Earthquake Geotechnical Engineering

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Lecture 36

Initiation of Liquefaction (Conti.)

I welcome you all for this NPTEL online course on earthquake geotechnical engineering. And we are discussing a very important topic of this course that is on liquefaction of soils. We are working on the module 4 of this course. The module 4 is on liquefaction and we already covered two chapters on this module, one is introduction and liquefaction susceptibility. So, we have covered 5 lectures so far and today is the 6th lecture of this module and we are going to start the third chapter that is initiation of liquefaction.

What we are going to cover in this chapter that is the third chapter of this which is two topics has been already covered flow liquefaction surface and influence of excess pore pressure. Today we are going to talk the third topic, that is evaluation of initiation of liquefaction which can understand by using two approaches one is called cyclic stress approach and another is cyclic strain approach. So, one of them, that is cyclic stress approach, we will discuss in very much detail. And in this approach what is required to be done that we need to characterize the earthquake loading as well as liquefaction resistance by the same terms whatever we decide accordingly we will characterize earthquake loading as well as liquefaction resistance.

And in fact, it is mostly in the cyclic stress approach it is in terms of cyclic shear stresses both are characterized. Now, coming to the characterization of earthquake loading, it will is done by two processes either simplified processor or what we call the ground response analysis. Similarly, characterization of liquefaction resistance is done based on laboratory or H2 test. So, we will discuss the first one characterization of earthquake loading today completely and characterization of liquefaction resistance will be discussed partially. So, coming to this today's lectures we are going to talk about cyclic stress approach after the introduction and then characterization of earthquake loading, and characterization of liquefaction resistance will be done.

And that will be based on the lab test only because we will not be able to carry in this lecture on the in-situ test we will continue in the next lecture for that. Now, coming to this like most of the stuff from this lecture, lecture number 36 is from the other reference by geotechnical earthquake engineering by Kramer. You know that we already discussed that steady state and flow liquefaction surface. So, we discussed two things in the last two lectures one was flow liquefaction surface FLS in short and another was steady state line SSL. So, using these two concepts, these two concepts provide a complete framework for basic mechanism of liquefaction can be understood by this framework.

This framework will integrate different steps of liquefaction which is three steps one is the liquefaction susceptibility, liquefaction initiation and the liquefaction effects. So, all three will be integrated together. This will illustrate influence of excess pore pressure generation on the extent of liquefaction related hazards. So, when the pore water pressure generates, how it influence the liquefaction that we are going to discuss in detail. As we discussed that there are two approaches one is cyclic stress approach, we will call in short CSA and another is cyclic strain approach we will call it CSNA.

So, we will discuss in the next three lectures including this one another two lectures cyclic stress approach only. Coming to CSA cyclic stress approach, when we talk about many advances in the state of knowledge of liquefaction is concerned, I think if you recall in the when I started this topic on liquefaction then we discussed two major earthquake of the world after which liquefaction started worldwide. So, one was in Japan which were in Alaska in USA one was which happened in March 1964 with magnitude 9.2 and another was in Japan Niigata earthquake that was also in June 1964 so within a span of three months. After that lot of studies started and the initial studies started from the work which is done by Harry Bolton Seed at University of California Berkeley, and it was done mostly like you know publications in 60s and 70s and later also.

So, this research was directly towards evaluation of the loading conditions required to trigger liquefaction. So, idea is that what is the loading required from the earthquake which will trigger the liquefaction so that was the objective of this study initial study of seeds. In that case the loading was described in terms of what is called cyclic shear stresses and liquefaction potential was evaluated on the basis of the amplitude and number of cycles of earthquake induced shear stress. So, what is done that loading is represented in terms of cyclic shear stress and then for the because cyclic loading is applied so in that case what is the amplitude of the loading and number of cycles that become important to for so and these amplitude and number of cycles will govern the cyclic shear stresses induced inside the soil which will trigger ultimately the liquefaction. The first of course, it could be there also, but very well known or established paper on the liquefaction first which was widely used is by Seed and Lee in 1966 which defined the initial liquefaction as a point at which the increase in excess pore pressure that is in short we called EPP is equal to the effective confining pressure that is let us say if I say U excess this u excess is nothing, but it represent your EPP I think we discussed in the last lecture also this thing.

