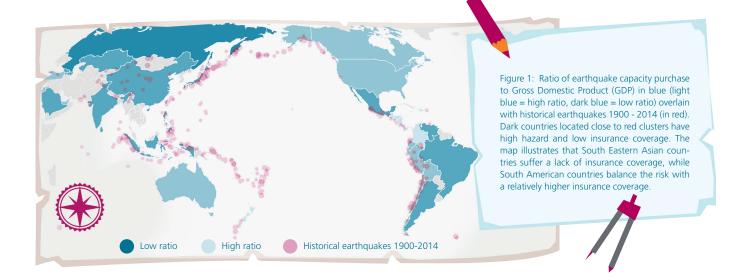# GUIDE TO EARTHQUAKES - PART I
## An introduction to Earthquakes: why and where they occur and how they are measured



Figure 1: Ratio of earthquake capacity purchase to Gross Domestic Product (GDP) in blue (light blue = high ratio, dark blue = low ratio) overlain with historical earthquakes 1900 - 2014 (in red). Dark countries located close to red clusters have high hazard and low insurance coverage. The map illustrates that South Eastern Asian countries suffer a lack of insurance coverage, while South American countries balance the risk with a relatively higher insurance coverage.

● Low ratio     ● High ratio     ● Historical earthquakes 1900-2014

## Overview

Five years have passed since the momentous 2010 - 2011 series of earthquakes across Haiti, Chile, New Zealand and Japan. This anniversary marks an opportune time to assess where we are in our understanding of earthquake risk, and the status of the models used to manage that risk within the (re)insurance industry.

Whilst the 2000s saw multiple losses, and some surprises, from hurricanes striking major insured concentrations along the coastline of the USA, more recently the headlines have been dominated by highly damaging earthquakes.

Many of these major events had some element of surprising behaviour when compared to the models used to assess the risk. The combination of an increasingly urbanised and rapidly growing global population, an ever more inter connected global economy and recent initiatives to extend insurance coverage means that it is becoming more and more important to understand this peril, its drivers and the models we use.

In global economic terms, earthquakes are a significant driver of losses from natural disasters. In a 2013 report, the United Nations Office for Disaster Risk Reduction estimated that natural disasters have cost the global economy US$2.5 trillion since 2000, and that average losses from earthquakes alone are expected to be about US$100 billion per year in the future, followed by cyclonic wind damages at US$80 billion per year. Of the total global earthquake loss potential, 76% is concentrated in Asia, 8% in Europe, 9% in North America and 5% in Latin America[1].

"THESE EVENTS HAVE HIGHLIGHTED THE VULNERABILITY OF BUILDINGS, INFRASTRUCTURE AND SOCIETIES TO EARTHQUAKES, AND THE SIGNIFICANCE OF THIS PERIL FOR THE INSURANCE INDUSTRY."

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In insurance terms, however, earthquake insurance penetration is estimated to be below 10% worldwide[2] with high disparities between countries. Figure 1 illustrates the ratio of purchased earthquake coverage to GDP, and proximity to high hazard zones, by country around the world. Several mid-sized economy countries, in South-East Asia especially, can be seen to be under-insured relative to the high level of hazard.

Even in the USA, where insurance penetration is generally high, earthquake penetration remains relatively low: it is estimated that only 1 in 10 householders in California hold earthquake coverage, approximately half the level as at the time of the 1989 Loma Prieta earthquake, which struck the San Francisco bay area. In contrast, high insurance penetration in New Zealand as a result of the government-run earthquake fund means that some 80% of the economic losses from the Christchurch quake were covered by insurance, compared to just 17% for Japan's Tohoku earthquake.

Increasing wealth and insurance penetration around the world, combined with a growing recognition of the advantages of insurance as an ex-ante facility to help communities and business rebuild following disasters, may change this landscape in the future. Initiatives are being launched by the United Nations, World Bank and others, such as the G7 Climate Risk Insurance Initiative announced in June 2015, aimed at increasing the take-up of insurance against natural catastrophes.

