Chapter 6 Study Guide and Case Studies: Earthquake Hazards

Key Concepts

- Damage and fatalities from earthquakes depend on many factors. Earthquake-related factors include size, depth and type of an earthquake and its geographic location as well as the epicentral distance from an earthquake. Other factors include the local geology, population density and building codes.
- The time of day may also determine fatality rates. The times related with highest fatality rates may be differ between regions. E.g. times during rush hour traffic may be bad for the Los Angeles basin but better in developing nations with poor building codes.
- Tsunami are different from ocean waves. The former are a result of waters displaced by vertical ground motion, while the later are generated by wind.
- The two types of ocean waves are shallow water wave and deep water waves.
- Deep water waves do not sense the bottom of the ocean, and travel speed depends on the wavelength of the wave.
- Shallow water waves sense the bottom of the ocean and waves of all wavelengths travel with the same speed. The travel speed depends on water depth.
- The wave height of ocean waves depends on the product of wind speed, duration of wind and the fetch (size of the area over which the winds blow consistently).
- The typical wavelength of ocean waves is hundreds of meters, while the typical wavelength of tsunami is several 100 km.
- In the open ocean, tsunami are barely noticeable. But the waves break coming to shore and build a wall of water, something several meters high.
- Tsunami travel across entire oceans. They travel approximately with the speed of an airplane.
- The typical period of a tsunami is on the order of 15 min, meaning that 15 min pass between wave crests. Many tsunami approach in a way that sea level first recedes, not unlike an outgoing tide but much faster.
- This is much shorter than the time between two high tides (about 12 h in most places). So a receding sea level on the order of minutes is a clear warning sign that a tsunami is coming.
- The first tsunami wave may not be the highest wave arriving at the beach. A later wave can be higher even though it arrives an hour later.

- Because it takes hours for a tsunami to cross an ocean, ocean tsunami warning systems are an effective tool to save lives.
- Liquefaction describes the process by which previously solid ground briefly behaves like a liquid when shaken. Liquefaction occurs particularly in loose sediments or weak layers that contain large amounts of water.
- Structures built on liquefying soil lose their support and are more likely to collapse during an earthquake than structure build on solid, hard rock.
- Liquefaction can occur on the surface but also in a weak layer at depth, below a strong hard layer. In the latter case, liquefaction causes the hard layer to break into pieces that briefly float on the liquefying layer.
- Liquefaction in a deeper layer can also cause sand and mud volcanoes where the liquefying material escapes to the surface through small openings.
- Earthquakes can trigger other natural disasters such as other earthquakes, landslides, floods, fires and volcanic eruptions.
- Earthquakes can also trigger other disasters such as pollution (air and ground), power outages, and the outbreak of diseases.

Key Terms

- Local geology
- Building codes
- Ocean wind waves
- Fetch
- Wave length
- Period
- Travel speed
- Shallow and deep water waves
- Tsunami
- Wave height
- Tides
- Liquefaction
- Sand and mud volcanoes

Questions for Review

1. Which earthquake-related factors control the damage and fatality rate from an earthquake?

2. How does each of these factors play a role?

3. Give and example how local geology controls earthquake damage.

4. How do building codes control earthquake damage?

5. How would the time of day of an earthquake control fatality rates?

6. What is the difference between ocean wind waves and tsunami?

7. Describe the difference between shallow-water and deep-water waves.

8. How fast to tsunami travel?

9. How can a person standing on a beach distinguish an outgoing tide from the approach of a tsunami?

10. For how long should I stay away from the beach after the arrival of the first tsunami wave?

11. Why would a tsunami not be noticeable on the open ocean but then become a big wall of water approaching the beach?

12. Describe what happens during liquefaction.

13. Describe how liquefaction can cause a mud volcano.

14. How could a structure built on loose sediments be made less prone to collapse during liquefaction?

15. Provide and describe five examples how earthquakes can trigger other disasters.

Case Studies

Case Study 1: Earthquakes and Liquefaction

Figure 6.C1 Liquefaction from the 16 June 1964 Niigata, Japan earthquake. Intact multi-story apartment buildings toppled over on liquefying ground. (source: Wikipedia)

Liquefying ground - The M_W= 7.6 16 June 1964 Niigata, Japan earthquake (Figure 6.C1) caused liquefaction over large parts of the city. The quake destroyed over 3500 houses and 11,000 were damaged. Most of the city is built on deposits from the Shinano and Agano river. These deposits have not yet consolidated to hard rock. By the time of the earthquake, Japan already built reinforced concrete buildings that can withstand earthquake shaking, such as happened during the Niigata earthquake. But the buildings toppled over, mostly intake, because the ground beneath liquefied. Similar buildings founded on piles reaching a firm layer at 20 m depth did not suffer damage. This earthquake also caused a 6m-high tsunami and 36 casualties. The first wave from the tsunami hit the city 15 min after the shaking. The first wave was the highest in many places but the third one was highest in other places.

