Earthquake Geotechnical Engineering

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Lecture 16

Laboratory Tests (Conti.)

I welcome you again for this NPTEL course on earthquake geotechnical engineering and we almost done with the 25 percent of the course. And today we are going to have lecture number 16 which is again part of the module 2. We are under chapter third of the module 2 which is on dynamic soil properties. Two chapters concept of stress and stress pass and field test has been already completed. So, as we discussed earlier there are total three lectures on laboratory test. So, this is the second one and then we will have one more on it. So, let us what we have covered in the this is part of this laboratory test that is the chapter number 3 of the module 2. And what we have done in the lecture number 15 which is listed here.

So, we have talked about in the laboratory test and how to collect the sampling for the laboratory test has been discussed. Then we have discussed low strain element test. However in the low strain element test in last lecture we have discussed only one test which is a resonant column test or in the short called resonant column apparatus that is RCA. So, now let us discuss what we are going to talk today in this lecture number 16 topics which we are going to cover. First of all there are two other test which is on the low strain element test which we are going to discuss today.

One is ultrasonic pulse test another is piezoelectric bender limit test. Then we are also going to talk high strain element test which include three tests cyclic triaxial test, cyclic direct simple shear test and cyclic torsional shear test. So, as a result we will complete today low strain element test as well as we are going to complete high strain element test. Now, let us talk the first one low strain element test and within this first category ultrasonic pulse test. So, these when we talk about low strain test naturally the level of strain is low compared to what you have in the high strain test.

And the low strain test are more resembles with the wave propagation and as a result wave propagation velocities can be measured in the laboratory by means of the ultrasonic pulse test. Ultrasonic transmitters and receivers are attached to platens that can be placed at each end of a specimen with the distance separating them carefully measured. So, what is done here in the ultrasonic pulse test? Suppose you have a soil specimen which may be cylindrical or may be rectangular in cross section you may have cubic. So, one like you in the there are two things. So, you attach one here another sensor receiver here and there is a mechanism for recording.

So, this is your specimen and specimen which is in this case soil specimen, and this complete the circuit. So, this is your data acquisition system which records. Here you have the receivers like you have this transmitters here. So, here you will have let us say A point and B points A and B you have transmitters which will transmits the waves. But you know the length of the specimen which is let us say h and the travel time from A to B is known then you can find the velocity v l which may be h divided by delta t travel time taken.

So, it is a simple that you find out the travel time for given distance. Similarly with this the transmitters and receivers are made of piezoelectric materials which exhibits. So, in the what is the basic property of the piezoelectric materials that there will be changes in the dimension when they are subjected to voltage across their faces or other way we can say if there is a changes in the dimension there will be changes in the voltage which is recorded. So, which produce a voltage across their faces when distorted. So, both are linked if there is change in the voltage that means there is a distortion if there is a distortion then there will be change in the voltage.

So, this is the like basic for the ultrasonic pulse test. A high frequency electrical pulse which is applied to the transmitter causes it to deform rapidly and produce a stress wave that travel through the specimen toward the receiver. So, A will be treated as a transmitter and B will be receiver. So, you have from you transmit the wave from A point and B will receive and distance is known. So, one is transmitter and another is receiver and that will travel through the specimen toward the receiver. And the ultrasonic pulse test when the stress waves reaches the receiver it generate a voltage that is measured. So, whatever the difference in the voltage it will be measured. And the distance between the transmitter and receiver is divided by the time difference between the voltage pulses to obtain the wave propagation velocity which we have already discussed.

The ultrasonic pulse test is particularly useful for very soft materials. For example, even sea floor sediments very soft materials can be performed while the soil is still in the sampling tube. So, keeping the soil in the sampling tube without taking out of the sampling tube still this test can be performed. Now the second one in the low strain category of the for the laboratories is like we in fact it is third one. The first one we have already discussed that is the RCA, second was ultrasonic pulse test, third is piezoelectric bender element test. So, in case of piezoelectric bender element test it allows measurement of shear velocity on laboratory specimens using piezoelectric bender elements. Bender elements are constructed by bonding two piezoelectric materials together. So, it is two different like piezoelectric materials which are like you know that they are bonded together in such a way that a voltage applied to their faces causes one to expand while the other contracts causing the entire element to bend as shown in the figure. So, what you have here? In this case you have these piezoelectric here. So, what we see that there are two piezoelectric elements they are like you know in this case this is 0 voltage there are three positions here in this figure shown.