In this three-part technical newsletter we review the physical characteristics of earthquakes, the global landscape of earthquake risk, provide insights into major events and discuss the earthquake catastrophe models used widely across the insurance industry in order to assess the risk. We start in part I with a review of what causes earthquakes, where they occur and how they are measured.

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# What is an earthquake?

An earthquake occurs somewhere on the planet every 30 seconds. However, earthquakes strong enough to have a noticeable effect happen approximately 100 times a year. Table 1 shows a selection of the most destructive earthquakes that have been experienced.

Table 1 : Some extreme measures (cost, fatalities and size) associated with earthquakes

| RECORD | YEAR | LOCATION | PARAMETER | VALUE | SOURCE |
|---|---|---|---|---|---|
| Costliest earthquake | 2011 | Japan | Economic cost | US$ 250 bn | Japanese Cabinet office |
| Costliest aftershock | 2011 | New Zealand | Economic cost | US$ 16bn | Insurance Information Institute |
| Deadliest earthquake | 1556 | China | Fatalities | 830,000 | USGS |
| Deadliest decade | 2001-2010 | India, Iran, Sumatra, Pakistan, China, Haiti | Fatalities | 700,000 | Holzer et al. (2013)[3] |
| Largest energy release | 1960 | Chile | Moment magnitude (Mw) | 9,5 | USGS |
| Largest aftershock | 2005 | Sumatra | Moment magnitude (Mw) | 8,7 | EOS, published 3rd June 2011 |

Earthquakes are caused by a sudden release of energy in the earth's crust. Stress within the earth's crust builds up over time until it exceeds the strength of the rock, which then fails by breaking along a fault, or weakness, in the earth's crust.

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1 - UNISDR. 2013. From Shared Risk to Shared Value – The Business Case for Disaster Risk Reduction. Global Assessment Report on Disaster Risk Reduction. Geneva, Switzerland.
2 - Linnerooth-Bayer J. & Mechler R. 2008. Insurance Against Losses from Natural Disasters in Developing Countries. United Nations World Economic and Social Survey (WESS) Working Paper No. 85.
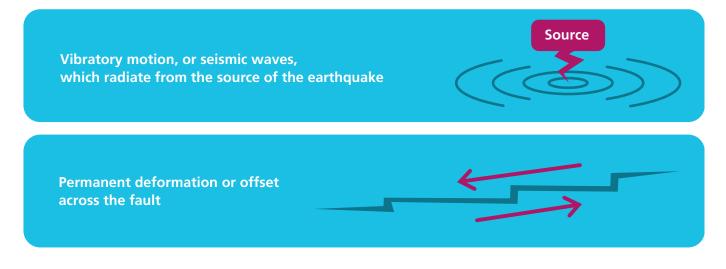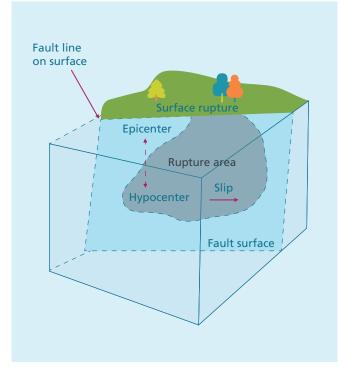3 - Holzer T.L. & Savage J.C. 2013. Global Earthquake Fatalities and Population. Earthquake Spectra: February 2013, Vol. 29, No. 1, pp. 155-175

# What types of motion are produced?

There are two types of motion produced:

**Vibratory motion, or seismic waves, which radiate from the source of the earthquake**

Source

**Permanent deformation or offset across the fault**

> The deformation may rupture the surface producing a horizontal or vertical offset (also known as a "scarp"). However, in many earthquakes, the earth's surface does not actually rupture, so the permanent deformation is limited to warping of the surface of the earth.

Figure 2: Illustration of the mechanics of an earthquake. The hypocenter is where the rupture originates within the fault and the epicenter is the point directly above it on the ground surface.

