Design Concepts for Seismic-Resistant Buildings

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Quantitative Shaking Evaluations

By

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To

Rie, Kenta, our parents, families, and friends.

Thank you for the love and encouragement over the years

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PREFACE

State-of-the-art seismic-resistant building design and technology have undergone tremendous developments. In modern seismic-resistant building design codes, a building structure subjected to a strong earthquake can experience considerably large deformations without collapsing. The design is permitted up to the limited strength before the building collapses. According to data on casualties compiled by JMA, Japan Meteorological Agency of Japan, the number of humans injured due to strong earthquakes is higher than the number of deaths/missing. Likewise, the number of buildings collapsed was less than the partially damaged ones. This fact implies that the design of buildings that are based on continuously revised seismic-resistant standards has good earthquake resistance. However, it also concludes that the human deaths/injury casualties were not the results of the buildings' collapse but mainly due to the strong vibrations (*SHAKING*) initiated by the earthquake. In most cases, the tumbling of non-structural things, such as ceilings, bookshelves, furniture, etc., fell onto human beings, causing casualties. This book brings an augmentation of quantitative shaking criteria to the state-of-the-art seismic design practice to implement the effect of shaking to prevent human casualties due to strong earthquakes.

I would like to express my deepest gratitude to Mr. Chiaki Kageyama, the founder of Living Environment Design Office Co., Ltd. The company mainly constructs small-scale steel pile foundations for the customers of the residential house with a direct foundation. The first moment Mr. Kageyama came to my laboratory was in the spring of 2015. I took the challenges inspired by Mr. Kageyama asking me to create a program that can evaluate the **quantity of shaking** of houses during strong earthquakes. The program also can predict how effectively the steel pile foundation can reduce the quantity of shaking compared to the direct foundation. The criteria use the JMA, Japan Meteorological Agency's Japan's Seismic Intensity Level

(SIL), to calculate the quantity of shaking. JMA's SIL in Japan is totally different from other countries. The JMA's SIL describes the degree of shakings that human feels during earthquakes. In contrast, Richter Magnitude perception is still being adopted to describe earthquakes in many countries, even until I finished writing this book.

The Richter Magnitude is an energy quantity released from the source of an earthquake deep beneath the ground surface. Thus, the complexity of sedimentary soil layers will significantly influence the waves' propagation to the ground surface. Therefore, the Richter Magnitude does not describe the intensity of shakings that human feels during earthquakes.

However, the JMA's SIL is only a prediction of shaking of the ground surface surrounding the source of the earthquake. I elaborate this feature to the building floors and apply Artificial Intelligence (Deep Neural Network) to skip the computation time to predict the shaking instantly. Because processing time reduction is highly important for early warning system development. And the pending research that needs further attempt is to measure human emotions against shakings by measuring the electrical wave distribution of the human brain. This research will furnish the reliability of JMA's SIL scale of intensities made in the past based on coarse human perceptions. This brilliant idea brought me to proceed with the research to finalize all the outcomes of the latest stage into a book.

This book is intended for architecture, civil and structural engineering, geological, and information science students beginning a series of courses in earthquake engineering and disaster mitigation. Practitioners in designer and consultant companies are starting to learn or adopt the shaking quantity for real-time monitoring and to extend their research in measuring the quantitative shaking of either the existing or new design buildings. The governmental agency involves disaster mitigation plans, communication service providers, mass media planners, and device manufacturers in commercial, research, and development purposes of earthquake early warning systems.

The writing of this book was an enjoyable experience for me. I received benefits, encouragement, and support from many colleagues and my students, who have taught me how to explain difficult concepts in modest expressions through simple explanations. While it is impossible to name all of them, without their help and support, it could not have been possible to finish writing this book.

My sincere thanks to my respected former Emeritus Professor Fumio Nishino at the University of Tokyo for his philosophies in teaching and research, which have been useful in my academic and professional lives. I greatly appreciate Professor Mitsuharu Kurata at Nihon University for constantly motivating me to find the real "truth" in science.

I am indebted to Prof. Han Ay Lie at Universitas Diponegoro for asking me to be her co-promotor in supervising our Ph.D. student Mr. Nanang Gunawan Wariyatno. Dr. Nanang has passed his final defense on the basic part of this book!! Congratulation! I hope Dr. Nanang will continue our research to contribute his achievements to benefit his own country, Indonesia.

