Geotechnical Earthquake Engineering

Prof. Deepankar Choudhury
Department of Civil Engineering
Indian Institute of Technology, Bombay

Module - 1

Lecture - 2

Introduction to Geotechnical Earthquake Engineering (Contd…)

Welcome to the lecture number two of NPTEL video course on Geotechnical Earthquake Engineering. Let us see on this slide - this NPTEL video course on Geotechnical Earthquake Engineering. We started with lecture number one in the previous lecture. And today, we are starting our second lecture for this video course. In that course, as we were going through the first module - module number one, which is Introduction to Geotechnical Earthquake Engineering. Before we start our today's lecture number two, we will quickly do a recap of what we have learnt in our first lecture.

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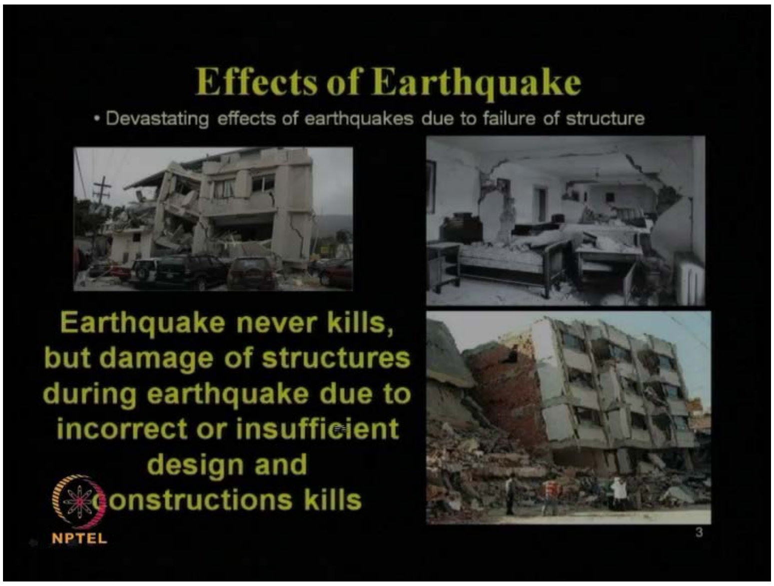

We have seen the various effects of earthquake like devastating effects of earthquakes due to failure of structures like this, which all of us are aware about. And one thing we have observed or discussed that earthquake never kills, but the damage of these structures during the earthquake - that finally kills. And why this damage of the structures occurred during an earthquake, either because of incorrect design and construction or insufficient design and construction, to withstand this earthquake forces.

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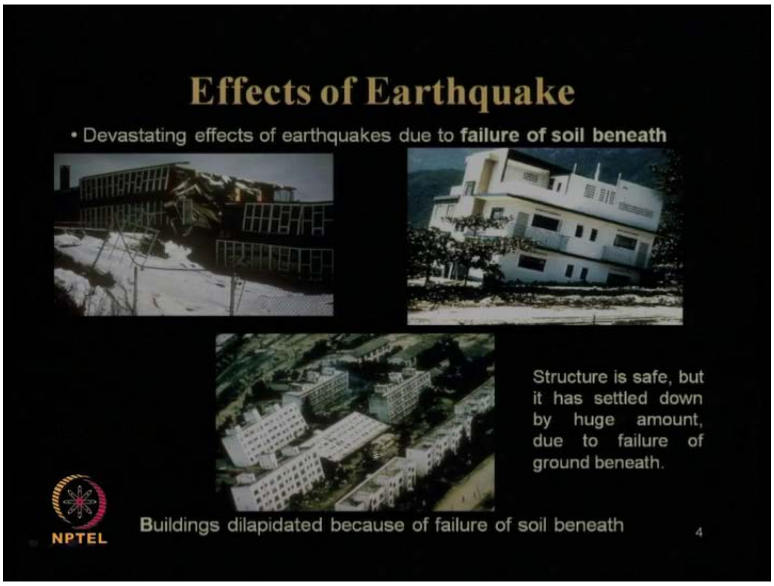

We have also seen the devastating effects of earthquake due to failure of the soil below the structure or in the foundation soil. So, it is not necessarily that the superstructure or the building failure will occur due to the earthquake; it may be the reason given to the behaviour of the soil during the earthquake process or the foundation failure. As shown through these slides already that the supper structure was designed perfectly fine to withstand the earthquake; however, the soil could not withstand that earthquake or the damage of the soil either in form of liquefaction or the in sufficient bearing capacity of the foundation; or, combination of them could have occurred; which finally, in turn will fail the superstructure though it was constructed and designed properly to withstand the structure. So, that automatically told us, what is the need of learning this course on Geotechnical Earthquake Engineering?

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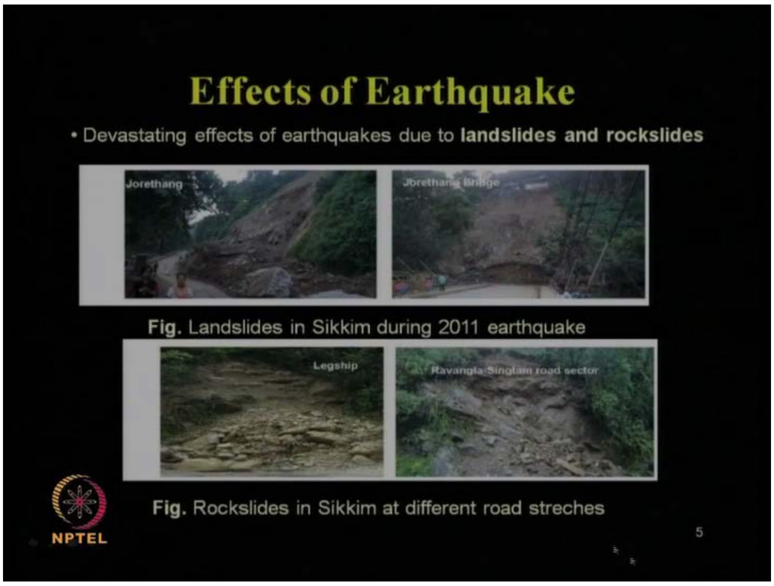

Then we have also seen other geotechnical aspects of this earthquake like slope failure or the landslide and the rockslide, which we have seen during very recent Sikkim 2011 earthquake in India in September 2011.

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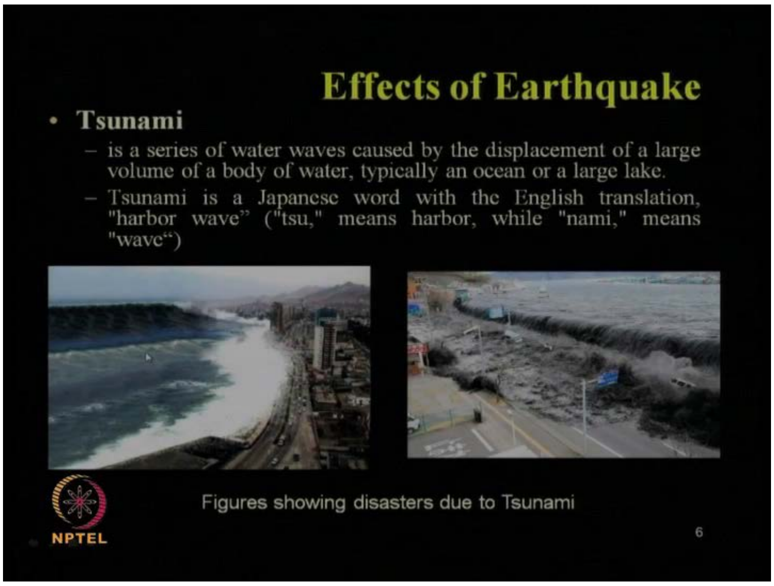

Also, we have seen other effects of earthquake. One of the major effects of earthquake is tsunami. We have seen tsunami is a Japanese word, and its English translation will become Harbor wave. And this figure shows the recent tsunami devastating effect, which occurred in 2011 in Japan after the Tohoku earthquake in March 2011. So, height of tsunami wave, etcetera, cause of this tsunami, etcetera can be due to an earthquake. But it is not necessarily that all earthquakes in the deep ocean or large water body will always create a tsunami. There are possible conditions, which need to be there to form a tsunami wave.

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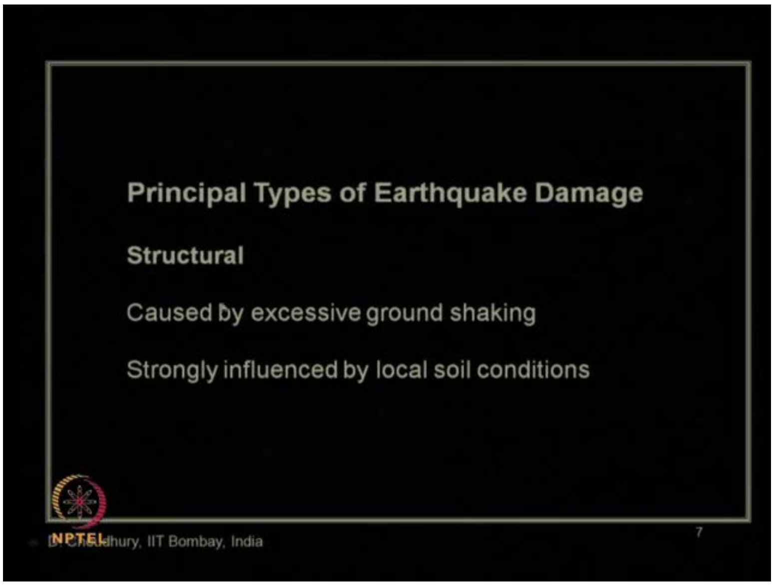

Then, we have gone through what are the principal types of earthquake damage. And, for that, the structural damage, which can be either caused by the excessive ground shaking; and, this is strongly influenced by local soil conditions.

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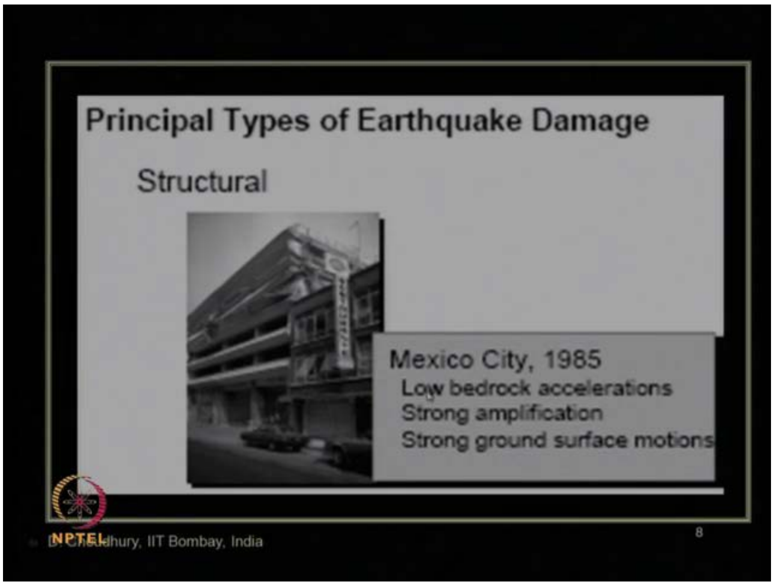

For that, we have seen a very good example of Mexico city earthquake, where the original bedrock seismic acceleration was pretty low. So, it was not supposed to make any such damage to the structure. But, unfortunately, the soil below the city in Mexico was pretty soft in nature, which caused the soil amplification in that location. So, that way, the original bedrock acceleration got amplified or increased, which finally, destructed all the structure in the Mexico city. So, that large devastation of Mexico city earthquake in 1985 was majorly due to the geotechnical aspects of earthquake engineering.

