Earthquake Geotechnical Engineering

Prof. B. K. Maheshwari

Department of Earthquake Engineering

Indian Institute of Technology Roorkee

Lecture 31

Introduction

I welcome you all for this NPTEL online course on earthquake geotechnical engineering. And today we are going to talk lecture number, we are going to start fourth module of this course which is on liquefaction of soils. And as I mentioned earlier that two of the topics of this course, one is on dynamic soil properties and another is liquefaction of soils, they are the biggest topics here. And each one consists of a full module of 10 lectures. So, we are going to cover during this module 4 which is on liquefaction of soils. Introduction on the subject, what is the liquefaction and theory part of liquefaction.

Then the second chapter of this module will consist of liquefaction susceptibility. So, the first introduction will consist of one lecture while the liquefaction susceptibility will consist of another two lectures. Third topic of liquefaction of soils which consists of initiation of liquefaction where we are going to talk about that about how to determine the liquefaction potential using field test as well as laboratory test where we are going to talk about cyclic stress ratio and cyclic stress, strain ratio approach. And the third chapter will consist of five lectures.

Finally, the last topic on this module is effects of liquefaction chapter number 4 of this module and which will consist of two lectures. So, this all together we have one, two and five and then we have another two lectures. So, let us start from the first one which is introduction which consists of only one lecture. Here when we talk about introduction what is going to be covered is introducing you with the liquefaction.

Theory, liquefaction related phenomena, two phenomena's one is called the flow liquefaction another is cyclic mobility we are going to discuss in detail. Evaluation of liquefaction hazard whether liquefaction hazard exist or do not exist we are going to talk about that and finally, we are going to talk a brief case study where liquefaction induced failure of a dam was observed in 1971 earthquake. Coming to the introduction part of the liquefaction I think if you recall that when I started this course in the first lecture itself many slides was shared where many examples of severe damage during due to the past earthquake has been shared and some of the examples was liquefaction induced bearing capacity failure of foundations and which was discussed in the beginning of this course.

The damage of some buildings and bridges particularly in 1964 Niigata earthquake, 1999 Chichi Taivan earthquake and 2001 Bhuj earthquake were discussed in detail with photographs in first lecture. So, you can refer to the first lecture of this course on the liquefaction induced failures and damages.

Coming to how the liquefaction studies started worldwide, this is one of the most important interesting complex and little bit controversial topics in earthquake geotechnical engineering. Why it is controversial because some of the things still are under debates among the researchers where there is no consensus about some issues which are related to liquefaction. In 1964 though this liquefaction term was coined in 1952 and 53 by Japanese scientist by some Mogabe. However, the actual worth of liquefaction studies can be considered from 1964 onwards where two largest earthquakes one was Good Friday earthquake of 1964 with a magnitude 9.2 which occurred in the Alaska province of United States in March 1964, and it was followed just after 3 months by Niigata earthquake with magnitude 7.5 in Japan in June 1964. So, in a span of 3 months there was two major earthquakes one was magnitude more than 9 another was magnitude more 7.5 and they occurred in the time the largest economy of the world two largest economy of the world United States and Japan. They shake it and the worldwide studies started after 1964 particularly the studies started at UC Berkeley and in US as well as in Japan for the liquefaction. So, now it is going to be almost 60 years next year it will be 60 years diametrically for this both the earthquakes.

So, it is long journey for liquefaction. So, we are going to discuss in this lectures what is development like in the last years. So, we are going to talk about that. So, both these earthquakes have produced spectral examples of liquefaction induced damages and those damages include slope failure and when the slope failed because both the Alaska and Niigata there was a huge landslide also, but many of the landslide was attributed to the liquefaction. Then failure of foundation bridges and buildings and flotation of buried structures.

So, these were the some of the outcome of these earthquakes and as I mentioned in the last 60 years lot of studies has been done worldwide by hundreds of researchers around the world. Now, coming to the theory part of liquefaction, what is the liquefaction how it occurred let us discuss that in the few next slides. In general, when we say liquefaction is a phenomena in which soil loses shear strength because when we talk about the soil the shear strength is the most important property of the soil and the loss of this strength shear strength takes place in sandy soils due to increase in pore water pressure. So, the increase in pore pressure is considered to be an hallmark of the liquefaction phenomena. So, whenever we talk about liquefaction, so basically this is USB for the liquefaction this is an hallmark for that that there will be increase in pore water pressure.