Fault line on surface

Surface rupture

Epicenter

Rupture area

Hypocenter

Slip

Fault surface

## Vibrations

The vibrations produced by earthquakes occur at frequencies of less than 0.2 Hz to over 20 Hz, just below the range of sound vibrations. All built structures have their own resonant frequency, which depends on the building characteristics such as height and the material from which it is constructed.

Damage to a building depends on both its properties and those of the earthquake ground motions, with the most damage occurring when the building is subject to vibrations near its natural resonant frequency. Tall buildings are most vulnerable to lower-frequency vibrations. Short buildings vibrate at high frequencies and do not sway much. Low-frequency vibrations can travel long distances, and will be felt by people in tall buildings but not shorter ones - for example tall office buildings in Tokyo are often reported by workers as swaying in response to earthquakes far away from the city.

# How and where are earthquakes created?

According to the accepted theory of plate tectonics, the earth's surface is made up of plates, or continents, on top of a more fluid interior mantle below.

These continents move relative to each other, through a process known as continental drift. For example Europe and North America are moving away from each other (divergent) creating rift zones as can be seen in Iceland, whereas Asia and the Indian subcontinent are moving towards each other (convergent), resulting in the Himalayan mountain range. Two plates sliding past each other form a transform plate boundary, such as the infamous San Andreas Fault along the west coast of the USA. Underneath the oceans, new crust is formed by volcanic activity along mid-ocean ridges where plates are moving away from each other. The outflow gradually cools and thickens in a process known as seafloor spreading. Where oceanic plates meet continental plates, the denser oceanic plate will usually plunge underneath the lighter continental plate, known as subduction.

More than 95% of global seismic energy release occurs along plate boundaries, and 85% is along subduction zones. Figure 3 illustrates that the majority of earthquakes are concentrated along the main plate boundaries, particularly larger magnitude events.

However, earth surface deformation can also occur across older continental plates causing intraplate earthquakes, such as along the Trans-Alpine belt that extends from the western Mediterranean through the Middle East and the north of the Indian subcontinent, within the New Madrid seismic zone in the south-eastern U.S.A, and accounting for damaging earthquakes across Australia such as the Mw 5.4 Newcastle earthquake in 1989. Therefore not all earthquake risk is associated with the major fault boundaries, and all sources need to be considered within an earthquake model, in order to avoid underestimating the risk away from the plate boundaries.
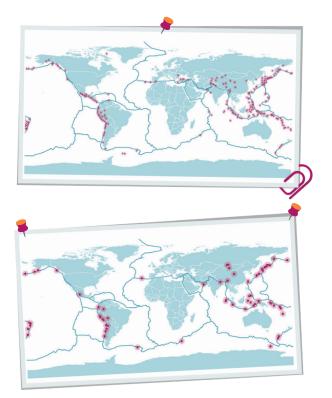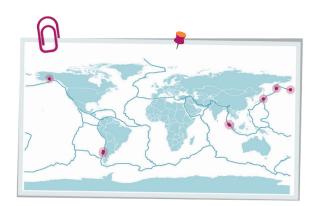
Figure 3:
Historical earthquakes since 1900
**Mw 7.5 to 8.0** (top left),
**Mw 8.0 to 8.6** (bottom left),
and **>Mw 8.6** (bottom right)
along with major plate boundaries. The pictures demonstrate that historical seismic activity is concentrated along main plate boundaries represented with red lines, but is also located within plate boundaries such as in China (source GEM)

# How are earthquakes measured?

There are different measures of earthquake size and hazard. Magnitude is a measure of the amount of energy released; peak ground acceleration (PGA) is a measure of the ground movement; and intensity is a qualitative measure of the damage caused.

Most people are familiar with the Richter scale, but there are actually a number of magnitude scales, based on different measuring techniques.

**The Richter scale, or Local Magnitude (ML) was originally developed in 1935, and measures the maximum wave amplitude as recorded by a specific type of seismometer at a known distance from the earthquake.**

However, it is not accurate for magnitudes greater than 8. Body wave magnitude (Mb) is determined by measuring the amplitude of longitudinal P-waves (movement is parallel to the direction of travel, like sound waves), which arrive first after an earthquake. Surface wave magnitude (Ms) is determined by measuring the amplitude of transverse S-waves (movement is perpendicular to the direction of travel, like light waves). The most reliable measure of earthquake size is moment magnitude (Mw) which is a measure of the total energy released, based on measurements of the distance of movement along a fault or fracture, and the area of the fault or fracture surface. Note that it is common for magnitudes to be revised after an event following a review of the data by a seismologist.