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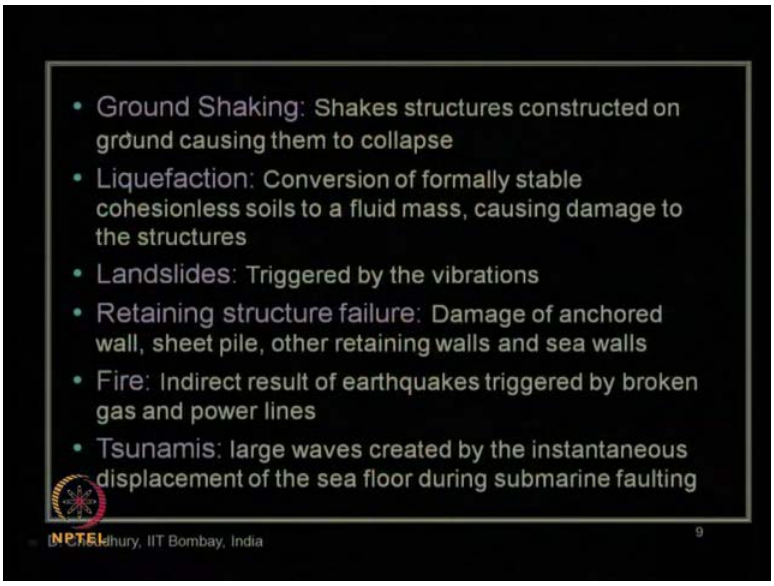

Then, we have discussed in the previous lecture about different aspects of earthquake like ground shaking, liquefaction, landslides, retaining structures failure and the indirect effect of earthquake like fire hazard and the tsunami.

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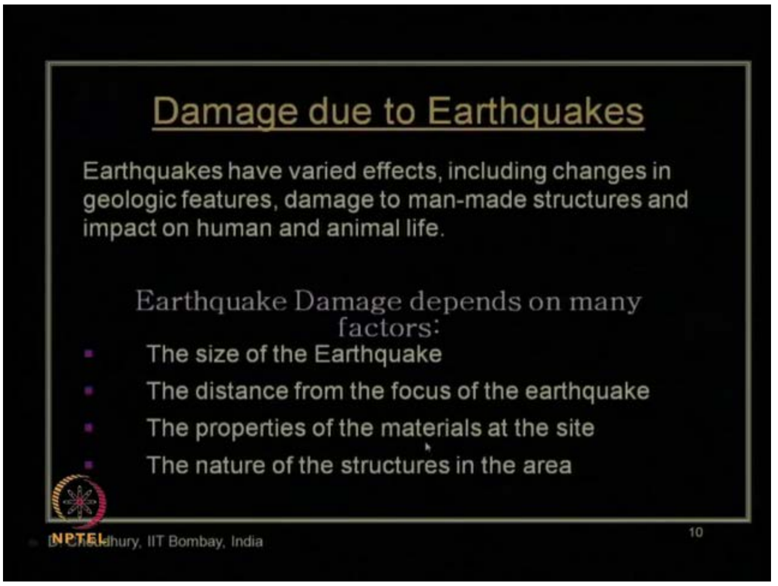

Then, we discussed about what are the various factors on which the earthquake damage depends on a particular structure. It depends on major four factors like size of the earthquake. As we know, as the size of earthquake will increase, chances of damage will increase. The distance from the focus of the earthquake to the concerned structure or the site of interest - so, if the distance increases, then chance of earthquake damage will reduce. The properties of the material at the site; that is, at the site, what kind of material is existing - local soil condition or rock condition; whether it is a soft soil or stiff soil or hardrock or fissured rock, etcetera, will decide on how much earthquake damage is going to occur at that particular site. Also, the nature of structure, which exists in that area like whether it is a wooden structure or reinforced concrete structure or unreinforced concrete structure are masonry structure or mud house; depending on type of the construction of the structure, the amount of earthquake damage also will depend on.

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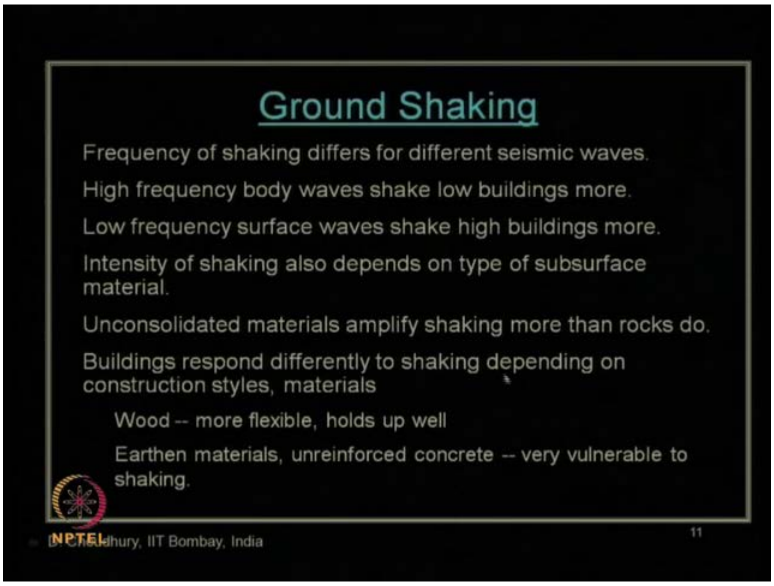

Then, we have discussed about the ground shaking. We have seen that frequency is the important parameter, which decides that different seismic waves which are generated during an earthquake process, they will have different frequencies of shaking. And, various frequencies will cause different behaviour of different heights of the building; like high frequency body wave will shake the low height building or like single storey building or two storeyed building more; whereas, the low frequency surface waves – they will shake more on the high raised buildings or tall storey building. So, the common layman idea that, always the tall storey buildings are more vulnerable during an earthquake is not always true. It is true only when the input earthquake surface wave, which are caused during the release of an earthquake energy - that is having a low value of the frequency; then only, the high or tall storey buildings are more vulnerable for the damage. Whereas, if it is having the high frequency body waves, then low raised buildings like even a single sturdy building also will be more vulnerable for the destruction due to earthquake.

Also, we have seen that intensity of that shaking also depends on type of subsurface material. As I said, like what type of soil? Whether it is loose soil or a stiff soil or a rock? Depending on that, that intensity also will depend. Also, we have mentioned in the previous lecture that unconsolidated material will amplify; that is, the material or the soil, which is still unconsolidated or has not consolidated fully yet, they will have a more chance to get amplify this ground shaking than the rock. And, buildings respond differently to shaking depending on construction style; that is, what style of construction? Whether it is a symmetric construction or asymmetric, etcetera? And what types of materials are used? Like whether it is wood or earthen material are unreinforced or reinforced materials? Depending on that, the earthquake vulnerability or the more dependency of the damage on these factors will depend on.

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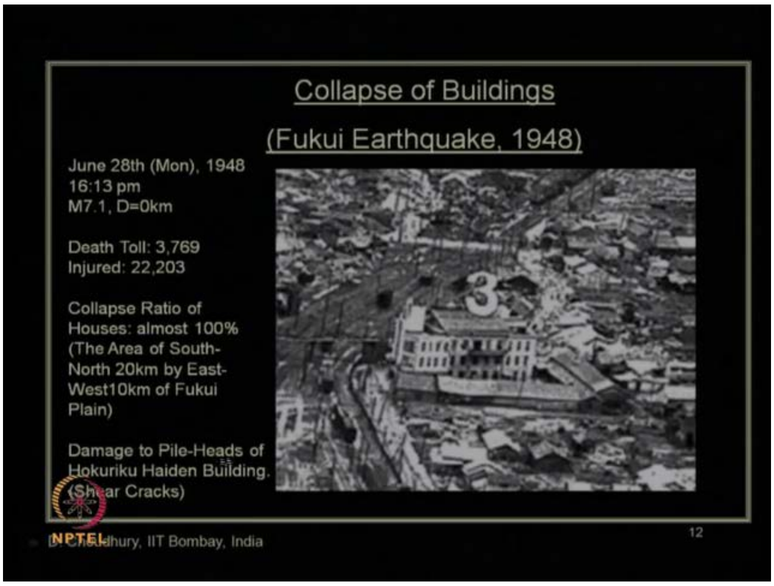

We have seen in the previous lecture about collapse of buildings - a case study from the Fukui earthquake of Japan, which occurred in 1948. This is the day and date and time with magnitude and epicentral distance of the earthquake; amount of loss of human life and injuries. Then, we have seen the collapse of the houses, which was almost 100 percent; that is, all houses got collapsed in the area of North-South direction by 20 kilometres; and, in East-West direction by 10 kilometres of Fukui plain. And, the damage to the pile heads were also observed. So, that was the damage to the d foundations, which were monitored.

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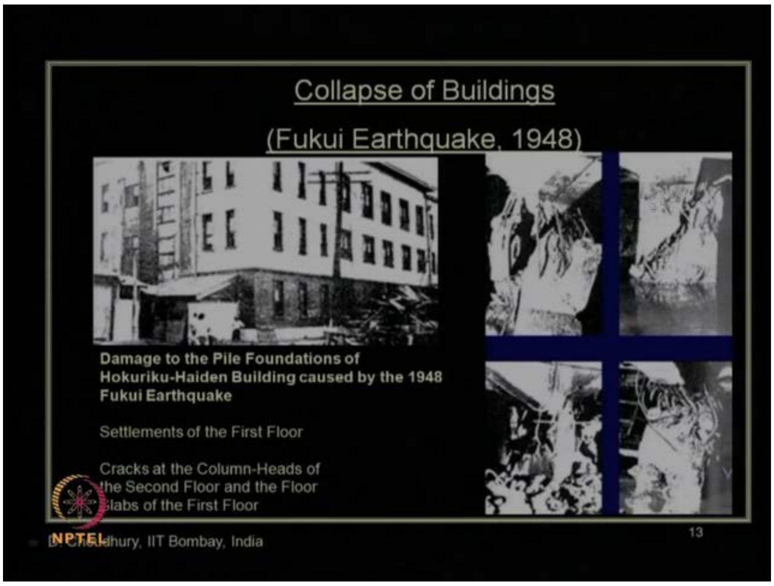

This is the picture, which we have discussed in the previous lecture about the damages of various pile foundations during this Fukui earthquake of 1948.

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Coming to today's lecture, we can continue further on this topic and we can say this picture, which shows the total damage of the Bachau in Kutch region of Gujarat after 2001 Bhuj earthquake. And, this is the picture of the total destruction of the area, total damage of the houses and buildings, etcetera in that Bachau region of Kutch in Gujarat in India in 2001 Bhuj earthquake.

