REMOTE SENSING FOR NATURAL HAZARD STUDIES

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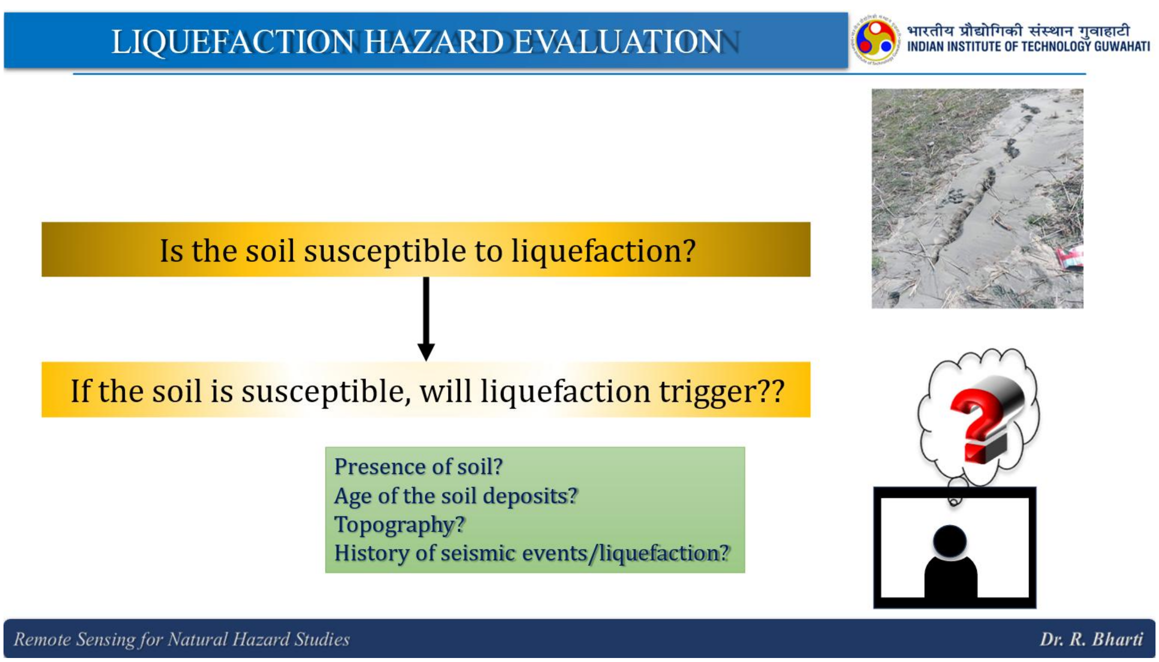
Lec 32a: Remote Sensing for Liquefaction Studies - I Part A

Hello everyone, today we will continue with module 9 on liquefaction, and this is the second lecture on the topic. Before we proceed, let us quickly go through this video, which I have also shown you in the previous lecture, and this will help you recall what exactly liquefaction is. So, basically, liquefaction is the state or condition of the soil when it does not hold the load and fails. So, because of that, we call it liquefaction, and this video will try to help you understand how liquefaction occurs. So, if you just see this video here, you have loose granular sediment, and then you have strong shaking. So, this is the layer of granular sediment, and then you have the groundwater, which saturates this particular layer, and at the same time, you have this earthquake.

