Earthquake Geotechnical Engineering

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Lecture 38

Initiation of Liquefaction (Conti.)

I welcome you again for this NPTEL online course on earthquake geotechnical engineering and this is lecture number 38 which is on liquefaction of soils, and we are discussing on initiation of liquefaction. We are under chapter number third of this topic on liquefaction under the module 4 and what in this chapter we already covered these topics flow liquefaction surface, influence of excess pore pressure EPP, evolution of initiation of liquefaction using cyclic stress approach and cyclic strain approach. So, we already started cyclic stress approach. So, we are under CSA cyclic stress approach and we already covered in lecture number 36 characterization of earthquake loading based on simple method and ground response analysis. Last lecture that is 37 we started this topic on characterization of liquefaction resistance based on the lab as well as in-situ test.

We continue with the in-situ test and within the in-situ test we already covered using SPT data standard penetration test data. Today we are in this lecture we are going to talk two of the field test one is cone penetration resistance test, and another is shear wave velocity test. And once characterization based on in-situ test is over we are going to talk about a numerical example how to calculate the liquefaction potential and finally, evaluation of liquefaction initiation will be done. So, here we continue characterization based on in-situ test and we come SPT is over we are going to discuss what we call in the short CPT that is based on the cone penetration test or cone penetration resistance.

Why like instead of SPT why people use cone penetration data? The important point is this one that when you get in cone penetration you get a continuous curve in SPT you get the scattered data that means the data which you get in SPT as different level because in SPT what you do you collect a sample and for testing that for the collection of the sample you need to take out. So, you do not get the continuous data, but in CPT good point you get the continuous data that is one point which goes in the favor of CPT. Another issue in the CPT that if you have some thin layer, it could be missing the SPT data, but it is not missing the CPT data. Then third point which goes in the favor of the CPT that you get more repeatability of the sample like the test can be repeated. So, this due to this pronounced advantage or the SPT I said detect the seams of loose sand and many other advantage CPT is getting.

Only the disadvantage of CPT, one you do not get the soil sample. Second, like in this case if you have very hard soil then SPT can be conducted, but CPT cannot be conducted. So, many times the data of the SPT, the CPT data should be supplemented with the correlation between SPT and the minimum cyclic resistance ratio CRR to have to cyclic resistance ratio for to have the liquefaction are generated. So, the exercise is similar what we have discussed in the last lecture. So, I think I will go little quickly compared to the last lecture.

Here the CPT and this is what we are going to discuss is again based on the code IS 1893. The CPT processes require normalization of measured cone tip resistance. What is cone tip resistance? It is in the short QC. QC is measured. In case of SPT we measured n value. Here we measured tip cone tip resistance and this tip resistance of the cone need to be normalized by atmospheric pressure PA and a correction for overburden CQ. So, the QC is a value measured in the field and this is normalized with PA. What is PA? Effective overburden pressure and multiply by a correction factor which is for overburden CQ and CQ will depends on your effective overburden pressure at the depth. The exponent n what is the value of n? The value of n depends on the type of soil. If you have it is for the sand it is 0.5, but if you have clay then the value of n is 1. So, everything is known here. So, QC is measured from this field and then we find the normalized this QC1 n. So, QC1 n is obtained from this equation and then we go further. One QC1 n which you obtained in the last equation is for the clean sand that means if this fine content was less than 5%.

$$q_{c1N} = C_Q\left(\frac{q_c}{P_a}\right)$$

$$C_Q = \left(\frac{P_a}{\sigma'_{vo}}\right)^n$$

Suppose in sand you have the fine content like in SPT we have applied correction. Similarly, in the CPT data also a correction factor KC multiplied by this value which you obtained in the last equation will give the equivalent value for the clean sand. Now what is KC? Naturally, KC will depends on your fine content. KC will be 1 if you have the IC equal to or less than 1.64. If your IC is greater than 1.64 then you need to use this long equation for calculate the value of KC. Now in this equation IC is coming. The question is what is IC? To calculate the IC this is another equation which depends on the Q and F and what is Q and F? Q is given from this relation and F is given by this relation. In the Q you have QC which is measured resistance of the cone sigma v naught if total overburden pressure where Pa is same as an atmospheric pressure and sigma v naught this is effective.