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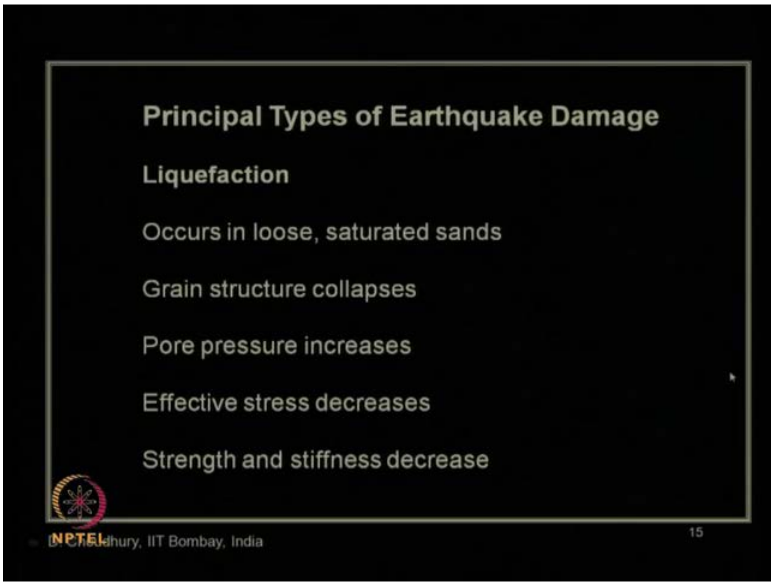

Then, we can discuss further on principal types of earthquake damage. Another important criterion is liquefaction. What is liquefaction? Liquefaction mostly occurs in loose, saturated sands. In this condition, the grain structure collapses and pore water pressure in the soil - that increases or develops. Automatically, it will reduce the effective stress, because we know that total stress equals to effective stress plus pore water pressure; or, in the other word, effective stress is nothing but total stress minus pore pressure.

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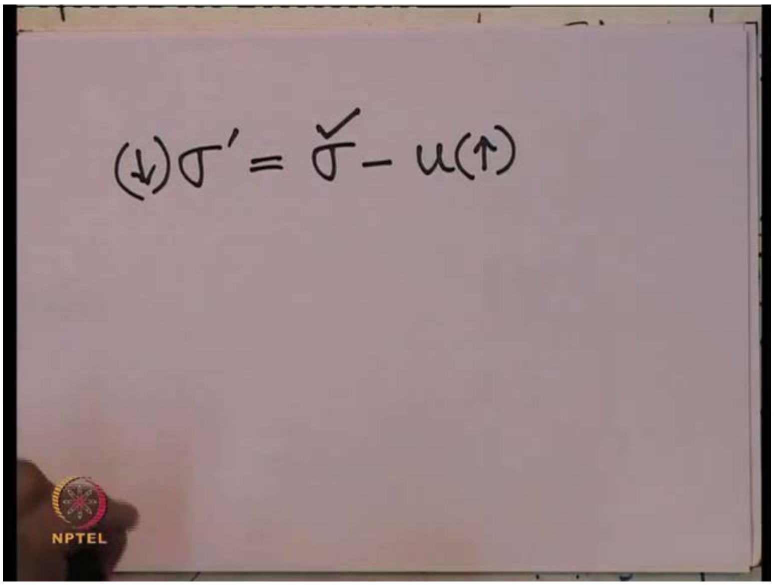

So, total stress remaining constant, if pore pressure increases, obviously, there will be reduction in the effective stress, because we can see this equation - the very well-known effective stress equation of Terzaghi. Effective stress is given by total stress minus pore water pressure. So, if this value of u increases during the earthquake process, what will happen? This sigma dash will decrease when this sigma, that is, total stress remains constant. That is what, once the effective stress of the soil reduces, it can be considered as the liquefaction either partial or fully depending on the various criteria, which we will discuss later on when we will discuss about the dynamic soil properties and the liquefaction chapter in this course. So, ultimately, what happens? That reduction in the effective stress will reduce the strength and stiffness of the soil. So, finally, that damage, that type of behaviour, which is known as liquefaction of the soil, will create the damage on the structure constructed on that type of soil, which is prone for liquefaction during an earthquake loading.

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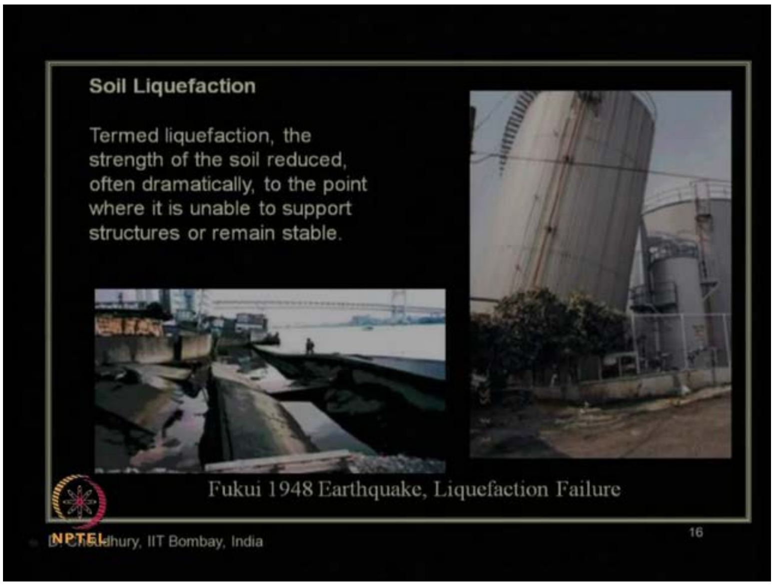

There are various examples of soil liquefaction related destructions during an earthquake or after earthquake. Soil liquefaction – termed liquefaction, the strength of the soil is reduced as we have seen just now; often, it reduces dramatically or very quickly; and, to the point, where it is unable to support the structures or remain stable; that means, this at full liquefaction, the soil particles will behave like fluid or watery material, which will start flowing. So, in that condition, obviously, whatever structure is constructed on the soil will no longer stand on a soil, but it will stand on a fluid by the conversion of this soil through this full liquefaction process during an earthquake. And, that is why, obviously, that fluid cannot further take the load of the huge structure, which is constructed on it. So, finally, the entire structure will get damaged or destructed or collapsed. So, this is the example of Fukui 1948 earthquake.

You can see in this picture, the entire area got collapsed and a huge lateral spreading or the spreading in this portion has occurred due to the liquefaction failure after the earthquake of the Fukui in 1948 in Japan. This is another picture, which shows that very tall structure like this, which got tilted and shifted like this due to the soil liquefaction of the foundation at this pocket or at this point.

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Let us take another example of case history of earthquake, which is 1964 Niigata Earthquake, which occurred on June 16th on Tuesday in 1964 at the local time of 01:02 pm; and, local magnitude was reported as 7.5. And, the reference of this can be obtained from the 1995 Great Hanshin or Kobe earthquake; and then, 1923 Great Kanto Earthquake. So, from these two, this Niigata earthquake also can be correlated. And, it was observed by several seismologies, geologies, structural earthquake engineer, geotechnical earthquake engineer, to study the behaviour of various structures after the Niigata earthquake.

The amount of death is mentioned over here. And, total burnt and collapse of houses is also listed on the slide. You can see here what are the major damages; major damages, where soil liquefaction. At various locations, the soil got liquefied after this earthquake. And as a result, the structure, which were constructed on this soil as considering as a stable foundation material, as it got liquefied or flowed like a fluid, the bridges, etcetera collapsed. And, fire of the oil storage tanks occurred, because this storage tank, etcetera collapsed similar to the previous picture what we have discussed just now. So, finally, that caused the fire in the entire area. And, remember that, fire continued for about 300 hours. So, such a long duration it was continuing. So, that is an indirect, but a very big or great damage of earthquake, which can be considered or should be considered for proper design of the structures in the earthquake prone region.

And, remember one important thing. This earthquake of Niigata occurred in June 16th; whereas, the Tokyo Olympic games – it was hosted by Japan in the same year 1964 between 10th to 21st of October. So, Japanese researchers, engineers, practitioners - they did an extremely good job to rectify the necessary structures, everything after this great damage of 1964 Niigata earthquake. So, they were fully prepared in the month of October just after few months of this Great Niigata Earthquake of 1964. And, they could host the Tokyo Olympic games.

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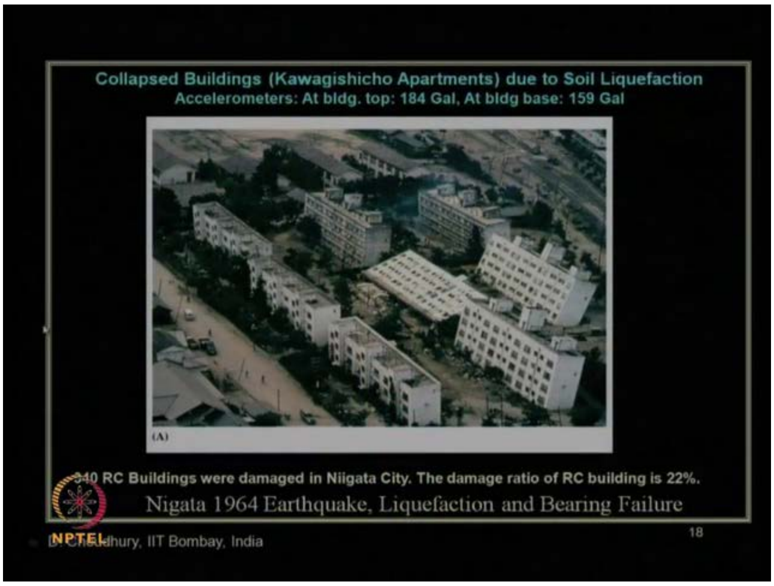

You can see in the next slide over here. This is the picture of the collapsed building. This is the very common picture. All of us can see this picture as a cover picture of the book of Geotechnical Earthquake Engineering written by Steven L. Kramer. As I have mentioned in the previous lecture that, is one of the most important reference book for this course. So, this is the cover picture of that book, which we are all familiar about those we have gone through that book or those we have seen that book. This picture shows the collapsed buildings of that Niigata 1964 earthquake either because of liquefaction failure or bearing failure or combination of that.

What were the details? Like 340 reinforced concrete buildings were damaged in that Niigata city. And, the damage ratio of reinforced concrete building was about 22 percent compared to the other unreinforced buildings, which were fully damaged. So, you can see in this picture, collapsed building Kawagishicho Apartments due to soil liquefaction. And, the accelerometers record at this location at this top of the building recorded as 184 Gal unit; and, at the base of the building, it was recorded as 151 Gal. So, this is the type of behaviour of a structure – reinforced concrete structure, which was designed perfectly fine by structural engineers. But the problem aroused because of the ill behaviour or non-proper behaviour of the soil during earthquake, which was probably not fully taken care of during the construction of this building on this soil. So, the liquefaction as well as the bearing capacity failure was the problem for this damage.