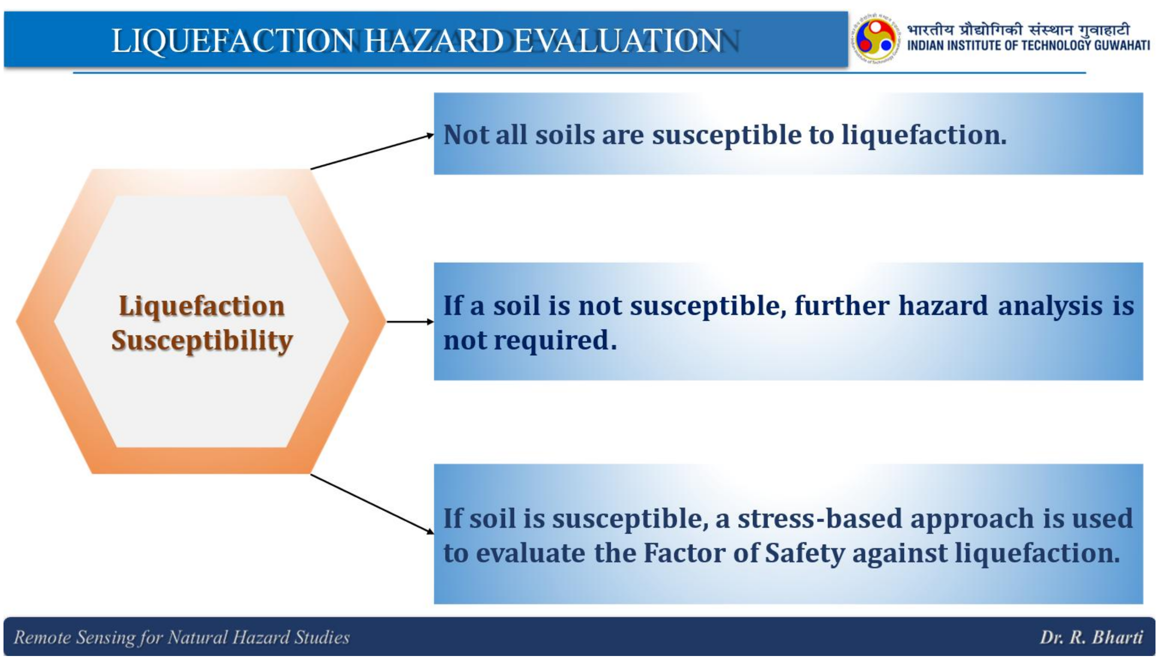
So, we also discussed the earthquake, and here is the situation when it fails. So, this is the example from San Francisco, and it occurred in 1906. So, before we proceed, let us try to understand why a particular soil fails or whether all soil fails. So, what is this different scenario under which soil fails?



So, that is why the soil is susceptible to liquefaction; that is the first question, and if the soil is susceptible, will liquefaction be triggered? So, susceptibility is one thing, but if liquefaction is happening, that is another thing.

So, here we have these points that we need to analyze for our soil. So, the presence of soil, whether the strata have a soil layer, is important because we are talking about the liquefaction that is possible in the soil column. So, the first one is the presence of soil, and the second one is the age of the soil deposit, whether it is newly formed soil or whether it is an old one. If it is a newly formed deposit, then what will happen is that it will not be compacted; it will be loose and granular. And then what type of grain sizes are present here? What type of soil is present here, which is equally important? Then what is the topography, whether we are talking about the elevated areas or the flat lands, which is also important. Then, the history of seismic events, whether this area has had any earthquakes or any specific location has shown liquefaction behavior. So, this is very, very important: what is the history of that area? So, when we talk about liquefaction susceptibility, not all soils are susceptible to liquefaction. If the soil is not susceptible, further hazard analysis is not required, and if it is susceptible, we will go for the complete analysis. So, when it is susceptible, a stress-based approach is used to evaluate the factor of safety against liquefaction. Now we will try to understand all the parameters and details about the stress-based approach.

So, we will go one by one and try to understand every component of the liquefaction.



Now, when we try to see the liquefaction susceptibility criteria, we have historical criteria, geological criteria, and compositional criteria. So, when we talk about the historical criteria, we try to refer to the historical information, and here we will try to refer to the geological information and the compositional aspects, which means what is the behavior and what are the properties of that particular soil. So, when we talk about this historical criterion, it has been observed that liquefaction repeatedly occurs in the same region. So, in the same area, we can expect again that there is an episode of liquefaction. This historic dataset is used to develop different models to assess the liquefaction susceptibility of soil. So, once we know that this is the area and these are the locations of liquefaction. Then we can have all the parameters of these locations that we will discuss, and we will try to train our models so that for any given new location, it will assess whether it is susceptible or not. So, that is the historical data. The historic datasets show liquefaction recurrence within a particular zone. So, this is the zone we are trying to analyze here. Worldwide data on liquefaction occurrence collected by Ambresci et al. (1988) show that there is a particular epicenter distance within which liquefaction tends to occur. So, suppose this is the area. And this is the epicenter of the earthquake.

So, we will have a different distance from this, and there is a particular distance from which this liquefaction is possible that is analyzed by this researcher. So, here you can see the epicentral distance to the farthest observed liquefaction feature; this is in kilometers and earthquake moment magnitude. So, he has drawn this particular line based on all these data sets to determine if the points are falling in this region, and for this reason, their behavior will be different. So, if the point, let us say, I have a location that is 10 kilometers away from the epicenter, and the moment magnitude of the earthquake was 7. So, where will it be? It will be here. So, this is towards liquefaction.

