Earthquake Geotechnical Engineering

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Lecture 37

Initiation of Liquefaction (Conti.)

I welcome you again for this NPTEL online course on earthquake geotechnical engineering. And we are at lecture number 37, which is for liquefaction of soils. And what we are going to discuss in this module 4, we already covered introduction, liquefaction susceptibility, we already partly covered initiation of liquefaction. So, in this initiation of liquefaction, the topics flow liquefaction surface FLS, influence of excess pore pressure EPP has been covered, evolution of initiation of liquefaction using cyclic stress approach has been started and we already covered characterization of earthquake loading based on simple methods and ground response analysis. So, the characterization of earthquake loading is over in the last lecture.

Today, in this lecture number 37, we are going to talk characterization of liquefaction resistance based on laboratory as well as in-situ test. Laboratory test have already started in the last lecture. And in this lecture, we are going to continue with the laboratory test and based on the in-situ test. As the in-situ test is concerned, we will be having characterization based on three types of in-situ test. One is standard penetration resistance, then cone penetration resistance and the shear velocity. So, in this lecture, we will cover based on the SPT and then in the next lecture, we will be covering based on the cone penetration and shear velocity. Coming to characterization which is based on the laboratory test, we continue and if you recall that this curve which is called cyclic strength curves has been discussed just in the last lecture. So, I will not repeat because that is what you can have in the last lecture. Now, what we are going to discuss in this lecture, how to use these curves if these curves are generated from the laboratory data and if suppose these curves are available to you, how to use this curve for like calculation in the field, for the field.

So, one of the example we are taking it here. A 2 meter thick layer of and this is from California Sacramento River sand and the properties of the layer E Young's and void ratio is 0.87 and phi is 33 and these properties are for this layer, the second layer 2 meter thickness. And this 2 meter thick layer is overlain by 4 meter compacted field and the effective overburden pressure is 91.3 kilopascal which is at the middle of the layer which we will check and show it.

The water table is at the bottom of the field which you can see here. Using the cyclic triaxial results, the question is to estimate the maximum cyclic shear stress which is required to initiate liquefaction in the sand in a magnitude 7.5 earthquakes. So, this is the sand layer here and it is compacted field layer. On the top of this you have compacted field layer. The top layer consist of compacted field and water table is here, so above water table because the soil will not be susceptible for liquefaction. So, we need to see the susceptibility of the sand layer for the liquefaction. For this what we do, we first of all find at the middle of the height of the layer effective overburden pressure which will be 4 meter into 2.1 for the top layer plus 1.91, 1 meter is the thickness and 0.91 is the submerged unit weight because it is saturated, and you are calculating effective overburden pressure. So, as a result here we need to use the submerged unit weight, this submerged unit weight rather than total saturated. Then it is g, so rho into g will be gamma 9.81, so ultimately you get 91.3 kilopascal, and this 91.3 kilopascal is very near to the data which is available to you from the lab which is the data available is done is at confining pressure, effective confining pressure 100 kPa.

So, these curves are at effective confining pressure 100 kPa. So, because this is very close to what is we are getting at the middle layer, so as a result we can use these curves for our analysis. So, what is this curve? Cyclic stresses which is required to produce initial liquefaction and 20 percent axial strain in isotropically consolidated Sacramento River sand, a triaxial specimen and which is after seed and lee 1965, these curves are from the after seed and lee of 1965. So, this is like we already discussed that what is on y axis and x axis, so what is done here? First of all, we are talking about the sand layer, so the sand layer e equal to 0.87 here. So, as a result we need to use a large curve which is for e equal to 0.87 from this and in this last curve we need to first select what is the amplitude of cyclic deviatoric stress which is coming in. So, amplitude of cyclic deviatoric stress can be calculated. First of all, a magnitude 7.5 earthquake is expected to produce about 14 uniform cycles, this we already discussed.