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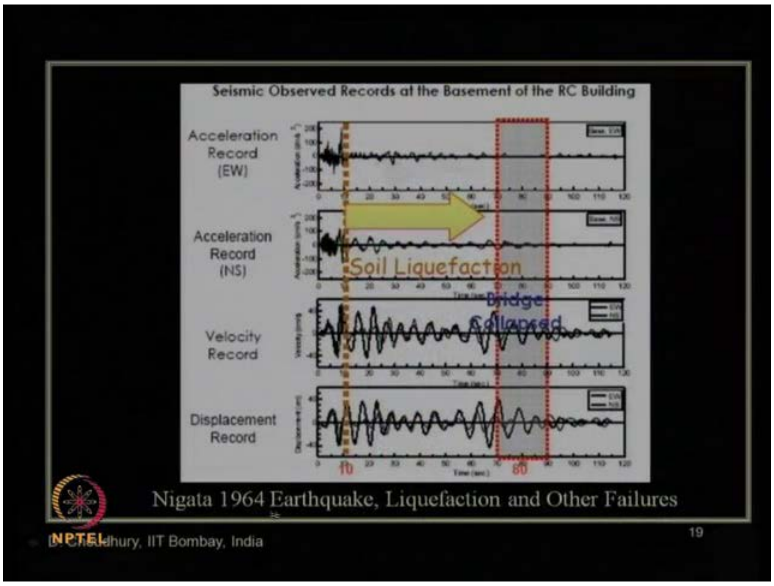

Now, let us see the various observations of Niigata earthquake. These are few more case studies we can discuss about; like the liquefaction and other failures of 1964 Niigata earthquake, these are seismic observed records at the basement of that reinforced concrete building. You can see the accelerometer recording acceleration record in East-West.

In this slide, we are showing the Niigata 1964 earthquake, liquefaction and other failures; what are the observations of seismic stations like seismic observed records, which was recorded at the basement of that RC building. This is the acceleration record - the first picture in the East-West direction. This is the y-axis - tells us about the acceleration value in centimetre per seconds square unit; and, x-axis is the time in second. This second picture shows the acceleration record in North-South direction. Again, acceleration verses time. This third picture shows the velocity record - velocity in centimetre per second unit verses time. And, the fourth or last record - it shows the displacement record; that is, displacement in centimetre verses time in second.

You can see over here the maximum value of the acceleration, which has occurred in East-West direction as well as in North-South direction, which can be seen through this velocity record also is typically close to about 10 seconds; whereas, if you see, when the soil liquefaction got started, it got started beyond this 10 seconds; that is, once it reach this maximum value, after that, the soil liquefaction started; whereas, they monitored from the case history that the bridge started collapsing during this about 80 seconds or so between 70 to 90 seconds. That is the time when the bridge started collapsing after the soil liquefaction has occurred. So, there is a few second time lag between the soil liquefaction starts and the collapse occurred of the superstructure, which is quite obvious, because this is the time taken by the soil to fully liquefy. And, once it fully liquefies, then the bridge started collapsing. And, you can see over here the displacement record, which is nothing but integration of this acceleration record twice. And, that gives us the maximum displacement occurring at this location, which finally causes the damage of the structures constructed on that site on this liquefied soil.

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Now, let us see another example of historical earthquake, the case steady of that through this slide, which is the 1995 Great Hanshin Earthquake; or, it is popularly known as Kobe Earthquake, because it occurred close to the Kobe city in Japan. The date of occurrence of this earthquake was January 17th, which was Tuesday of 1995 at the local time of 05:46 in the early morning - am. And, epicenter was at Awaji Island; fault depth was 14 kilometres - the hypocentral depth from the ground surface. And, the magnitude was recorded as 7.2. The number of death and heavy injured and light injured and missing - all are reported in the slide over here. Completely destroyed houses about close to a lakh - 1 lakh; you can see huge number of damage. And, partially destroyed houses - more than a lakh - more than 1 lakh; and collapsed bridge total - 46 bridges got collapsed after this Kobe earthquake; and, collapsed or heavily damaged building - more than 3000; and, total monetary loss was about 96 billion US dollars.

Before this 2011 Great Tohoku Earthquake of Japan, this Kobe earthquake of Japan of 1995 was the largest or biggest disastrous earthquake, which occurred in Japan with magnitude of 7.2. But, remember, the Tohoku earthquake was much more than this magnitude; it was close to about 9 - 9.1. So, the Tohoku earthquake - that is why, it was much more devastating though from 1995 to 2011, the seismic design and construction techniques have improved a lot, which has been adopted at various parts of the Japan. But, still then, always, we cannot ensure at very high magnitude like 9 or 9.1, so that all the structures will stand perfectly fine.

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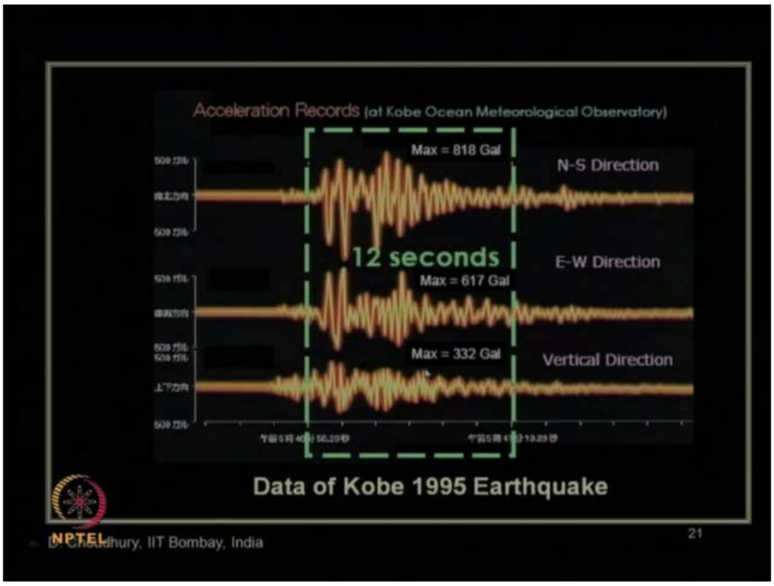

This data, this slide shows the basic data of the Kobe 1995 Earthquake. This is acceleration record at the Kobe Ocean Meteorological Observatory. This is the North-South direction horizontal acceleration record. This y-axis is in Gal unit; the Japanese people - they use the Gal unit. The typical conversion you can do with this is, if you take 818 Gal, will be close to about 0.818 G. So, that can be a typical conversion what from a Gal unit to SI unit one can do. The second acceleration record shows the East-West direction record of the horizontal acceleration. And, the third record shows the vertical acceleration record - acceleration verses time.

You can see over here the typical duration of the major earthquake, which occurred in Kobe, that was for about 12 seconds. So, it is the starting point; this is the ending point - almost close to ending point you can say. And, the maximum value of North-South direction horizontal acceleration was 818 Gal. In the East-West direction, the maximum value was recorded as 617 Gal, which is close to 0.617 G. And, in the vertical direction, it was maximum value recorded as 332 Gal, which can be considered typically close to 0.332 G.

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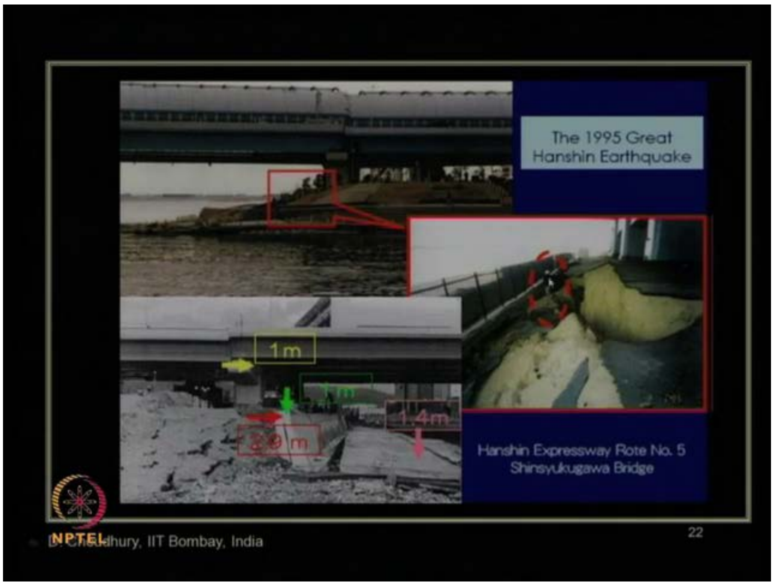

These are the damages one has observed after that 1995 Great Hanshin/Kobe Earthquake. You can see over here this was the apartment foundation. This apartment of the bridge - that has moved after the soil liquefaction, etcetera, has occurred over here. You can see the lateral displacement occurred at this site. After the liquefaction, what happens? The soil is no longer a solid material, but behaves like a fluid or watery material. So, obviously, they start flowing from a higher slope to a lower slope; that is, higher gradient to lower gradient. So, once they flow out or move out from that place, obviously, entire structure, water was constructed on that, starts moving or collapsing; that collapse can be both in vertical direction as well as in horizontal direction. So, after this Kobe earthquake, this particular apartment portion of this bridge - they moved horizontally.

You can see over here by about close to 3 meters; 2.9 meters was the horizontal movement; this vertical movement at this location was 1 meter. At this level, the horizontal movement was 1 meter; at this level, the recorded vertical movement was 1.4 meters. Such huge amount of movement in both horizontal and vertical direction was observed. You can see over here; this was initially together; then, after this part liquefied and flown out, the total destruction or vertical movement as well as horizontal movement occurred at this location. You can compare easily; this is the height of a human being; this is the typical height of a person; compared to that, see the height of the amount of displacement - the vertical height, which is much more than the height of the human being or people. So, this huge amount of damage can occur, which was also observed during this 1995 Kobe earthquake in Japan.

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This is another picture, which shows the damage of a bridge. This is the approach bridge, which was completed in the year 1993. And, span of the bridge was 52 meters. You can see over here – this is the span of the bridge. And, the design seismic coefficient, which was used for the design of this bridge, was 0.3 G as per their design code of Japan at that time. And, Caisson foundation was used for this bridge. But, after this Kobe earthquake of Japan in 1995, what happened, this portion of the soil got liquefied; and finally, this apartment or this support sinked into the soil; and finally, everything got collapsed like this. So, this is the Nishinomiya-ko Ohashi bridge after its collapse caused by lateral spreading. As I was mentioning, once the soil gets liquefied, it starts flowing in the... As it flows in the gradient wise for the case of water for higher to lower gradient, the same thing occurs. So, lateral spreading induced soil liquefaction caused the damage of the structure constructed on this site.

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Next, let us see a picture on the ground surface, where the soil liquefaction has occurred. This slide shows a picture of the sand boiling, what we call in another term – sand boiling or soil boiling or the soil liquefaction. This is the ground water – the underground water, which is close to the ground surface, are rushing out or coming out to the surface after the liquefaction takes place at the site. This is the picture, which occurred at the Kandla Port in Gujarat soon after the Bhuj earthquake in 2001 in India. So, that sand blow in mud flats used for salt production South-West of Kandla Port Gujarat. So, this is the soil boiling or sand boiling due to the liquefaction on the ground surface.

