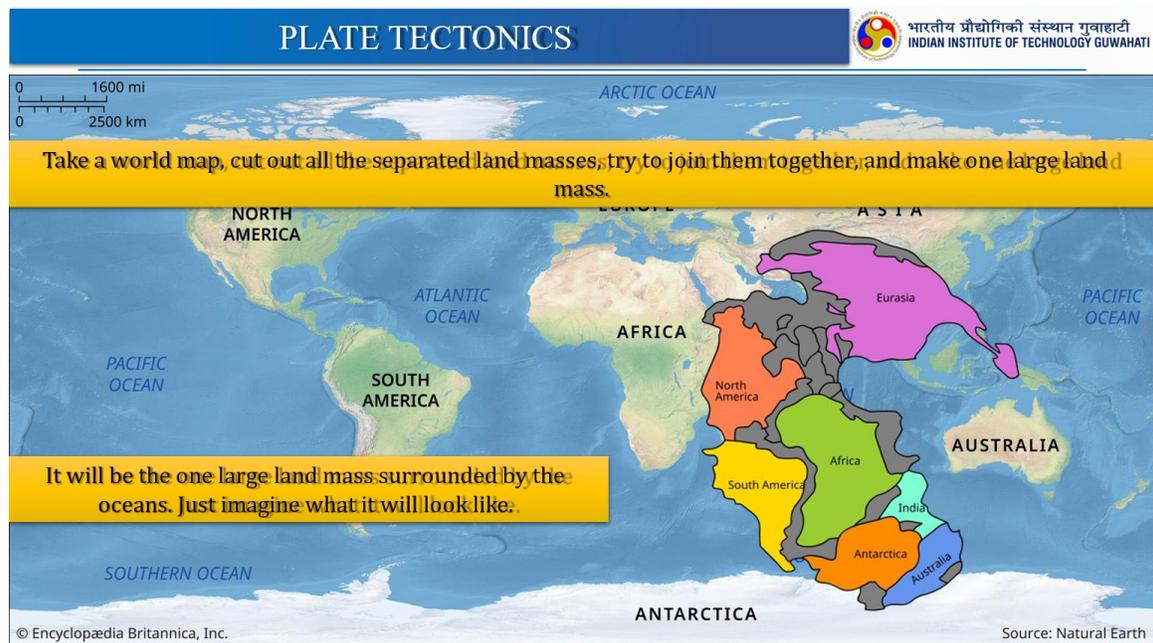


REMOTE SENSING FOR NATURAL HAZARD STUDIES

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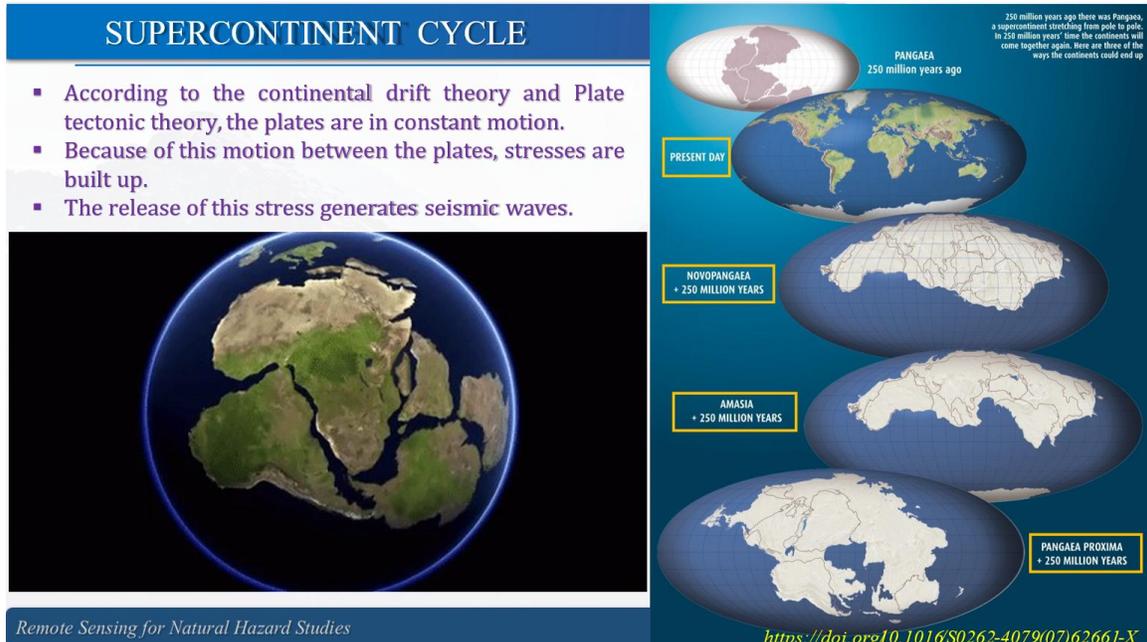
Lec 31a: Introduction to Liquefaction- Part A