So, this is EPP excess pore pressure and if the excess pore pressure become equal to the effective confining pressure which could be said as minor principle stress sigma 3 c or in the triaxial test it is also called cell pressure or confining pressure. If excess pore pressure is equal that is the condition of for initial liquefaction the ratio of u excess pore pressure and divide by u excess divided by sigma 3 c is called nothing, but this ratio of these two is called Ru which is short in called short in pore pressure ratio. So, another way I can say that when Ru become 100 percent then that is the condition for initial liquefaction. So, initial liquefaction could be produced in both loose and dense specimen which is like you know that for the flow liquefaction the condition is that the sample should be loose, but cyclic mobility could occur in the loose sample as well as dense sample. So, initial liquefaction can occur in both cases as loose as well as in the dense sample only the when it will triggered that will different for the depending on the relative density.

Now, continue with the cyclic stress approach it is conceptually very simple and why it is simple because the earthquake induced loading, or we say in the in simple word seismic loading is expressed in terms of cyclic shear stresses and it is compared with the liquefaction resistance of the soil. So, one side you have the cyclic shear stresses which is induced inside the soil due to the earthquake loading. On another side you have the liquefaction resistance of the soil which is also represented in the same number same terms that is in terms of cyclic stresses only and then what you do at the locations where the loading exceeds the resistance what will happen liquefaction is expected to occur. So, this is a simple. So, this way like both it is represented in terms of cyclic shear stresses both loading as well as resistance.

From continue with this one now in the CSA, the next step is how we characterize of earthquake loading. So, we will discuss first characterization of earthquake loading and once it is over then we will discuss characterization of liquefaction resistance. So, next few slides will be on characterization of earthquake loading. The level of EPP that is excess pore pressure required to initiate liquefaction, is related to the amplitude and duration of earthquake induced cyclic loading.

How much pore pressure is developed inside the soil that will depend on your loading condition and when we talk about loading condition this loading condition is related to the amplitude and duration of cyclic loading. The cyclic shear stress approach CSA in short is based on the assumption that the EPP generation is fundamentally related to the cyclic shear stresses. Hence, seismic loading is expressed in terms of cyclic shear stresses simple. Here one side we are saying that liquefaction who is responsible for liquefaction it is increase in pore water pressure. So, the thus what happens when you induce the loading inside it will create excess pore pressure and we are linking with the generation of cyclic shear stresses.

So, the loading can be predicted which is like due to the seismic load in terms of cyclic shear stress by using two methods. One is detailed ground response analysis which is called GRA in short and another is what we call the using a simplified process. Ground response analysis also has been covered in pretty much in detail during this course only we where we carried out 1D analysis and 2D ground response analysis. So, that way also it can be done. But suppose if you do not have means to carry out the ground response analysis then we can go for simplified process.

Let us discuss first about GRA approach and then we will discuss the second part that is simplified process. So, as for ground response analysis it can be used to predict time histories of what shear stresses. That means, the ground response analysis will give you the variation in shear stress with the time at various depth and this will vary with the depth it is not going to be constant rather at level different level of depth inside the soil that this time will be different. Such analysis produce time histories with the transient irregular characteristic of actual earthquake motions. However, what happens when we carried out ground response analysis you plot time history which looks like this one. This kind of time history you will get. And this is what this time history this is on y axis you have shear stress on x axis you have like time. So, in this time history it is very irregular, but it has been observed that the data which has been obtained from the laboratory data says uniform time history. If you want to find the liquefaction resistance using the laboratory data, then in that case you need to find the uniform time history. That means, peak values are equal and here peaks are not equal.

So, usually obtained so, what we do here therefore, for comparison of earthquake induced loading with laboratory determined resistance require conversion of an irregular time history which has been obtained using GRA to an equivalent stress of uniform stress cycles. So, you have the peaks, peaks are going some peaks are high some peaks are low, but we require uniform shear stress time history. To convert the seed in 1975 suggested a weighing process to a set of shear stress time histories from recording from ground motion to determine the number of uniform stress cycles. And what was the process? From many data from the field uniform stress cycles which is nq, nq means number of cycles which have an amplitude of 65 percent of the peak cycle shear stress that is toe cycle where toe cycles you can say the average cycle shear stress is about 65 percent of the maximum value that is 0.65 toe max. That will produce an increase in pore pressure equivalent to that of regular time history. The equivalent number of uniform stress cycles will increase with increasing earthquake magnitude. So, now the number of cycles one side first you put uniform cycles and you for uniform cycle you need to just simply the peak value is maximum value is multiplied by 0.65 that is there. But on another side how many number of cycles need to be considered that will depend on your magnitude of earthquake.

