsilon a (that is axial strain) on the X-axis. So, here we can see with respect to this particular point, which is actually representing the initial state of the soil. Now, when we say about the initial state of the soil, it means the state of the soil before you started applying any external loading condition, because this can trigger liquefaction basically. So, before this particular loading condition has initiated, which is triggering liquefaction, the sample at a particular site will also be having some value of initial confining pressure as well as initial effective stress. So, this is basically the initial state of the soil, not the initial state at which the soil was, I mean, before the start of the building; you can say the load from the building or surcharge load is already there in the soil. So, this initial state of the soil is corresponding to that particular load. You can say even this particular part is resembling external loading or surcharge load, corresponding to which one can determine how much the initial state is after which, when the soil sample is subjected to additional load, which is due to static loading conditions or dynamic loading conditions, in addition to these, can actually trigger liquefaction in the specimen.

So, here we can see, if we recollect whatever has been discussed in the previous slides with respect to the initial state, if we are talking about any loose specimen. So, a loose specimen initially showed some sign of peak strength, corresponding relatively high value of confining pressure at low axial strain, followed by which, again, the sample will undergo collapse, and the same will continue to larger strain. So, this is specimen number 1, which is an indication of liquefaction. Now, here we can say liquefaction means with respect to peak strength. That means if you are interested in finding out the flow characteristics, one can represent this particular point, which is basically indicating the steady state where the sample has reached. This was the state at which the sample was subjected to increased load because of the external loading condition, which was higher than the steady state corresponding loading in the sample. So, this is typically representing the sample corresponding to liquefaction; this is again continued. So, this will continue like this up to larger axial strain, corresponding to liquefaction.

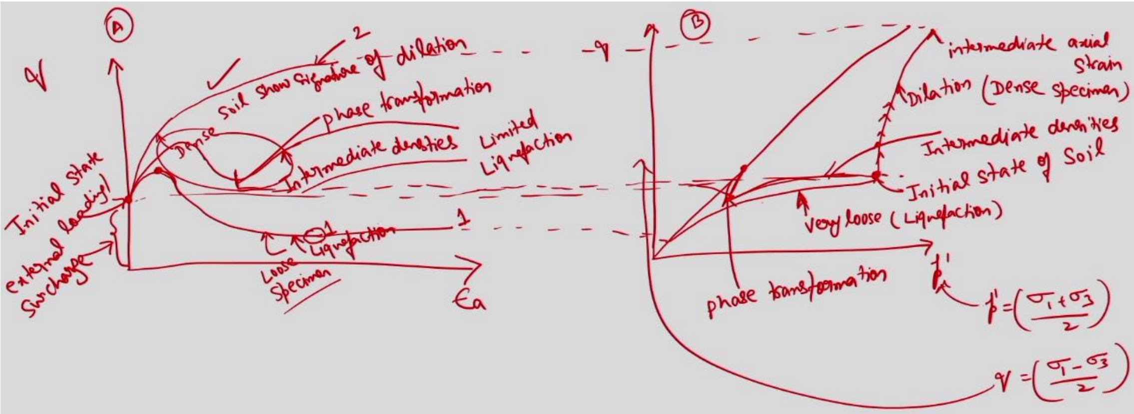
Again, there can be another sample. So, this is liquefaction, or we can say with respect to loose specimen. Loose specimen initially marked peak strength, followed by which the sample collapsed, and then it continued for reduction in the confinement, and the same thing happened at low confining pressure, and then subsequently it continued the contractive behaviour. It continued, and subsequently there was an increase in pore water pressure and reduction in the confinement, which continued to large axial strain. Again, there are additional samples, which are corresponding to... initially, there was contractive behaviour, followed by which there was strain softening, and the sample continued to show some kind of dilation. So, here we can see there is an increase in the confinement, after which, though there is an increase in confinement, there is also a significant increase in the axial strain as well. So, we are discussing about the samples here. This was a sample for loose specimen; another sample which is corresponding to dense specimen. Initially, there was contractive behaviour, the sample started taking the load, and this continued to an intermediate stage, after which there is an increase in the confinement, but at the same time, there is an increase in the axial strain as well. So, that means the sample, though it is subjected to an increase in confinement or reduction in the pore water pressure, but that is correspondingly also anticipated with respect to increase in the axial strain, and this process will not continue to a very large value of strain. It will only restrict itself to intermediate values of strain.