Hello everyone, today we will start module 9, which is on liquefaction, and this is the 31st lecture of remote sensing for natural hazard studies. So, let us try to understand what liquefaction is. and then we will go ahead with the studies related And liquefaction before we start digging deep. So, we will try to understand what liquefaction is. So, here you can see that liquefaction is a phenomenon observed in soil due to earthquake loadings. So, because of earthquake events due to seismic activities, this soil loses its strength temporarily or maybe permanently. As a result, such events occur. So, basically, it is because of the earthquake and the seismic activities. So, earthquakes are primarily caused by the movement of tectonic plates; I hope you all are aware of it. And we also know that Earth's lithosphere is divided into seven continental-sized plates.



So, the first one is the African plate, then we have the South American plate, the Antarctic plate, the Australia-India plate, the Eurasian plate, the Pacific plate, and the North American plate. So, here it is. So, this is from the USGS, and it was given in 2015.

When we see these tectonic plates, basically, these pieces of Earth's top layer that are carrying the continents and oceans are called tectonic plates. So, basically, here you can see this particular video.



So, it is carrying the load; it may be your ocean, or it may be your continent. And these plates are not anchored in place but slide over a hot and bendable layer of the mantle. So, here you can see that this is not anchored. So, it is continuously moving. So, this is a subduction zone. So, here you can see this plate is going inside this, and then it reaches the mantle, and this plate is moving in this direction. The tectonic plates are always moving slowly, but they get stuck at their edges due to friction. So, what happens during this movement is that you can see it getting stuck for a moment, and because of that, what will happen is the generation of stresses, and earthquakes are a result of those stresses. So, when the stress on the edge overcomes friction, there is an earthquake that releases energy from the Earth in waves that travel through the Earth's crust and cause the shaking that we feel, which we call an earthquake. So, basically, this is the temporary stacking of these plates with each other, and during that time, stress will be generated, and once they slip again, those energies will be released, resulting in seismic waves. So, here you can see this map. So, here are all the continents; these are the shapes you can see. So, do you think that these were like this from the beginning of the Earth? It is not possible because we have talked about the tectonic plates and their movement. So, this is moving as well. So, what you do is take a world map, cut out all the separate landmasses, try to join them together, and make one large landmass, and that will be like this. So, this was the beginning of the Earth. So, there was Tangia, and then all the landmasses were together, and it was surrounded by the ocean. But subsequently, over time, what is happening because of the

continental drift? Because of plate tectonics, these land masses are getting separated from each other, and some are also colliding with each other. So, here you can see that this is the collision part with the Eurasian plate. This is a very nice video that explains how the continents are moving. So, this is known as continental drift. So, the map shows the view of India's northward movement towards the Eurasian plate through time. So, you can see how it is moving and colliding. So, this is the Eurasian plate, and because of this collision, we have the Himalayas. So, is this the Himalayan region? So, because of this collision, we have the Himalayas in the northeastern part of India.

According to the continental drift theory and plate tectonics theory, the plates are in constant motion; because of this motion, stresses are built up, and the release of these stresses generates seismic waves. This is what we discussed in the previous slide, also. So, because of that, you can see that around 250 million years ago, this was the condition of Earth where all the land masses were together, and then this is the present day. And subsequently, it will take the form of this, which we will call Novo Pangea, then 250 million years later, after this Novo Pangea. And then you will have this again after 250 million years; that is Pangea Proxima.

So, this work is linked here. This nicely explains continental drift and the future movement of our continents. So, as we learned, this liquefaction occurs because of the earthquake or earthquake loadings. As we have seen in the previous slides, the earthquake loadings cause liquefaction.

SEISMIC WAVES (BODY WAVES)

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- Body waves travel through both solid and liquid mediums.
- P-wave and S-wave are the two kinds of body waves.