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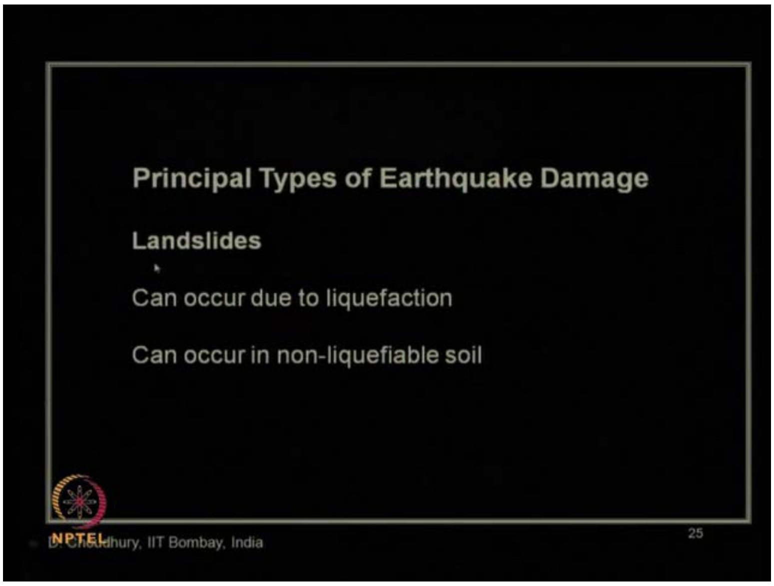

Let us see other types of principal earthquake damages like landslide. Landslide is another type of principal damage of earthquake. It can occur either due to the liquefaction or it can occur also in non-liquefied soil. Even in the rocky slope, that landslide can occur due to the earthquake. So, it is not necessarily it has to be a liquefied soil; if it is liquefied soil, obviously, due to the liquefaction, the slope stability failure and the lateral spreading will occur. But, also, in non-liquefied soil or rock also, that landslide can occur due to earthquake.

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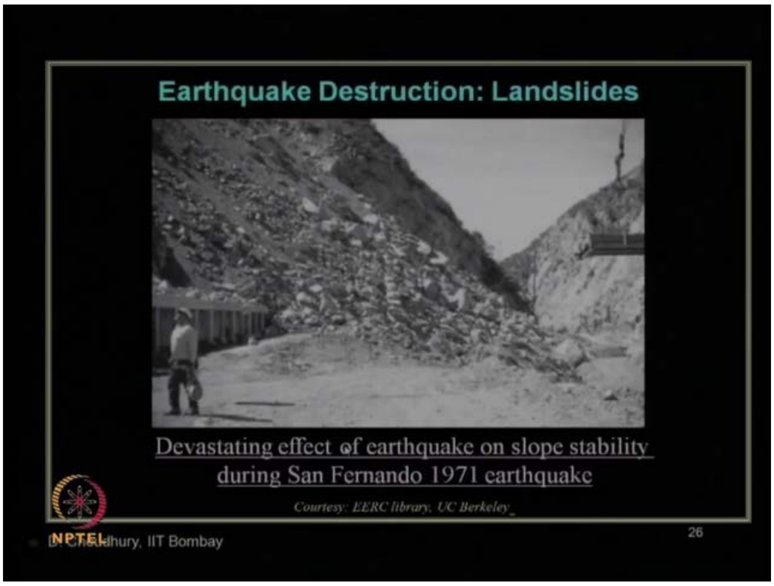

This picture shows a landslide due to the earthquake, which occurred after 1971 San Fernando earthquake. This is the devastating effect of slope instability due to the earthquake. This picture has been taken form EERC library.

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We can see some more earthquake damages. This is the devastating effect of earthquake damage on the pavement foundation. This was the initial pavement foundation. After the earthquake, the entire thing here got collapsed. This is the picture after the 1960 Chile earthquake. So far, in the history, we know that the 1960 Chile earthquake is the highest recorded earthquake so far in the world.

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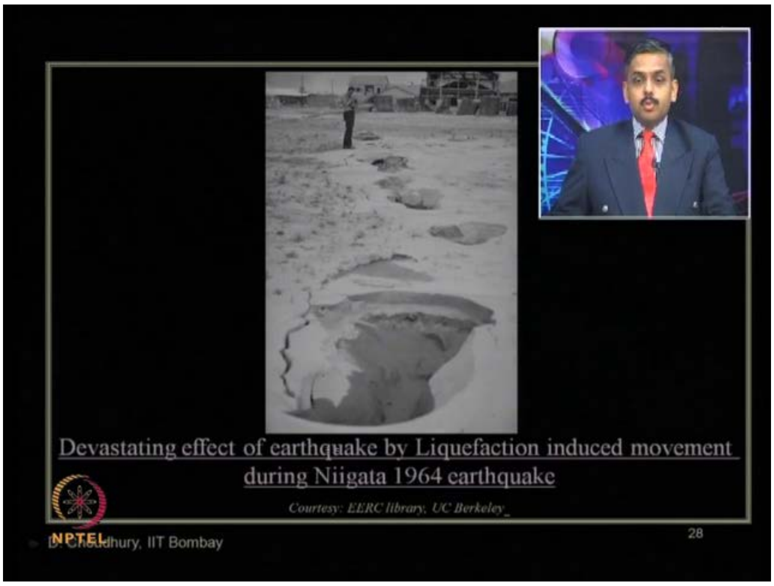

This is another picture, which shows the devastating effect of earthquake by liquefaction induced movement. So, after the liquefaction, the soil or watery soil – I should mention –

has moved out from this location and created these big voids. So, this liquefaction induced movement occurred at this site after the Niigata earthquake in 1964 in Japan.

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This is another picture, which shows the devastating effect of earthquake by the liquefaction induced bearing capacity failure during Turkey 1999 earthquake. Here also, one can notice, there is not much damage on the superstructure, but the problem was with the soil liquefaction. That is the reason why geotechnical earthquake engineering needs to be studied properly to understand this problem and to make liquefaction resistant or the earthquake resistant construction of foundations also properly to take care of the local soil conditions.

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This picture shows the effect of liquefaction or liquefaction-related phenomenon as I have mentioned, which is known as lateral spreading. Lateral spreading is nothing but after the soil gets liquefied, it starts flowing; as it becomes a fluidic state, it starts flowing from higher slope to a lower slope. This is the picture after the soil flown from higher slope to lower slope or higher gradient to lower gradient after the liquefaction occurred at that portion. So, upslope portion of the lateral spread at Gujarat after that 2001 Bhuj earthquake in India – this is the picture.

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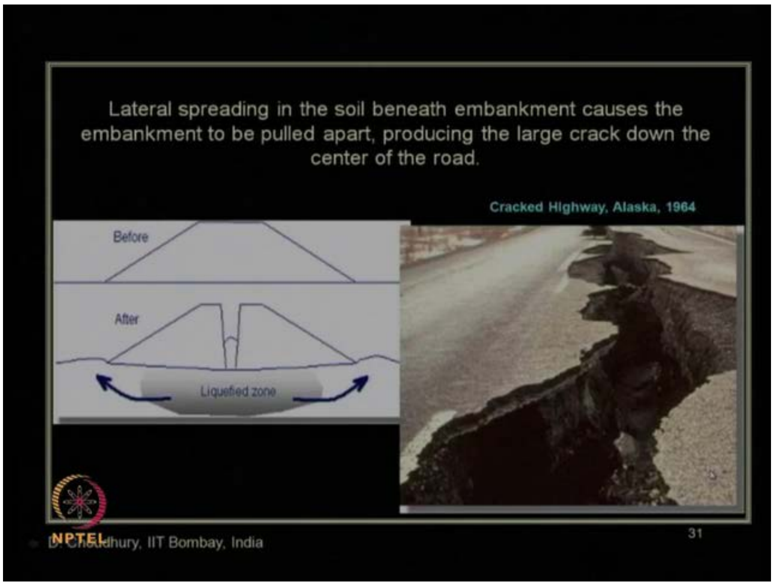

This is another picture, which shows the lateral spreading in the soil beneath the embankment, which caused the embankment to be pulled apart. You can see this is the initial picture of the embankment. After the soil below this embankment – if it gets liquefied, it pulled apart like this and producing a large crack on the center of the road. You can see this occurred in the Alaska 1964. After the earthquake, this much of total destruction of the embankment occurred. And, this is nothing but again geotechnical earthquake engineering problem.

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Coming to other form of earthquake destruction like retaining structure failure or retaining wall failure, this is the initial retaining wall. You can see one portion of it got collapsed over here after the 1999 Chi Chi earthquake in Taiwan. This is the close view of that collapse of that retaining structure or retaining wall after that earthquake.

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Then, liquefied soil – they start exerting higher pressure on the retaining wall. Why? Because when we design a retaining wall, it has supposed to withstand the earth. And, as we know, in the active state of earth pressure, earth pressure coefficients are typically less than 1; whereas, if the soil starts becoming or behaving like a liquefied material, it is nothing but a fluidic material. So, for that, the pressure coefficient or lateral coefficient will be 1, which is much more than the active earth pressure coefficient, which is considered for the design of any retaining wall under active state of earth pressure. So, automatically, the liquefied soil starts exerting much higher pressure on the retaining wall; and, which can cause finally, the retaining wall to tilt or slide if it is not a designed properly to withstand that amount of lateral thrust coming from the fluidic soil or the liquefied soil. So, this is the picture of a retaining wall failure after the soil liquefaction.

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Another picture shows here the increased water pressure, which causes collapse of the dam. You can see over here at this portion, the dam has been totally collapsed. This is due to the increase water pressure during the earthquake condition.

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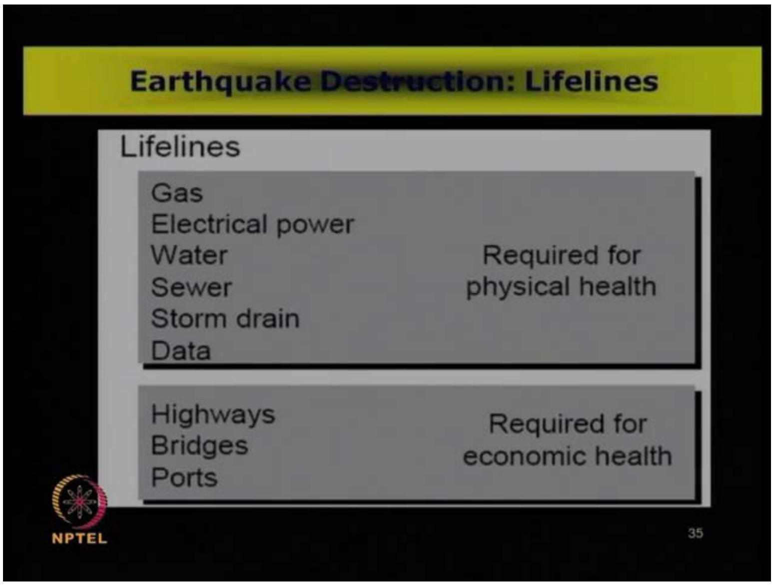

Some more earthquake destructions, that is, the destruction of the life lines due to earthquake. What are the lifelines? We can categorize them into two major categories: one – lifeline, which are required for the physical health of human being; and, another is required for the economic health of a country or of a place or of a state. So, for these lifelines, which are required for the physical health of human being or the society or a mankind, are like gas, electric power line, water lines, sewer lines, storm drain, data, etcetera. So, these things should not get damaged due to earthquake. So, these are the lifelines. If any of them got damaged, then we can understand the lifeline of a human being or a society gets also totally affected or damaged. Some other lifelines, which are required for the economic health of a country or a location or a city or a state like highways, bridges, ports, etcetera - these also should not get damaged due to earthquake, because again, if one or combination of them got damaged, then total economic health of a country get damaged due to the earthquake process.