So, this is again dilative; this is dense soil, and the behaviour is subjected to show a sign of dilation. In dense soil, though there was an increase in the confining pressure, this nature of the soil has already reached its steady state, corresponding to some value of axial strain. So, this was related to dense soil, we can also mark it as sample number 2; this was sample number 1. In addition to these two samples, which are neither corresponding to very loose samples nor achieving very high relative density, there are intermediate samples also, which will show some value of initial peak, followed by which there was strain softening, then dilation, and then further that will continue. So, this is corresponding to intermediate densities. The sample has been subjected to intermediate densities and stress control tests. So, this is the representation here. We can see, initially, it was showing some sign of contractive behaviour, reaching peak strength, and then, followed by which, suddenly, it is showing some signature of dilation, which is corresponding to dense sample. So, in between the two, we may see also here, it is showing some signature of phase transformation. Initially, the sample was showing the signature of loose material, where some peak strength was achieved. After this, there was strain softening. Later on, the sample continued to show the signature of dilation and then continued for a larger value of strain. So, in between the prominent features, which is an indication of loose specimen and an indication of dense specimen, there has been a phase transformation. So, all the samples corresponding to intermediate densities or showing phase transformation are classified as samples related to limited liquefaction. So, these are the samples that may or may not undergo liquefaction, but always at boundary conditions. So, if favourable conditions are given in terms of confining pressure, in terms of void ratio, then these samples can undergo liquefaction. If those favourable conditions are not given, the sample may not undergo liquefaction.

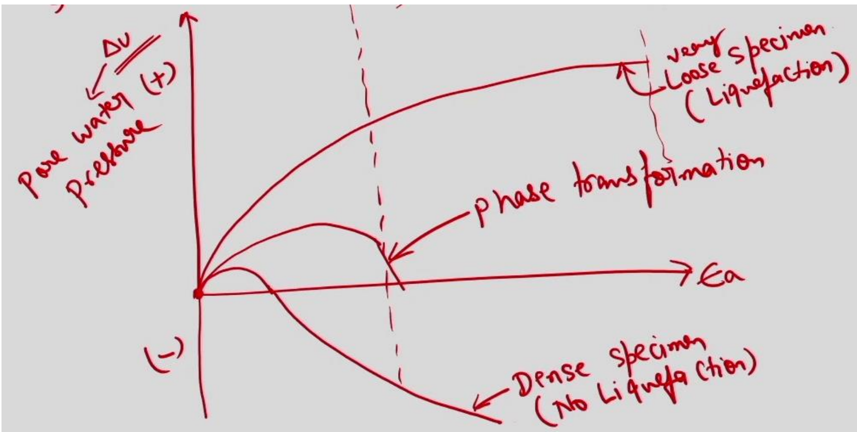


So, the same thing, if we are interested in finding out, we can also develop this in terms of effective mean principle stress and average confining pressure. That is, P equals to sigma 1 plus sigma 3 over 2, and Q equals to sigma 1 minus sigma 3 over 2. So, sigma 1, sigma 2 corresponding to confining pressure, and sigma 3 is corresponding to major principal stress. Then, in this, sigma 1 is corresponding to major principal stress, and sigma 2 and sigma 3 are corresponding to confining pressure in orthogonal directions. So, this is going to represent the average or mean principal stress, and this is going to represent the confining pressure. Now, here, if we are interested, corresponding to liquefaction, it has been observed like all the samples with respect to the initial state of the soil. So, with respect to the initial state, the samples can be located over here, corresponding to the initial state of the sample. There might be some value of mean effective stress or mean principal stress, which can be located over here, with this particular point representing the initial state of the soil. So, this is the initial state of the soil. Now, with respect to the initial state of the soil, two samples are there. One is liquefaction, so all the samples which are corresponding to loose specimen. Initially, there will be some contractive behaviour, followed by which the sample will continue like this and reach a very high value of axial strain, that is, corresponding to a very low value of q. So, here also we can see this is the same level of confining pressure, which is shown in figure number one or figure number A, figure number B. So, the value of q, which is shown on the Y-axis in figure number A, the same values of q will be transferred to figure number B.