HISTORICAL CRITERIA

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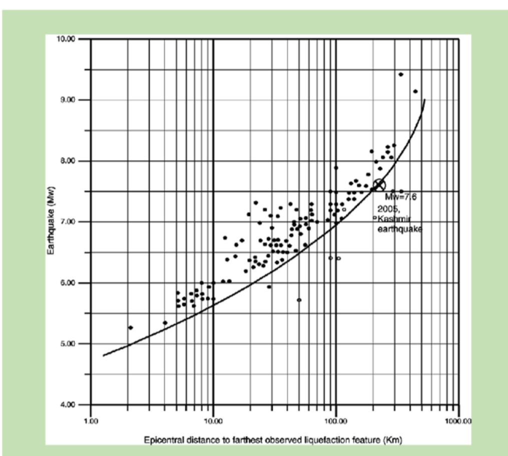

Liquefied- Non-liquefied locations with epicentral distance and magnitude taken from Ambrassey et al. (1988) in Papadopoulus and Lefkepoulos (1993)

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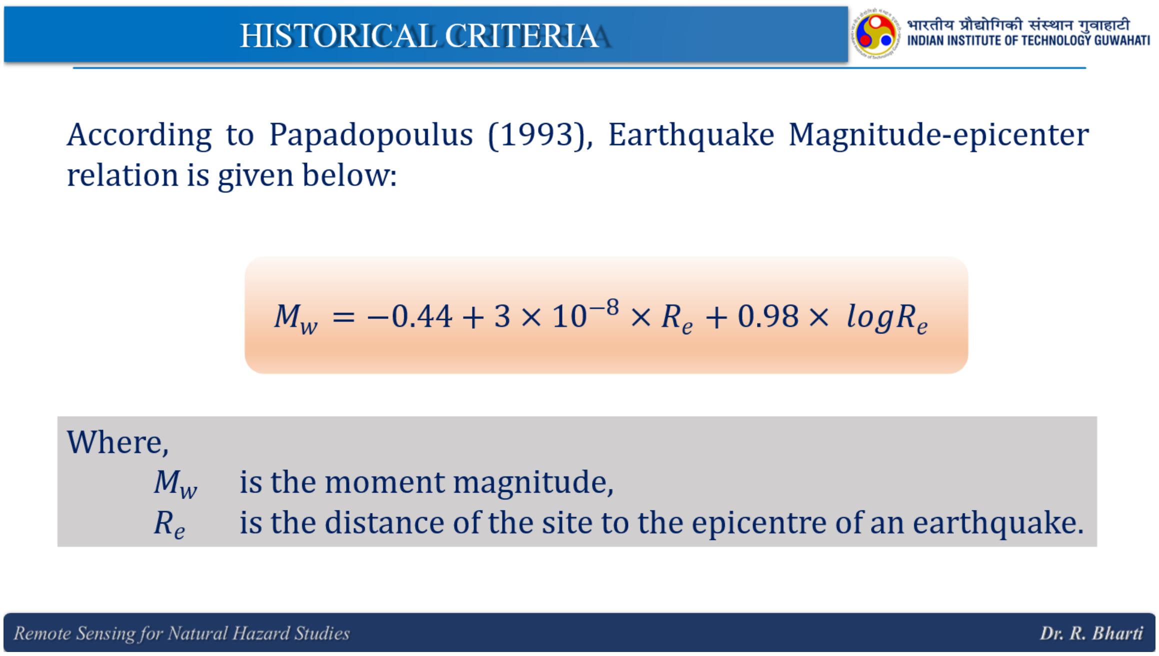
So, this is the liquefiable zone. This is a non-liquefiable zone. So, if my points are falling in immediately, we can say that this location has liquefaction susceptibility. So, here it is written about non-liquefied locations with epicentral distance and magnitude taken from

Ambresci et al. (1988) in this paper, and here they have nicely provided this particular line. And this line segregates or separates the liquefiable zone and the non-liquefiable zone. So, this is the equation of that particular line that we have just seen. So, here you can see that for this line, we have this equation. So, this is the magnitude of moments, and here Re is the distance from the site to the epicenter of an earthquake.