$$q_{c1N} = C_Q\left(\frac{q_c}{P_a}\right)$$

$k_c = 1.0$ for $I_c \le 1.64$

$k_c = -0.403\, I_c^4 + 5.581\, I_c^3 - 21.63\, I_c^2 + 33.75 I_c - 17.88$

for $I_c > 1.64$

So, in this equation both total overburden pressure and effective overburden pressure is coming while F depends on another factor which is measured sleeve friction. So, basically in the cone penetration data you are measuring two things from the field. One is tip resistance QC and another is you are measuring the sleeve friction FS. So, sleeve friction and you mind it that in these all equation right hand side is dimensionless. This is a ratio of stresses this is also ratio.

$$I_c = \sqrt{(3.47 - logQ)^2 + (1.22 - logF)^2}$$

$$Q = \left(\frac{q_c - \sigma_{vo}}{P_a}\right)\left(\frac{P_a}{\sigma'_{vo}}\right)^n$$

$$F = 100\left(\frac{f_s}{q_c - \sigma_{vo}}\right)$$

This is FS and QC should be in the same unit. So, this will be ratio. So, irrespective of whether it is kilo Pascal or it is in pound square that is not going to make a difference because there is cancel down. So, Q and F is calculated from these equations you put in this top equation get the value of IC and if your IC is greater less than 1.64 then KC will be simply 1, but if it is more than 1.64 then KC is calculated from this relation given here. Then once this is calculated that means we are ready with QC1 and CS. Once QC1 and CS is known to you then this QC1 here in this of course it is written QC1N, but because we have taken the care of the CS is simply saying that this data is taking care of fine content also. So, whatever QC1N or QC1N CS is found for that you find out the value of CRR from this chart. Again, in this chart we will use CRR only we will be going with the CRR rather than CSR and this chart is developed for magnitude 7.5 per kth as was the case for. So, using this chart you can find read the value of CRR 7.5 that can be done, but alternatively what you can do if you do not have this chart we can use these equation to calculate the CRR 7.5 and the top equation is used when your QC1N CS is coming between 0 to 50, but if this QC1N CS is between 50 to 160 then you get this. And here if you go in the last equations here this QC1N this is the equation it is dimensionless. QC is not dimensionless. QC dimension it is tip resistance it will be the unit in the stress and then you have Pa atmospheric pressure. So, both will be dimensionless. So, QC1N will be simply a number it is here. So, here simply QC1N CS will be also a number and using QC1N CS so it is dimensionless. If it is between 0 to 50 then we can use this equation which is divided by 1000 and multiply 0.883 and you get this one, but if it is between 50 to 160 then this equation it will not be more than 160 like this. So, ultimately we calculate CRR 7.5 and once CRR 7.5 is known then you can calculate applying what is the magnitude scaling factor MSF, find the value of CRR and again which we discussed in the last lecture for SPT factor of safety is given by this one.

If your factor of safety is less than 1 then the soil is assumed to liquefy otherwise we say there is no liquefaction. So, this was based on the what we call the CPT data. Similarly, using the shear velocity data also used improved method of in-situ shear velocity measurements and studies related to the development of the cyclic strain approach have contributed to the recognition of shear velocity as a useful measure of liquefaction resistance. So, if suppose you do not have a SPT data, you do not have a CPT data in the field, but you may have the MASW data using the shear velocity in that case those data can also be used to calculate the liquefying resistance. And applying correction for overburden stress by shear velocity vs for clean sands using this relation, the correction this is for clean sand, shear velocity is obtained for the clean sand from the field and then we apply this correction.