The earthquake also triggered flooding and fires near the airport. Pipes of a gasoline tank ruptured from the shaking. Gasoline from the tank was brought to the sea surface by pushing water from the tsunami and in the liquefying ground. The gasoline ignited 5 h after the earthquake, causing the explosive of additional tanks. The fire destroyed parts of the airport, spread to nearby residential areas and lasted 12 days.

Figure 6.C2 Damage from the 19 September 1985 Mexico City earthquake. An eight-story structure with brick infill walls broken in two. The foundation also came off. (source: M. Celebi, USGS)

Liquefying ground - The M_W=8.0 19 September 1985 Mexico City earthquake (Figure 6.C2) caused violent shaking in the city (intensity IX on the Mercalli scale) even though the epicenter was 350 km away, off-shore. The quake killed between 5,000 and 40,000 people (number somewhat uncertain) and injured tens of thousands more. 412 buildings collapsed and 3124 more were damaged.

The city experienced so much shaking and destruction not lastly because the city is built on an ancient lake bed where the water-bearing volcanic sediments have not yet consolidated to hard rock. The city is therefore vulnerable to extensive liquefaction. A survey by the government found that few of the 1-5 story buildings and buildings taller than 15 stories were seriously damage. The lake bed resonates with seismic waves at certain periods (around 2.5 s) that also cause certain 6-15-story buildings to resonate and ultimately collapse.

Drawing from experience of earlier large earthquake (1957, 1979) Mexico city had a building code in place. But the intensity of the shaking during 1985 earthquake was larger than previously experienced. One remarkable survivor building was the 44-story Torre Latinoamericana. It was constructed with two hundred piles extending down over into the stable layer 30 m below the surface.

Figure 6.C3 The 17 October 1989 Loma Prieta Earthquake earthquake caused widespread liquefaction in the Marina District in San Francisco. Left: an automobile lies crushed under the third story of this apartment building. The ground levels are no longer visible because of structural failure and sinking due to liquefaction. (source: USGS)

Figure 6.C4 Another building in the Marina District that was severely damage by the 1989 Loma Prieta earthquake. The lack of adequate shear walls on the garage level exacerbated the damage. (source: USGS)

Figure 6.C5 Roadbed collapse on the San Francisco-Oakland Bay Bridge caused by the 17 October 1989 Loma Prieta Earthquake, and one fatality. The bridge was reopened only a month later. (source: USGS)

Liquefying ground - The M_W=6.9 17 October 1989 Loma Prieta Earthquake was an oblique strike-slip earthquake on the San Andreas Fault and about 70 km south of San Francisco. The quake caused an estimated $6 billion in damage. It caused severe damage in San Francisco's Marina District and in Oakland as a result of liquefaction (Figures 6.C4, 6.C5). Other effects included sand volcanoes and landslides. The Marina District was built on a landfill made of a mixture of sand, dirt, rubble, waste and other materials containing a high amount of ground water. Some of the rubble came from clean-up after then 1906 earthquake but most came from debris laid down for the 1915 Panama-Pacific International Exposition. Seven buildings collapsed and four were destroyed by fire. The buildings that collapsed where older so-called ‘soft story buildings’ with ground floor garages. The fire was caused by a ruptured gas main, similar to the 1906 earthquake. Another 63 building were found to be too dangerous to live in.

A total of 63 lives were lost. The Cypress Viaduct of Interstate 880 in Oakland collapsed, killing 42 people. Some parts of the San Francisco - Oakland Bay Bridge also collapsed (Fig. 6.C5). Because the quake occurred during a national live broadcast of the 1989 World Series, rush-hour traffic on the Bay Area freeways was lighter than normal which prevented a larger loss of lives. An estimated 1.4 million people lost power as a result of damaged electrical substations.