I want to thank my former master's students at the beginning of this work, namely, Mr. Yasuhiro Anzai, Mr. Naomichi Kobayashi, and Mr. Arata Chiba. My 2nd-grade master's student, Mr. Rito Yamakawa, for helping me carry out enormous structural dynamic analyses using the API interface of STRAND7. We are creating a databank of JMA's SIL shaking scales using thousands of earthquake data for AI implementations.

I appreciate the help and patience of the Commissioning Editor: Ms. Helen Edwards, the Typesetting Manager: Ms. Amanda Millar, and the Designer: Ms. Sophie Edminson of Cambridge Scholars Publishing, during this book's preparation and publication. It took a long time to finish this book since the contract was made around the autumn of 2018. Although the flooding incident in 2019, continued by the Covid-19 pandemic, came across, it cannot be an excuse for me to extend the submission of this book. Under the authority of Ms. Helen Edwards helped me finish this book.

Most books are not free from errors, especially those with many mathematical equations and numbers. I wish to thank in advance those readers who are willing to draw attention to any typos and errors using the following e-mail address:

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Buntara S. Gan
Koriyama, December 2022
Fukushima, Japan

CHAPTER ONE

ALL YOU NEED TO KNOW ABOUT EARTHQUAKES

Big earthquakes in history

At the beginning of the nineteenth century [1], records of human disasters and damage due to big earthquakes were collected. The magnitude of earthquakes was estimated based on historical and old archival reports. Table 1.1 shows the list of known big earthquakes with an estimated Richter magnitude of 8.5 or higher in history since 1500, sorted in ascending order of time.

Table 1.1 List earthquakes with a magnitude higher than 8.5 from 1500-2012 [2].

Date	Location	Naming	Magnitude
Dec. 16, 1575	Valdivia, Chile (then part of the Spanish Empire)	1575 Valdivia earthquake	8.5
Nov. 24, 1604	Arica, Chile (then part of the Spanish Empire)	1604 Arica earthquake (undocumented)	8.5
May 13, 1647	Santiago, Chile (then part of the Spanish Empire)	1647 Santiago earthquake	8.5
Oct. 20, 1687	Lima, Peru (then part of the Spanish Empire)	1687 Peru earthquake	8.5
Jan. 26, 1700	Pacific Ocean, USA, and Canada (then claimed by the Spanish Empire and the British Empire)	1700 Cascadia earthquake	8.7–9.2
Oct. 28, 1707	The Pacific Ocean, Shikoku region, Japan	1707 Hōei earthquake	8.7–9.3

Date	Location	Naming	Magnitude
Jul. 8, 1730	Valparaíso, Chile (then part of the Spanish Empire)	1730 Valparaíso earthquake	8.7
Oct. 17, 1737	Kamchatka, Russia	1737 Kamchatka earthquakes	8.5
Oct. 28, 1746	Lima, Peru (then part of the Spanish Empire)	1746 Lima–Callao earthquake	8.6
May 24, 1751	Concepción, Chile (then part of the Spanish Empire)	1751 Concepción earthquake	8.5
Nov. 1, 1755	Atlantic Ocean, Lisbon, Portugal	1755 Lisbon earthquake	8.5–9.0
Apr. 2, 1762	Chittagong, Bangladesh (then Kingdom of Mrauk U)	1762 Arakan earthquake	8.8
Mar. 28, 1787	Oaxaca, Mexico (then part of the Spanish Empire)	1787 Mexico earthquake	8.6
Nov. 19, 1822	Valparaíso, Chile	1822 Valparaíso earthquake (undocumented)	8.5
Nov. 25, 1833	Sumatra, Indonesia (then part of the Dutch East Indies)	1833 Sumatra earthquake	8.8
Feb. 20, 1835	Concepción, Chile	1835 Concepción earthquake	8.5
Feb. 16, 1861	Sumatra, Indonesia	1861 Sumatra earthquake	8.5
Aug. 13, 1868	Arica, Chile (then Peru)	1868 Arica earthquake	8.5–9.0
May 9, 1877	Iquique, Chile (then Peru)	1877 Iquique earthquake	8.5
Jun. 15, 1896	The Pacific Ocean, Tōhoku region, Japan	1896 Sanriku earthquake	8.5
Jan. 31, 1906	Ecuador – Colombia	1906 Ecuador–Colombia earthquake	8.8
Nov. 10, 1922	Atacama Region, Chile Catamarca Province, Argentina	1922 Vallenar earthquake	8.5
Feb. 1, 1938	The Banda Sea, Indonesia (then part of the Dutch East Indies)	1938 Banda Sea earthquake	8.5