If you recall like number of cycles, there was a curve, and this kind of curve was there a line, and this was going like this and here you have number of cycles n and here you have magnitude and here you have n on x axis number of cycles was there. So, then you can read the number of cycles from this, and this number of cycles related to you get 10 for 7 magnitude earthquake. So, if this is for 7 and this is 10, so the number of cycles was 10 for 7, but for 7.5 it was 14 uniform cycles. And for 14 uniform cycles we read the deviatoric stress from this curve. So, what I do I need to use this one. So, this is 14 here somewhere and you find out 14 will be here, so 14 because it is log scale, so 14 will be somewhere here. So, what you get for 14 cycles it get about 39 or so 14 will be somewhere here. So, it comes about 39 kilo Pascal. So, for 14 cycles from using this chart and using the last curve you read the value is 39 kilo Pascal.

Now, for phi equal to 30 degree which is given for this soil layer k naught can be calculated 1 minus sin phi 0.46. For this k naught we calculate what we call the CR correction factor, which is 1 plus k naught divided by 2, so you get 0.73. Now, CSR triaxial can be calculated sigma dc by 2 sigma 3c, so 39 divided by 2 and sigma 3c is 100 to 0.195. CSR field will be 0.9 into CR into CSR triaxial. So, what we get in the field 0.9 multiplied by CR into this one. So, if I put the numbers then I get 0.128. And for this CSR field tow cycles can be calculated simply CSR field multiplied by sigma v naught. Here you need to understand this is effective overburden pressure, it is not the total. So, this will be the CSR field multiplied because the CSR is calculated based on this the effective overburden pressure. So, you get 11.7 kilo Pascal. Once you get this average tow cycle. So, tow max will be if I divide this value by 0.65 then you get the maximum shear stress which is 18 kilo Pascal. So, this way a peak shear stress of 18 kilo Pascal would be required to initiate liquefaction in this layer. So, here in this layer middle of this layer the cyclic maximum shear stress tow max which is required for the liquefaction to occur will be 18 kilo Pascal.

So, this much stress will be required. So, this is the final answer that you require a stress of cyclic shear stress of 18 kilo Pascal to start the liquefaction to initiate the liquefaction. Now, this was based on the laboratory test simply continue with the laboratory test characterization based on the laboratory test. These tests can also reveal the manner in which the excess pore pressure is generated. For stress controlled cyclic test with uniform loading Lee and Albaisa (1974) and DeAlba et al. (1975) found that the pore pressure ratio is related to the number of loading cycles by this relation which is simple relation half means 0.5 and thus here sine inverse. So, in this case in the bracketed quantities are just a ratio you get n by n L and 2 multiplied by 1 by alpha. Suppose I get alpha equal to 1 then it will be simply n by n L minus 1. So, if you put the value you check this relation if I put in this relation n equal to n L then what will happen irrespective of any value alpha the bracketed quantity will be 1 and sine inverse 1 will be pi by 2. If I get the sine inverse 1 then it will be pi by 2.

$$r_u = \frac{1}{2} + \frac{1}{\pi} sin^{-1}\left[2\left(\frac{N}{N_L}\right)^{1/\alpha} - 1\right]$$

So, then 1 by pi so it will be half plus half so in that case when n equal to n L the Ru you obtained from this relation is 1. So, simply at when n equal to n L your pore pressure ratio is 1 from this and this is expected. So, using this equation where what is in this equation n L, n L is the number of cycles which is required to produce initial liquefaction. Naturally the value of n cannot be more than n L maximum value of n is n L and when n is equal to n L then Ru equal to 1 and alpha is a function of the soil properties and test conditions. For example, for alpha equal to 0.7 the chart is like this here the dotted line this dotted line is for this curve is for alpha equal to 0.7. Here in this case when n or this ratio n equal to n L is equal to 1 then Ru is 1 but when this n or n L equal to 0 then Ru will be 0 because n equal to 0 means there is no cycles or that is in that case there is no chance of liquefaction because there is no loading basically. So, here this is the rate of pore pressure generation in cyclic CMPR test and this curve are nothing but they can be generated using this equation which we have already discussed. So, this was characterization based on the laboratory test and for this for a number of years liquefaction resistance was commonly characterized by cyclic stresses determined from laboratory test.