The center position is 0 voltage position neutral positions. So, in that case both remain in contact and the same length. But when the positive voltage is applied then what will happen? One outside will expand while the inside will be the contract. So, there is a contraction of one element for example, in positive case this is contracted and this is expanded. But if you apply the negative voltage this is other way around.

So, it will be opposites and they are on the bearing plate. So, this is piezoelectric bender element positive voltage causes elements to bend one way and negative will be naturally on another way. And this is arrow is showing direction of shear wave propagation. So, this is in the similar fashion a lateral disturbance of the bender element will produce a voltage. So, the bender elements can be used as both S wave transmitter and receivers.

So, it can be transmit as well as it can receive. In fact, these are used in a pair ultrasonic pulse stress also in case of so one will be transmitter another will be receiver. In most setup the bender elements are stick from the opposite ends of a soil specimen a voltage pulse is applied to the transmitter element which causes to produce an S wave. So, basically there is not much difference in ultrasonic and the this bender element as both are piezoelectric material. The second thing is that in this case bender element attached you have two like principle and then in that case one contract inside one will contract outside will be expanded. When the S wave reaches the other end of the specimen distortion of the receiver element produces another voltage pulse and the time the similarly the time difference between the two voltage pulses is measured with an oscilloscope and used to divide distance between the tips of the bender elements to give the shear velocity of the specimen. So, once you noted down the time difference the distance between transmitter and receiver is already known. So, distance divided by that time will give the shear velocity. These elements have been incorporated into conventional and cubical triaxial devices, odometers and modulators. In fact, like there are different devices we have used it using the cyclic triaxial test.

So, cyclic triaxial apparatus which we are going to talk later. So, with that this can be used. The difference like piezoelectric bender elements are low strain test. In fact, and the specimen is not disturbed here during the bender it can be specifically tested for other soil characterization. Most of the important application of bender element test is to find what we call the maximum value of shear velocity vs max. And vs max is the link with the g max which is g max by rho. So, what we do? We find the vs max using bender element test and then you can calculate the value of g max equal to rho vs max square. So, this is the most important application and the reason being simply because it is a very low strain test. So, this is used to find the maximum shear velocity. So, with this we have done with low strain element test.

Now, let us talk about high strain element test. In high strain element test we are going to talk about three tests. One is cyclic triaxial test, cyclic direction pressure and the last one is cyclic torsional shear test. The first one is the most popular one cyclic triaxial tests and this is an extension of the normal triaxial test. So, there is a little difference in the cyclic triaxial test. So, let us talk about that and continue with the high strain element test. First thing is that higher strain shear strain amplitude soil will generally have two types of behavior. One is it may exhibit volume changes tendencies. If there will be change in the volume, if you allow the drainage that means in that case pore water pressure will not be developed and it will there will be a change in the volume. So, this is manifested in two form.

In case of drain loading when you allow the drainage the first condition then there will be volumetric change tendency will manifested in what we call the volumetric strain. But no development of pore water pressure. So, in this case you can note down that there will be the drainage no pore pressure develops. But in another case under undrained condition there will be change in the pore pressure, but it will happen at constant volume.

So, if drainage is not allowed then there will be development of pore water pressure. So, and this in this case because you know that soil behavior is governed by the effective stresses. So, all methods of testing soils at high strain level must be capable of controlling pore water drainage. So, if you want to control the pore water drainage in that case you need to have like you know that there will be equipment which are able to measure the pore water pressure from the specimen and at the same time there could be the partially development of pore water pressure there could be a combination also. So, it is not there necessary because depending on how for how long you apply allow the drainage you may not allow the drainage completely partially in that case there may be change in the volume as well as development of pore water pressure.

So, like in the high strain element test let us first talk about the cyclic triaxial test. As I mentioned, this is the most popular test among all three and we will talk about the cyclic triaxial in detail and then about two other tests also. So, cylindrical triaxial or cyclic triaxial test a cylindrical specimen of the used place which is placed between top and bottom loading platens, and this is surrounded by thin rubber membrane. So, the sample will be surrounded by rubber membrane. The specimen is subjected to a radial stress usually applied pneumatically and in axial stress. So, you have radial stress is applied all around the specimen like here you can see this figure here. So, let us discuss this figure first. Here you have the soil specimen which is cylindrical and this soil specimen is surrounded by rubber membrane. It could be normally you know this is like this in this specimen is not dry it have the moisture and it is surrounded by the rubber membrane and at the top and bottom you have O ring for sealing it this one.