Date	Location	Naming	Magnitude
Aug. 15, 1950	Assam, India – Tibet, China	1950 Assam–Tibet earthquake	8.7
Nov. 4, 1952	Kamchatka, Russian SFSR, Soviet Union	1952 Kamchatka earthquakes	9.0
Mar. 9, 1957	Andreanof Islands, Alaska, United States	1957 Andreanof Islands earthquake	8.6
May 22, 1960	Valdivia, Chile	1960 Valdivia earthquake	9.4–9.6
Oct. 13, 1963	Kuril Islands, Russia (USSR)	1963 Kuril Islands earthquake	8.5
Mar. 27, 1964	Prince William Sound, Alaska, United States	1964 Alaska earthquake	9.2
Feb. 4, 1965	Rat Islands, Alaska, United States	1965 Rat Islands earthquake	8.7
Dec. 26, 2004	Indian Ocean, Sumatra, Indonesia	2004 Indian Ocean earthquake	9.1–9.3
Mar. 28, 2005	Sumatra, Indonesia	2005 Nias–Simeulue earthquake	8.6
Feb. 27, 2010	Offshore Maule, Chile	2010 Chile earthquake	8.8
Mar. 11, 2011	The Pacific Ocean, Tōhoku region, Japan	2011 Tōhoku earthquake	9.1
Apr. 11, 2012	Indian Ocean, Sumatra, Indonesia	2012 Aceh earthquake	8.6

Figure 1.1 shows countries struck by strong earthquakes with magnitudes higher than 8.5 since the sixteenth century. Although Japan is well-known as the “Country of Earthquakes,” it has only been hit three times. However, Chile has been struck by strong earthquakes twelve times.

Figure 1.1 Distribution map of earthquakes with a magnitude higher than 8.5 in history from 1500 to 2012.

Chile

The first documented Valdivia earthquake in 1575 led to the flooding of Valdivia city due to the excessive overflowing of rivers. In 1604, the next earthquake, which was not recorded, occurred in Arica. In 1647, another big earthquake struck Chile almost a century later. This earthquake in Santiago brought nearly all the buildings in the city to the ground. It is assumed that this earthquake was the most damaging in the history of Santiago city. Almost another century later, in 1730, the Valparaíso earthquake hit Chile again, which caused severe damage from La Serena to Chillán. The Valparaíso earthquake triggered a major tsunami along the coastline for more than 1,000 km. Just two decades after the Valparaíso earthquake, in 1751, the strongest and most destructive earthquake, Concepción, struck the central valley of the country and destroyed the cities of Concepción, Chillán, Cauquenes, Curicó, and Talca. Eighty years later, in 1835 (Figure 1.2), near the neighboring cities of Concepción and Talcahuano, the Concepción earthquake struck the area causing human disaster and triggering a tsunami in the coastal region.

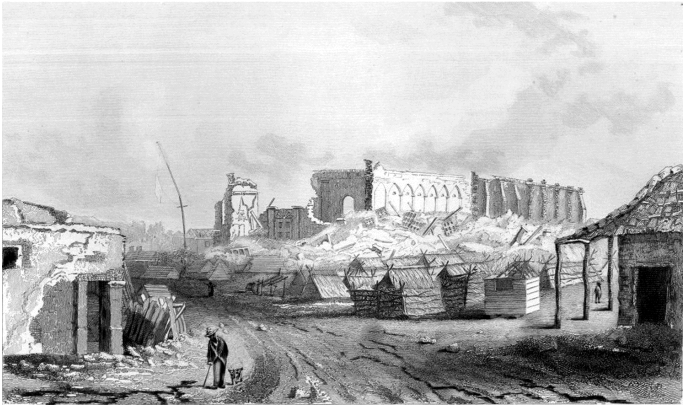

Figure 1.2 The remains of the Cathedral in Concepción (a drawing by John Clements Wickham 1798–1864 Engraving: S. Bull fl. 1838–1846, from Wikimedia Commons).