So, referring to the initial state of the soil, the samples corresponding to very loose soil actually showed, initially, contractive behaviour, followed by which loss of confinement, and the same will continue to a very large value of axial strain. So, this is corresponding to loose specimen, and you can call it as this is the state in which the soil is able to explain the initiation of flow, how the characteristics of the medium change with respect to the initial state, such that a situation favourable to flow is triggered in the soil specimen at the site. Again, at the same time, dense specimens are there. So, you can see this is continuously undergoing dilation, initially we can see there is significant change. Here if we focus, we will see that the increase in confining pressure is happening at a much faster rate and not that much increase in the external loading condition. But after the intermediate stage, or in between the lower axial strain and intermediate axial strain, there will be a dominated behaviour of dilation, followed by which, though there is an increase in confinement, there will be a significant jump in terms of axial strain as well.

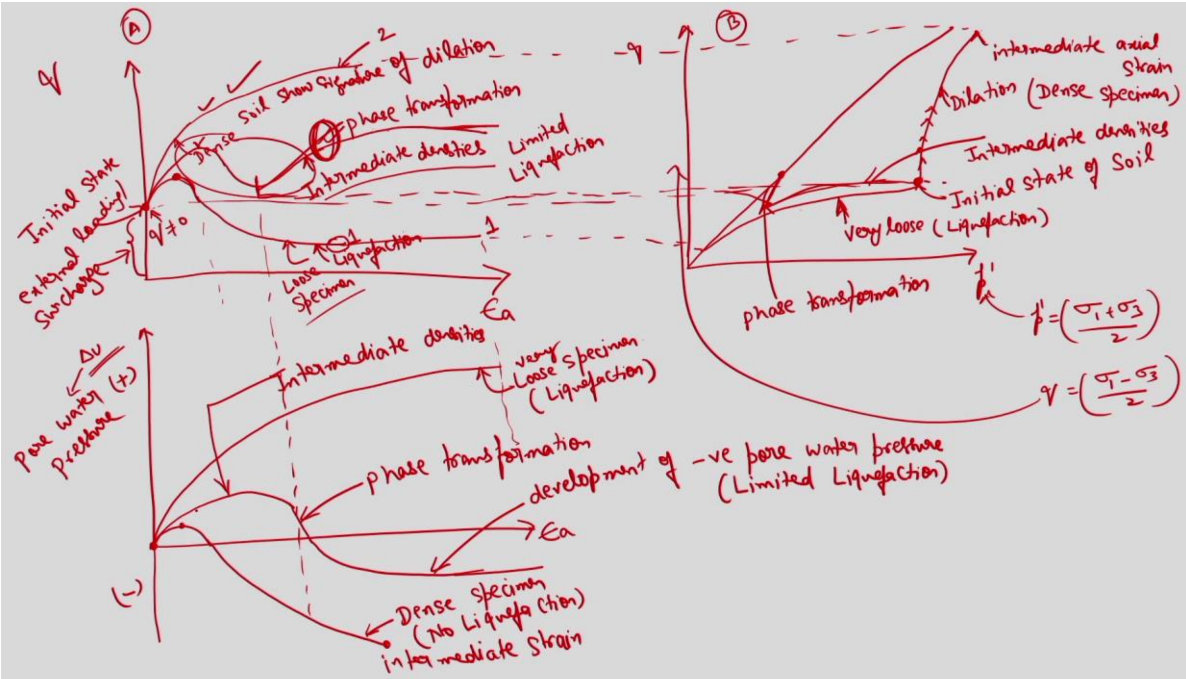


So, this will continue corresponding to the same procedure given here. So, this is corresponding to intermediate axial strain, and this was corresponding to a low value of confining pressure, which is a representation of a very high value of axial strain. Now, in between the two, this is corresponding to intermediate axial strain. This is dilation, possibly an indication of dense specimen. So, dense specimens are there which are showing the behaviour of dilation. In between the two, there were also intermediate samples, which will initially show the characteristics of loose specimens, followed by which there was phase transformation. So here we can see phase transformation is happening over here, so this particular level, if we continue like this, that will be an indication of phase transformation. So, we can mark this phase transformation corresponding to this particular site, and then finally, the sample is also reaching more or less to the same state of the soil, which is happening at a very high value of axial strain. So, this is corresponding to intermediate densities. Samples, which initially showed the signature of loose specimens, showed peak confining pressure, peak strength is there, and then, followed by which there is contractive behaviour that will continue to larger strain, followed by which, in between, it also showed the signature of phase transformation, which is marked by this particular location in intermediate sample, phase transformation or phase change, followed by which the samples started showing the signature of dilation, and that continued even to a larger value of strain. So, this is again phase transformation.