As one example of the differences that can arise between these scales, the ML of the 2009 L'Aquila earthquake was originally reported as 5.8, half a unit less than its Mw of 6.3. Such variations are common and reflect differences in the way that magnitude scales have been calibrated, as well as variations in the amplitudes of different seismic waves due to rupture orientation and geological differences.

Magnitude scales are logarithmic because of the large range of earthquake energies: each integer increase (i.e. +1) in magnitude represents a 10 times increase in amplitude, with a release of approximately 32 times the energy. This means that an M4 earthquake is the energy equivalent to 56,000 kg of explosive, whereas a M 5 earthquake is the energy equivalent of 1,800,000 kg of explosive, as shown in Figure 4.

## In general communications quakes are often categorized as either:

> **"small"** earthquakes with magnitude less than 5.0,
> **"moderate"** earthquakes up to magnitude 6.5,
> **"large"** earthquakes up to magnitude 8.0,
> **"great"** earthquakes which have a magnitude greater than 8.0.

The magnitude of an earthquake is related to the fault rupture length. The fault that ruptured in the Mw 7.8 Nepal earthquake was about 250 times larger in area than Christchurch's February 2011 Mw 6.1 quake.

Figure 4: Energy equivalence of the seismic energy release from a range of earthquake magnitudes (http://www.mgs.md.gov/seismic/education/no3.html)
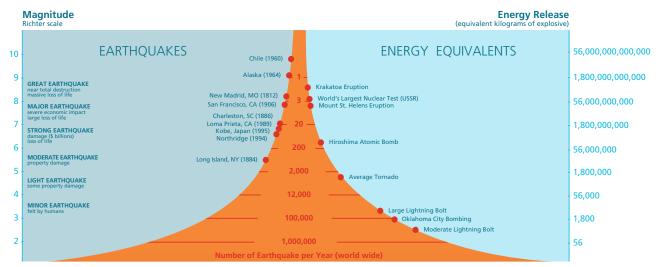
Table 2 illustrates the typical size, fault length and frequency associated with a range of magnitude values.

Table 2: Typical size and recurrence of earthquakes.

| Magnitude value | Fault | | Worldwide annual rate |
| --- | --- | --- | --- |
| | Length (km) | Slip (m) | |
| 9.0 | 800 | 8 | <1 |
| 8.0 | 250 | 5 | 3 |
| 7.0 | 50 | 1 | 20 |
| 6.0 | 10 | 0.2 | 200 |
| 5.0 | 3 | 0.05 | 2000 |

## What is a great earthquake?

As we can see, great earthquakes produce very long rupture lengths and slip amounts, and fortunately are rather rare.

The resulting peak ground acceleration (PGA) is measured in terms of gravitational force, or units of 'g'. Generally the ground acceleration will decrease with distance away from the fault, but values of ground acceleration show a high variation even within small areas. Variations in subsurface geology influence the very different PGA values recorded during earthquakes.

For example, in the Mw 6.1 Christchurch New Zealand earthquake, the peak ground acceleration was 2.2g, recorded at Heathcote Valley Primary School. In the Mw 7.8 Nepal quake, the highest recorded acceleration was 0.6g. In the September Mw 7.0 Canterbury 2010 quake in New Zealand it was 1.25g. The highest PGA recorded to date is 2.7g, recorded at Miyagi prefecture following the Mw 9.0 Tohoku earthquake in 2011.

