Earthquake Geotechnical Engineering

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Lecture 32

Liquefaction Susceptibility

I welcome you again in this NPTEL course on earthquake geotechnical engineering and this is lecture number 32. That is the second lecture on fourth module of the course which is on liquefaction. As we discussed earlier, under this module we have four chapters and in with this lecture we are going to start the second chapter on liquefaction susceptibility which will consist of lecture number 32 as well as 33. According to this liquefaction susceptibility what are going to cover during this chapter factors affecting liquefaction and liquefaction susceptibility which will consist of four criteria's historical criteria, geologic criteria, composition and state criteria. So, we are going to discuss these criteria one by one and today we are going to talk about the first three criteria and state criteria will be bigger which we will discuss in lecture number 34. Coming to the factors affecting liquefaction.

The factors which affect the liquefaction are listed here there are the nine factors. One is grain size distribution of sand, density of deposit, initial relative density which is denoted as DR, vibration characteristics, location of drainage and dimensions of deposit, magnitude and nature of superimposed loads, method of the soil formation, period under sustained load, previous strain history and entrapped air. So, we are going to discuss these factors one by one in the next slides. As for grain size distribution of sands is concerned fine grain sands are more prone than the coarse grain sands.

Since so, this is for the sands itself within the sand if you have fine grain because you have three types of sand one is fine grain then medium grain and coarse grain sand. So, between fine grain sands and coarse grain sand, fine grains are more prone between fine and medium grains. So, in fact, fine grain sand and medium grain sands are subjected to liquefaction, but coarse grain sand is only subjected to liquefaction only remotely. So, this is rare. Since the permeability of coarse sand is greater and what is the reason why the like compared to the fine grain like coarse grain sand because coarse grain sand have the higher probability compared to the fine sand as a result the pore pressure which is developed during vibration or during shaking get dissipate more easily and the chances of liquefaction reduces.

So, the chances of liquefaction are less in the coarse grain soil compared to fine grain soil. Then uniformly graded soil or what we call the poorly graded soils are more susceptible liquefaction than well graded soils sands. If you have the sand composition which is well graded chances of liquefaction will reduce with grading if grading is improved. Second factor initial relative density and you know this factor is directly linked to the what we call the void ratio. So, void ratio when the void ratio increases initial relative density will decrease, when the void ratio decreases initial relative density will increase.

So, chances of liquefaction and excessive settlement are reduced with increase in relative density, or I can say it decrease in void ratio, increase in relative density is same thing increase or decrease in void ratio, void ratio e. So, when the e decreases the chances of liquefaction reduce. Loose sands are more prone to liquefaction compared to dense sands. So, this is about the relative density. Coming to vibration characteristics, if you have the shock loading or what we call the impact loading may able to lead liquefaction at a faster range than the steady state vibration.

Only horizontal vibrations are more severe than vertical vibration. During the earthquake you get the horizontal vibrations and that is the reason that chances are more in during the earthquake for liquefaction rather than the normal loading vertical loading. If you have multi directional shaking which is the case in the earthquake you not only have the horizontal like vibration, but you have the vertical also is considered to be more severe than the one direction shaking for the liquefaction. Dimension of drainage and dimension of deposit also make a difference on the liquid and susceptibility. Sands are generally more pervious than fine grain soils.

Fine grain soils means you have the clay and silt, and sands are naturally more pervious than this one. However, if a deposit has large dimension and the drainage path increases then during earthquake the deposit may behave as if it were undrained because if you have a long drainage path it does not dissipate the water that path is longer than it may behave like a impervious material and particularly during it was undrained case. So, the drainage is not and then when undrained cases happens then there is increase in pore water pressure and that results in the liquefaction. Therefore, the chances of liquefaction are increased and for that the gravel dents are introduced to stabilize a potentially liquefiable sand deposits. The next magnitude and nature of superimposed loads.

Large initial effective stresses if soil is subjected or soil deposit is subjected to large initial effective shear stresses then it will reduce the possibility of liquefaction in isotropic stress condition. If the initial stress condition is not isotropic that means it is anisotropic then the stress condition causes liquefaction depending on the k 0 value. What is k 0? k 0 is nothing but here coefficient of lateral earth pressure across and for higher value of k 0 chances of liquefaction increases. So, when the k 0 increases chances of liquefaction will increase. As for method of soil formation is concerned, liquefaction characteristics of saturated sands under cyclic loading are significantly influenced by the method of sample preparation and by the soil structure.