Then you have the cell wall. So, and all this rubber membrane as well as the sample is surrounded by this is inside the cyclic triaxial chamber and in this side chamber you have this fluid. So, you have the fluid here and then in this case cell pressure is there and axial load is applied which is in this case cycle axial load is goes up and down that is cyclic basically that means you can control its amplitude as well as frequency and then for the measurement of the load you have the load cell while you have the LVDT which measure your volume change the displacement linear voltage displacement transducers. So, this was a schematic of the typical triaxial apparatus. By virtue of these boundary conditions in the triaxial principal stresses in the specimen are always vertical and horizontal.

So, one will be vertical and horizontal. So, you will see that vertical stress is maximum principal stress and the horizontal stress is the minimum principal that is the minor principal stress. So, we will discuss how it applied. The difference between the axial and the radial stress is called the deviatoric stress. In fact, how the stresses are applied let us discuss that first and that deviatoric stress is applied cyclically either under stress control condition or under strain control condition. So, you have let us say this cylindrical specimen and this specimen is subjected to what we call the confining pressure all around which is a radial stress sigma c which is applied radially sometimes it is written sigma r also and this sigma c is applied not only around this shaft, but this is applied at the top as well as bottom.

So, that means this sigma c is also applied here. So, you have here this is also applied sigma c. In addition to this in axial direction, you apply one more stress which is called sigma d. So, all together the total in the axial direction which is called sigma 1 which is sigma a is nothing but sigma c plus sigma d and in the radial direction which is a minor principal stress sigma 3 is same as a sigma c. So, as a result deviatoric stress sigma d can be called sigma 1 minus sigma 3.

So, deviatoric stress is the difference of major principal stress and minor principal stress. And you see the major principal stress in this fractional stress is applied vertically in the axial direction sigma 1 while sigma 3 is applied in the all around. But sigma 3 is applied here, here as well as here as a result you need to add only sigma d on the top to get the major principal stress. So, the difference between major and minor principal stress will be simply sigma d. Now coming to here, the deviatoric stress is applied cyclically under either under stress controlled or strain controlled test.

What is the meaning stress controlled and strain controlled? Two types of tests are popular in cyclic triaxial. In stress controlled test, the maximum stress is fixed while testing that means during the test you will not exceed that maximum stress, you set up the maximum value of stress and then strain you find the corresponding strain then custom. Similarly in the strain controlled test, maximum value of strain is set out and then you noted down the value of stresses corresponding. This we already discussed. Continue with the cyclic reaction or they are most commonly performed with the radial stress held constant and the axial stress cycle at a frequency about 1 hertz.

So normally for the samples, they are tested at about 1 hertz frequency though most of the cyclic triaxial system including which we have at IIT Roorkee is capable of quite high frequency include 10 hertz or even more than that. But for the soils, you do not require so high frequency otherwise because the soil sample will fail immediately if you have very high frequency. So normally testing is done either 1 hertz, 2 hertz or 3 hertz like this rather than more than 5 hertz. The cyclic triaxial test can be performed under isotropically consolidated or anisotropy consolidated conditions thereby producing the stress path which is shown later. So, there are two conditions, one is isotropic, and another is anisotropic.

So, the first case here there are three cases A, B, C. On the left hand side there are two figures. So on the left hand side you have time versus deviatoric stress. On y axis you have the deviatoric stress, half of the deviatoric stress that is sigma d by 2. On axis you have time, how it is varying with the time. So you see in the first case which is for basically for isotropically consolidated condition, when you have the isotropically conditions that means the stress applied in both the direction whether positive or negative will have equal.

So this is reflecting here, it looks like a sine wave. So it is a sine wave. So you have 0 here, maximum at B and then C again 0. So here in this case, A case, the amplitude in the positive and negative direction is same. So if you measure this, this will be the same thing, steady state move here. And if you draw the corresponding stress path, A and C will be at 0 positions while B will have value of q as sigma d by 2, same ordinate and P will be changing because you are moving like when you have this difference, you have the higher value of sigma d.