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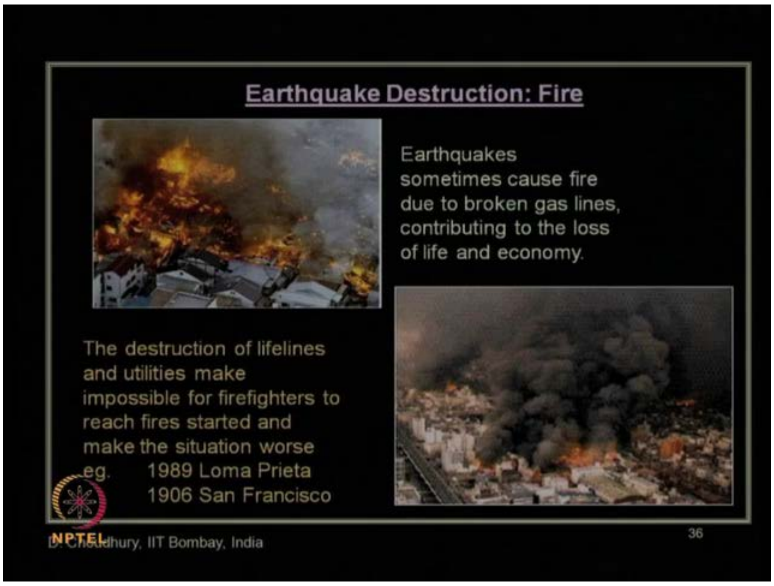

Now, let us discuss about the indirect effect of that earthquake, which we have mentioned initially, that is, the fire; that is, the fire is the indirect result of earthquake destruction. You can see in this picture, earthquake sometimes cause fire due to broken gas lines and contributing to the loss of life and economy. That will be most disastrous. You can see from these pictures, after the earthquake, the entire city caught by fire. And, that is because of the broken gas lines. The destruction of lifelines and utilities make impossible for the firefighters to reach at that fire start, where the fire started; and, that makes the situation more worst. Already, earthquake-related damages are there. In addition to that, this fire creates much more problem in that vicinity. And, example of those type of damages of fire-related hazard due to earthquake or after earthquake, is 1906 San Francisco earthquake in California in USA and in 1989 Loma Prieta earthquake again in California in USA. These two have witnessed this kind of fire-related destruction soon after the earthquake in addition to the earthquake destruction.

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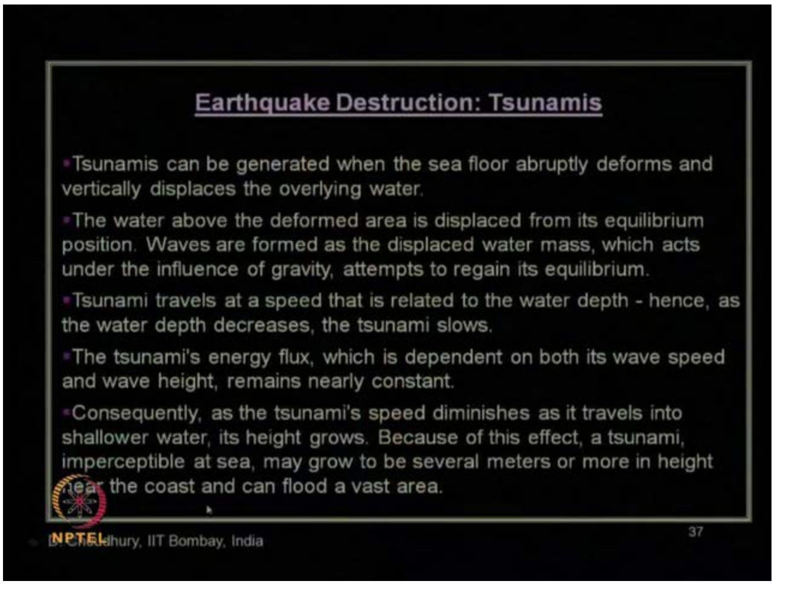

Then, another indirect result of earthquake destruction can be called as tsunami. As we have little discussed earlier, let us finally go through this detailed version of what are the type of destruction can occur due to tsunami. This tsunamis can be generated when the sea floor abruptly deforms and there will be a vertical displacement of the overlying water. So, as I have already mentioned earlier, there must be a vertical movement or vertical displacement of the seabed, which will cause this destruction. This vertical movement of the seabed is necessary to create the tsunami after an earthquake. The water above the deformed area is displaced from its equilibrium position due to this vertical shifting of the floor – seafloor. Hence, waves are formed as the displaced water mass, which acts under the influence of gravity, it attempts to regain its equilibrium, because originally, it was in equilibrium; and, by shifting of that seafloor, that water standing on it got displaced, equilibrium position has changed. So, it will try to regain or go back to another state of equilibrium.

And, to do that, what happens, you can see over here in this slide that tsunami travels at a speed that is related to the water depth. And hence, the water depth decreases, the tsunami speed slows down, but the height increases. Why? Because... Let us see next point. The tsunami’s energy flux – the total amount of energy, which is getting released through this tsunami, which is dependent on both the wave speed and the wave height – that remains nearly constant. So, once the energy flux remains constant in the deep sea, where the tsunami gets generated due to the abrupt deformation of the seafloor in the vertical direction, that creates a very high speed of tsunami, but very less wave height to maintain a particular value of energy flux. So, as that tsunami wave travels from deep sea to close to the shore or close to the boundary of the solid surface, that height increases and speed diminishes or speed slows down, which ultimately makes the energy flux of that tsunami, remains constant.

Consequently, as the tsunami's speed diminishes as it travels into the shallower water, that is, close to the shore, it heights grows. Because of this effect, a tsunami, which is imperceptible at sea... So, sometimes it happens that some tsunami cannot be seen at the deep sea level, because it is not having any particular height; it is having high speed, but it is not having any perceptible height. So, imperceptible tsunami may grow to a several meter of height or more when they come near to the coast or the shore and can flood the entire area.

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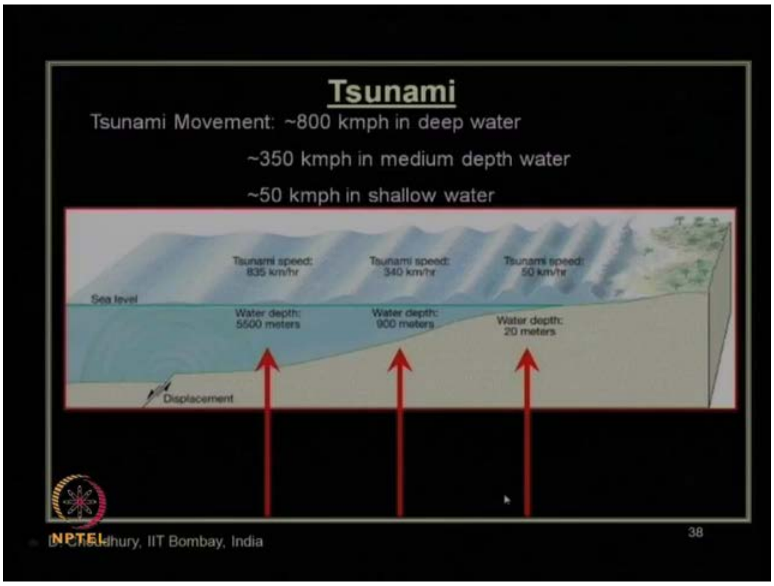

This is the picture, which clearly shows how the tsunami wave movement occurs. First, this is the seafloor movement should occur; this displacement there should be a vertical component of this movement as I have already mentioned; and, that creates the waves over here. And finally, this energy flux has to remain constant. So, at deep sea level, there is higher speed of this tsunami, but very less amount of height over this static sea level. But, as it travels close towards this coast or the shore, you can see, this height increases, but speed reduces. So, speed reduces.

The typical tsunami speed is listed over here. At deep sea, where the depth of the water is more than 5000 meters, the speed is about 800 kilometres per hour in the deep water. When the water depth is about close to 1000 meters, then medium depth water, the velocity or speed is about 350 kilometres per hour; whereas, in shallow water, that is, about 20 meters of water depth, where it comes, at that location, the tsunami movement speed will be about 50 kilometres per hour in shallow water. But, height will be tremendously high and that can be even few meters.

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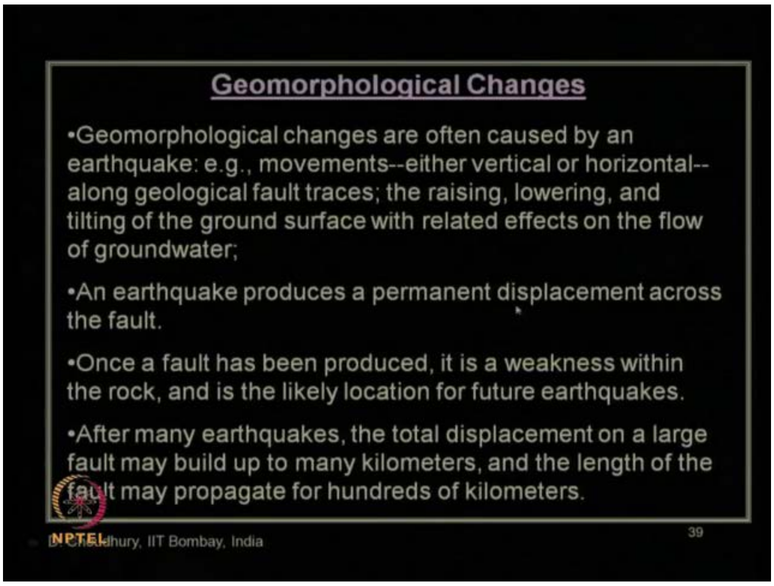

Now, due to the earthquake, what are the geomorphological changes occurred at a place? Let us see the criteria of geomorphological changes; like geomorphological changes are often caused by an earthquake. What does it mean geomorphological changes? Like movement of the ground surface - either it can be the vertical or horizontal; alone, the geological fault traces and the raising or lowering and tilting of the ground surface with related effects on the flow of groundwater; that is, once the ground surface, everything, got tilted or moved or somewhere the ground surface has raised, somewhere it has got down or somewhere the ground surface got tilted, then at those location, automatically, the original ground water table, where it was located, either they come up or come down;

or, change of ground water table location also will occur. That is nothing but one of the major form of the geomorphological change.

An earthquake produces a permanent displacement across the fault. Remember, after the earthquake, there is no way that displacement can be regained or come back to original position; it becomes a permanent displacement at that fault. Once a fault has been produced, then it remains as a weakness within the rock forever; and, is the likely location for the future earthquake; that means, whenever there is a movement in a fault, which is of course a permanent movement, that remains forever. There is a fault or weakness in the rock that remains forever; and, there is no chance that weakness can be recovered. Moreover, those weakness points are the future possible locations of the earthquake, because already there is a weakness in the rock. So, whenever the earth’s interior energy will try to open up or dissipate, those are the points, where it will get there weakness in the rock to get dissipate the energy.