However, subsequent work showed that cyclic stress based measures of liquefaction resistance are influenced by factors other than the initial density and stress conditions. For example, liquefaction resistance is influenced by difference in the structure of the soil or soil fabric produced by different methods of specimen preparation. So, as a result the history of prior seismic straining also influences liquefaction resistance. For example, liquefaction resistance of a specimen that has been subjected to prior seismic straining is greater than specimen which are not subjected. Also, this liquefaction resistance will increase with increasing over consolidation ratio and lateral earth pressure coefficients.

So, that means the liquefaction resistance depends on many other factors which perhaps we are not accounting in the laboratory. For example, prior straining because a sample in the field is subjected to the prior straining or maybe over consolidation ratio is different or lateral earth pressure coefficient. So, in that case so many factors are there which you are not accounting in the laboratory when doing the cyclic triaxial test or simple shear test. As a result, many of these factors which is for example soil fabric, history of prior seismic straining OCR, then you have K naught, K naught that is the coefficient of lateral pressure at rest, length and time under sustained pressure, liquefaction resistance and difficulty in obtaining truly undisturbed samples suggest that liquefaction resistance should be characterized as far as possible based on the in-situ test. So, now we will switch over on the in-situ test.

We discuss, we complete characterization of liquefaction resistance based on the laboratory test and we are going to start characterization based on the in-situ test. When we talk about in-situ test we already discussed that we are going to using three type of test, one is based on SPT data, then the second one is based on the cone penetration test data and third is based on the shear velocity data. So, coming to this one characterization based on in-situ test. So, previous case histories can be characterized by the combination of loading parameters, two parameters, one is loading parameter which is L and another is liquefaction resistance parameter by R which can be plotted with symbol that indicates whether liquefaction observed or not. A boundary can then be drawn between these two parameters that have and not produce liquefaction.

For example, here is the case. Here on y-axis, you have the loading parameter, on x-axis you have the resistance. So, naturally when the resistance is more than the loading parameter then the liquefaction will not occur. So, if I go along this axis more than no liquefaction will occur. If I go more on the y-axis then liquefaction will be observed. So, in this case the solid circles, black dots, they represent the positions where the liquefaction was observed while the hollow circles are the case where the liquefaction, no liquefaction was observed.

So, continue with this boundary is normally drawn conservatively. So, to be on the safer side. Usually the cyclic resistance ratio which is called CRR in the short is used as a loading parameter and the in-situ test parameter that reflect the density and pore pressure generation characteristics of the soil are used, liquefaction resistance parameter. So, in fact, on the x-axis liquefaction resistance parameter may be your standard penetration resistance, it could be cone penetration resistance or it could be a shear wave velocity. While on y-axis in all the three cases we have one parameter which is called cyclic resistance ratio or CRR.

So now let us discuss based on the standard penetration. In fact, most of the studies which is based on the field test are used standard penetration test data. Why? Because standard penetration test data, SPT data are widely available. These are the tests conducted and they are not only popular in our country India, but they are worldwide very much popular including in Japan or USA. So, this because and the simple reason being that standard penetration test because you can get the sample also.

Standard penetration test has been widely used as the in-situ test characterization of liquefaction resistance. Factors that tend to increase liquefaction resistance for example, density, prior seismic straining, over consolidation ratio, lateral earth pressure and time under sustained pressure also tend to increase SPT resistance. So, this is very important which goes in the favor of in-situ testing that better we go for in-situ testing for liquefaction resistance rather than only simply laboratory testing. Because some of the factors which influence the liquefaction resistance, for example, written here density is there, prior straining, over consolidation, they will also increase the SPT resistance. So, as a result, SPT resistance is already like suppose you have SPT data.

So, n value will reflect having the effect of these factors which may not come in the laboratory data. So, the initial work was like by Seed et al. 1983. Compare the corrected SPT resistance which is said in N160, there is a term N160 and cyclic resistance ratio CRR for clean sand and silty sand sites at which liquefaction was or was not observed in earthquake of magnitude 7.5 to determine the minimum CRR value at which liquefaction could be expected in a clean sand of a given SPT resistance.