As a result, effective stress will decrease, and shear strength will reduce and if shear strength is reduced to almost 0 that is the point where we say the liquefaction. This phenomena occurs mostly in loose and saturated sands. The increase in pore pressure cause a reduction in the shear strength which may even be lost completely. So, if there is complete loss of the shear strength that is the point where we say that it is the liquefaction. Soil that loses its shear strength will behave like a viscous fluid and the behavior of the soil becomes like a fluid.

So, that is the point where we say the liquefaction. Now, coming to some equation small equations. When we talk about the sand where c equal to 0, in that case shear strength will come mostly from the internal friction which is due to phi. So, for a steady case the shear strength may be written as sigma n minus u into tan phi where phi is angle of internal friction. What is sigma n? Sigma n is the normal pressure or normal stress, and u is pore water pressure which can be said gamma w into z where gamma w is the unit weight of the water and z is the depth where you want to find the pore pressure.

$$\tau = (\sigma_n - u) \tan \phi$$

So, this can be also explained using this figure that this but now this normal stress at point z at a depth z can be represented by sigma n equal to gamma saturated into z where gamma saturated is nothing but saturated unit weight of the soil. Thus, for a steady case the shear strength will be the gamma sat into z minus gamma w z into tan phi and this can be expressed in the compact form using what we call this effective stress. So, this is effective stress, effective normal stress while gamma v is you know that submerged unit weight of the soil. So, thus using the submerged unit weight of the soil and the depth you can find what is the shear strength of the soil particles at a depth z. But all these was without when in a steady case when there is no shaking.

$$\sigma_n = \gamma_{sat} z$$

Thus for static case,

$$\tau = (\gamma_{sat} z - \gamma_w z) \tan \phi$$

which can be expressed as

$$\tau = \overline{\sigma_n} \tan \phi = \gamma_b z \tan \phi$$

When you shake this, what happens? If we put a piezometer here and after shaking before shaking the level of water inside this piezometer will be only up to the ground level it will not be increased. But when you shake it then water level that increases in this tube which is piezometer, and it is increased let us say by an amount h w. So, this additional head is created by this due to the shaking and what is the implication of this. During earthquake there is increase in pore pressure and this increase in pore pressure can be represented by delta u we see delta u is nothing but gamma w into h w due to shaking of ground. And shear strength in this case may be expressed as tau equal to gamma submerged into z minus delta u into tan phi where delta u is nothing but the increase in pore pressure due to the earthquake or due to shaking.

Now, this increase in pore pressure can be represented by the additional head which is created by the shaking that is simply gamma w into h w. So, this is the delta u basically this is nothing but delta u additional head which is created. Now, when you have in this equation if gamma b z and gamma h w is same equal in that case this is the condition for tau to be equal to 0. In this case shear strength will be completely lost and it will be 0. In this case this can be simplified using where gamma v is submerged unit weight g minus 1 1 plus e what is g here g is not shear modulus rather here g is specific gravity of the soil specific gravity of the soil particles.

Here for the typically for a soil if I consider void ratio equal to 0.6 e equal to and g equal to 2.6 in that case I cr will be 1 and h w will be z. That means for in this case for the soil property with a specific gravity 2.6 and void ratio 0.6 the additional head required for complete loss of strength is same as the z. So, in this case you will have equal to the depth of the deposit is required. So, in this case both will be the same. In this case h w and z will be the same the additional head required is the same as the depth of z. So, this is the condition where you can say that soil lose its strength completely.

And this loss of strength occur what we called physically this was mathematically what we have discussed. Physically what happens the loss of strength in the soil will occur due to transfer of inter granular stress from grains to pore water. If this transfer is complete, then there will be complete loss of strength. However, if a stress is only partially transferred from the grains to the pore water only partial loss of strength will occur. So, depending on that like in this case what happens if whole of the load is transferred to the pore pressure, then we say that complete transfer has occurred while if it is only like partly transferred then it will be the partial loss of strength.