What about San Diego? Potential disaster areas in San Diego that are subject to liquefaction because of building on water-saturated sediments: Mission Bay (artificially built), Lindbergh Field, North Island (Navy Base)

Figure 6.C6 Left: An expressway collapsed during the 17 January 1995 Kobe, Japan earthquake. Right: Retrofitted support columns of many freeways in southern California withstood the 1994 Northridge earthquake, while non-retrofitted failed. (source: ME and USGS)

Liquefying ground - The M_W=6.8 17 January 1995 (Great Hanshin) Kobe, Japan earthquake (Figure 6.C6) caused widespread liquefaction on Awaji Island, killing 6434 people (4600 in Kobe) and leaving 300,000 homeless, and causing $102 billion in damage. This was Japan's worst earthquake in the 20th century after the Great Kanto earthquake in 1923 that claimed 105,000 lives. Although located in a subduction zone, this earthquake was a strike-slip earthquake, with many aftershocks.

Damage was extremely widespread and severe. On the order of 400,000 buildings were damaged beyond repair. Numerous elevated road and rail bridges, and 120 of the 150 quays in the port of Kobe were destroyed. Images of the collapsed elevated Hanshin Expressway made front page news around the world. Artificial islands in Kobe suffered subsidence caused by liquefaction, where water reached the surface. The quake triggered around 300 fires, disrupted water, electricity and gas supplies.

This quake was a major wake-up call for Japan's disaster prevention authorities. Most people though that the steel-reinforced concrete expressways were safe. While later inspection revealed that most structures were constructed properly. But building codes had changed over time and only new constructions were built to the latest code. Subsequently, buildings were placed further apart to avoid a falling-domino effect and rubber shock absorbers were installed under bridges.

Case Study 2: Earthquakes and Tsunami

Figure 6.C7 Liquefaction destroyed a neighborhood in Turnagain Heights, Alaska after the "Good Friday" 27 March 1964 earthquake. (source: USGS)

Liquefaction of a subsurface layer, tsunami - The M_W= 9.2 27 March 1964 "Good Friday" Alaska earthquake (Figure 6.C7) caused widespread liquefaction. The quake lasted over 4.5 minutes and remains the most powerful earthquake recorded in North American history. The megathrust earthquake ruptured 970 km along the fault, and the ground moved up to 18 m. It caused fissures, landslides, tsunami, and 131 people perished.

The quake also caused liquefaction. In Turnagain Heights, a large area failed when a weak and water-saturated subsurface clay layer liquefied and the strong layer above broke into pieces. Locally, the ground dropped by several meters.

Of the 131 people killed by this earthquake, 122 died from the subsequent tsunami. The tsunami reached a height of 8.2 m in Prince William Sound, with an incredible run-up of 67 m at Shoup Bay. In the village of Chenega, the tsunami claimed 23 of the 68 people who lived there. It traveled down the west coast of North America and killed 5 people in Oregon and 13 people in Crescent City, CA. Minor damage to boats reached as far south as Los Angeles. This tsunami also caused damage in Hawaii.

Figure 6.C8 Maximum recession of tsunami waters at Kata Noi Beach, Phuket, Thailand at 10:25 am, prior to the third – and strongest – tsunami wave. (source: Wikipedia)

Tsunami - The Mw=9.2 26 December 2004 Sumatra-Andaman Earthquake (Fig. 6.C8) claimed over 220,000 lives in 14 countries, including some in Africa across the Indian Ocean. Most of the victims perished in the tsunami. The megathrust earthquake lasted some 10 minutes, the longest ever recorded. It ruptured for 1300 km.

The subsequent tsunami reached heights of 30 m and may have been enhanced by submarine landslides triggered by the earthquake. The level of destruction was extreme in Banda Aceh, where 167,000 people perished. In Sri Lanka, the tsunami was up to 9 m high, claiming 35,000 lives and destroying 90,000 buildings. In India, 12,000 people lost their lives. And in Thailand, the tsunami reached 10 m, claiming 5400 lives (+ 3100 missing).

The northern regions of Sumatra were hit quickly. The tsunami reached Banda Aceh, near the epicenter, 20 min after the initial shaking. On the other hand, some people feeling the shaking had a chance to react before the tsunami arrived, and the island of Simeulue, also near the epicenter, was evacuated. Also, some aboriginal populations evacuated and survived because of tales and oral folklore from previous earthquakes raised awareness.