And by Seed et al 1975 number of equivalent uniform cycles that is n equivalent for earthquake of different magnitudes are given in this figure. So, here you have three curves in this figure central curve is mean curve. So, normally we will be using the middle one. So, in the middle curve if you want to read, so use for 7 magnitude earthquake what I get for 7 magnitude earthquake you get almost 10. If you go for 7.5 then about around 15 or 14 you get. So, for 7.5 magnitude you have this one here this will go like this one. So, this is around less than 15 around 14. Similarly, for 8 magnitude around 20. So, roughly if you want to find magnitude and n cube m and n cube if I link for 7 magnitude earthquake. So, you have 10 here then you have 7.5 around 15 and 8 magnitude around 20. So, this can be read from here. Coming to this like this characterization in this case this is a typical irregular time history of shear stress, and this has been by a magnitude 7. So, naturally the number of equivalent number of cycles will be for this as we just discussed is 10, it will be approximately 10. And here in this case the peak value is though it is in terms of here in pounds per square feet. So, the peak is here. If you convert this peak into equivalent kPa then you get 37.4 kilo Pascal and the toe cycle for this maximum value will be 0.65 toe max. So, you get 24.3 kilo Pascal. So, that means, this time shear stress time history which has been generated using what we call ground response analysis GRA will be have equivalent uniform shear stress with magnitude 24.3 kilo Pascal and number of cycles as a 10. So, that will be the answer here. So, this way we carried out the ground response analysis.

This way we find out the equivalent number of cycles toe cycle and the number of cycles using ground response analysis. Now, this characterization of earthquake loading can also be done using what we call the simplified process, and this simplified process is written in the short as SP. Here SP stands for simplified process. This simplified procedure was given by Seed and Idriss in 1971. So, the uniform cyclic shear stress amplitude for level or gently sloping sites can also be estimated using the relation here. What has been said by the simplified procedure if suppose you do not have the ground response analysis, but you know the peak value and this peak value is peak ground horizontal acceleration which is not related to shear stress because shear stress we are calculating based on this. So, Amax if is known then ratio of Amax by G will be dimensionless multiplied by sigma v. What is sigma v? Total overburden pressure in the vertical direction and Rd is a reduction factor and this Rd is the value of a stress reduction factor. This is called a stress reduction factor at the depth of the interest. At the ground level when at z equal to 0 the value of Rd is 1.

So, once toe max is known then toe cycle can be simply calculated 0.65 multiplied by toe max that means 65 percent of the value of toe max. As far Rd is concerned, Rd can be calculated from this graph. Here you have again depth is in the feet which is 0 to 100 meter 100 feet 100 feet is roughly 30 meter and the value of Rd is given. You see when at ground level the value of Rd is 1 and when the depth increases it decreases and what we do if we use this chart then we use the average values because it is a range for different soils. So, normally if you use the average values and then if I extend this chart then it will be like this. So, you can extend it and then it can be used. However, in the absence of this chart the Leo and Whiteman this chart has been given by Seed and it is 1971. So, this is this chart and Leo and Whiteman have suggested following equations two equations.

$$r_d = 1.0 - 0.00765z \text{ for } z \le 9.15 \text{ m}$$
$$r_d = 1.174 - 0.0267z \text{ for } 9.15 \text{ m} < z \le 23 \text{ m}$$

If your depth is less than 9.15 meter, then reduction factor can be found out one where z is the depth of the point where you want to find in terms of meter not in feet. So, the z in this equation is in terms of meter. So, putting this value of z in meter we can calculate the value of Rd from this formula. Similarly, if your depth is more than 9.15 meter however less than 23 meter then we can use the second equation.