The following chart is prepared from these three data that is Pan American data that is all over the America, then Japanese and Chinese. So, this chart is there and the data, different data are listed here, the different notations that these are from US, these are from Japan or China. Now, what you have in this curve, you have three curves and in these three curves, the lowest one is for less percentage fine is less than 5%, 15%, 35%. And these SPT clean sand base curve is for magnitude 7.5 earthquake, and this is from a research paper by Yau et al. in 2001. So, what is the here, on X axis you have corrected blow count N160, what is N160 we are going to discuss in detail later, that is the corrected value of SPT resistance that is the N value, where N is the number of blows in SPT. So, you have number of blows, and this has been corrected for 60% hammer energy and at 1 bar effective overburden pressure which we will discuss. So, once N160 is there, so what we do from this chart, for given value of N160, for example 20, we pick up the value of cyclic resistance ratio. Here in this chart, both are written cyclic stress ratio or cyclic resistance ratio, but we will stick with one of them that is CRR only. So, when we read this chart, we say that CRR is obtained from this chart, the value of CRR in the short cyclic resistance ratio.

So, the liquefaction potential assessment procedures may be used with either standard penetration test blow count or cone penetration test. So, this is like what we are going or maybe the shear velocity which is measured within the deposit which is described as follows. And what we are going to discuss later, they are basically based on the code IS 1893 part 1, 2016 and in this code, there is annex-F is nothing, but it describes the simplified procedure for calculating the liquefied potential. So, because this code, Indian standard is easily available, so I will suggest that you go through that annex-F of the code. Now, evaluation of liquefied potential as given in this code, what we are going to discuss is already given in the code, I am going to explain each and every step one by one, but the data which is shown here is coming from the IS code.

So, in the step one, the subsurface data which is used to access liquefied susceptibility should include the location of the water table number 1, naturally you should know where the water table is there. Either SPT blow count N or cone tip resistance QC of a CPT cone or shear velocity VS, three data you require either N, QC or shear velocity. Then, out of these three, one data is required at least. Then, you need unit weight of the soil and fine content of the soil that is what is fine content? Percentage by weight which passing through the IS standard sieve number 75 micron.

So, which passes through the 75 micron sieve. 75 micron sieve can be said as a 0.075 mm, so 0.075 millimeter sieve. So, these are the data required in step one. Second step, you will let total vertical over burden stress that is sigma v0 and mind it here, it says total not effective and the second effective vertical overburden pressure. So, both total is also required and effective is also required and this need to be calculated different depths for all potentially liquefiable layers within the deposit. So, this need to be calculated for all the layers and we will discuss one example on this and then all the steps will be very clear. Then step three, what we need to find? We need to find the stress reduction factor Rd which can be found out using the either of these two equations which we already discussed in the last lecture depending on the depth z where z is the depth in meter below ground surface. Once Rd and the sigma v0 is noted then you can calculate cyclic stress ratio which is called in the short CSR which is induced by earthquake loading is given by this relation. CSR equal to tau average and this is tau average need to be divided by the effective overburden pressure.

So, in this case on the right hand side you have everything dimensionless 0.65 a max by g, a max by g will be dimensionless because a max is represented in terms of g. And another ratio total overburden pressure divided by effective overburden pressure multiplied by Rd, what is Rd here? Rd is reduction factor due to the depth, a max is the peak. So, sigma v0 and sigma v0 they will depends normally in this case this will be gamma into hz with the depth and this will be gamma effective, this will be gamma effective into z. So, only one unknown that left out is a max if you put the value first because Rd can be calculated with the depth using the chart or using the equation which is given here.

$$CSR = \left(\frac{\tau_{av}}{\sigma'_{vo}}\right) = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) r_d$$