Continuing with this since the stress condition is cyclic particularly when you talk about an earthquake or dynamic loading a momentary transfer was cyclic in the cyclic what happens like you have the load one side and then you have the load reversal. So, because this in the cyclic loading what happens thus this may be momentarily transfer because when there is a load reversal then it may be again may come in the original position or maybe at least it is reduced. So, since this due to the cyclic nature of the loading a momentary transfer of all initial effective confining pressure to the pore water may not be of great significance if the subsequent behavior of sand is satisfactory from consideration of load carrying capacity in dense sands. So, it is not necessary that whenever the liquefaction occurs always there will be damage because this liquefaction phenomena could be momentarily where the load is transferred to the pore pressure only for a few fraction of seconds and then again in the next cycle reversal of cycles takes place then it is alright satisfactory behavior is there. During liquefaction a decrease of effective stress means a reduction in strength hence greater strength or settlement will take place.

What happens in that during liquefaction? We expect there are two issues particularly related to foundation. One issue is related to that the bearing capacity of foundation may decrease number one. At the same time the settlement may be excessive settlement or that could be large settlement due to the liquefaction phenomena. Therefore, as soon as partial transfer of stress occurs settlement tend to start. In case soil remain liquefied it behaves as viscous material and the structure resting on such a material where the behavior of the soil becomes fluid starts sinking into it.

So, the rate of sinking will depend upon the structure, the viscous properties of the suspension that is of basically soil material and its mass density. The total amount a structure sinks depends upon the time for the sand remains liquefied because as we discussed during the load reversal this liquefaction phenomena may be recovered again, or the dissipation may take place. The structure may settle if the stress transfer from the soil grain to pore water is partial. So, there could be the settlement if this load transfer mechanism from to the pore pressure is partial, but structure can be simply sink if the soil is completely liquefied. Continuing with the theory part, as soon as liquefaction occurs the process of consolidation starts and that will be followed by surface settlement that results in a closer packing of sand particles.

So, that is another phenomena. When the liquefaction occurs, some water will come on the top, but the remaining part of the soil there will be close packing of the particles and the its density may increase. During this process the pore pressure start dissipating and water flows upwards. So, the like what has been seen I think if you recall in the beginning of this lectures or during the Bhuj earthquake there was lot of liquefaction was there and the water comes from the fountains like in the form of fountains and it was a liquefaction related phenomena where the water comes out of the sand bowls, but some people attributed that phenomena as a revival of the river Saraswati. So, this was about theory part of the liquefaction. Now, we have there are different phenomena which are related to liquefaction, and we are going to talk about these phenomena.

These two phenomena are one is the flow liquefaction, and another is called cyclic mobility. So, into two main groups flow liquefaction. In case when the flow liquefaction takes place, shear stress is greater than the shear strength of the soil. So, flow liquefaction will occur only when the shear stress inside the soil exceed the shear strength of the soil. So, its strength shear stresses are more than shear strength the flow liquefaction occurs, but in case of cyclic mobility which even can occur when the stresses shear stresses are less than the shear strength of the soil, but it occurs because repeated stress loading and the repeated loading phenomena is very common when we talk about the cyclic loading particularly during earthquake.

Both flow liquefaction and cyclic mobilities are very important and any evaluation of liquefaction hazard should carefully consider both of these phenomena. So, we will discuss in detail both of these phenomena in next few slides. In the field flow liquefaction occurs much less frequently than cyclic mobility. So, because for flow liquefaction shear stresses which is generated need to be exceeded shear strength. So, as a result this phenomena occurs frequency is less compared to the cyclic mobility.

Cyclic mobility can occur under a much broader range of soil and site condition than the flow liquefaction and its effects can also be very damaging. Sometimes it could be insignificant, but it could be highly damaging. So, effects of the cyclic mobility will vary from insignificant to highly damaging. Flow liquefaction produces the most dramatic effects that is tremendous instability known as flow failures. So, flow liquefaction and flow failures as we discussed that for the flow liquefaction the condition required that shear stresses generated inside the soil should exceed the shear strength.