So, this is a very, very important relationship between earthquake magnitude and epicenter that defines or will exactly say whether your location is liquefiable or non-liquefiable. Then come the geological criteria. The geologic environment for liquefaction susceptibility is very narrow and specific. So that means there are certain parameters that trigger liquefaction. So, this susceptibility is very narrow and specifically, that is stated by Eud et al. (1991). This includes the hydrological setting. So, what is the hydrological condition of that area, the depositional environment, and what are the depositional environments, because we are talking about the geological criteria? And the age of the deposit. I mentioned this in the first slide: the age of the deposition also tells you what the compactness of the soil is, what the depositional environment is, and what the hydrological setting is. Then comes uniform soil, producing more susceptibility, which means if you have one type of soil with one type of grain, what will happen? They will be more susceptible to failure or liquefaction. Why? Because they will have pore spaces that will be available for this water. When you have different gradations, what happens is that these pores are filled with fine grains. And then this soil will not be susceptible. So, we will see that in the other part. So, here it says that the geological process manifesting uniform deposits, in turn, produces liquefaction susceptibility. So, we need to be very careful about the hydrological setting, depositional environment, and age of the deposition.

GEOLOGICAL CRITERIA

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Liquefaction is more observed in Fluvial, Colluvial and Aeolian deposits.

Fluvial deposit

Sediments transported and deposited by rivers in a continental environment.

Colluvial deposit

Sedimentary material that gathers on slopes, within caves, or in rock shelters.

Aeolian deposit

Sediments such as sand, silt, and clay that are carried and laid down by wind action.

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Then, liquefaction is more often observed in fluvial, colluvial, and aeolian deposits. So, here are the fluvial deposit sediments transported and deposited by rivers in a continental environment that is fluvial. Then colluvial sedimentary material gathers on slopes within caves or in rock shelters. Then come the Aeolian sediments, such as sand, silt, and clay, that are carried and laid down by wind action.

So, that is the characteristic of Aeolian deposits. So, these three types of deposits have a higher probability of liquefaction. Soils from the Holocene; Holocene is the most recent one. If you see the different time frames of the geological periods. So, the Holocene period is more susceptible to liquefaction compared to the Pleistocene period.

GEOLOGICAL CRITERIA

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Soils from the Holocene period are more susceptible to liquefaction compared to those from the Pleistocene period.

Holocene Soils

Often found in low-lying areas such as floodplains, deltas, or coastal regions, these soils are more likely to be saturated with water. High water content increases pore pressure during seismic shaking, leading to liquefaction.

Pleistocene Soils

Typically located in older, more elevated terrains, these soils are often drier and less saturated, reducing the likelihood of pore pressure buildup and liquefaction.

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So, when we talk about the Holocene, often found in low-lying areas such as flood plains and coastal regions, these soils are more likely to be saturated with water because water plays a significant role here. High water content increases pore pressure during seismic shaking, leading to liquefaction. And, when we talk about the Pleistocene, typically located in older, more elevated terrains, these soils are often dried and less saturated because we are discussing the elevated regions. Reducing the likelihood of pore pressure buildup and liquefaction. So, that is the major difference between the two.

So, Holocene sediments are more susceptible to failure or liquefaction. Human-made soil deposits, like those created by anthropogenic activities, also need attention. Uncompacted loose fields are highly prone to liquefaction because they are not compacted, and during a seismic event, there will be shaking. If there is water availability and the groundwater is nearby, then you will have a higher chance of liquefaction. The stability of hydraulic dams and mine tailings piles, where soil particles are loosely deposited through water sedimentation, continues to be a significant modern seismic hazard. Well-compacted fields are unlikely to liquefy, though if manmade or anthropogenic activities are involved, this is very unlikely to fail. When we talk about this compositional criterion, we have two things: excess pore pressure and volume change. Liquefaction susceptibility depends on the development of excess pore pressure, which is influenced by compositional traits affecting volume change behavior.

For example, you just imagine it is not related to liquefaction, but certain clays tend to expand. So, whenever contacted with water, they expand, and the volume changes. Similarly, certain types of soils expand their volume, and when they expand, the compactness will be less; during that time, if you have seismic events, that particular deposit will have a high liquefaction potential. Volume change potential and susceptibility. Compositional features linked to high-volume change potential generally correlate with increased liquefaction susceptibility. Then, from this, we can say that the key compositional characteristics are particle size, particle shape, and particle gradation. So, when you have different types of particle sizes or a very good distribution of particle size, you have less vulnerability to liquefaction.