Period under sustained load older deposits are less prone to liquefaction while the newer deposits are more prone to liquefaction. Strength increases with age may be due to some form of consolidation or welding which may occur at contact between sand particles. Prior sand history, Seed in 1976 publication showed that although the prior strain history caused no significant change in the density of the sand, it increased the stress that caused liquefaction by a factor of 1.5. So, if you have previous like it is already subjected to strain in the then chances are there that chances of liquefaction increase.

But if you have the trapped here air inside the voids then it will have to reduce the possibility of liquefaction because the voids may be filled with air rather than water. So, the chances of liquefaction reduces. So, these are the different factors which affect the liquefaction phenomena. Coming to the next, a liquid susceptibility. As we discussed earlier also in the last lecture, not all soils are susceptible to liquefaction.

Consequently, the first step in a liquefaction hazard evaluation is usually the relation of liquefaction susceptibility. If your soil conditions are such that they are not susceptible, then you can terminate your liquefaction hazard analysis irrespective of the shaking and other things. If the soil at a particular site is not susceptible to liquefaction hazard do not exist and the liquefaction hazard evaluation can be ended as we discussed earlier. But if the soil is susceptible to the in that case, we need to consider the liquefaction initiation and effects must be addressed. So, first whether liquefaction will be initiated or not and if it is initiated then what will be its effects that need to be discussed.

As we discussed there are several criteria by which liquefaction susceptibility can be judged and some of these are different for flow liquefaction and cyclic mobility. So, these criteria can be categorized in the four category. First is historical criteria based on the history and the past literature. The second is geological criteria based on the geology tectonics of sites. Third one is compositional criteria where what is the composition of the soil, grain size diffusion all these things will come.

The first last one is the state criteria. So, today we are going to discuss the first top three criteria. So, let us start from historical criteria. As for the historical criteria is concerned a great deal of information on liquefaction behavior has come from past earthquakes. So, from past so this should be from the come from the post-earthquake field investigation.

So, this is from the whenever an earthquake occurs. Some field investigation has been done after the earthquake which have shown that liquefaction often recurs at the same location. At the same location, liquefaction may occur chances are more that so if some site is subjected to liquefaction in the past chances are there that it may be further again subjected to liquefaction during the next earthquake. Particularly when soil and groundwater condition have remained unchanged. If because for the one of the condition for the liquefaction water table should be not very deep.

So, if the water table conditions are similar to earlier case it does not change then the it is chances that the same site may undergo the liquefaction. Therefore, this liquefaction characteristic can be used to identify specific sites or more general the condition that may be susceptible to liquefaction in future earthquakes. Post earthquake I have also shown that liquefaction effects have historically been confined to a zone within a particular distance of the seismic source. So, you have seismic source means basically epicenter of an earthquake and normally it has been observed that this liquefaction sites are within some kilometers along the epicenter. It is not very thousands of kilometer away from the epicenter.

So, what has been done by Ambraseys in 1988 compiled worldwide data from shallow earthquake to estimate a limiting epicenter distance beyond which liquefaction has not been observed in earthquakes of different magnitudes and this is given in the slide. What is in the slide? On the y axis you have moment magnitude of earthquake while which is on the normal scale which is varying from 5 to 9 while on x axis you have epicenter distance which is in kilometer, but x axis is on the log scale it is not a normal scale. So, you have 2 kilometer, 5 kilometer, 10 kilometer. So, for example, if epicenter distance or let us say if earthquake magnitude is less than 6 then you could see that if for less than 6 magnitude earthquake this if I draw a line here then it says and these are the earthquake. So, to occur the liquefaction these are the dots or the solid dots on the top of this line are the points where the liquefaction is occurring while the circles, hollow circles below this line are the points which are showing no liquefaction occur.