After many earthquakes, the total displacement on a large fault may build up to many kilometres like several kilometres; the length of the fault can be several kilometres after several earthquakes. And, the length of the fault may propagate for hundreds of kilometres; that is, its width or depth of the fault also can be few kilometres; even the length of the fault also can be few hundreds of kilometres. That big opening can occur or that big weakness can occur in the rock.

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List of Major Historic Earthquakes in World

Year	Location	Deaths	Magnitude
1556	China	5,30,000	8.0
1906	San Francisco	700	7.9
1960	S. Chile	2,230	9.5
1964	Alaska	131	9.2
1976	China	7,00,000	7.8
1985	Mexico City	9,500	8.1
1989	California	62	7.1
1995	Kobe	5,472	7.2
2001	Gujarat, India	1,00,000	7.7
2004	Sumatra	2,20,000	9.1
2005	Pakistan	1,00,000	7.6
2008	China	90,000	7.9
2010	Haiti	2,22,000	7.0
2010	Chile	50,000	8.8
2011	Japan	1,00,000	9.1

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Let us see in this slide, which lists typical major historical earthquakes around the wall. There are of course, several other major earthquakes. But, it has been listed only some typical major earthquakes all over the world starting from like 1556 in China; number of deaths are listed over here; magnitude is listed over here. And then, 1906 San Francisco earthquake - the magnitude - 7.9; South Chile earthquake of 1960 of magnitude 9.5; 1964 Alaska earthquake - magnitude - 9.2; 1976 China earthquake - magnitude - 7.8; 1985 Mexico city earthquake; then, 1989 Loma Prieta earthquake in California, USA; then, 1995 Kobe earthquake in Japan.

Then, 2001 Bhuj earthquake in Gujarat in India; then, 2004 Sumatra earthquake of magnitude about 9.1; 2005 Kashmir earthquake or Pakistan and India border earthquake - 7.6; 2008 China earthquake of 7.9; 2010 Haiti earthquake of about 7; 2010 - this Haiti earthquake was in January and 2010; February was Chile earthquake, which was magnitude of 8.8. But, Haiti - number of deaths and destruction was much more than the Chile earthquake. We will discuss all these things later on in this due course of time for this course. And, 2011 Japan earthquake, where of course, the destruction was pretty huge not only due to the earthquake, but more due to the tsunami; and, this was the magnitude of the earthquake 9.1.

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This is another list, which shows some significant earthquakes in India and in its neighbourhood. You can see various date, latitude, longitude of epicentre, the location of earthquake - various Indian earthquakes; and, their corresponding magnitudes are shown over here. Like 1819 on June 16th, this Kutch Gujarat earthquake - it experienced 8 magnitude earthquake; then, 1869, January 10th near Assam - there was a magnitude of earthquake 7.5; then, 1885 in Jammu and Kashmir - 7 magnitude earthquake; in 1897 in Shillongplateau earthquake, 8.7; in 1905, Kangra in Himachal Pradesh - a magnitude 8; 1918 - again in Assam, 7.6; 1930 in Dhubri again in Assam in 7.1; 1934 - Bihar-Nepal border earthquake - 8.3; 1941 - Andaman island - 8.1; 1943 in Assam again - 7.2; 1950 – Arunachal Pradesh earthquake – 8.5.

1956 - Anjar Gujarat earthquake of 7; 1967 - Koyna earthquake in Maharashtra - 6.5; 1975 in Kinnaur in Himachal Pradesh - 6.2; 1988 - Manipur earthquake - 6.6; again 1988 - Bihar-Nepal border earthquake; 1991 - Uttarkashi earthquake; then, 1993 Lathur earthquake; 1997 - Jabalpur earthquake; 1999 - Chamoli earthquake; and, 2001 - Bhuj earthquake. After that, there are several other earthquakes; latest one, major one was 2011 earthquake in September 2011 at Sikkim earthquake. So, all these data of the earthquake can be obtained from the USGS website as well as IMD of India government website, from where you will get the basic data or basic information about all these date of earthquake, the epicentral locations in terms of latitude and longitude and their magnitude. All these details are available from USGS website, PEER website and IMD website. And, there are other several sources for this information.

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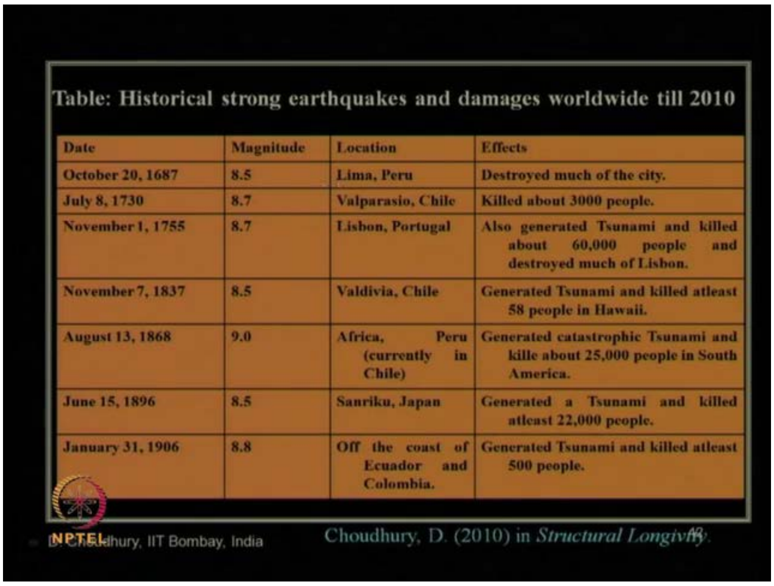
Table: Historical strong earthquakes and damages worldwide till 2010

Date	Magnitude	Location	Effects
October 20, 1687	8.5	Lima, Peru	Destroyed much of the city.
July 8, 1730	8.7	Valparasio, Chile	Killed about 3000 people.
November 1, 1755	8.7	Lisbon, Portugal	Also generated Tsunami and killed about 60,000 people and destroyed much of Lisbon.
November 7, 1837	8.5	Valdivia, Chile	Generated Tsunami and killed atleast 58 people in Hawaii.
August 13, 1868	9.0	Africa, Peru (currently in Chile)	Generated catastrophic Tsunami and kille about 25,000 people in South America.
June 15, 1896	8.5	Sanriku, Japan	Generated a Tsunami and killed atleast 22,000 people.
January 31, 1906	8.8	Off the coast of Ecuador and Colombia.	Generated Tsunami and killed atleast 500 people.

Let us see the historical strong earthquakes and damages worldwide till the year 2010. These details are available in the journal paper. If somebody is interested, can go through this journal paper; this is the name of the journal - Structural Longivity by myself. In 2010, it has been published. It listed all the historical earthquakes, which caused major damages like 1687 Peru earthquake of magnitude 8.5. These effects are mentioned over here - like destroyed much of the city; then 1730 in Chile earthquake; then Portugal earthquake, Chile earthquake again and so on.

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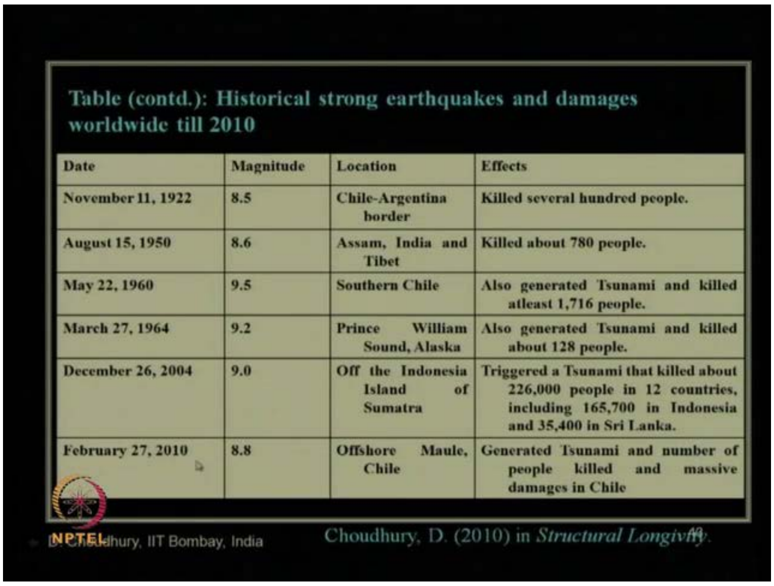

Table (contd.): Historical strong earthquakes and damages worldwide till 2010

Date	Magnitude	Location	Effects
November 11, 1922	8.5	Chile-Argentina border	Killed several hundred people.
August 15, 1950	8.6	Assam, India and Tibet	Killed about 780 people.
May 22, 1960	9.5	Southern Chile	Also generated Tsunami and killed atleast 1,716 people.
March 27, 1964	9.2	Prince William Sound, Alaska	Also generated Tsunami and killed about 128 people.
December 26, 2004	9.0	Off the Indonesia Island of Sumatra	Triggered a Tsunami that killed about 226,000 people in 12 countries, including 165,700 in Indonesia and 35,400 in Sri Lanka.
February 27, 2010	8.8	Offshore Maule, Chile	Generated Tsunami and number of people killed and massive damages in Chile

Again, other earthquakes you can see over here like 2004, December 26 earthquake of Sumatra; that triggered also a tsunami. You can see some of these earthquakes caused the tsunami if (( )) it originated in a deep ocean or seabed and with a vertical movement of that seabed. And also, you have seen that Chile earthquake of February 2010; that also generated tsunami and number of people killed.

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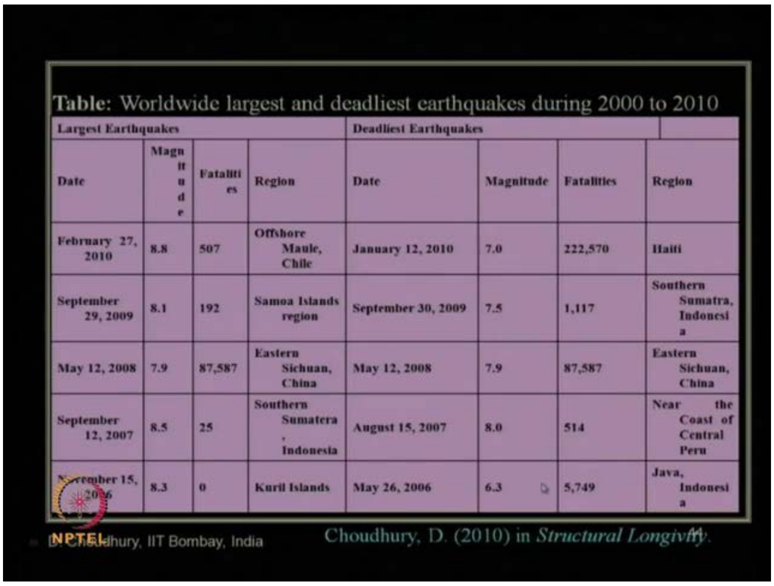

Table: Worldwide largest and deadliest earthquakes during 2000 to 2010

Largest Earthquakes				Deadliest Earthquakes			
Date	Magnitude	Fatalities	Region	Date	Magnitude	Fatalities	Region
February 27, 2010	8.8	507	Offshore Maule, Chile	January 12, 2010	7.0	222,570	Haiti
September 29, 2009	8.1	192	Samoa Islands region	September 30, 2009	7.5	1,117	Southern Sumatra, Indonesia
May 12, 2008	7.9	87,587	Eastern Sichuan, China	May 12, 2008	7.9	87,587	Eastern Sichuan, China
September 12, 2007	8.5	25	Southern Sumatera, Indonesia	August 15, 2007	8.0	514	Near the Coast of Central Peru
November 15, 2006	8.3	0	Kuril Islands	May 26, 2006	6.3	5,749	Java, Indonesia

Now, I want to mention in this slide that worldwide largest and deadliest earthquakes during the year 2000 to 2010. One should remember that it is not necessarily that largest earthquake will be the deadliest one; it is quite obvious, because the largest earthquake is in terms of the magnitude. Now, if that largest earthquake occurs say in a deep ocean or in a desert, where hardly any human being is living or there is no human habitant staying at that location. Then obviously, though the magnitude is high, the number of damage will be very less or almost nil. So, that will not be a deadliest earthquake. So, deadliest earthquake are those, which cause maximum number of damages of the structure and which kills maximum number of human beings. So, that is called deadliest earthquake.