If z is more than 23 meter you may not require it because mostly below so much depth liquefaction may not occur. So, anyway we can use this equations because that they are straightforward, and they can be programmed also in excel sheet. So, we are set we know the A max we know this G only the thing sigma v effective overburden pressure and that will vary with the depth. If you know the unit weight then sigma v is simply can be calculated, sigma v is nothing but for the particularly if you have total stress sigma v is gamma into z where z is the depth gamma is unit weight of the soil.

Now, continue with the simplified procedure. The uniform cyclic stress shear stress is assumed to be applied for the equivalent number of cycles equivalent number of cycles which depends on the earthquake magnitude which we already discussed. Regardless of whether it detail ground response analysis, or the simplified procedure is used to characterize the earthquake loading you have two process one is simply a ground response analysis another is simplified process which we already discussed here. The earthquake irrespective of the process you use any of the process. The earthquake induced loading is characterized by a level of uniform cyclic shear stress that is applied for an equivalent number of cycles and this equivalent number of cycles depends on your earthquake magnitude. If your earthquake magnitude is higher equivalent number of cycles will be high, if it is low, it will be low. Now, coming to this one of the example where you can see that how we can characterize this what we discussed earlier in the characterization of earthquake loading using simplified procedure because here it is difficult to deal with the ground response analysis. In this case a site is subjected to earthquake shaking and this earthquake shaking produce a peak ground acceleration of 0.22g. So, simply what it is saying your A max is 0.22g. Plot the variation of maximum shear stress that is toe max with depth and also equivalent uniform cyclic shear stress toe cycle with the depth. So, you need to plot the variation with that and this is simple what is happening you have three layers of the soil first layer is 3 meter top then 2 meter and 5 meter water table is located at the top of the second layer at the base of the second layer at the top of the third layer and the unit weight that is dry unit weight is varying 15, 16 here it should be not dry because once you have the water table. So, you assume that this is the kind of saturated or so this is hypothetical because this will be saturated will be the higher value but this will not be dry because water table is here. So, coming to this data now here using the simplified procedure of seed the maximum shear stress can be estimated from the relation toe max equal to A max by g sigma v into rd where toe max by g is given to you 0.22 sigma v into rd.

Using this relation, we can find here what you need to use you need to have the sigma v and rd reduction factor. So, variation of toe max with the depth requires evaluation of the variation of vertical stress and rd which has been done in the table here. So, in this case calculation has been done sigma v will be gamma h here because in this equation you need to understand in this equation or in the last equation which we have discussed sigma v is total stress a total overburden pressure it is not effective. So, when you find the cyclic shear stresses induced inside the soil due to earthquake loading then total overburden pressure need to be used not the effective this is a common mistake which is done many times. So, whenever you have any numerical you have try to understand that toe max or toe cycles due to earthquake loading will be calculated based on the total.

So, once you calculate total stress then what location of water table is not going to make a difference because ultimately you are not going to calculate the effective stresses and the total stress is not going to be vary so in this case so this is calculated for example at the depth 0 naturally you do not have sigma v will be 0 at 3 meter level 15 into 45 the next level it is something will be added, and this continue to be added. So, here I think one mistake is here. So, we can correct it this is 20 here basically this value is 20 and this should be treated as gamma saturated this is all right.

So, this is misprinting here. So, this is gamma saturated 20 kilo Newton per meter cube this has been taken 20 here if you calculate here in this table the parameter gamma saturated is taken 20 this all right here. So, this way you have sigma v has been calculated and for 3 depths sigma v can be calculated rd as we discussed rd will be varying with the depth at that 0 it will be 1.98, 0.97, 0.93. So, toe max can be calculated using this relation which is in k p a kilo Newton per meter square and toe cycles. Because sigma v is increasing with the depth so as a result your both toe max and toe cycle will be increasing with the depth but only the difference that this last column toe cycle will be 65 percent of the toe maximum and once you plot then this plot will be looking like this one that how the shear stress varies with the depth the with the depth the basically shear stress is increasing. So, this way and this calculation should be done in the tabular form to avoid anything. So, this was one of the example on simplified process to calculate the shear stress induced inside the soil due to the earthquake loading. Here this looks a straight line, but it will not be straight line actually because the reason being that because the slope might be different because the gamma is not constant.