When we talk about particle shapes, if you have similar grain sizes, you have a lower potential for liquefaction when you have rounded, triangular, or irregular shapes; they will help to compact this deposit. So, a similar type of shape will be more vulnerable to liquefaction; different types of shapes available in soil will be less susceptible to liquefaction. Similarly, this is gradation; so, if the distribution is good, then you will have less susceptibility to liquefaction.

COMPOSITIONAL CRITERIA

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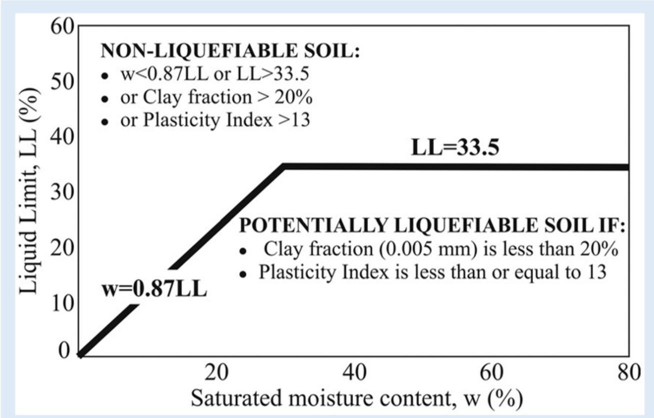
Chinese Criteria (Wang et al, (1979)):



Chinese criteria for susceptibility to liquefaction adapted to ASTM definitions of soil properties (after Perlea et al., 1999)

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So, this is one of the widely used criteria; it is called the Chinese criteria, and it was given by Wong et al. in 1979. He proposed this graph, and here you can see that this line is basically separating the liquefiable and non-liquefiable zones. So, this is the part

where it is liquefiable. So, understand it carefully. So, this part is liquefiable, and this part is non-liquefiable, and this is separated by this line, and the equation of this line is w is equal to 0.87 times the liquid limit. So, here on the x-axis, you have saturated moisture content, which is the weight percentage, and here you have the y-axis, liquid limit, which is in percent. So, this line has the equation w equals 0.87 LL, where LL is the liquid limit. Now, here you can see that this part is non-liquefiable.

So, here **w** is less than 0.87 LL, or LL is greater than 33.5. So, it is less than this equation. So, **w** is equal to 0.87 LL, which separates these two zones. And again, if the liquid limit is more than 33.5, that will again be non-liquefiable. So, that is the criterion here: the clay fraction is greater than 20 percent, or the plasticity index is greater than 0. These are the criteria that you have to check for your soil before you go for the hazard analysis. If your points fall in this region, your deposit and your soil column are safe.

If they are falling in this, how will you check that using this clay fraction is less than 20 percent? The plasticity index is less than or equal to 13, or w is equal to 0.87; if LL is less than that, it will be non-liquefiable; if more than that, it will be liquefiable, and if the liquid limit is greater than 33.5, it is non-liquefiable; if less than this. It will be liquefiable. So, this particular method is widely used to assess whether your soil column has liquefaction potential or not.

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Chinese Criteria (Wang et al, (1979)):

$$\mathbf{w} = \frac{\text{weight of water}}{\text{weight of solid}} \times 100$$

where **w** is Water content

It can be obtained in lab by with use of oven drying.

So, when we talk about this weight percentage, it is calculated using this equation. So, where **w** is the water content, it can be obtained in the lab by using oven drying. Now, when we talk about PI, which is the plasticity index, it can be calculated using the liquid limits and the plastic limits. So, the liquid limit of a soil is the moisture content at which the soil transitions from a plastic to a liquid state. The plastic limit is the moisture content at which soil transitions from a plastic state to a semi-solid state.

COMPOSITIONAL CRITERIA

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Chinese Criteria (Wang et al, (1979)):

PI = LL-PL

- ❖ The Liquid Limit **(LL)** of soil is the moisture content at which the soil transitions from a plastic to a liquid state.
- ❖ The Plastic Limit **(PL)** is the moisture content at which a soil transitions from a plastic state to a semi-solid state.
- ❖ Plasticity Index **(PI)**: The **(PI)** is a measure of the range of water content over which a soil remains in a plastic state. It is calculated as the difference between the **LL** and the **PL**.