Now, collectively, the same thing if you are interested to find out based on axial strain versus change in pore water pressure. So, delta U is there, which is an indication of pore water pressure, how the pore water pressure is changing, and with respect to pore water pressure, this is again the same value of axial strain. So, if 3 samples are there. If you remember dense specimens, dense specimens, when these are subjected to an increase in tabiotic stress, what will happen? The sample will undergo strain softening, the particles will start moving, collapse will be there, as a result, there will be a reduction in the pore water pressure or development of negative pore pressure, as a result of which there will be an increase in the confinement. So, if we discuss with respect to pore water, which is mentioned over here, this is pore water pressure. So, dense specimens will be showing an indication of initial contractive behaviour. That means initially, the sample was undergoing contraction, there was reduction in the void ratio, subsequently, there was positive pore pressure, which was generating. And once the sample started showing the signature of strain softening, the development of negative pore water pressure, which is shown by as a result with respect to this origin, you can see the behaviour has actually gone down or there is development of negative pore pressure. So, if this you consider as positive, this is basically negative. So, negative pore pressure has been generated in the soil sample, which is corresponding to dense specimens, and we can also say no liquefaction.

On the contrary, the loose samples were there. So, corresponding to loose samples, we can see continuously the sample was showing contractive behaviour. Initially, there was peak strain, collapse was there, but if we say in terms of pore water pressure, continuously, with respect to the initial state of the soil, the sample has been subjected to an increase in pore water pressure. Now, here we can see I am starting the curves with respect to dense specimens or with respect to loose specimens as well, loose or very loose specimens. So, all those samples I am starting with pore water pressure equals to 0, that means, as far as liquefaction initiation is concerned, whether it is related to static loading condition, whether it is related to blasting, construction activity, earthquake loading condition, the situation at the site is such that before these external loading conditions, which actually triggered liquefaction, were not applied to the sample. The sample was showing no signature corresponding to the development of excess pore pressure. That is why the value of delta U in all these are corresponding to 0 value. So, there is no signature corresponding to delta U. On the contrary, if we go into figure 1, those were indicating that when the sample was subjected to external loading conditions, which might have triggered liquefaction, because we are interested to learn here about initiation of liquefaction with respect to the initial state of the soil. In such a case, whatever might be the external loading condition, because of static loading, dynamic loading, construction activity, explosion, these are additional states of stress, but before these states of stress have come into the picture, the sample, whether it is located at the soil which is located, may be at the foundation level, it may be used for parking space, it might be used for railway embankment, it might be used as the base of retaining wall, bridge abutment, at each of these conditions, there was some initial state of the soil which was not corresponding to 0. That means, because of the loading condition, before the sample was subjected to additional loading, which triggered liquefaction, the sample was having some minimum value of confining pressure. So that is not indicated by q is not equal to 0 at the initial state. q is not equal to 0. It is representing some minimum value of stress, which is a representation of how much stress is because of external loading conditions, at which your designer declared that the soil is under static loading, under given static loading condition, the foundation is safe, bridge abutment is safe, there is no indication of differential settlement or total settlement because of additional force, which is likely to induce liquefaction in the soil. So, this is corresponding to very loose specimens. Though initially, it was showing some sign of peak value, but overall, if you see, the nature is a representation of contractive behaviour. As a result, this can also be indicated by means that there is continuous increase in the pore water pressure in loose specimens, which is also an indication of liquefaction.