All the corrections carry two factors one is atmospheric pressure Pa and effective overburden pressure including Cn for the SPT data. So, using this correction which is basically for overburden pressure then we get the value of Vsn where Vsn is the overburden stress corrected shear velocity. But here Vsn will not be dimensionless rather Vsn will have the same unit as Vs. So, and if Vsn is known then using this chart we find out the value of CRR. Again, we say cyclic stresses I will delete it cyclic we go with the cyclic resistance ratio that is CRR only. And in this case overburden stress corrected velocity Vs1 is used on the x axis. Once Vsn you read and Vsn is not dimensionless it is in meter per second. So, you have here that between 100 to 200 and if shear velocity is going more than 200 then it exponentially increases the value of CRR and it is expected. And this result which you read from this chart is CRR it is for 7.5 magnitude of the earthquake. So, once you after reading this if you need to calculate for other magnitude then you need to apply correction factor. So, alternatively CRR 7.5 rather than calculating from this chart they can also be calculated from this relation. In this relation Vs1 is as we already discussed A and Vs1 star, star is used as a limiting upper value of Vs1 for liquefaction occurrence. So, that means this is the higher than the Vs1.

A and B are curve fitting parameters. The values of A and B in these figures are 0.0022 and 2.8 respectively. So, using this can also be done. But the shear velocity is insensitive to factors for example, the factor soil fabric over consolidation ratio for prior cyclic straining these factors influence the liquefaction resistance.

$$CRR_{7.5} = a\left(\frac{V_{s1}}{100}\right)^2 + b\left(\frac{1}{V_{s1}^* - V_{s1}} - \frac{1}{V_{s1}^*}\right)$$

But the shear velocity which you measure in the field it is not influenced by these factors. So, it is discouraged to use the shear velocity for calculating the liquefaction resistance best way is to calculate the SPT data or the if SPT or CPT data. So, that means. So, this was about the characterization of liquefaction resistance. Now here a comparison of different tests has been done. Three tests which we have discussed one is for SPT another is CPT and Vs. The data for SPT and CPT are available in abundant but for shear velocity is limited though it is due to availability of MASW it is not no more limited it you can get the data. Then stress strain behavior partially drained large strain, repeatability is very good particularly in the CPT it is poor to good in this case of. So, repeatability is SPT data cannot be repeated. So, if the same site you conduct the SPT test again you may get the different number of you know the n values.

So, that depends on the skill also. Good for closely non gravel site it can be used and this is okay for soil sample is retrieved only in SPT you get the soil sample in other case you could not get the soil samples. So, this is basically advantage and disadvantage of various. So, this was all about the in-situ test. Now we go to the next part of this lecture that is liquefaction potential one of numerical example we are going to discuss very simple numerical example and this numerical example is based on the SPT data. Suppose SPT data is given to you available to you for a site now you need to determine whether liquefaction will occur or not if liquefaction occurs up to what depth it will occur and after what depth it will not occur.

So, this is a simple example and please try to understand this example clearly. It says that determine the liquefaction susceptibility of a site in a zone third what is when we say this zone third that basically it is hydrate seismic zone third this is seismic zone third for an earthquake of magnitude 7.5 using seed and this method and data given for the soil are fines content in soil less than 5%. So, the fine contents are less than 5% and magnitude of earthquake is 7.5. So, that means you no need to apply correction for magnitude. Saturated unit weight of soil is gamma sat is given 20 kilo Newton per meter cube unit of water is 10 kilo Newton per meter cube. So, as a result these two data submerged unit weight gamma submerged will be gamma saturated minus gamma w which comes out to be 10 kilo Newton per meter cube because so this data will be there. Values of n 1 60 of course varies with the different depths and it is an example these data are not real data for depth 5 meter 10 meter 20 meter for simplicity in the calculation n 1 is here 10 15 20 25. So, the actual condition they do not increase and the depth which you are selecting is lower interval it is not that you can take the data at 5 meter 10 meter or like this one rather you have almost every meter or sometime at 0.75. Water table is at the ground surface. So, first of all for the zone third PGA can be taken from the core seismic IS 1893 as a 0.16 g as a result your A max by g will be 0.16. So, the average cyclic shear stress which is given by the relation 0.65 sigma v naught A max by g into r d can be simplified from here and you ultimately end up 0.10 sigma v naught into r d. What is sigma v naught? Sigma v naught is total overburden pressure. What is r d? Reduction factor and let me emphasize it again when you calculate the value of tau average it should be total overburden pressure not the effective overburden pressure. Most of the students make the mistake here that in this equation they use effective overburden pressure as a result their whole calculation further becomes wrong. So, be careful otherwise if you use effective overburden pressure here in this equation you will get the 0 marks. Here like what you have in this equation you calculated, and the calculation is done in the tabular form.