So the P value will increase here. But this was the case for isotropic. Now B and C are cases for anisotropic conditions. That means the anisotropic means on the amplitude in the positive and negative side is not the same. So you could see in this case, it is quite more greater in positive side but less in the negative side. And the corresponding stress path is for the point, this point is, this is starting point and then you get the peak values and then you come back here.

One point is important here. So in this case, you have in the B case, the anisotropic condition is cyclic deviatic stress amplitude greater than the deviatic stress during consolidation. So deviatic stress during consolidation is here, from here to here. This is deviatic stress during consolidation. And the first part, the amplitude of the cyclic deviatic stress amplitude, so cyclic deviatic stress amplitude will be double of this.

So if I like peak to peak, double amplitude basically. So this value, double amplitude is greater than this. So if I say this is A, this is B. So in this case, A is greater than B. So A will be greater because A starts from here to a double amplitude.

But in the second case, my double amplitude will be like this. This is A and B will be this value from 0 to peak value. So in this case, second case, A will be less than B. That means double amplitude is less than the positive values of this. So what happens, as a result, you do not get any stress reversal. Always it is positive, whether peak value is also in positive direction and then you have the trough, this is also in the positive direction. So in the C case, there is no stress reversal. While in the B case, there is a stress reversal. If you have A equal to B, if we have a condition A equal to B, then there may not be any stress reversal again, but then the trough will take the value 0. So, it will touch this line to at 0 when it comes down. So, you have the peak values and then it is coming down. So this was about stress reversal. Continue with this cyclic triaxial test. The stresses and strains measured in the cyclic triaxial test can be used to compute the shear modulus and damping ratio. So the most important is that it is used for the shear modulus and damping ratio. That means you find the value of G and damping ratio which will be used for example using for equivalent linear model which we will discuss later.

The cyclic triaxial test, they allow the stresses to be applied uniformly. All the stress concentration can exist in the cap and the base and this allows drainage condition to be measured accurately or controlled. So the good point with the cyclic triaxial is that you can measure the drainage condition, you can control the drainage condition. If you allow the drainage, then there is no development of pore water pressure. If you do not allow it, then there will be development of pore pressure which can be also measured in this case.

When you want to convert a standard triaxial testing machine which is without like you know standard means it is basically for the static case rather than cyclic loading, then it requires only minor modification that means you require an actuator which may apply the loading in the vertical up and down with control on your amplitude and frequency. But the limitation of the cyclic cannot, it cannot model stress condition that exists in most actual seismic wave propagation problems. So mostly like you know that it can model, but the stress conditions will be difficult to reproduce. Then there could be bedding errors and system compliance effects generally limit the measurement to shear strength which is greater than about 0.01%. So that means normally triaxial testing as we said this is for high strain testing and the level of strain should be more, greater, not smaller than this value in general. However, still it can produce sometime like you know that local strain measurements can be done as low as 0.0001%, so at quite low, but this is local. So local strain measurements rather than the global strain measurement, but in general we should stick to this range that this is greater than this one, strain are greater than shear strain.

So basically, it is already listed, so strength greater than about 0.01%. So this was about all about cyclic triaxial test. So most important issue is for the finding the shear modulus and damping, but this cyclic triaxial is also used for one most important application which is liquefaction studies.

Now cyclic direct simple shear test. The cyclic direct simple shear test is capable of reproducing earthquake stress conditions much more accurately than is the cyclic triaxial test. So compared to cyclic triaxial it is better, more accurate and this is also commonly used for liquefaction testing as was the case for the cyclic triaxial, but cyclic triaxial is also used for shear modulus and damping ratio while the cyclic simple shear is mostly used for the liquefaction. In the cyclic direct simple shear test, a short cylindrical specimen is restrained as lateral expansion by what you call the Rigid boundary platen, which is different like inventors name Cambridge type device, a wire reinforced membrane which is NGI type device where NGI stand for Norwegian Geotechnical Institute or a series of structuring which is SCI type device. So what you have in this case, this is NGI type device which is NGI cyclic simple shear reference and here soil specimen is contained within wire reinforced rubber membrane.