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So, let us understand what these seismic waves are and how they interact with the surface. So, when we talk about the earthquake waves, there are two major categories. The first one is the surface wave, and then we have body waves. And the body waves

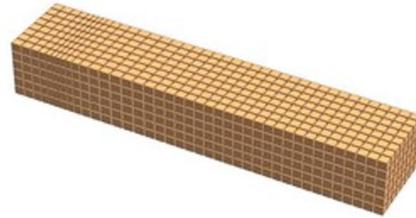
had two different types: the first one is the P wave, and then we have the S wave. When we talk about the surface waves, they are the Rayleigh wave and the Love wave. So, these four different types of waves are generated during an earthquake event. Now, let us try to understand each of them separately, so that you will understand their impact, how they propagate, and at what velocity they move, and that will give you more clarity about the earthquake loading on the soil or maybe the surface.

When we talk about body waves, we note that they travel through both solid and liquid. So, remember that both P and S waves travel through solids and liquids, and the P and S waves are the two kinds of body waves.

SEISMIC WAVES (BODY WAVES)



- P-waves, known as primary waves, are the fastest in terms of wave speed and are longitudinal in nature.
- It can travel through all mediums.
- Velocity is 5-8 km/s in Earth's crust, and >8 km/s in Mantle.



<https://makeagif.com/gif/s-waves-seismic-waves-earthquake--IZNju>

When we talk about this P wave, which is one of the body waves, it is also known as the primary wave. They are the fastest in terms of wave speed and are longitudinal in nature. So, you can see here how they propagate through a medium and how they are propagating. It can travel through all mediums because this is a body wave, and the velocity is 5 to 8 kilometers in the Earth's crust and greater than 8 kilometers per second in the mantle. So, you can see this is very fast in liquid or semi-liquid, whereas in the Earth's crust it is 5 to 8 kilometers per second. Then comes the second body wave, the S wave, also known as the secondary wave or shear wave, which is transverse in nature.

So, this is how it propagates; you see, it cannot travel through a liquid medium. So, it is only propagating through solids. So, the Earth's crust is the only target; the velocity is 3 to 4 kilometers per second in the Earth's crust and more than 4.5 kilometers per second in the mantle. So, this is how the S-wave travels.

Then comes the surface wave, so these waves travel through the Earth's surface and result from the interaction of body waves with the surface of the Earth. Now remember the body waves that were generated because of the earthquake events, and now these surface waves are the result of the interaction of body waves with the surface waves. Rayleigh waves and Love waves are the two kinds of surface waves. So, here you can see how the Love wave and the Rayleigh wave propagate. So, here you can see this is the direction, and here this is in this direction.

So, Lord Rayleigh was the first one in 1855 to predict the Rayleigh wave, and this is how the Rayleigh wave propagates. Rayleigh waves have particle motion like a stone thrown in a pond, with a velocity of 50 to 300 meters per second on the ground surface. So, here you can see how it will shake if I keep a target here. Love waves were invented by Augustus Edward Howe Love in 1911. Love waves have vertical particle motion and are generated by large earthquakes. So, this is the vertical particle motion; here, you can see how it is propagating, and it is also known as the Q wave. So, sometimes the Love waves are also referred to as Q waves in books or maybe in journal papers. And now let us understand what the history of liquefaction is. So, liquefaction, as we have understood, is the phenomenon that is happening on the surface of the earth. So, liquefaction has been one of the most studied phenomena in geotechnical earthquake engineering.

Engineers have started studying liquefaction after the Good Friday earthquake in Alaska in 1964. And that earthquake had a magnitude of 9.1. Now, you can just imagine how devastating it could be when we have a 9.1 magnitude earthquake. Three months later, the Niigata earthquake in 1964 had a surface magnitude of 9.5, and it produced the same effect because the earlier one, if you remember, was 9.1; here it is 9.5. So, they both had a similar impact. Both earthquakes produced liquefaction features that started the study of this phenomenon around 60 years ago.

PAST HISTORY OF LIQUEFACTION



- Three months later, the Niigata Earthquake in 1964, with a Surface Magnitude of 9.5, produced the same effects.
- Both Earthquakes produce liquefaction features, which started the study on this phenomenon 60 years ago.