In the table you have 4 depths here which is shown. For 4 depths, depths 5 meter 10 meter. In the first column because here we assume that your the soil conditions are uniform that means gamma is constant from top to bottom. In actual case it may not be there but for simplicity we are assuming all the 4 layers have the same gamma and the water table is at the top. So, here in this case total overburden pressure will be simply gamma into H which will be gamma saturated into H.

So, you have 20 multiplied by depth so 100, 200, 300, 400. However, effective overburden pressure will be calculated using gamma submerged into H where H is the height actually. So, as a result depth so you have half because gamma submerged is half for this given problem so you have 50, 100, 150, 200. The reduction factor R d in this case is calculated from the equations which we have discussed which is based on the Z. So, 0.98, 0.93, 0.83. Then toe average which is 0.104 into sigma v because both are known here now, but while you calculate use in this equation total not effective you calculated the cyclic average shear stress. Then N 160 this is given to you. Corresponding to N 160 using the chart or using that equation you find out the value of cyclic resistance CRR and this CRR is for 7.5 magnitude.

But in this example the magnitude is given itself is 7.5 so you do not require any correction further. So, toe which is the cyclic shear stress required to cause liquefaction is simply CRR multiplied by effective overburden pressure. Now here it is effective overburden pressure. It should not be total. In this case it is total here while effective. So, you should not swap or you should not use total both places or effective both places. So, at one place is total when you calculate the cyclic shear stresses caused inside the soil due to earthquake loading then total overburden pressure will be used. But when you find the what is the shear stress required to cause the liquefaction then you will calculate using effective overburden pressure. So, ultimately you have calculated this column and this column. The ratio of these two will give you because this column give you the resistance so toe divided by toe average will give you the factor of safety against the liquefaction.

And you see the toe of two layers have less than 1 and this third layer have the factor of safety more than 1. So, certainly there will be liquefaction up to 10 meter but there will be no liquefaction after 15 meter. So, that means liquefaction will occur beyond 10 meter also but before it will stop before 10 meter but exactly you cannot say with this data. So, liquefaction will stop somewhere here that where the factor of safety is 1. So, this was an example a simple example to calculate the liquefaction potential.

Now, we have the last part of this lecture which is on the evaluation of initiation of liquefaction. How this liquefaction starts initiated in the field that is we are going to discuss one by one. So, here once the cyclic loading which is imposed by an earthquake and the liquefaction resistance of the soil have been characterized using what the same parameter normally we do using cyclic stresses. Liquefaction potential can be evaluated. The cyclic so basically what we are doing we are summarizing it here using the cyclic stress approach which is we call in the short CSA.

So, in this next few slides we are summarizing the steps of the CSA cyclic stress approach. So, in the first step earthquake loading by the amplitude of an equivalent uniform cyclic stresses. So, this is earthquake loading is represented and this is done using two methods ground response analysis or simple process simplified process which is given by seed and

Idriss. For the second step liquefaction of one is related to earthquake loading. The second is liquefaction resistance of the soil which is characterized by the amplitude of uniform cyclic stress required to produce liquefaction in the same number of cycles.

