GEOLOGICAL HAZARDS: EARTHQUAKES, LANDSLIDES, AND TSUNAMIS

Li Juan and **Chen Yong**
China Seismological Bureau, Beijing, China

Keywords: Earthquake, Earthquake hazards, Intensity scale, Seismic hazard, Landslides, Slope stability, Triggering of landslides, Tsunami

Contents

Summary

Natural hazards can be categorized under two main sections: weather induced hazards and geological hazards. Geological hazards are covered in this article under the following paragraph headings: earthquakes, tsunamis, and landslides. The first one presents the worldwide distribution of earthquakes and volcanoes, together with a presentation of the scales for measuring earthquake magnitude and intensity. This is followed by a description of the presence of earthquake hazards. One of the major phenomena generated by earthquakes is the tsunami; this phenomenon is described in the latter part of the article, together with a presentation of major, worldwide tsunami disasters. The prediction of tsunami incidence in the Pacific region is then discussed. The last paragraph discusses landslides, opening with a description of soil strengths, pore-water pressure, and rigid, elastic, and plastic solids. Land instability is then classified and described under the headings: factors influencing landslides; triggering of landslides; and preventive measure.

1. Earthquakes

Of all the natural hazards, earthquakes release the most energy in the shortest possible time. On average, each year earthquakes kill 10 000 people and cause US$20 billion property damage. Earthquakes can be regarded as one of the most destructive forces for human beings.

1.1 Introduction

Earthquakes demonstrate that the Earth continues to be a dynamic planet, changing each day through internal tectonic forces. The crust of the Earth consists of various elastic rocks in which energy is stored during crustal deformation caused by the tectonic forces. When the strain builds to a level that exceeds the strength of a weak part of the Earth's crust, such as along a geological fault, then opposite sides of the fault suddenly slip, and an earthquake occurs. The common parameters for describing the characteristics of an earthquake source are the location of the hypocenter or the epicenter (the point on the Earth's surface immediately above the hypocenter). Measures of the strength of shaking and the total energy release in the earthquake are also needed.

We know that the Earth's crust is not a continuous skin; instead it is like a completed jigsaw puzzle with the actual pieces of crust termed "plates." Most earthquakes occur along the plate boundaries, which are called inter-plate earthquakes, other earthquakes occur in the inner parts of continents; these are called intra-plate earthquakes. The intra-plate earthquakes are more dangerous to human beings because most people live in continental regions (See *Natural and Human Induced Hazards*).

In most cases, the empirical relation between magnitude m and seismic wave energy released E (unit: ergs) can be written as:

$$\log E(\text{in erg}) = 11.8 + 1.5\, m \qquad (1)$$

This equation indicates an about thirty-fold ($10^{1.5}$) increase in seismic wave energy when the magnitude m increases by one unit. For example, the seismic energy released by an earthquake of magnitude m=6.5 is about 30 times greater than that of an event of magnitude m=5.5 (which is the same as that released by the explosion of the atomic bomb in Hiroshima in 1945), and the seismic energy release of an event of m=7.5 is about $30 \times 30 \approx 1000$ times greater than that of m=5.5 (equivalent to about 1000 Hiroshima atomic bombs).

Earthquakes are generally regarded as the most destructive of all the various natural forces. Figure 1 shows the comparison of energy released by earthquakes and other kinds of energy in nature**.**

Modern seismographic networks record millions of earthquakes every year; over 99% of these events pose no danger because they are small. An important scaling relationship is the relation between earthquake size and frequency of occurrence. Gutenberg and Richter first proposed that in a given region and over a given period of time, the frequency of occurrence could be represented by:

$$\log N(\geq m) = A - b\,m \qquad (2)$$

where the $N(\geq m)$ is the number of earthquakes with magnitude m or above, A and b are empirical constants determined through statistical study, and m is the magnitude of earthquakes.