Sri Lanka, the east coast of India and Thailand were hit roughly 1.5 – 2 h later. The tsunami reached Thailand later despite being closer because the tsunami slows down in shallower waters. Despite this delay, nearly all victims were taken by surprise. People on the beaches gathered the fish flapping in the sand after sea level receded before the first tsunami wave hit. In Thailand, single incidents of evacuations of small groups were reported because a few tourists were aware of the tsunami tell-tale signs. The tsunami reached Somalia some 7 h after the quake, at noon local time, where it killed some 290 people. The tsunami reached heights of 9 m in some places. Large tsunami occur less frequently in the Indian Ocean than in the Pacific Ocean for which an international tsunami warning system exists. At the time, Indonesia and the Indian Ocean had no functioning tsunami warning system. There are reports that the last missing piece in the system was a phone line. Apart from the missing warning infrastructure, there infrequent tsunami occurrences also cause a lack of collective memory and awareness of the tsunami risk.

Case Study 3: Earthquakes and other disasters

Figure 6.C9 Destruction at the Fukushima, Japan power plant after the 11 March 2011 Tohoku earthquake and tsunami struck. (source:Wikipedia)

Nuclear Meltdown - The Mw=9.1 11 March 2011 Tohoku Earthquake (Figure 6.C9) was a tsunami-genic megathrust earthquake. It was the most powerful earthquake ever recorded in Japan. The tsunami reached heights of up to 40.5 m and traveled at 700 km/h up to 10 km inland in Sendai. Initial reports lamented 2000 fatalities, but this number was revised a few years later and now stands at nearly 16,000, with 2500 still missing. Most people died in the tsunami where residents of Sendai had only 8-10 minutes of warning.

Four years after the quake, nearly 230,000 people were still living away from their homes. As of a report in 2018 over 122,000 buildings totally collapsed, 281,000 partially collapsed and another 700,000 buildings were damaged. The value of property damage is difficult to assess as many structure were not insured and so not accounted for by insurance companies as is typically done. But damage is estimated as high as $360 billion (the World Bank's estimate stands at $235 billion), making it the most costly natural disaster worldwide.

The most shocking incident that caused the subsequent phase out of peaceful nuclear power generation in some European countries was the meltdown of the Fukushima-Daiichi nuclear power plant. While the plant and reactors withstood the shaking, the 14-m tsunami overtopped the 5.7-m seawall and caused flooding in the plant. The subsequent power outage caused failure of the cooling, and the nuclear reactors overheated. At least three reactors exploded within days after the earthquake, releasing radioactivity into the environment. Residents within a 20 km radius of the plant had to evacuate. Radioactive caesium, iodine, and strontium were found in the local soil, but many radioactive hotspots were found outside the evacuation zone, including Tokyo. Food products were also found contaminated. A month after the quake, fishing of sand lace was banned after discovering that its caesium level was above legal limits. Two years later, some beef was still contaminated on Tokyo markets. The Fukushima site remains highly radioactive, and the cleanup will take 40 years or more.

Case Study 4: The 2002 Denali Earthquake and the Trans-Alaska Pipeline

Figure 6.C10 Arial photo of the Trans-Alaska Pipeline System (TAPS) near the Denali fault. Here, the pipeline is supported by rails on which it cane move freely in the events of fault offset. The pipeline moved during the 2002 earthquake but no break occurred. Note the break in the street near the bottom of the photo. (source: Division of Geological and Geophysical Surveys, Alaska State Department of Natural Resources)

Figure 6.C11 View along the TAPS in the zone where it was engineered for the Denali fault. (source: USGS)

On Nov 3, 2002 a large magnitude 7.9 earthquake occurred along the Denali fault, about 160km south of Fairbanks/Alaska. There have been smaller earthquakes in the past (e.g M 7.2 in 1912, M 6.2 in 1958). The predominantly right-lateral strike-slip event caused the surface to rupture for a total length of 320 km (Figs. 6.C10, 6.C11). The earthquake caused numerous debris flows, avalanches, snow slides and rock falls along the fault and significant horizontal displacement. For example, scientists measured an offset of 2.5 m on the Richardson Highway while a section of the Trans-Alaska Pipeline did not break. The pipeline is built above ground and sits on a frame. During transport the oil is to be kept warm to flow and burying the pipeline in permafrost would melt the ground and make it unstable. In areas prone to earthquake shaking, the pipeline's frames sit on rollers. The pipeline was designed to withstand magnitude 8 earthquakes and though the pipeline was shaken off its frame, it did not burst.