So, with that there may be tremendous instabilities as a flow failure. Flow liquefaction can occur only when the shear stress required for the static equilibrium of soil mass that is static shear stress is greater than the shear strength of the soil so which is we already discussed. Once triggered the large deformations produced by flow liquefactions are actually driven by static shear stresses. So, the flow liquefaction is a phenomena which is driven by static shear stresses and these static shear stress, in this case static shear stress need to be exceeded shear strength of the soil. So, that is we already discussed shear strength of the soil.

So, when the static shear stress exceed the shear strength of the soil then this phenomena occurs. While the cyclic stresses, this is not cyclic mobility. So, there are two part, still we are discussing flow liquefaction only. So, cyclic stresses should not be confused with cyclic mobility.

Cyclic mobility is different phenomena. The cyclic stress is some stresses generated inside the soil due to static loading, then additional stresses will be generated by the cyclic loading and the cyclic stresses will be on the top of static stresses may simply bring the soil to an unstable state at which its shear strength drops sufficiently to allow the static stress to produce flow failure. So, static stresses was already exceed the shear strength and on the top of it when the cyclic stresses are added, then what will happen? The flow will start. The soil particles will start moving with the water. Flow of liquefaction failures are characterized by the different, what are their characteristics, the certain nature of their origin, they are suddenly appear. They occurs at a very high speed, the speed which they develop and the large distance or which the liquefied material often move.

So, if the flow liquefaction occurs, then it is going to be very highly damaging. So, once flow liquefaction occurs, it is going to be highly damaging. Its damages are not going to be insignificant. On the other hand, the damage which is caused by cyclic mobility may be insignificant or may be highly damaging. So, the range is wide, but for flow liquefaction if it occurs, it is sure the damage is going to occur.

Now, let us discuss about cyclic mobility. This can also produce large permanent deformation during earthquake shaking. In contrast to cyclic mobility, flow liquefaction, cyclic mobility occurs when the static shear stress is even less than the shear strength of the liquefied soil. The deformation which is produced by the cyclic mobility failures develop incrementally during earthquake shaking. That means, in fact, the cyclic mobility is in incremental process, it is not a sudden phenomenon like the flow failure, flow liquefaction. In this case, in number of cycles, this cyclic mobility may not start in the beginning, but with the different number of cycles, when the stresses are generated incrementally, then the cyclic mobility may take place when the number of stresses, number of cycles have increased.

In contrast to flow liquefaction, the deformation which is produced by cyclic mobility are driven by both cyclic and static shear stresses. So, here this is the difference, this is the major difference between flow liquefaction and cyclic mobility. Flow liquefaction was driven by static shear stresses, while cyclic mobility is driven by the combination of cyclic and static shear stresses. So, the static shear stresses itself is enough to develop flow liquefaction, but for developing cyclic mobility, you require not only static shear stress, but you require both cyclic and static shear stress.

So, this is the difference between these. These deformations which are termed as a lateral spreading, lateral spreading is a liquefaction related phenomena and it is basically related to cyclic mobility. So, cyclic mobility will lead to the lateral spreading which can occur on very gently sloping ground or on flat ground which is adjacent to bodies of water. For example, if you have some river or you may have some lake or nearby that and you have almost flat ground not a very sloping ground, gently sloping ground, then lateral spreading may occur where the in the lateral spreading the cracks will develop in the lateral direction. When structures are present, lateral spreading can cause significant damage and some of the examples like could be seen in the past earthquake that the cracks has been developed along the sea shore or along the like you know the river bodies or water bodies.

So, that in that case that is the lateral spreading. Then there are another phenomena which is related to cyclic mobility only called level ground liquefaction. A special case of cyclic mobility is level ground liquefaction because static horizontal shear stress that could leave lateral deformation do not exist. Level ground deformation can produce large and chaotic movement known as ground oscillations during earthquake shaking but produces little permanent lateral soil movement. So, here the oscillation may be large, but permanent soil movement or displacement produced is maybe smaller. Continuing with level ground liquefaction, these flows are caused by the upward flow of water that occurs when earthquake induces excess pore pressure dissipates.