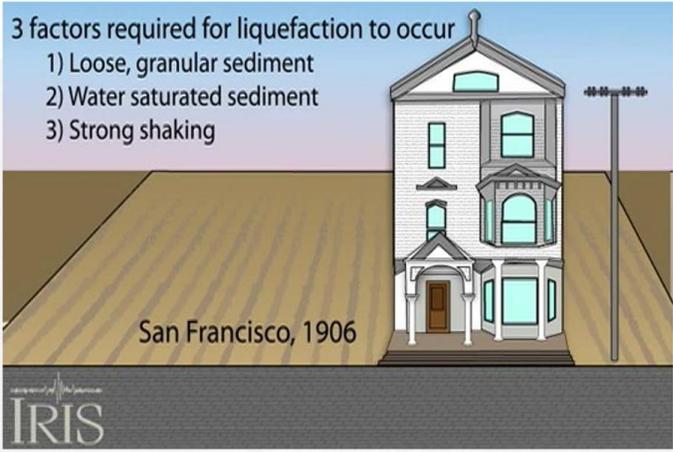
*Building Tilted Due to 1964 Niigata Earthquake
(Ishihara et al, 1981)*

So, here you can see some real images and the building tilted due to the 1964 Niigata earthquake, and this is from this paper.

THEORY OF LIQUEFACTION

3 factors required for liquefaction to occur

- 1) Loose, granular sediment
- 2) Water saturated sediment
- 3) Strong shaking



San Francisco, 1906

IRIS

An example of liquefaction occurrence (IRIS Earthquake Science, YOUTUBE)

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So, the theory of liquefaction says that seismic waves cause cyclic loading, which is basically repeated stress or strain, and causes the soil to undergo liquefaction. So, we will try to understand what we mean by liquefaction. So, in general, liquefaction is a phenomenon in which soil loses its shear strength, and the reason behind the soil losing its shear strength is the excess pore pressure generation.

Now, just try to understand this concept while you are having a cup of dry soil. And try to just pour it here. So, what will happen if it is dry? It will spread. If you add some amount of water here, then it will be saturated, not oversaturated; a little bit saturated, maybe 10 percent to 20 percent moisture, you can add here. So, what will happen is that this will try to hold the particles together because they will have cohesion, and because of that, this whole column will stand. Now you try to put more water here: 30, 40, 50, 60, 70, 80 percent, and then try to pour it here again. Then what will happen? Immediately, it will flow. Because this is a cohesionless soil. So, because of this, the soil loses its shear strength due to the excess pore pressure generation. Once the soil completely loses its shear strength, it behaves like a viscous fluid. If you remember, we also talked about the shear stress and shear strength in landslides, and there we also tried to understand what would happen if there were a reduction in the shear strength and an increase in the shear stress. So, here we are also talking about the shear strength of the soil. Once the soil loses its shear strength, what happens? It will behave like a viscous fluid. I gave you the example of 1 cup of soil or sand with more saturated water. Then you try to pour it out, and it will start flowing.

So, that will start to behave like a viscous fluid. It is unable to bear any kind of load because let us assume, there is a condition where there is a soil column that is oversaturated. And it is behaving like a fluid because it does not have any shear strength, and you have a building on top of it. So, what will happen? Will this sink, or will this get tilted because this particular column is not able to support this foundation? So, in such situations, we observe this liquefaction. So, it is unable to bear any kind of load when there is a reduction, or the soil loses its shear strength.

This causes any structure on it to fail. Failure means either it will sink, or it will get tilted. Liquefaction is observed in loose granular deposits with a high groundwater table because we are discussing the soil. And it is getting saturated. So, from the bottom, we have the groundwater, and from the top, you have this loading. So, when this groundwater reaches this column, it will start reducing its shear strength, and then this column will fail. So, here is the condition when you have soil particles, pore water, and groundwater surface subsidence during an earthquake event, and then this is settling because the pore spaces, as you can see, are more here and less there. So, this is before the earthquake; this is after the earthquake. This is a very nice video that explains the liquefaction phenomenon. So, here you can see this building, and here you have this layer. So, look below the surface; here you have loose, granular sediments.

Now, loose granular sediment is saturated by groundwater, so when groundwater has reached this, you have an earthquake event, and because of that, you are experiencing the failure of this soil. So, what happened? The building is tilted. So, why did this happen? earthquake waves caused water pressure to increase in the sediment, sand grains lost

contact with each other, leading to a loss of sediment strength and liquid-like behavior, and this is what we call liquefaction. This is the photograph from the San Francisco earthquake area of 1906, which is underlain by mass deposits that were covered by artificial fill in the 1800s, and this is from the USGS. So, this is a very nice video that explains the theory of liquefaction.