Description	**Magnitude**	**Average annual frequency**	**Energy released (ergs)**
Great	>8.0	1	$> 5.8\times10^{23}$
Major	7.0~7.9	18	$2\sim42\times10^{22}$
Strong	6.0~6.9	120	$8\sim150\times10^{20}$
Moderate	5.0~5.9	800	$3\sim55\times10^{19}$
Light	4.0~4.9	6200	$1\sim20\times10^{18}$
Minor	3.0~3.9	49 000	$1\sim26\times10^{15}$

Table 1. Frequency of earthquakes since 1900

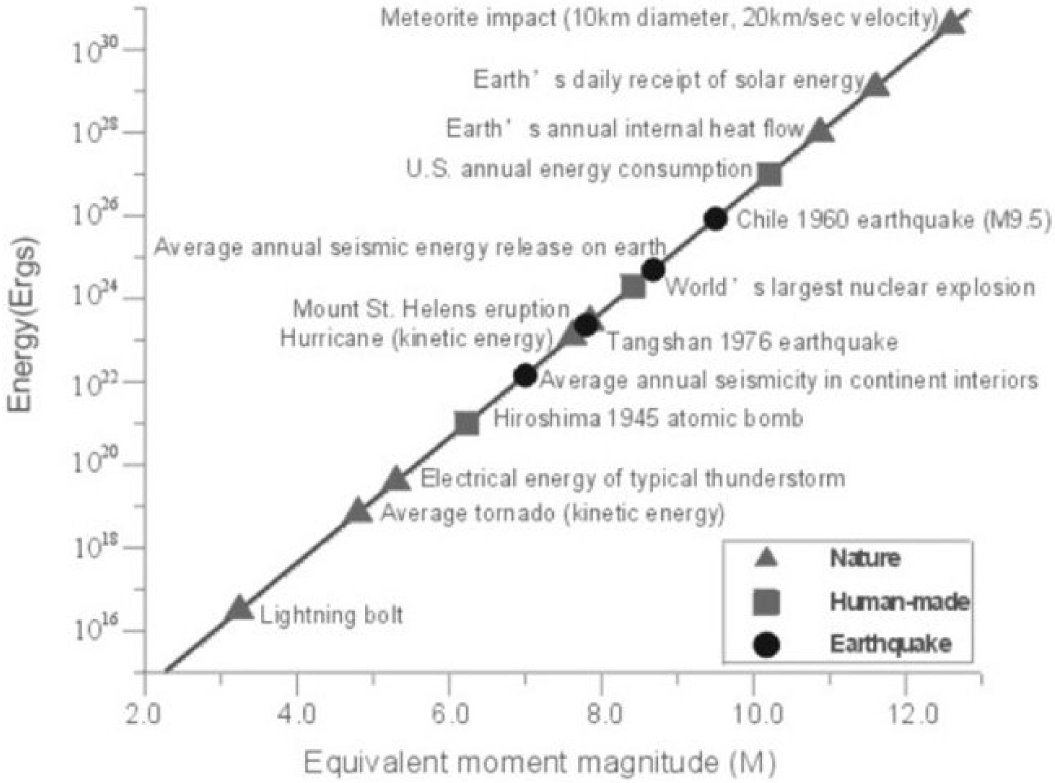

Figure 1. Comparison between the energy released by earthquakes and other kinds of energy release in nature

1.2 Earthquake Hazards

Strangely, the release of all energy from earthquakes beneath the surface of the Earth poses little direct danger to the individual person. Humans are not "shaken to death" by earthquakes. The greatest danger comes from the interaction between the ground motion caused by earthquakes and man's own structures. The dangers of being crushed in a falling building, getting burned by fire, being swept away and drowned in a flood from a burst reservoir, or getting buried beneath earthquake-induced landslides are very real.

Earthquake-caused damages include the following four aspects:

- Ground shaking is generally the most severe direct cause of damage. Crowded buildings that cannot be evacuated quickly may collapse during ground-shaking and result in a major loss of life as well as property.
- Surface rupture is the horizontal or vertical displacement of the ground surface along the narrow fault zone. While affecting a much smaller area compared to ground shaking, it can severely damage structures located adjacent to faults.
- Ground failure is an indirect cause of damage, but it may be widespread and produce some of the most devastating loss of life.
- Tsunamis are ocean waves produced by earthquakes, which may sweep ashore, causing damage at points thousands of kilometers from the earthquake epicenter.