So here you see this is your soil specimen, which is written here. So soil specimen is highlighted here. And soil specimen is on the base plate it is situated, you have this porous stones on the bottom as well as top and then. So what is done in this case, in this case soil specimen is moved horizontally, it is on the roller, this is horizontal load cell. So this apply the loading here and this plate moves in the horizontal direction. And when it moves in that case, you can measure the, there is a LVDT for horizontal displacement, how much it get displaced due to the shaking.

So, because our objective in the seismic analysis is more for the lateral loading rather than the vertical loading, so because in the cyclic, this cyclic direct simple shear test, you are applying the horizontal load itself. So as a result, this test is considered to be better or more accurate compared to cyclic triaxial. By applying cyclic horizontal shear stress to the top or bottom of the specimen, the test specimen is deformed in the same way as an element subjected to vertically propagating shear waves in case of cyclic triaxial. The simple shear apparatus or applies the shear stress only on the top and bottom surfaces of the specimen, that means it apply on the top as well as bottom, but not in between. Since no complementary shear stress are imposed on the sides, the moment caused by the horizontal shear stress must balance by non-uniformly distributed shear and normal stresses. So the shear stress is applied only one phase on the horizontal phase, not on the vertical phase. As a result, you may get like you know that force will balance, but there will be coupled, so that is balanced by the deformed shape of the specimen. So here the effects of non-uniformity of stresses can be reduced by increasing the diameter or height ratio of the specimen and such effect are considered to be or small if diameter to height ratio are greater than about 8 to 1. So that means you are like you have this specimen which diameter is quite high compared to its height, so that it looks like a disc where your thickness is small, but diameter is large, 8 times of the thickness of this. So, in this case, like because here no complementary shear stress is applied, so what you have the deformed shape like this, then only it can sustain.

You have the shear stress acting this phase and this phase, but nothing on the vertical phase. So it is possible because if it is, this is okay, but if I say it is like you know the rectangular and then I apply this, then this is not possible because no complementary shear stress is applied. So this is okay, but another combination where you have the rectangular, in that case you require the complementary. If I apply the shear stress on these phases, then I need to apply the shear stresses here also in opposite. So, they will be going clockwise, anticlockwise and they will create anticlockwise, so they will balance here. Here balancing is done by this deformed shape. So out of these three, first and third is possible, second is not possible. So this was about cyclic direct simple shear test. Similarly with this, conventional simple shear rupture stress have their limited inability to impose the initial stresses, which is other than those corresponding to what we call the K naught conditions. Small scale bi-directional cyclic simple shear rupture have also been developed.

Now the last one on the cyclic torsional shear test for the case of high strain test. Many of the difficulties which are associated with the cyclic triaxial test and cyclic direct shear test can be avoided by loading cylindrical soil specimen in torsion. So here you apply axial loading in cyclic reaction. The horizontal loading in case of cyclic direct simple shear test, higher in the torsional you apply the torsional in the, you use normally cyclic torsional shear test. It will allow you isotropic or anisotropic initial stress conditions and can impose cyclic shear stresses on the horizontal planes with continuous rotation of principal stress axis.

So, there are rotation of principal stress axis that is. These cyclic torsional shear tests, these are most commonly used to measure the stiffness and damping characteristic over a wide range of strain levels to increase the radial uniformity of shear strains. For example, which are the some of the researchers develop what is called hollow cylinder cyclic torsional shear apparatus. So that is sometime called hollow cylinder apparatus.

So that is also used in this case. This looks like this one. In the cyclic torsion this is a hollow cylinder apparatus. So what you see here, torque is applied, torque is applied here in this form and then you have the axial stress which is acting from the top and then you have on the cylinder external pressure may be due to fluid and the internal pressure. And then doing the analysis we carried out this is radial stress sigma r, this is in the direction of that periphery sigma theta and the sigma z is vertical. So all three are there in case of cyclic torsional shear test. The specimen is enclosed within internal and external membranes on which the internal and external pressures can be applied independently as we seen.

Application of cyclic torque induces cyclic shear stress on horizontal planes. While hollow cylinder test offer perhaps the best uniformly and control over stresses and drainage specimen preparation can be difficult normally and the equipment is not widely available. This cyclic torsional shear test or hollow cylinder test is not widely available. So, this completes all the tests on the laboratory test including low strain test as well as high strain test. But then there are some special tests also which we will discuss in the next lecture. Thank you very much for your kind attention.