In 1868, an earthquake struck a wide area around Arica, Tacna, Moquegua, Mollendo, Ilo, Iquique, Torata, and Arequipa, including the southern part of Peru [3] (Figure 1.3). The earthquake caused an estimated 25,000 human casualties and brought a tsunami to the coasts of Peru and Chile. In 1877, in the vicinity of the coastal area of the Tarapacá and Antofagasta regions, an overwhelming earthquake with a maximum intensity of XI (extreme) on the Mercalli intensity scale was reported. The earthquake's aftermath triggered a devastating tsunami on Fiji island, which caused 2,385 human casualties. Since the start of the twentieth century, the frequency of big earthquakes in Chile has significantly reduced. The 1922 Vallenar earthquake was followed by a destructive tsunami in the Atacama region, near the border with Argentina.

Figure 1.3 "The Late Earthquake in South America: Ruins of Arica, in Peru & Ruins of Arica from the Sea" October 24, 1868 (illustrated by London News South America, from Wikimedia Commons).

The earthquake caused extensive damage in a zone ranging from Copiapó to Coquimbo. Newspapers estimated more than 1,000 human casualties due to the earthquake, at least 500 of which were in Vallenar. Following the earthquake, a destructive tsunami killed several hundred people in coastal cities, especially in Coquimbo. Forty years later, the most powerful earthquake ever recorded in Chile was reported in Valdivia with a magnitude of 9.4–9.6, lasting less than ten minutes. This earthquake caused catastrophic damage due to its proximity to the hypocenter of the 1960 Valdivia earthquake (Figure 1.4).

The 2010 Chile earthquake occurred off the coast of central Chile, having a magnitude of 8.8, with intense shaking lasting for about three minutes. According to the United States Geological Survey (USGS), the cities experiencing the strongest shaking of VIII (Severe) on the Modified Mercalli intensity scale (MM) were: Concepción, Arauco, and Coronel. Chile's Seismological Service Concepción reported that the Concepción area experienced the strongest shaking at IX (Violent) on the MM scale. The earthquake generated a tsunami that devastated several coastal towns in south-central Chile and damaged the port at Talcahuano (Figure 1.5).

Figure 1.4 Earthquake damage to good quality, wooden-framed houses in Valdivia, Chile, 1960 (a photo credited by Pierre St. Amand, from Wikimedia Commons).

Figure 1.5 After the tsunami in Talcahuano, Biobío Region (a photo credited by Zelocaro from the source: Marcelo Caro Frías, in Wikimedia Commons).

South America

In Peru, the 1687 and 1746 earthquakes caused severe damage to the cities of Lima, Callao, and Ica. Similarly, the earthquakes brought about the subsequent tsunamis that caused human casualties. The 1787 Mexico earthquake also brought about a big tsunami that affected the coast at the boundary of Mexico. In 1906, the Colombia earthquake caused a destructive tsunami that affected the coast of Colombia with at least 500 human casualties. The 1922 Vallenar earthquake occurred in the Atacama region of Chile near the border with Argentina (Figure 1.6). This earthquake triggered a big tsunami that caused major damage to the coast of Chile.

Figure 1.6 Destruction in the Atacama Region in the 1922 Vallenar earthquake (a photo credited by Gustavo Bruzzone Rocco, in Wikimedia Commons).

Indonesia

The 1833 Sumatra earthquake occurred with an estimated magnitude of 8.8–9.2. The earthquake caused a large tsunami that flooded the island's southwestern coast. The 1861 Sumatra earthquake was the last in a sequence of earthquakes that ruptured adjacent parts of the Sumatran segment of the Sunda megathrust. It caused a shocking tsunami that led to several thousand human casualties. The 1938 Banda Sea earthquake happened with an estimated magnitude of 8.4 and a Rossi–Forel intensity of VII (very strong tremor). This oblique-slip event generated destructive tsunamis of up to 1.5 meters in height in the Banda Sea region, but no human casualties were reported. The 2004 Indian Ocean earthquake and tsunami occurred with the hypocenter off the west coast of northern Sumatra. It was an undersea megathrust earthquake recorded with a magnitude of 9.1–9.3, reaching a Mercalli intensity scale of up to IX in particular areas. The earthquake was caused by a rupture along the fault between the Burma Plate and the Indian Plate. The underwater seismic activity formed a series of tsunami waves of up to 30 meters (100 ft) in height. Communities along the surrounding coasts of the Indian Ocean were seriously affected, and the tsunamis caused an estimated 228,000 human casualties in fourteen countries (Figure 1.7). The Indonesian city of Banda Aceh was reported to have had the largest human casualties. The earthquake was one of the deadliest natural disasters in earthquake history. The earthquake was the third-largest ever recorded and had the longest duration of faulting, between eight to ten minutes. It caused the earth to vibrate as much as 10 millimeters (0.4 inches) and remotely triggered earthquakes as far away as Alaska. Its hypocenter was between Simeulue Island and mainland Sumatra.