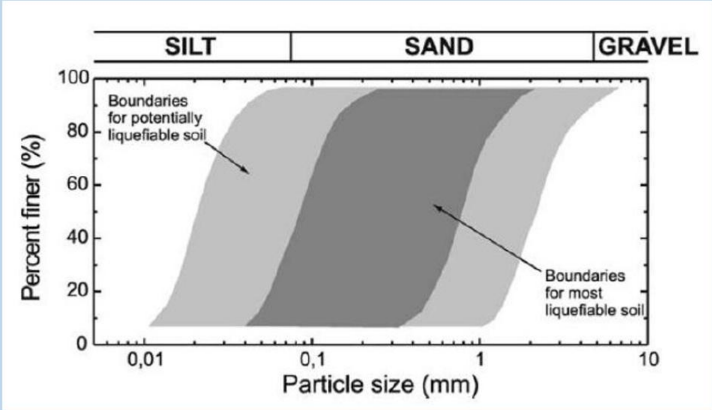
And, the plasticity index, the PI, is a measure of the range of water content. over which soil remains in a plastic state. It is calculated as the difference between the LL and the PL. So, we are using the liquid limit and plastic limit to calculate the plasticity index, and that is very, very helpful when we use this Chinese criterion to assess our soil, whether it is susceptible or not. The clay fraction of soil refers to the proportion of soil particles that are smaller than 0.002 millimeters or 2 micrometers in size. And the clay particles are the finest fraction of soil and play a significant role in determining the soil's physical and engineering properties, such as. Plasticity, cohesion, and water retention. So, this plasticity we have already seen in the previous slide; the cohesion is basically how cohesive the grains of your soil are. If you have more water content, the cohesion will be reduced, and you also need to evaluate the water retention capacity of your soil to assess its properties. Then, other than this Chinese criterion, we also have the Andrew and Martin criteria proposed in 2000, and here, according to this criterion, the potential liquefiable soil will have less than 10 percent clay fraction and less than or equal to 32 percent of the liquid limit.

For the non-liquefiable soil, the clay fraction is greater than 10 percent, and the liquid limit is greater than 32 percent. So, other than the Chinese criteria, the Andrew and Martin criteria is also being used to initially evaluate whether your area has liquefaction susceptibility or not. Then we have this Tsuchida criterion that was also proposed in 1970. So, the range of grain size distribution for liquefiable soil is used. So, the x-axis represents the particle size, and the y-axis represents the percent finer.

So, what percentage is present? When you see a particular soil column, here, if you have different types of grains or different types of soil, then we assume this is very good, it is safe, and liquefaction is not possible. So, if you assess the particle size distribution of any soil, and it falls within all these regions that also contain silt, sand, and gravel, the particle size and the percent finer are also changing. So, in this situation, this soil is not susceptible to failure, but if a soil column has only one type of material, only sand, only gravel, or only silt. So, in such situations, these are susceptible to failure because they will not be compacted when there is a seismic event. When you are experiencing shaking due to seismic events and have different types of grains present in this soil, they will come together and become compacted.

Tsuchida Criteria (1970)

Ranges of grain size distribution for liquefiable soils (Tsuchida., 1970)



So, that is the basis for having this Tsuchida criterion. So, this is also one of the alternatives other than your Chinese criteria to evaluate the potential of your soil to be liquefied. Is the soil susceptible to liquefaction? Using the previously explained methods, such as the Chinese criteria or the Tsuchida method, you can assess whether your soil is susceptible to liquefaction or not. If it is liquefiable, then we go for the evaluation of liquefaction potential; if not, then no further evaluation is needed. So, when we are going for further evaluation, by chance, if it has come to the liquefaction zone, then we can have all these parameters: earthquake intensity, earthquake duration, building load, groundwater table, depositional environment, ageing and cementation, confining pressure, drainage conditions, soil type, soil relative density, particle shape, and particle size distribution.