If gamma is constant with homogeneous soil, then you will get the straight line like this. Coming to the next part of the today's lecture this lecture we have done with the characterization of earthquake loading or seismic loading and we discussed two methods one is ground response analysis another is simplified procedure. Now how to characterize the liquefaction resistance that is the strength of the soil and we already said it can be characterized by two methods one is laboratory another is field test. So, the failure state for flow liquefaction is defined using the flow liquefaction surface and its initiation is easily recognized in the field. So, recognizing whether flow liquefaction is started or not it is easy to guess but for it is difficult for cyclic mobility like where at what is at what point cyclic mobility is starting.

So, that is not a distinct point and there is no distinct point at which cyclic mobility failure can be defined. So, as a result what is done some like you know that strain or some pore pressure is estimated. So, cyclic mobility is failure is generally considered to occur when pore pressure becomes large enough to produce ground oscillations. So, that is the point where the pore pressure becomes large enough and the ground oscillations are produced laterally spreading or other evidence of damage at the ground surface. So, the cyclic mobility have started where you have excess pore pressure and pore pressure reach to the point where laterally spreading started or there are other damages on the ground surface have started in that case, we shall assume rather than like in the flow liquefaction soil started flowing but soil may not start flowing in the case of cyclic mobility.

So, characterization of liquefaction resistance is developed along two lines methods based on the results of laboratory test and methods based on the in-situ test as we discussed earlier. Now, coming to the characterization which is based on the laboratory test. Most laboratory tests were performed on isotropically consolidated triaxial specimen or what we call K0 consolidated simple shear specimens. In this test liquefaction failure was usually defined as the point at which the initial liquefaction was reached or at which some limiting cyclic shear strain amplitude which is commonly 5 percent for dense specimen is reached. So, you have liquefaction failure, to define the liquefaction failure and this liquefaction failure is defined it will be which point where initial liquefaction was reached.

Now, the issue is sometimes it is difficult to judge whether initial liquefaction is started. For judging that cyclic strain amplitude which is normally considered to be 5 percent for dense specimen for the and when you reach to the 5 percent like strain then we say that this liquefaction have started. So, sometime it is based on the strain value or sometime it is based on the pore pressure value. So, that is coming to the continue with the laboratory test. Laboratory test shows that the number of loading cycles which is required to produce liquefaction failure N L decreases with increasing shear stress amplitude and with decreasing density.

So, what is here? Suppose if you increase the amplitude of your loading then it has been observed that liquefaction will occur in a smaller number of cycles. At the same time if you decrease the density of the sample so, in sample your loose sample will have liquefaction in a smaller number of cycles compared to dense samples and those data can be seen in the next cycle figure. While liquefaction failure can occur only in few cycles in loose specimens subjected to large cyclic shear stress thousands of cycles of low amplitude shear stresses may be required to cause liquefaction failure of dense specimen. So, this has been done here. So, in this case the in this figure laboratory data is shown from the two test part A is for the loose sample and which is have a relative density of about 47 percent dense relative density and the B is related to the dense end which have 75 percent relative density.

So, what happens here this is the number of cycles and what you could see there are two way to judge whether liquefaction is started. The top figure shows the cyclic shear stress with respect to time, second figure is shear strain and third figure is pore pressure. So, if in the second figure shear strain reaches to a point about 5 percent then we can say that liquefaction is started that is one way. Another way we say that pore pressure ratio Ru should be 1. So, if you see this is clearly touching the Ru here at this point and this is related to about number of 10 cycles.

So, this is about 10 cycles because it go in the 10 cycles. So, in the loose sample the liquefaction start in the 10 cycles and here one thing is the loose sample the loading amplitude is 20 kilo Pascal. Now, in the dense sample loading is applied amplitude has a 60 kilo Pascal which is 3 times of what has been applied to the loose sample, but still even you are applying the loading 3 times is still liquefaction the strain is not here you see this strain is 5 percent only here the scale was up to 20 percent. So, you even reaching 5 percent is taking so many cycles it is coming here around 5 percent. Similarly, if you see the value of Ru, so Ru is not touching to 1 it is barely touching here at the end here.