Damage can be severe where the waves move forward up the shoreline or over dams, allowing downstream areas to be inundated.

1.2.1 Ground Shaking

Traditionally, engineers have been interested in acceleration, particularly Peak Ground Acceleration (PGA), which is related to the dynamic force and can be reliably measured. The unit of PGA is *g*, which is the gravitational acceleration at Earth's surface (1 *g* is approximately 9.8 m/sec^2).

The most powerful vibrations from an earthquake are in frequency range 0.5–5 Hz and are at near and regional distance. A typical building of ten stories has a natural period of about 1 s. Each story adds about 0.1 s and a 20-storey building has a period near 2 s. Taller buildings have the advantage of flexing more than short, stiff buildings, and are usually designed to bend with the wind. Thus, those over 20 stories may fare relatively well. But, with their longer periods, they are sensitive to distant earthquakes, such as that in Mexico City in 1985. Therefore, anti-seismic design may include estimates of the buildings' responses and the frequencies of various vibration modes.

It should be emphasized that multi-parameters for describing ground motion are really needed because the effect of ground motion on the damage of buildings depends upon the amplitudes, duration, and frequency content of ground motion. In addition to the above mentioned ground motion parameter PGA, there is another form of ground motion effect—intensity scale created first by M. S. de Rossi of Italy and F. A. Forel of Switzerland at the end of the nineteenth century. The Rossi-Forel Intensity Scale (RF), has proved to be of great importance in the evaluation of ground motion from the point of view of earthquake hazard. Often the choice of earthquake intensity scale is a matter of local, that is, national preference. For example, in Southern Europe, the 12-level Mercalli-Cancani-Sieberg intensity scale (MCS) is used. The intensity scale used by the Japanese Meteorological Agency (JMA) is based on seven levels that refer to earthquake effects on typical Japanese items such as latticed sliding doors and wooden houses. Alternatively, the Medvedev-Sponheuer-Karnik intensity scale (KSK), a 12-level scale, was developed by Central and Eastern European scientists. The intensity scale currently used in China and United State is the Modified Mercalli Intensity scale (MMI). An increase in intensity describes a more severe effect on what people feel and what can be observed around them. Figure 2 gives a comparison of various seismic intensity scales.

A detailed description of various scales can be found in the book (Grunthal G, 1993) published by the European Seismological Commission. The intensity scale is used widely as the hazard parameter as it describes exclusively the effect of an earthquake on the surface of Earth, and it also integrates numerous parameters (such as ground acceleration, duration of an earthquake, and subsoil effects).

All the ground motion and intensity parameters mentioned above are used in seismic hazard analysis.