So, to liquefaction to occur for near the epicentral distance even you may require less magnitude of earthquake. So, even up to if your magnitude of earthquake is less or I can put it other way that if your magnitude of earthquake is less than 6 then the liquefaction will occur only near the epicenter at up to a distance let us say this distance will be because it is on the log scale. So, this will be about 25 kilometer. So, the epicentral distance should be less than 25 kilometer if your magnitude of earthquake is less than 6 to liquefaction occurs. So, if you are going let us say 50 kilometer, 100 kilometer away from this epicenter if I let us say I go 100 kilometer away from the epicenter then magnitude required is almost 7.

So, suppose an earthquake occurred at some site with magnitude 7 then you can expect that liquefaction at the most can occur up to a distance 100 kilometer. Beyond 100 kilometer chances of the liquefaction may decrease. Similarly when you increase here when you are increasing the magnitude of earthquake the chances of liquefaction it is that it may occur at far away, but here like even for 9 magnitude earthquake 500 kilometer.

So, you may not expect the liquefaction beyond 500 kilometer distance from the epicenter of the earthquake. So, that is this is from the historical data.

This is not the theoretical or thumb rule there could be exception, but these data are coming from the worldwide data. So, if you increase the magnitude then chances that liquefaction may occurs far away, but if magnitude is less than the liquefaction phenomena will be confined to a certain distance up to the from the epicentral distance. So, depending on that. So, in general because like soil may not be susceptible sometime so it is maybe rare that if your magnitude of earthquake is less than 6 chances are there that liquefaction may not occur because even if it occurs then it may be only confined to the very close to the epicenter. So, this was what we have discussed.

Continue with the historical criteria. The distance to which liquefaction can be expected increase dramatically with increasing magnitude. This is not a linear relationship rather the curve is going like this. So, that is exponential increase with the magnitude the distance up to which it occurs is increasing dramatically. It is not that if you jump from 6 to 7 magnitude then distance will be double rather distance is going from 25 to 100 kilometer.

When you go from 7 magnitude to 8 magnitude then distance is going or 7 to 9 magnitude then distance is going from 100 kilometer to 500 kilometer. These relationship shown in the figure though this is a general imperial like based on the data, but it does not offer any guarantee that the liquefaction may not occur less than these distances. So, exception is there. So, this was all about historical criteria.

Now about the geologic criteria. Soil deposits that are susceptible to liquefactions are formed within a relatively narrow range of geological environment which was like given by paper by Yaud in 1991. So, there is a narrow range. The deposition environment, hydrological environment, hydrological environment means it is related to what we say that water conditions and age of a soil deposit all contribute to its liquefaction susceptibility. Geologic process that source soil into uniform grain size diffusion and deposit I mean loose stress produced soil deposited with high liquefaction susceptibility. If the condition is loose, then the chances are more that liquefaction will occur.

Continue with this geologically this criteria from geologic point of view. If you have the fluvial, colluvial and aeolian deposits, all these terms are related to geology. You have fluvial, colluvial and aeolian deposits and when they get saturated, they are likely to be susceptible to liquefaction. Liquefaction has also been observed in what we call alluvial plain, breach, terrace deposits, but they are not as consistent as those listed in previously. That means in these deposits' liquefaction may occur or may not occur.

Then susceptibility of older soil deposit to liquefaction is generally lower than that of newer deposits. So, this we discuss also earlier for the soils and the same is applicable for geological that means for the rock also. If you have the older soil deposits the chances are reduced. Soils of Holocenic age are more susceptible than the soils of Pleistocene age. That means the soils which are the older formation are less susceptible.

Soils of the Holocene newer formation, so you can say this is the newer, relatively newer and this is older formation. So, more susceptible. If so age when the age increases chances of liquefaction decreases. The liquefaction of the Pleistocene deposits is rare. If you go even older than this one, then chances are very low.

Liquefaction occurs only in saturated soils. So, the depth of groundwater either influences liquefaction susceptibility or it is direct relation. When the groundwater is at shallow depth then the chances of the liquefaction increases, but if your water table is very deep then the chances decreases. Then susceptibility decreases with increasing groundwater depth. So, when the groundwater depth increases that means like you know the water table is going down then effects of liquefaction are most commonly observed at sites where groundwater is within a few meters of the ground surface. For example, in the Roorkee Haridwar region the water table is highly variable.