So, in the second step we try to have number of cycles equivalent number of cycles where the liquefaction occurs. So, this will be denoting the liquefaction resistance of the soil. So, if the liquefaction resistance is high you will get more number of cycles. If liquefaction is low you will get less number of cycles. And then the evaluation of liquefaction potential is thus simply reduced to a comparison of loading and resistance throughout the soil deposit of interest. The evaluation is easily performed graphically, and the steps are given here. The first step the variation of equivalent uniform cyclic shear stress that is due to earthquake loading which is denoted as two cycle with depth is plotted as given in the figure that is the number of equivalent cycles Neq corresponding to earthquake loading must be determined if the liquid resistance to be characterized using laboratory test result. If you are using the laboratory test data for characterization of liquid resistance, then you need to denote how many number of cycles and this number of cycles can be find out using the magnitude of earthquake that is there. But if you are using the data from the field then number of cycles is not required because you apply a correction factor what is called MSF which is magnitude scaling factor is applied on the CRR 7.5 multiplied by MSF give you the value of CRR for other magnitude of earthquake.

So, there are different philosophy. We use number of cycles in the laboratory data but we use MSF in case of liquid resistance found from the field two test data. So, here what you do in this graphically it is explained here that how to find the liquid resistance potential of a site. In this curve this is the curve where equivalent cyclic shear stress induced by an earthquake. This is due to seismic loading this curve is due to seismic loading that is the stresses induced inside the soil and this is cyclic shear stress required to cause liquefaction. So, what is this represent? This curve is for this one first of all this is this curve is representing and this is nothing, but this is representing liquefaction resistance. So, this liquefaction resistance will come either from the laboratory data or from the field data. From field here we will calculate in this case using SPT data, SSTU data. So, wherever this like cyclic shear stress which is induced is more than the resistance liquefaction occur.

So, this is the zone of liquefaction. So, zone of liquefaction is lies. So, this layer will liquefy. So, that means liquefaction will not occur no liquefaction here and below this also no liquefaction. So, liquefaction is confined to some zone.

So, this way we can find out. So, this was the step one. In the step second the variation of cyclic shear stress which is required to cause liquefaction with the depth is then plotted on the same graph which must correspond to the same earthquake magnitude or same number of equivalent cycles and then we compare. Liquefaction can be expected depth where the loading exceeds the resistance or when the factor of safety angle is liquefaction is less than 1 and factor of safety, we already discussed is expressed here cyclic stress required to cause liquefaction divided by equivalent cyclic shear stress induced by an earthquake. So, tow cycle L divided by tow cycle or simply CRR divided by CSR give you the factor of safety and if factor of safety is less than 1 then the liquefaction occurs. Now the issue is here sometime it has been noted that even significant excess pore pressure can be developed even if the computed factor of safety is greater than 1. So, we are saying factor of safety is more than 1 it does not mean the pore water pressure will not develop, excess pore water pressure may develop and particular level ground side for example, the magnitude of this EPP can be estimated as given in the next figure.

The reduction in effective stress which is associated with such EPP can reduce the stiffness of the soil and as a result significant settlement can occur as when the EPP dissipate. Factor of safety against the liquefaction having greater than 1 is not enough because still if there is a development of excess pore water pressure and when the excess pore water pressure get dissipated in that case it may lead to the large settlement and the calculation of this excess pore pressure can be estimated from this chart here. And here what you have in this chart on x axis you have Fs which is the factor of safety, and its liquefaction and Fs is varying from 1 to 2.6 while on y axis you have Ru pore pressure ratio when Ru is 1 then pore pressure ratio is maximum when Ru is 0 pore pressure ratio is pore water excess pore pressure is 0. Now in this chart it has been divided into two categories this is sand here and this shaded line is for the gravel. Let us discuss for the sand so what do you have when Fs is almost 1 then you get Ru equal to 1 but as the factor of safety increases from 1 to 2.6 you see the value of Ru decreases. Even let us say when I have factor of safety equal to 1.2 which is quite more than 1 but still if I draw and I connect it here then what will happen that you can roughly, so the value of Ru is about 0.2 that is 20 percent.

So, that means even your factor of safety is greater than 1 but that does not mean the pore pressure will not develop still the pore pressure may develop and which can be calculated from this. So, this was all about initiation of liquefaction and we have completed with this lecture all the topics related to cyclic stress approach. In the next lecture that is lecture number 39 we are going to talk about cyclic strain approach. Thank you very much for your kind attention. Thank you.