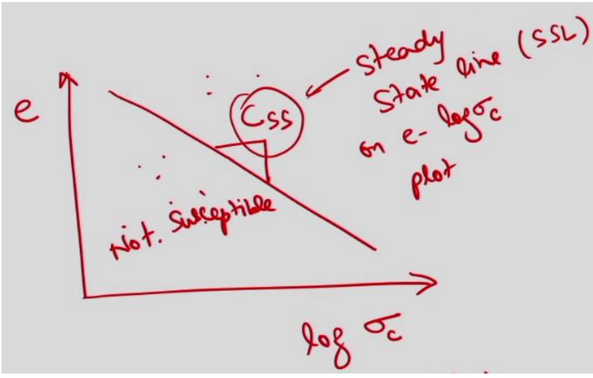


Dense specimens, there is no liquefaction. Very loose specimens, there is liquefaction. And again, if you are talking about limited liquefaction, so there were samples if we are taking this phase transformation into account. So here we can talk about the samples. Initially, there was the sample started taking load, contractive behaviour was there, it reached to peak value, subsequently, there was an increase in pore water pressure, and subsequently, the sample also started showing some signature of dense specimens. That means dilation, it was shown. The moment the sample shows dilation at this particular point. That is why it is also marked here as phase transformation. So initially, when the sample was showing signature corresponding to loose specimens, there was development of pore water pressure. The sample reached peak strength, followed by which there was some strain softening, and then the sample showed this is about intermediate samples. So here also, we can write as it is corresponding to intermediate densities. So intermediate density again, there is phase transformation, then we can see the sample is showing dilation, and as a result of which there is development of negative pressure, negative pore pressure development. Of course, this particular development of negative pore pressure will not be as high as corresponding to dense specimens because with respect to the initial state of the soil and with respect to the density of the medium. So, development of negative pore pressure, this subsequently was shown over here with respect to whether we are talking in terms of dense specimens or whether we are talking in terms of intermediate soil, in both the cases, it was represented by means of an increase in confinement. So, negative pore pressure, that means there will be an increase in the confinement. So, development of negative pore water pressure in intermediate samples, in intermediate samples. So, this is again indication of limited liquefaction. It is always called as limited liquefaction because, based on the densities of the medium, it is very difficult to bifurcate this understanding of intermediate samples or phase transformation to a dense sample or to loose samples. So, this is showing collective signature with respect to loose as well as dense specimens. At lower values of axial strain, it is showing more or less the signature corresponding to this specimen reaching peak value, then strain softening is there. As it reaches intermediate value, the same sample which was initially showing contractive behaviour, will also start showing some signature of dilative behaviour at intermediate axial strain. There will be an increase in which is mentioned over here, there is an increase in axial strain which is mentioned over here. Also, this particular phase is an indication of an increase in the confining pressure or development of negative excess pore pressure, as a result of which there is an increase in the confinement at intermediate axial strain, and the same procedure will continue to larger axial strain. So, this continues even to a larger value of axial strain, and this will continue. So, unlike dense specimens, where the dilation was arrested till intermediate strain, this is corresponding to intermediate strain. In the case of loose specimens, the same procedure continues to a very high value of axial strain.

If we are talking about intermediate, though it was showing some signature of dilation, but it was the rate at which the increase in confining pressure was shown; it was more or less constant. So, it was not further increasing as was shown in the case of a completely dense specimen. As a result, this procedure, this nature of showing an increase in confinement, did not further happen, and we can see over here also that this particular phase of increase in confinement initially happened, and then it continued further with respect to the initial state of the soil. Though there is a decrease in the pore water pressure or development of negative pore pressure, for that, beyond intermediate axial strain, this particular phenomenon—further increase in negative pore pressure—will not continue for the intermediate sample. As a result, now collectively, if we see over here what is happening when we loaded these sorts of samples and tested in a stress control test, we are trying to understand, how there is a change in the confining pressure, which is also giving when the favorable condition related to the flow of soil (liquefaction means the soil has almost transformed from the initial state, which was quite stiff, to almost a state that resembles flow). So, wherever, the moment the soil is subjected to a state where either there is a reduction in the confinement, which is again an indication of flow because now the soil can undergo flow, or there is a state which is triggering in the soil, which is mentioned over here also—like the moment where the soil is subjected to any additional load, which is more than the load, which is more than the state of stress, which is developed in the soil corresponding to a very high value of axial strain—that means the in-situ strength of the soil is significantly low, and the additional load has generated significantly higher values of stresses. In such a case, the soil will undergo failure, which is also a representation of the flow characteristics of liquefaction.