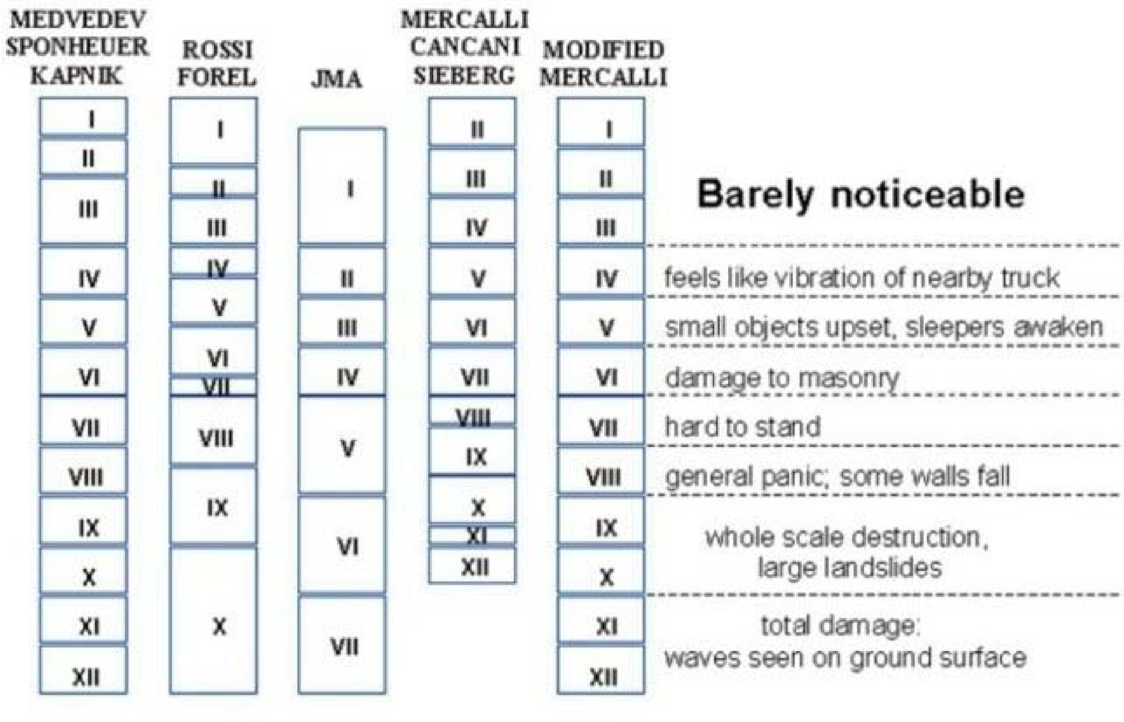

Figure 2. A comparison of different seismic intensity scales

1.2.2 Surface Rupture and Other Related Hazards

Surface rupture and movement along the fault are obvious hazards. The offset between rocks on the surface rupture, or on the opposite sides of the fault, can break power lines, pipelines, buildings, roads, bridges, and other structures that actually cross the fault.

Surface rupture sometimes closely relates to shaking. Ground shaking may cause a further problem in areas where it is relatively wet. The process by which poorly consolidated mud and other fine-grained sediments become fluid during shaking is called “liquefaction,” and it affects what appear to be solid, compact mud or silts. When wet soil is shaken by an earthquake, the soil particles may be jarred apart, allowing water to seep in between them, reducing the friction between soil particles that gives the soil strength, and causing the ground to become somewhat like quicksand. When this happens, buildings can just topple over or partially sink into the liquefied soil; the soil has no strength to support them.

Solid bedrock is the most stable foundation, and buildings on it have a good chance of riding out all but the most severe earthquakes. Where the underlying soils or sediments are weak and poorly consolidated, however, the story is different. The risk factor from ground displacement is often exacerbated in urban areas where land is at a premium, and many cities have expanded into wetlands and shallow coastal regions by using artificial fill to increase the land area.

1.2.3 Indirect Hazards

An indirect hazard of earthquakes in cities is fire, which may be more devastating than ground movement. Prior to the modern electrical service, most city dwellers used wood- or coal-burning stoves for heat and cooking and open flames or lanterns for light, all of which were often toppled by the shaking during earthquakes. Even today, the combination of electrical short-circuits caused by destruction of service poles and transformers and the presence of broken gas mains can produce enormous risk from fire. In Kobe, about 10% of the fatalities were fire-related, about two-thirds apparently caused by leaking gas or electrical problems. The problem of fire is exacerbated by broken water mains, loss of water pressure, and the inability of fire companies to negotiate the rubble-strewn streets of an earthquake-damaged city.

As with fire, the collapse of the social infrastructure—municipal water supplies, sewage treatment facilities, burial of the dead, isolation of outlying areas from food and medical care—contributes to a general decline of social services. Cholera and other epidemics are common in more remote areas of the less-developed world in the aftermath of earthquake destruction. In 1993, an earthquake centered on Khillari, 300 miles southeast of Bombay, killed perhaps as many as 22 000 people. In the aftermath, shortages of water and proper sanitation resulted in epidemics of gastro-enteritis and malaria, although the far more dangerous spread of cholera and diphtheria was prevented by the rapid response of public health officials.