So, that is the reason you can see over here from this slide that in 2010 when we take the example, that February 2010 Chile earthquake is the largest earthquake with magnitude 8.8; whereas, the deadliest earthquake of 2010 is the Haiti earthquake of January, which magnitude is 7, which is much lower than the Chile earthquake. But, in terms of the fatalities and damages, it was the maximum. So, that is why, the deadliest is different and largest is different, which is easily understandable; whereas, in 2009, you can see over here like largest earthquake and deadliest earthquake - that also differs. In 2008, largest and deadliest earthquake - they are same. So, obviously, there may be a chance that largest earthquake if it occurs in a highly populated area, then it can be a deadliest earthquake of course. Then, 2007 also - this is the largest earthquake; but this is the deadliest earthquake; and, so on. All the details can again be seen in this journal paper.

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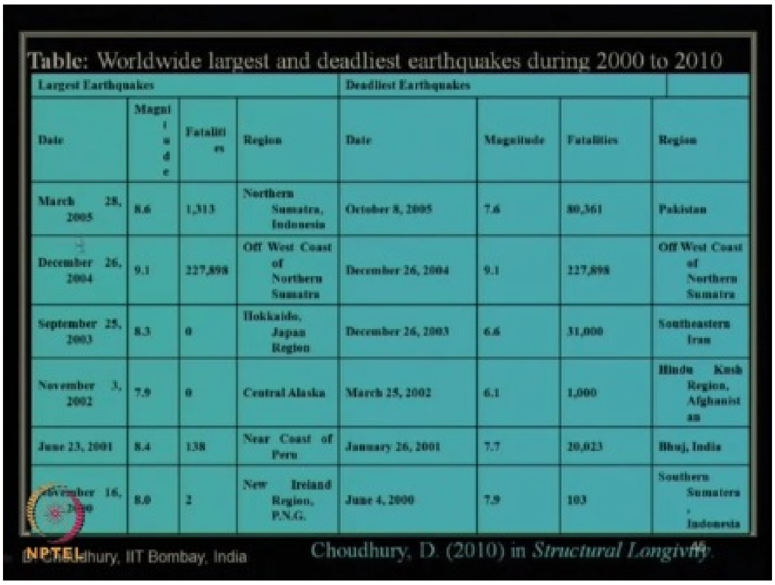

Table: Worldwide largest and deadliest earthquakes during 2000 to 2010

Largest Earthquakes				Deadliest Earthquakes			
Date	Magnitude	Fatalities	Region	Date	Magnitude	Fatalities	Region
March 28, 2005	8.6	1,313	Northern Sumatra, Indonesia	October 8, 2005	7.6	80,361	Pakistan
December 26, 2004	9.1	227,898	Off West Coast of Northern Sumatra	December 26, 2004	9.1	227,898	Off West Coast of Northern Sumatra
September 25, 2003	8.3	0	Hokkaido, Japan Region	December 26, 2003	6.6	31,000	Southeastern Iran
November 3, 2002	7.9	0	Central Alaska	March 25, 2002	6.1	1,000	Hindu Kush Region, Afghanistan
June 23, 2001	8.4	138	Near Coast of Peru	January 26, 2001	7.7	20,023	Bhuj, India
[illegible]vember 16, 2[illegible]0	8.0	2	New Ireland Region, P.N.G.	June 4, 2000	7.9	103	Southern Sumatera, Indonesia

This is some more details about the largest and deadliest earthquake, which can be seen.

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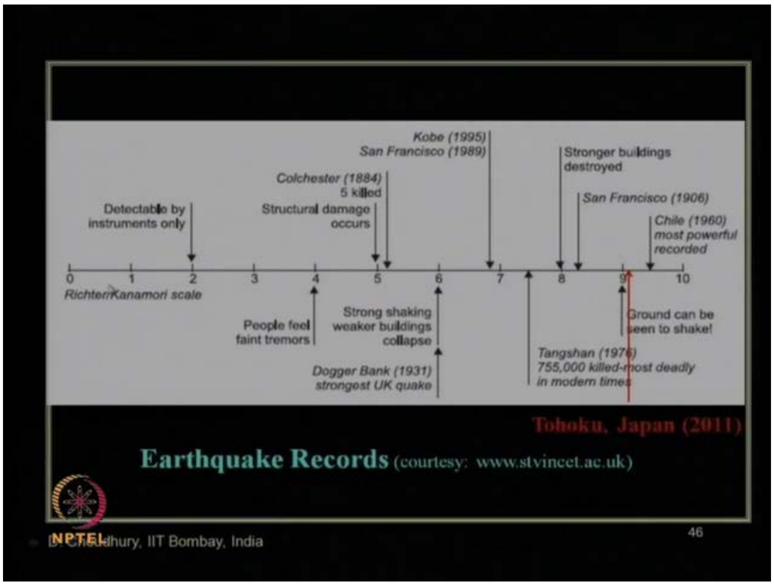

From the earthquake record, this is the Richter scale; starting from 0 to 10 scale is shown over here. The latest Tohoku, Japan, 2011 earthquake is somewhere here - 9.1. You can see this is the San Francisco 1906 earthquake; this is the Kobe 1995 earthquake; San Francisco Loma Prieta 1989 earthquake; and, several other earthquakes are listed over here. This is the Chile earthquake of 1960, which has so far recorded the highest magnitude earthquake in the world - about 9.5 in this scale.

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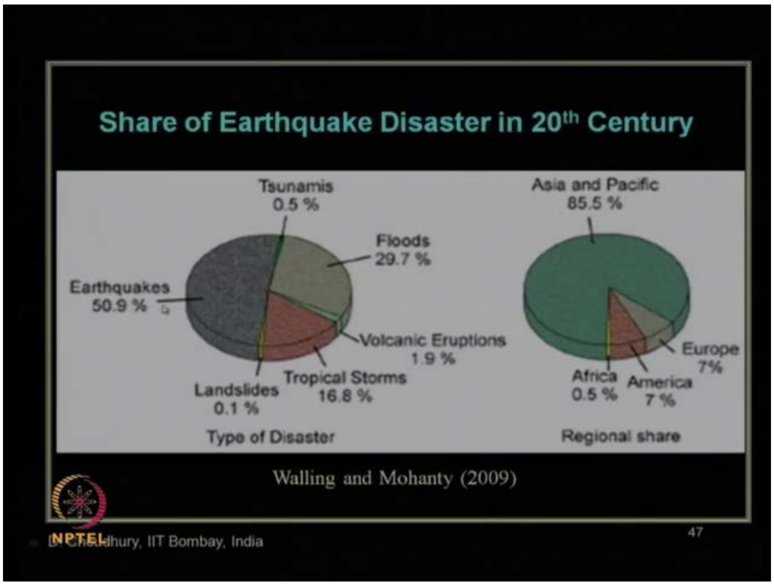

Now, why we should study the geotechnical earthquake engineering or earthquake engineering as such? You can see from this slide that how much is the share of earthquake disaster in the entire 20th century. As given by Walling and Mohanty in 2009, you can see among all the disasters, earthquake takes the share of more than 50 percent, close to about 51 percent. Next highest important disaster is flood, which is close to 30 percent. Next highest disaster is tropical storm, which is about 17 percent. Next highest disaster is volcanic eruption, which is close to 2 percent. Next highest disaster is tsunami, which is about 0.5 percent. And, the last one disaster is landslide. So, among all various disasters, earthquake takes the major share.

And not only that, if you see the regional share of that earthquake disaster, this pie chart shows here that Asia and Pacific region takes maximum share of more than 85 percent of the world for this earthquake disaster share compared to America - 7 percent, Europe - 7 percent and Africa - only 0.5 percent. So, that automatically shows why we should study the earthquake engineering and geotechnical earthquake engineering in particular; also in India, where we are from the Asia region, we should more study on this aspect, because of the local behaviour, local problems on this earthquake disasters, which has been reported through this slide, which occurred in the 20th century.

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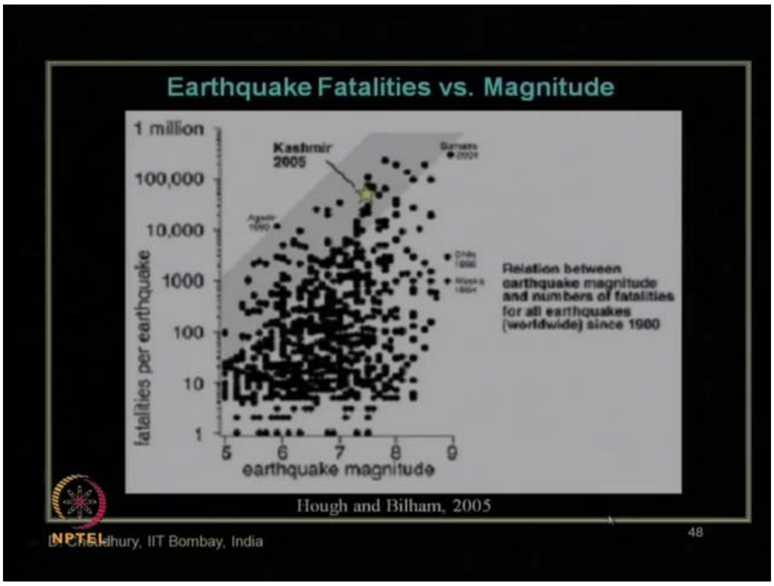

This is the typical picture given by Hough and Bilham in 2005. The relationship between number of fatalities verses earthquake magnitude, you can see the points; obviously, as we know, earthquake magnitude increases, if it is a highly populated area, number of damages of fatalities will increase; but it is not always so. Sometimes, you can see with a large magnitude, number of fatalities is less; that means, probably, either the construction was pretty good, design was pretty good, which could take care of that high magnitude of earthquake; or in that locality, there was less number of people, who were staying at that location. With this, we have come to the end of module 1 of this geotechnical earthquake engineering video course. We will continue further in the next lecture.