So, everything is known except a max. Normally if nothing is given then a max can be linked with the seismic zone. Naturally in higher seismic zone, zone 5 it will be the higher for example, in a max in zone 5 you can take 0.36, in zone 4, 0.24 or then you can have 0.16 or 0.10 like that. So, once CSR can be found in step 4. Now in step 5, obtained cyclic resistance ratio CRR by correcting standard cyclic resistance ratio CRR 7.5 for which is an earthquake magnitude 7.5, high overburden stress level at high initial shear stress using. So, CRR can be calculated, CRR 7.5 is read from the chart or from the equation which we are going to give later, multiplied by MSF. What is MSF? MSF is nothing but it is called magnitude scaling factor. So, MSF is nothing but magnitude scaling factor, short of the magnitude and that means depending on the earthquake magnitude the MSF will vary. In IS code 1893 suggest that MSF can be calculated using this relation where Mw is the magnitude, moment magnitude of the earthquake.

$$MSF = 10^{2.24}/M_w^{2.56}$$

So, this using this relation MSF can be calculated. Normally when the magnitude of earthquake 7.5 then MSF will be 1. So, you will get the MSF equal to 1. MSF equals 1 for 7.5 magnitude. But if magnitude is higher than 7.5 then MSF is more than 1. But if magnitude is lower than 7.5 then MSF will be less than 1. So, this way we can find the MSF. Now in this equation CRR 7.5 from the chart or equation this is known, only two factor k alpha and k sigma is left out. And what these two factors define which is here, the correction for high overburden stresses is called k sigma is required when overburden pressure is high that means depth is more than 15 meter then only, we this require this correction and this correction can be found using which is equation given sigma v effective overburden pressure divided by atmospheric pressure. And naturally when you use this equation then both overburden effective overburden pressure as well as atmospheric pressure, they should be represented in the same units multiplied by the f minus 1 and where f is a constant which is exponent which is like depends on the soil property.

So, f is arranged depending on the relative density of the soil. So, this was k sigma. Then another factor k alpha is coming k alpha depends on if you have sloping ground or you have the flat ground k alpha is taken 1. So, both the factor in fact for most of the simple analysis we take both of these factor 1, 1. So, if you take 1, 1 then they becomes neutralized they become redundant. So, for most of the analysis these factor may not be considered they may be required if you have very high overburden pressure or you have the sloping sides rather than gentle slopes.

So, now coming to this one let us assume that we calculated CRR which is CRR 7.5 and this. Then what we do how to find the value of CRR 7.5. Now the issue is this here CRR 7.5 how it is calculated as we said CRR 7.5 can be calculated using different methods. We are going to discuss in the next few slides based on the SPT that is standard penetration test data. So, what you do you will let the SPT blow count N 1 60 for a hammer efficiency 60 percent at an effective overburden pressure 1 bar which is 100 kPa roughly 96 like kPa. So, that is why it is called N 1 60. One subscript says that it is at effective overburden pressure 100 kPa 1 bar and 60 says it is calculated for a hammer efficiency 60 percent.

So, suppose if your hammer efficiency is different then this can be calculated E m is the measured energy and this is free fall energy. So, normally E m will be at least 60 percent of E f f. So, if suppose if I take very conservative approach and if I put E m equal to 0. E f f in this equation then what will happen if this is the case then this factor becomes 1. If it is 70 80 percent like E m m is 0.72 it will be 1.2. So, normally this ratio will not be less than 1. So, for the conservative side many times this ratio is taken 1 as a result this equation this part is neutralized. Now, two other factors are what is N m? N m is the measured N value of N using SPT data in the field while C n is a correction which is called correction due to overburden pressure and this correction can be applied using either this equation 0.77 log 10 2000 sigma v naught. Here sigma v naught is in terms of kilo Pascal kilo Newton per meter square or using this equation.

$$(N_1)_{60} = C_N N_m \frac{E_m}{0.60 E_{ff}}$$

$$C_N = 0.77 \log_{10}\left(\frac{2000}{\sigma'_{vo}}\right) \text{ or } C_N = \sqrt{\frac{P_a}{\sigma'_{vo}}} \leq 1.7$$