During monsoon what happens? The water table comes almost on the ground surface, but during the peak summer it goes very down. So, as a result the chances of liquefaction is quite high during the monsoon period, but it is in the peak summer when the water table is deep the chances may reduce. At sites where groundwater levels significantly fluctuate liquefaction hazards may also fluctuate. One of the example is as I said let us say Roorkee Haridwar region where the groundwater table fluctuate depending on the season very much. Then continue with the geologic criteria human made soil deposits that is manmade soil deposits also deserve attention and because normally you may not get the natural state of the soil the chances because you may have the loose fields such as those placed without compaction are very likely to be susceptible to liquefaction.

In this case I think one of the case which is terminology if you heard it is called reclaimed land, for example, Singapore city is mostly on the reclaimed land. Similarly, one of the example in our country for reclaimed land is Navi Mumbai. In Navi Mumbai what has been done the land has been created by dumping the sea. So, and then the artificial land has been created, but when this land is created it is not in the natural form and it there could be the loose compaction. If the soil is susceptible then the chances are there that in the loose compaction the chances of liquefaction is more.

The stability of hydraulic filled dams and mine telling piles in which soil particles are loosely deposited by setting through water remains an important contemporary seismic hazard. Well compacted fills are unlikely to satisfy state criteria for liquefaction susceptibility. So, once you have if you have well compacted fills that means, filling has been done and compacted properly then chances of the liquefaction reduced. Since liquefaction requires the development of excess pore pressure, liquefaction susceptibility is also influenced by what we call the compositional criteria. So, we already discussed historical criteria, then geologic criteria and now we are going to discuss compositional criteria.

And liquefaction susceptibility is quite much influenced by the compositional criteria and these compositional characteristics in fact influence the what we will say the volume change behavior. So, volume change behavior takes place. The components with the high volume change potential tend to be associated with high liquefaction susceptibility. So, here you can simulate like this one. If you have the some soil deposits where you apply particularly in the dry case when you apply the stress and if there is a large change in the volume, chances are there that when you do not allow the drainage then there will be high development of pore water pressure and chances of liquefaction is more.

These characteristics for composition include particle size, shape and gradation some of these we already discussed when we discussed the factors affecting liquefaction. For many years liquefaction related phenomena were thought to be limited to sands that means, earlier it was thought that only sands may be subjected to the liquefaction. Fine grain soils which consists of clay and silts were considered incapable of generating the high pore pressure commonly associated with liquefaction and coarse grained soils are considered to be too permeable to sustain any generated pore pressure long enough for liquefaction to develop. So, earlier what has been observed like thought that only fine grained soils only the fine sands will be subjected to liquefaction fine grained soils as well as coarse sands may not be subjected to liquefaction. However, more recently the bounds on gradation criteria have been broadened and how this has been broadened this is based on what is called the plasticity, but in general this composition of criteria given in the slide is based on the old thought of school.

Here what is done, and this is the most like vulnerable range for liquefaction. So, in this slide you have what is the we call the classification of the soils based on the different. Here you know 75 micron sieves divide between fine grained soils and coarse grained soils. So, on the left hand side you have fine grained soils, on the right hand side you have coarse grained soils.

And up to let us say 0.002 mm you have the silt. Then within coarse grained soils you have sand, gravels and then later other cobbles and boulders. So, when you have sand and within the sand you have three types one is fine, medium and sand. So, when you chances of liquefaction is high for fine and medium sand, but less for the coarse sand. This is the most vulnerable range like within this ellipse the soil susceptible to liquefaction and which consists of basically fine sand, medium sand and silt. When we talk about silt it is basically non plastic silt, silt could be plastic and non plastic.

If you talk about clay, clay will always be plastic for when you talk about clay the plasticity will be there, but the for the silt plasticity may be or may not be there. So, liquefaction of non-plastic silt have been observed in the laboratory and as well as in the field indicating that plastic characteristics rather than grain size alone influence the liquefaction susceptibility of fine grained soils. So, for fine grained soils we need to link with the PI. If PI is high, plasticity is high then the chances reduces, but if it is non plastic silt chances are most. Coarse silt with bulky particle shape which are non plastic and cohesion less are fully susceptible to liquefaction as recommended by Ishihara in 1993.