Figure 1.7 A village near the coast of Sumatra lays in ruins after the tsunami struck (a photo credited by Photographer's Mate 2nd Class Philip A. McDaniel of the U.S. Navy, in Wikimedia Commons).

The 2005 Nias–Simeulue earthquake occurred off the west coast of northern Sumatra, Indonesia. More than 900 human casualties were reported, mainly on the island of Nias. The earthquake caused panic on the island, which had already been shocked by the massive tsunami triggered by the 2004 Indian Ocean earthquake. Still, this earthquake generated a relatively small tsunami that caused little damage. It was the third most powerful earthquake since 1965 in Indonesia.

Japan

The 1707 Hōei earthquake struck south-central Japan. The earthquake was the largest in Japanese history until the 2011 Tōhoku earthquake renewed the record after three centuries. The earthquake triggered a destructive tsunami that caused more than 5,000 human casualties in southwestern

Honshu, Shikoku, and south-eastern Kyūshū. The earthquake is also said to have triggered the last eruption of Mount Fuji 49 days later. About a century before the 2011 Tōhoku earthquake occurred, the 1896 Sanriku earthquake struck Japan in almost the same locations. The 8.5 magnitude earthquake brought about two tsunamis that destroyed about 9,000 residential houses and caused at least 22,000 human casualties (Figures 1.8, 1.9). At that time, the waves reached a record height of 38.2 m, until the record was renewed by more than 2m additional height in the 2011 Tōhoku earthquake.

Figure 1.8 Destruction in Kamaishi city, Iwate prefecture due to the Sanriku earthquake (a photo credited by Matsuchi Nakajima, 1850–1915, in Wikimedia Commons).

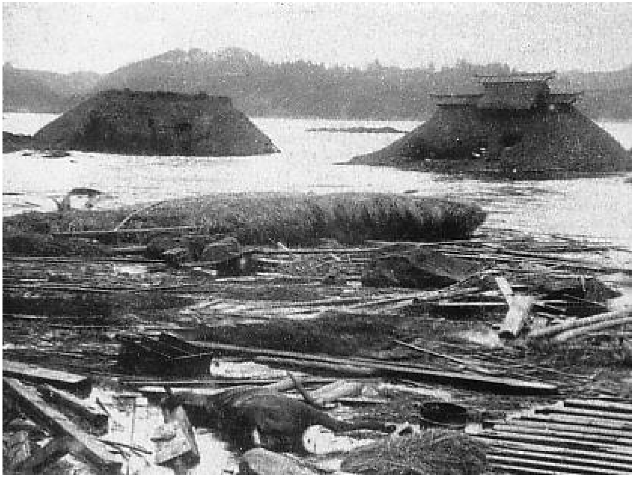

Figure 1.9 Destruction by the tsunami following the Sanriku earthquake (a photo credited by Imperial Household Ministry (present-day "Imperial Household Agency"), in Wikimedia Commons).

The 2011 earthquake off the Pacific coast of Tōhoku had a magnitude of 9.0–9.1, with the hypocenter approximately 70 kilometers east of the Oshika peninsula. The earthquake was the strongest earthquake ever recorded in Japan (Figure 1.10). The earthquake also triggered the most powerful tsunami waves that reached 40.5 m in height. The tsunami caused more than 15,000 human casualties and destroyed the Fukushima Daiichi Nuclear Power Plant nuclear facilities (Figure 1.11).

Figure 1.10 The Rikuzentakata, Iwate, after being swept by a tsunami on the Pacific Coast following the Tōhoku earthquake (a photo credited by Mitsukuni Sato, in Wikimedia Commons).