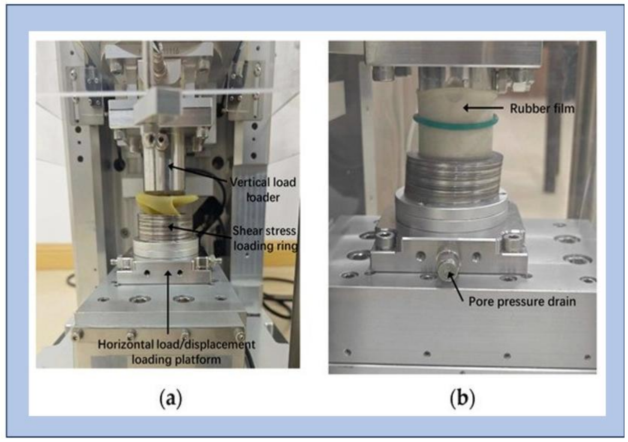
All these will be used to assess whether your soil is susceptible to liquefaction or not. So, when we talk about all these parameters, some of them can be measured in the field, that is, in situ measurement, while others are measured in laboratory conditions. So, in the laboratory-based method, we have the cyclic triaxial test. So, we talk about how cyclic loading is simulated in the cyclic triaxial test, and the response of the soil is reported. The number of cycles for liquefaction initiation is observed here.

Now, we will try to see at which cycle this liquefaction occurs. So, the number of cycles will be noted here.

Laboratory Based Method

Cyclic Simple Shear Test

- Shear stresses induced by seismic waves is simulated which is more realistic than the triaxial test.
- Stress Strain Behavior is also noted.



Cyclic Simple Shear Test Cell (Yu et al. (2024))

Then comes the cyclic simple shear test. So, here is the cyclic simple shear test cell from You et al.2024. So, it says shear stresses induced by seismic waves in simulated tests, which is more realistic than the triaxial test. Stress-strain behavior is also noted here. So, that is being used for further analysis of liquefaction. Then comes the resonant-column test. So, here the dynamic properties of soil, such as shear modulus and damping ratio, which are critical for liquefaction analysis, are evaluated.

Laboratory Based Method

Resonant Column Test

- The dynamic properties of soils, such as shear modulus and damping ratio, which are critical for liquefaction analysis, are evaluated.
- The shear modulus and damping ratio are derived from the resonant frequency and decay of vibrations which is used in liquefaction potential analysis.

Resonant Column Test Apparatus(https://www.gdsinstruments.com)

So, this is a typical resonant-column test. The shear modulus and damping ratios are derived from the resonant frequency and decay of vibration, which are used in liquefaction potential analysis. So, these are the methods or these are the instruments used in the lab to evaluate the potential of liquefaction for a given soil, and the soil will be collected from the area that has shown the properties, and it has come into the liquefiable zone, maybe using the Chinese criteria, or maybe using the Tsuchida criteria, or maybe some other criteria, and then we are moving towards the characterization.

EVALUATION OF LIQUEFACTION POTENTIAL

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Laboratory Based Method

Shake Table Test

- Ground shaking is simulated and the soil's response is observed under more realistic conditions.
- Direct observation of liquefaction behavior is done under simulated various seismic conditions.

Shake Table Apparatus

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Then we also have a shake table test; ground shaking is simulated here, and the soil's response is observed under more realistic conditions. So, here you can see the diagram of the shake table apparatus. Direct observation of liquefaction behavior is done under various simulated seismic conditions.

This will provide you with the input to analyze whether your soil is liquefiable. This is another one that is called SPTN; when we talk about the laboratory-based method, these are very hectic. You have to visit the field, collect the samples, and then analyze various parameters. You should have access to these advanced instruments; then only will you be able to study liquefaction. To overcome this challenge, Seed and Idriss (1971) came up with the stress-based approach that I will be discussing in the next few slides. In this approach, they correlated the liquefaction potential to the standard penetration test based on the results of SPTN. This was done because SPTN is very common in geotechnical engineering studies. Now we have seen an instrument that can be used in liquefaction potential evaluation.

These instruments are not available to everyone. So, to have an alternative, we thought of this Seed, and Idriss has thought of having another parameter that can be evaluated easily.

So, they have investigated this SPTN value to determine whether we can utilize it for the evaluation of liquefaction. So, this SPTN is a very common property that is measured in geotechnical investigations. So, it is a very common one. So, that is why this has been investigated to find whether it has any correlation with the liquefaction.

So, we will discuss this further in the second part of this lecture. So, this is the first part; we are ending it here.

So, thank you very much.