So, that means, it requires 17 cycles. So, for the dense sample you require more cycles number 1 at the same time you require higher amplitude of loading compared to the loose sample. So, these are the observations from the laboratory test. Continue with the characterization, the relationship between densities, cyclic stress amplitude and number of cycles to liquefaction failure can be expressed graphically from the laboratory data and that is called cyclic strength curves, and these curves are normally obtained from the cyclic triaxial test. Cyclic triaxial test we have discussed in detail when we talk about dynamic soil properties and this is shown in the figure in the next cycle. Cyclic strength curves are frequently normalized by the initial effective overburden pressure to produce what is called cyclic stress ratio and this is called CSR which we will discuss again in the next lecture in detail.

So, here the cyclic stress curves are there cyclic what is in this curves on y axis you have deviatoric stress sigma dc which is in kilopascal here on x axis you have number of cycles, but this number of cycles is not on the normal scale rather it is on the logarithmic scale. So, you see 10, 100, 1000, 10000 or like this. So, here you see that there are four curves in this figure and these four curves are for different voids ratio.

First one is top one is for a void ratio 0.61 and the bottom is for 0.87. When the void ratio is increasing that means your sample is getting loose. So, the top sample is the dense sample while the bottom curve belong to the loose sample. Now, what we see here first of all when the I decrease the deviatoric stress if for let us say if your deviatoric stress is more than 120 then for liquefaction you require only one or two cycles, but as the deviatoric stress decreases when the curve if it is decreases. So, it should be read on the y axis if I decrease the deviatoric stress then the number of cycles which is required for liquefaction increases tremendously. For example, here it was almost one cycle, but if I go here for this amplitude which is 80 you will require 1000 cycles.

So, at one place it was 1 and another place 1000 very large difference. Similarly, if suppose for the same deviatoric stress for example, if I draw a line here 60 for the same deviatoric stress, here this is loose sample it is dense sample. So, if I go from loose to dense sample then the number of cycles for the same deviatoric stress is increasing tremendously. So, this are and these data are from the actual data or test data from the laboratory. In the laboratory the samples has been tested and this has been verified and that is why this how the hypothesis or theory on the liquefaction has been created.

So, this is the last part of this lecture. For the cyclic simple shear stress the CSR, which is called cyclic stress ratio it is taken as the ratio of the cyclic shear stress to the initial vertical effective stress. So, cyclic shear stress is defined this one. And here what is SS? SS denotes your simple shear test. This that this stress is generated from the simple shear test. But it has been observed that the data which you obtain from cyclic triaxial and then simple shear they will correlate only when we have some relation.

So, cyclic is if I find the same parameter using cyclic or from triaxial test then it is defined in the triaxial rather than having cyclic stress we have the deviatoric stress sigma dc and in fact, sigma dc q is nothing but sigma dc by 2. So, if I divide sigma dc by 2 by sigma 3c then you get this ratio cyclic stress triaxial. And it has been observed they are not if I find the CSR value from triaxial or simple shear they are not the same rather than there is a relation if I get the value from triaxial then it can be converted into which belong to the simple shear by multiply by a factor correction factor CR. And this correction factor the value of this correction factor lies in the range 0.55 to 1.15 and depend on k0 and theory. What is k0? k0 is a coefficient of earth pressure at rest which can be find out using normally like you have 1 minus sin phi or this. So, here what you have different theory fin et al and then different equation. So, the value of k0 is if it equal to 0.4 then we can use this column if k0 increases then the CR increases.

For example, k0 equal to 1 minimum value of CR is 1. So, the fact this correction factor will be 1 but for most of the soil you will find the k0 in this range in that case you select the value from this and or you can use this equation for the CR is given or this equation can be used if you have the k just put the value of k0 in this equation and find out or in another equation. So, this CR can be find out and the CR the relation can be found. But it has been seen further that in contrast to laboratory cycle simple cyclic triaxial tests are produced shear strain in different directions which we already discussed. But in the field rather than having simple shear or the triaxial you have multi-directional shaking and it cause pore pressure to increase more rapidly than does unidirectional shaking. So, as a result if you find the CSR value in the field then this is about 90 percent of CSR for the simple shear and then CSR for simple shear can be done using what we say the CSR for the triaxial.

So, ultimately CSR field can be obtained 0.9 times of CSR and CSR triaxial. In the next lecture that is lecture number 37 we are going to discuss one example using this data which this data these curves which will again come on the next lecture and using this data and we are going to discuss one example on characterization based on the laboratories. So, with this I stop it here this lecture number 36 and thank you very much for your kind attention. Thank you.