Finer silt with flaky or plate like particles generally exhibit sufficient cohesion to inhibit liquefaction. So, to inhibit means to avoid the liquefaction so chances reduces. So, if you have the finer silt and a plate like particles then chances are reduced, but in the coarse silt when you have particularly bulky particle shape then the chances the liquefaction is high. But in general, you can say non plastic silt are subjected to liquefaction while plastic silt may not be subjected. Continuing with the finer soils, clay remain non susceptible to liquefaction although sensitive clays can exhibit strain softening behavior similar to that of liquefied soil.

So, what we call the clay may also lose its shear strength due to loading, due to shaking, but this will be treated as strain softening behavior rather than a liquefaction for the clay. Fine grain soils that satisfy each of the following four Chinese criteria may be considered susceptible to significant strength loss. So, for fine grain soils these are the four criteria, and all these four criteria need to be satisfied for liquefaction susceptibility. If even one of them is not satisfied, then we say that chances of liquefaction is not there.

First criteria said the fraction which are finer than 0.005 millimeter should be less than 15 percent, it should not be more than 15 percent. If it is more than 15 percent, then you no need to check other criteria. So, then you can rule out the susceptibility. If answer of the first question is yes then you say liquid limit should be less than 35 percent, it should not be more than 35 percent.

Then natural water content should be 90 percent of liquid limit. So, this is the third criteria and then liquidity index should be less than or equal to 0.75 and for a soil to be susceptible mind it all these four criteria need to be satisfied simultaneously. Even if one of them is not satisfied then we will say that soil is not susceptible to liquefaction. Now, coming to the gravels we talk about the fine sands particularly the clay and silt, but what happens to gravels? So, normally gravels are not considered to be you know susceptible to liquefaction, but it has been this is on another end of the grain size spectrum one side you have clay and sand another side you have gravels. Liquefaction of gravels has been observed in the field as well as in the laboratory.

The effects of membrane penetration are now thought to be in response of high liquefaction resistance observed in early laboratory in the field of gravel soils. So, what has been observed in the early investigation in the labs that the liquefaction there is high liquefaction resistance that means chances of liquefaction is less and this was due to the what is called the effects of membrane penetration. So, now the effect when we avoid the effect of membrane penetration later investigation has been pointed out that even gravels are susceptible to liquefaction. When pore pressure dissipation is impeded by the presence of impermeable layers, so that truly undrained condition exists gravel is soil can also be susceptible to liquefaction. So, if you have the impermeable layers where the permeability get reduced then the chances even is for this chances are there that liquefaction occurs even in the gravels.

According to the continue with the compositional criteria there is one of the issues related to gradation. Liquefaction susceptibility is influenced by gradation and well graded soils are generally less susceptible to the compared to the poorly graded or uniformly graded soils this has been we already discussed. Because what happens in the well graded soil there is a filling of voids between the larger particles by smaller particles in a well graded soils. This results in lower volume change potential under undrained condition and consequently lower excess pore pressure under undrained condition. So, you side one side you have drained condition another side you have undrained condition.

So, lower volume change potential will be there when you have you when you allow the drainage then volume change potential will be lower, but when you do not allow the drainage. So, then will be excess pore water pressure will be developed and this may lead to the liquefaction. Field dependence indicate that most liquefaction failure have involved uniformly graded soils rather than the well graded soils. Then the particle shape also make the difference particle shape also influence the liquefaction susceptibility. Soils with rounded particle shapes are more susceptible to liquefaction compared to if you have the angular particles grain soils.

So, angular grain size soils are better to avoid the liquefaction than the rounded particle shapes. Particle rounding frequently occurs in the fluvial and alluvial environments where loosely deposited saturated soils are frequently found and liquefaction susceptibility is often high for these areas where you have alluvial environments. So, this was all about liquefaction susceptibility. So, three criteria's one is historical criteria, second geological criteria, third is compositional criteria we have discussed and the last criteria which is based on the state criteria we will discuss in the next lecture that is lecture number 33. With that thank you very much for your kind attention. Thank you.