So, for soil to bear any load, shear strength is one of the most important factors; otherwise, how will it bear the load that is on top of this surface? Shear strength gives us an idea of the capacity of the soil to resist shear failure. That means if you know about shear strength, you can understand what the capacity of the soil is against shear failure or, under certain circumstances, whether this building will sustain and whether this soil column will support the structure or not. To compute the shear strength, engineering properties of the soil are needed. Now we can calculate the shear strength, and because of that, we need to analyze our soil sample and derive the engineering properties of the soil. So, liquefaction occurs in cohesionless soil only because we are talking about saturated soil.

- Liquefaction occurs in cohesionless soils only.

$$\tau = \sigma_{eff} \times \tan\phi$$

where, τ is static shear strength,
 σ_{eff} is effective stress, and
 ϕ is the internal friction angle.

- In cohesion-less soil, the C (cohesion) is not considered

So, here we try to calculate static shear strength. So, we need effective stress; it is here, which is multiplied by the tangent of the internal friction angle. So, that is needed here. So, once we have these two values, effective stress and the internal friction angle, we can calculate the static shear strength of the soil, and here cohesion is not considered because we are talking about cohesionless soil; otherwise, this liquefaction will not occur. For effective stress, the unit weight of the soil is required, as well as the groundwater table depth. Now, here you can see this effective stress; to calculate it, we need the saturated unit weight of the soil and the unit weight of the water, which is here, and h is the height of the soil column. So, if the building is here and this is the soil column, then maybe rocks will start. So, what is this height? This is h .

- Due to shaking, the depth of the soil column (h) increases.
- The increase in the unit weight of water \times depth of soil column ($\gamma_w \times h$) term is known as excess pore pressure generation.
- Effective stress (σ_{eff}), becomes 0 when significant excess pore pressure is generated.
- Soil loses its shear strength.

So, due to shaking, the depth of the soil column increases. So, due to shaking when there is an earthquake, what will happen? The soil column height will increase. The increase in the unit weight of water, which is multiplied by the depth of the soil column, is known as excess pore pressure generation. This is what we started discussing. So, now we have come to the generation of this excess pore pressure. The effective stress that we calculated in the previous slide becomes zero when significant excess pore pressure is generated. So, this is zero, and this is when the soil loses its shear strength.

So, now we have come to a conclusion about when the effective stress is zero. This soil is going to fail because there is no shear strength. Let us try to understand the liquefaction again from a different perspective. So, stress transfers from intergranular friction to pore pressure; that is the first step. Then, when the transfer is complete, the soil loses its full strength. Partial strength is lost when the transfer is partial; in the case of an earthquake, there is a condition of load reversal because, when there is a soil column, let us say this is the soil column, this is the edge. So, during the earthquake event, let us say this is the water table. During the earthquake, because of this interaction, this particular soil loses its shear strength, and because of that, this building is getting tilted. But whether this shear strength failure is permanent or temporary depends on the behavior of this particular soil. So, during the earthquake, what happened because of the seismic activities? So, these waves trigger this interaction, and then the soil loses its shear strength, but after the

earthquake, this soil may regain its original shear strength, and then this will be as it was before, but the building gets tilted. This is one of the examples. So, there is a condition of load reversal. Hence, there is a momentary transfer of stress. So, what is happening? This stress will get transferred. When the load reversal occurs, the soil may attain its original strength.

This happens only if the sand's behavior is satisfactory. So, again, we need to look into the engineering properties of the soil, or this sand in this case, during the load reversal. If the excess pore pressure generated has the scope of dissipating, it will dissipate, and the sand will become comparatively densely packed. So, this is after the load reversal. So, again, it is getting densely packed, but if the soil column is confined, there is no space for the dissipation of pore pressure. Suppose this is one column, this is another column, and this is the soil column, and this is confined.

So, in this case, the stress is not getting transferred. So, this pore pressure will be confined to this column; in that case, the loosely packed sand will not take denser packing. So, this will not be densely packed after the load reversal. In such cases, a complete transfer of stress occurs to pore pressure. So, what is happening here? The transfer of stress happens to pore pressure. Subsequently, liquefaction occurs. So, this is the flow of liquefaction to understand the phenomenon; I hope it is very clear to you. Now, let us talk about the different types of liquefaction. So, the first one is flowing

liquefaction, and the second one is cyclic mobility. So, let us understand both separately and see how they are different from each other. So, when we talk about flow liquefaction, it occurs when shear strength is less than shear stress. When we talk about cyclic mobility, shear strength is greater than shear stress. Now it is less frequent; it is more frequent, very severe; it is less severe. So, this cyclic mobility is less severe than flow liquefaction. So, both of them are different types of liquefaction. So, with this, I will end the first part of this lecture, and we will continue this lecture in the second part.