1.3 Earthquake Hazard Assessment

In earthquake hazards assessment, the first question we should make clear is where the danger is and, therefore, who is in danger and to what degree the loss will be. The answer to these questions is critical to earthquake disaster mitigation and can be broken down into two main aspects: seismic hazard analysis, which involves the identification and quantitative description of strong ground motion caused by future earthquakes; and seismic risk analysis, which involves the vulnerability analysis of buildings and other man-made facilities to earthquake damage, and the losses that may result from this damage.

Earthquake hazard is the probability that a certain value of a macroscopic intensity or of a ground motion parameter (i.e. particle acceleration, velocity and displacement) will not be exceeded at a specific site in a specific period of time.

Today, many maps have been developed to help public officials prepare for earthquakes. Such maps are based on mapping active faults, studies of geologic features that allow dating of earthquake-produced scarps, landslides, offsets and liquefaction features, and the historical record of seismic activity. Figure 3 is a global seismic hazard map compiled the Global Seismic Hazard Assessment Program (GSHAP). GSHAP was launched in 1992 by the International Lithosphere Program (ILP) with the support of the International Council of Scientific Unions (ICSU), and endorsed as a demonstration program in the framework of the United Nations International Decade for Natural Disaster Reduction (UN/IDNDR). The GSHAP project terminated in 1999.

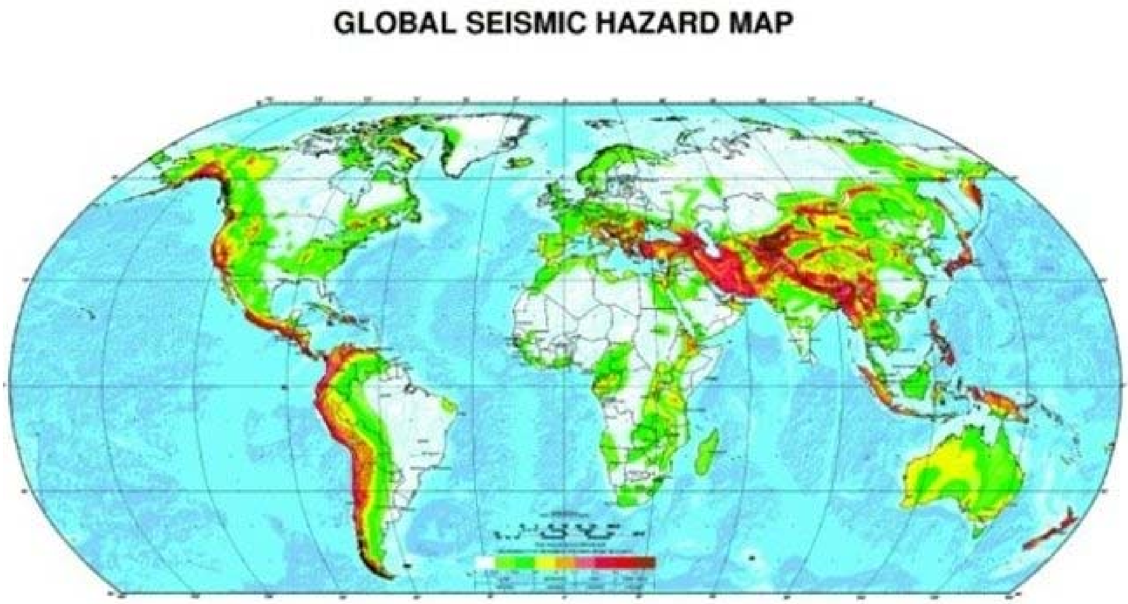

Figure 3. Global seismic hazard Assessment map by GSHAP

Seismic risk is the expected degree of losses caused by earthquakes and therefore the product of seismic hazard and vulnerability. Vulnerability is the expected degree of loss within a defined area resulting from the occurrence of earthquakes. Vulnerability is expressed on a scale of zero (no damage) to one (full damage). Thus, an equation could be used like this:

$$\text{Risk} = \text{Hazard} \times \text{Vulnerability} \qquad (3)$$

Seismic hazard describes the potential for dangerous, earthquake-related natural phenomena such as ground shaking, fault rupture, or soil liquefaction. These phenomena could result in adverse consequences to society, such as the destruction of buildings or the loss of life. Seismic risk is the probability of occurrence of these consequences. The output of a seismic hazard analysis could be a description of the intensity of shaking of a nearby magnitude eight earthquake or a map which shows levels of ground shaking in various parts of the country that have an equal chance of being exceeded.

The results of seismic hazard analysis provide basis for anti-earthquake design, which is the main engineering measure for the reduction of earthquake disasters. The seismologists performing seismic hazard analysis are really carrying out one part of an engineering process or one part of the social disaster reduction process. The end-product of this analysis is an expression of seismic hazard or threat that is oriented toward some specific use. This product may be in the form of simple, single-value characterizations of earthquake ground motion such as Modified Mercalli Intensity (MMI) or Peak Ground Acceleration (PGA), or the more complex, multi-value characterizations, such as response spectra.

-

-
-

Bibliography

Bolt B. A. (1999). *Earthquakes and geological discovery*. Berlin: Spring Verlag [Gives a good description of concepts like earthquake hazard, seismic wave, measuring the magnitude of an earthquake.]

Bryant E. A. (1991). *Natural hazards*. Cambridge: Cambridge University Press. [This book gives a good description of natural hazards that we must face today and related issues.]

Grunthal G. (1993). *European Macroseismic Scale 1992* (Up-dated MSK Scale). Luxembourg. [Presents the concepts of magnitude and intensity of earthquakes, and gives comparison of various intensity scales.]

Montgomery C. W. (1997). *Environmental geology*. fifth edition, New York: WCB/McGraw-Hill Company. [This book presents geology applied to living, like how geologic processes and hazards influence human activities and related environmental problems.]

National Research Council, U. S. National Academy of Sciences, U. S. National Academy of Engineering (1987). *Confronting Natural Disasters*. Washington, D. C.: National Academic Press [Overview of tsunamis and landslides, see the NRC (National Research Council) at http://www.national-academies.org/rap].

Reiter L. (1990). *Earthquake Hazard Analysis*. New York: Columbia University Press [Earthquake hazards and hazard assessment.]

RMS (Risk Management Solution) (1995). *What if the 1906 Earthquake Strikes Again? A San Francisco Bay Scenario*. Risk Management Solution, Inc. [San Francisco earthquake's scenario as an example of earthquake hazard assessment.]

Rogers J. J. W. and Feiss P. G. (1998). *People and the Earth – Basic Issues in the sustainability of Resources and Environment*. Oxford: Cambridge University Press. [Hazards affecting human life and that are affected by humans.]

Steinbrugge K. V. (1982). *Earthquakes, Volcanoes, and Tsunamis, An Anatomy of Hazard*. New York: Skandia Amenica Group. [Detailed description of tsunamis and landslides.]

Solov'ev S. L. and Go Ch N. (1974). *A Catalogue of Tsunamis on the Western Shore of the Pacific Ocean.* Moscow: Academy of Sciences of the USSR "Nauka" Publishing House [The catalog of tsunamis on the western shore of the Pacific ocean.]

Yeats R. S., Sieh K., and Allen C. R. (1997). *The Geology of Earthquakes*. New York: Oxford University Press [This textbook presents the essential aspects of causes of earthquake.]

http://www.netc.net.au/enviro/fguide/mass.html

http://spike.geophys.washington.edu/tsunami/general/physics/physics.html

Biographical Sketch

Li Juan graduated from University of Science and Technology of China, and now is candidate Dr. Student of Institute of Geophysics, China Seismological Bureau. Her research focuses on seismic hazard and risk analysis, and simulation of rock failure. Member of Chinese Geophysical Society.