What happens? During a shaking, during liquefaction, excess pore water pressure develops, but a point will come where it gets dissipated. Depending on the length of time required to reach hydraulic equilibrium, level ground liquefaction failure may occur well after ground shaking has ceased. Excessive vertical settlement and consequent flooding of low-lying land and the development of sand boils are some of the examples are related to the level ground liquefaction. Now, coming to the evaluation of liquefaction hazard, we are going to discuss that how to evaluate. Both flow liquefaction and cyclic mobility can produce damage at a particular site and a complete evaluation of liquefaction hazard require that the potential for each be addressed.

That means, if you want to have the complete evaluation of liquefaction hazard, then we need to consider both flow liquefaction as well as cyclic mobility. There could be possibility of both of these phenomena either of them. When faced with such a problem, the earthquake geotechnical can systematically relate potential of liquefaction hazard by addressing following three questions. First question, is the soil susceptible to liquefaction? The second, if the soil is susceptible, will liquefaction be triggered? Third, if liquefaction is triggered, will damage occur? So, you need to give the answer of these questions one by one. If the answer of the first question is the soil susceptible liquefaction is no, then you can terminate the liquefaction hazard analysis and no need to answer the second and third question.

But if answer of the first question is yes, then we need to go to the second question and again if the answer of the second question is no, then we can stop our analysis at the second point. But if answer of the second question is yes, then we need to move to third question. Yes, the liquefaction will be triggered, but it is not necessary that damage will always occur. So, the soil may be first thing for liquefaction damage, you need to first, susceptibility should be yes, second liquefaction should be triggered, third, damage will depends on your structures, on the locality and extent of liquefaction, it may not be always even when the liquefaction is occurring. So, these questions pertain three most critical aspects of liquefaction hazard evaluation, susceptibility, initiation and effects and these all three susceptibility, initiation and effects we are going to discuss in detail in the next lectures.

Now, the finally to conclude the first lecture of this module fourth, there is a case study, liquefaction induced failure of a dam, a failure of lower and upper San Fernando dam in USA in 1971 earthquake. The lower San Fernando dam, 26 meter of the dam was constructed by the hydraulic film method and the height was raised to ultimately up to 42.7 meter by some another technique. The foundation consists of about 10.5 meter of sand and stiff clay overlying soft rock. So, you have below soft rock and on the top of soft rock you have the sand and stiff clay. So, here is a photograph of the dam. So, this is the lower San Fernando dam, typical cross section through embankment, on the top is before the earthquake and at the bottom after the 1971 earthquake. So, what happens you can see when the earthquake occurs, this dotted line is showing, this dotted line is showing that top portion of the dam is toppled that get failed that is taken away by this. But fortunately, what happens when this earthquake occurred on February 9, 1971 with a magnitude 6.6 and its epicenter was located about 14 kilometer northeast of the dam. 14 kilometer is not a large distance for an earthquake and it was very close, so epicenter was very close to the dam site. Maximum ground acceleration which varies quite high 0.5 to 0.6 for a period of about 12 seconds. So, with that the Tp was for 12 second period it was about 0.5. During the earthquake a major slide occurred on the upstream phase taking within the crust and the upper 9.2 meter of soil on the downstream side. So, the 9.2 meter of the top portion was washed away by this earthquake. However, at the time of earthquake the water level was 10.5 meter down from the top from the crust.

So, as a result if even after the taking this like 9.2, so a free board of about 1.3 meter remained available after the slide. So, there was not like casualties of course, there was lot of damage. So, but there was about 80,000 persons had to be evacuated in very hurry manner. And however, conventional pseudo-static analysis did not for warrant against the near failure which actually occurred for this dam. So, that later on said the pseudo-static analysis may not be enough for the dams and we are going to talk about that in the module 4, 5th module. So, this was all about introduction on the liquefaction with one example on the dam failure and we will continue in the next lecture for the susceptibility issue of the liquefaction. Thank you very much for your attention. Thank you.