In this equation sigma v naught and p a they should be represented in the same unit. So, it is not necessary that it should be in kilo Pascal but the unit of p a and sigma v naught should be the same as a result this ratio will be neutralized and this says ultimately this C n which you find should be less than or equal to 1.7. So, the code suggests that the value of C n in the calculation of this C n in this formula should not be taken more than 1.7. So, this is how we find the value of N 1 60. Once N 1 60 is known but it has been observed that this N 1 60 which we are obtaining is for the clean sand where you have the percentage fines is less than 5 percent. But it has been observed that the presence of fines affect the SPT resistance and how they affect the SPT resistance. When the fines increases then the SPT resistance will increase, or liquefaction resistance will increase. When the liquefaction resistance is increased that liquefaction resistance increase in liquefaction resistance can be taken care that we increase the corresponding value for the clean sand N 1 60 C s that is for clean sand here.

And if you have this some constant alpha and beta that depends on your fine content. So, in this list when fine content is less than 5 percent then alpha equal to 0 and beta equal to 1. So, that means N 1 60 C s will be same as N 1 60. When between 5 to 35 percent alpha can be calculated using this equation and beta from this. But if your fine content is more than 35 percent then alpha is taken 5 and beta equal to 1.2. So, this value of alpha and beta depending on the fine contents can be taken from this list and as a result finally, we are able to calculate what we call N 1 60 C s and that is then the value of N 1 60 for clean sand. Now, as we discussed there are charts was given by Yaw et al if you recall this these are chart which we have already discussed. But to find the value of CRR and this CRR which you find from this chart is for 7.5 magnitude earthquake. So, basically the CRR which you obtain from this chart which is CRR 7.5. This can also be obtained without using this chart using some equations which is given here and these equations are coming from the IS 1893. So, this equation in this equation on the right hand side you have only one parameter which is N 1 60 C s. That means this is the value of N 1 60 which is for the clean sand that means correction for the fine contents has been already applied.

$$CRR_{7.5} = \frac{1}{34-(N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{\left[10(N_1)_{60cs}+45\right]^2} - \frac{1}{200}$$

And once CRR 7.5 is known then what you do you can find the value of CRR which is we already discussed CRR is find out from this equation. So, CRR is here 7.5 is known then CRR is obtained and then finally, what we call the factor of safety against liquefaction is found simply ratio of CRR versus cyclic stress ratio. If your factor of safety is less than 1 then soil is assumed to be liquefied otherwise not to be liquefied. So, this was the case when we using this chart, but in the code IS code these charts are given like this in the IS 1893 the charts are given for 5 percent 15 percent and 35 percent, and this is again for 7.5 magnitude earthquake, and you need to apply the correction factors as required. It can be observed the CRR required to initiate liquefaction for when N 1 60 increases then it will increase. Now, the last part of this lecture this even on the resistance and the data it has been observed that the cyclic resistance ratio it is influenced by the plasticity in the soil and not only one side is the fines. Here when we talk about fines it means they are the nonplastic fines, non-silts and other things, but in case you have plasticity some Pi then they also influence resistance and it has been observed that they try to exhibit excess pore pressure as a result the liquefaction resistance increases. And laboratory test also indicate that little influence of plasticity indices if Pi is less than 10 then there is no effect, but if Pi is more than 10 then there is effect. So, what is a factor f is if Pi is greater than 10 then you use factor f equal to 1, but if your Pi is greater than 10 then this equation should be used where the value of f which you obtain from this equation will be more than 1.

So, the CSR which you obtain this should be actually CRR here. The CRR which you obtain from the charts or the equation should be multiplied by this factor f and then we use the same for further calculation. Since most sandy soils the man-made fields have indices the effect of fine plasticity is usually small because Pi less than normally less than 15. So, as a result the effect of the plasticity is considered to be small on this. And then you have the data from strong ground motion. The cyclic resistance ratio CRR required to initiate liquefaction decreases with increasing magnitude. So, this was all about. Thank you very much for your kind attention. Thank you.