Figure 1.11 The Fukushima First Nuclear Power plants after the 2011 Pacific Coast Tōhoku earthquake and tsunami (a photo provided by Digital Globe, in Wikimedia Commons).

United States

The 1700 Cascadia earthquake occurred with an estimated Magnitude of 8.7–9.2 from Vancouver Island in Canada along the Pacific Northwest coast to the south to northern California. Two centuries later, no big earthquake with a Magnitude over 8.5 occurred until the 1964 Alaska, and 1965 Rat Islands earthquakes consecutively struck the United States. The 1964 Alaska earthquake, also known as the Great Alaskan earthquake, occurred in the south-central area of Alaska, destroying buildings and triggering tsunamis that caused human casualties (Figure 1.12).

Figure 1.12 Damage to Fourth Avenue in Anchorage, Alaska, caused by the 1964 Alaska earthquake (a photo credited by the U.S. Army, in Wikimedia Commons).

In the following year, the 1965 Rat Islands earthquake occurred within the Alaska region with a magnitude of 8.7. It triggered a 10m height tsunami on Shemya Island. However, the tsunami caused almost no destruction.

Russia

Three earthquakes that occurred off the coast of the Kamchatka Peninsula in the far east of Russia and the Soviet Union in 1737, 1952, and 1963 were big for the country and caused tsunamis. Little destruction and few human casualties were reported due to earthquakes and tsunamis.

Portugal

The first big earthquake with a magnitude of 8.5–9.0 in a European country was recorded in Portugal in 1755. The earthquake caused fires and tsunamis and almost destroyed the city of Lisbon (Figure 1.13). The number of human casualties was estimated to be between 10,000 to 100,000, making the earthquake one of the deadliest earthquakes in history.

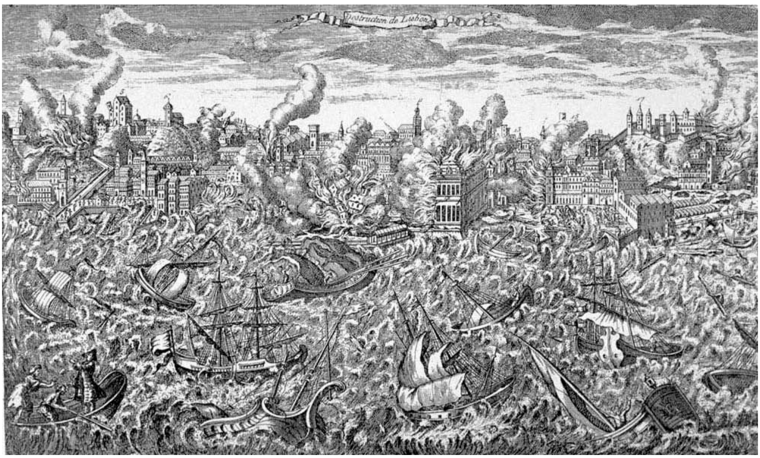

Figure 1.13 Lisbon, Portugal, during the 1755 great earthquake. This copper engraving shows the city in ruins as tsunamis rush upon the shore (a photo retrieved from the Earthquake Engineering Online Archive, Jan Kozak Collection: KZ128, in Wikimedia Commons).

East Asia

The 1762 Arakan earthquake occurred at an estimated magnitude of 8.8 and the maximum estimated intensity of XI (Extreme) on the Mercalli intensity scale. The earthquake triggered a local tsunami in the Bay of Bengal and caused at least 200 human casualties. About two hundred years later, the 1950 Assam–Tibet earthquake occurred with a magnitude of 8.6. The earthquake was destructive in the Assam (India) and Tibet (China) regions, and approximately 4,800 human casualties were reported. The earthquake was notable as being the largest recorded earthquake caused by continental collision rather than subduction and was also notable for the loud noises produced by the earthquake and reported throughout the regions of both countries.

Building damage due to earthquakes

Physical damage due to earthquakes can be divided into two major categories:

1. Damage to the infrastructure of human-made structures
2. Damage to the geological elements supporting the structures below the soil and ground level

In the former, the physical damage to human-made structures is usually a result of design strength insufficiencies against the bigger earthquakes in history. In the latter, the physical damage to the supporting soil and ground is due to larger historical earthquakes and natural disasters in the area of concern.

Table 1.2 lists 25 earthquakes that caused approximate damage worth more than 500 million USD from 1976 to 2017.