So, further definition about flow liquefaction and cyclic mobility will be discussed in Lecture 23. Now, corresponding to this understanding, where we are trying to understand more or less how the void ratio of the soil sample, particularly in a drained test, is changing for three states of the soil with respect to what was the initial state of the soil and what was the density of the medium. So, based on which we understood that there is a unique relationship between the void ratio that is actually triggering the favorable condition with respect to whether it is the generation of pore water pressure or negative pore pressure and confining pressure, or we can more specifically mention as effective confining pressure, and this is usually happening at large axial strain. As far as flow is concerned, this is a phenomenon corresponding to large axial strain, so we are taking larger axial strain. So, when this particular relationship is plotted on the void ratio and confining stress curve or graph, again, it shows unique behavior.

So, observing the same things, where you are interested to find out corresponding to this particular void ratio, which is basically an indication of—like after this particular void ratio or after this particular confining pressure—there will be continuous flow in the material, this is an indication of the steady state of the soil. So, based on this, it has shown unique behavior—the locus of all points at various confining pressures. So, corresponding to different values of confining pressure, again, there will be a state which is a representation of flow. A plot a plot parallel to and also lower to the CVR line is obtained.



So, here again, we can see if we can recollect the CVR line; it was again the void ratio versus sigma c. Here, in this particular case, now we know. Similar to that, we are also getting in this particular case, also this particular line, which is a representation of the state of the soil at different values of confining pressure, which is representing the point of continuous flow, or the void ratio corresponding to the state after which there is continuous flow, which will be a representation of the loss of confinement and will continue to a very large value of strain. So, accordingly, a state—this is called the critical state steady state line. The steady state line, basically, it is a projection of the steady state line on the e-log sigma c curve. So, here we are discussing about a steady state, or a state is defined as a state where continuous deformation, at larger strain, corresponds to constant void ratio, constant effective stress. So, this is basically an indication of a state of the soil where there is continuous larger deformation happening at larger strain at constant void ratio and constant effective stress. So, this particular plot, which is a representation of the locus of all points, representation of the same void ratio—representation, like after this particular, there will be larger deformation, representation of continuous flow. This particular state, it is called the steady state line in the soil medium.

So, with respect to this particular line, again, if one is interested to find out whether the soil at a particular site will undergo liquefaction or not—because this has been identified, or the steady state line has been identified, we can also call it as SSL—it has been identified based on the initial state of the soil as well as the void ratio corresponding to larger deformation. So, with respect to this particular line, one can also identify SSL. SSL is useful in identifying soils likely to undergo liquefaction or not. So, here we can say, all the samples, soils with the initial state below SSL are not susceptible. So, all the samples, which, based on the initial state, are located over here, these are not susceptible to liquefaction, and this is now reclassified with respect to the steady state line. Similarly, all the samples which are located above—not susceptible—similarly, soils which are with the initial state above the steady state line are susceptible to liquefaction. So, based on this particular state, which is identified as the steady state of the soil, which is a representation of low liquefaction in terms of larger strain and loss of confinement, it is basically now this particular line with respect to which, taking the initial state of the soil, one will be able to identify whether it is falling in the non-susceptible zone or it is falling in the susceptible zone. So, all the soils which are above it, that will be called as potential to liquefaction, which are below, which are not susceptible to liquefaction. As far as limited liquefaction is concerned, one has to take into account the characteristics of external loading conditions in terms of increase in the confinement or reduction in the confinement. Subsequently, that can be correlated also with respect to pore water pressure, negative or positive generated during the loading condition. So, that collectively will help in understanding whether the soil is susceptible to liquefaction or not with respect to the steady state line.

So, in the next lecture, in Lecture 23, we will be discussing about two phenomena, which are actually representing liquefaction at the site with respect to the initial state, which we have discussed over here. We will try to find out what is happening when the soil sample is subjected to external loading conditions representing the flow liquefaction or cyclic mobility. So, thank you, everyone. Here, we will close this particular lecture.