## "INTENSITY QUANTIFIES THE EFFECTS OF AN EARTHQUAKE ON THE EARTH'S SURFACE, PEOPLE AND MAN-MADE STRUCTURES."

The most widely used intensity scale is the Modified Mercalli Intensity scale (MMI) which ranges on a scale from I (not felt) to XII (total destruction). It reflects differences in elements such as the depth of the earthquake, local conditions, population and building standards. This means that the same magnitude earthquake can cause different levels of damage depending on where it occurs. The MMI scale has its origins in the late 1800s, reaching its current format as a 12-point scale in the 1930s. The MMI scale is described in the following table:

Table 3: Abridged version of the MMI scale, source United States Geological Survey (http://earthquake.usgs.gov/learn/topics/mercalli.php)

| INTENSITY | SHAKING | DESCRIPTION/DAMAGE |
| --- | --- | --- |
| 1 | Not felt | Not felt except by a very few under especially favourable conditions. |
| 2 | Weak | Felt only by a few persons at rest, especially on upper floors of buildings. |
| 3 | Weak | Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated. |
| 4 | Light | Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably. |
| 5 | Moderate | Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop. |
| 6 | Strong | Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight. |
| 7 | Very strong | Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. |
| 8 | Severe | Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. |
| 9 | Violent | Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations. |
| 10 | Extreme | Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent. |

# A dying concept

The characteristic earthquake: Parkfield, California. An important concept in earthquake science has been that of characteristic earthquakes. This arose from the observation of repeated similar events on some faults, and apparent relationship of those earthquakes to physical characteristics of those faults. However, the concept increasingly looks like it is becoming obsolete with recent events.
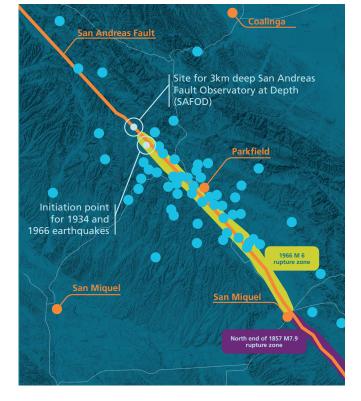
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## "THIS CONCEPT WAS THE BASIS OF THE FAMOUS PARKFIELD EARTHQUAKE PREDICTION EXERCISE."

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Moderate-size earthquakes of around magnitude 6 have occurred on the Parkfield section of the San Andreas fault in California at fairly regular intervals - in 1857, 1881, 1901, 1922, 1934, and 1966 - suggesting a pattern of ruptures every 22 years. Similar-sized foreshocks also occurred 17 minutes before each of the 1934 and 1966 Parkfield earthquakes. This "characteristic event" was predicted to recur before 1993 with a 95% probability. Unfortunately, although of a similar size in magnitude, the anticipated event did not happen until 2004, 11 years later than predicted and without forewarning or obvious precursors.

The underlying assumptions of the characteristic earthquake model – that the characteristic earthquake is the largest possible on a given segment and exhibits periodic recurrence - can lead to an overestimation of the frequencies of characteristic magnitude earthquakes. This is accompanied by an underestimation of the maximum severity and frequency of larger events[4]. Examples of the latter are the 2004 Sumatra and 2011 Tohoku earthquakes, each of which ripped through several segment boundaries - a scenario not anticipated by the characteristic earthquake model.

Figure 5: The Parkfield location on San Andreas fault.





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4 - Kagan, Y. Y., Jackson, D. D. & Geller, R. J. 2012. Characteristic earthquake model 1884–2011 R.I.P. Seismological Research Letters 83(6): 951–953.

## Summary

Whilst exposure penetration rates for earthquake insurance are relatively low globally, public-private partnerships are under discussion in order to extend insurance coverages for natural disasters, and recent earthquakes have highlighted that significant insured losses can occur.

The series of great earthquakes over the past decade have challenged long-held theories such as the characteristic earthquake model. New research is underway to understand the dynamics of subduction zones around the world, in an effort to update our global understanding of the potential earthquake risk.

In the second issue of our 3-part series, we will focus on risk assessment. We will discuss a number of historical earthquake events which are notable for modelling and the industry, and whether earthquakes are linked with each other. We will examine the debate over whether it's possible to predict earthquakes, using seismic hazard maps and probabilistic forecasts, and how these feed into risk management and mitigation assessments. In the third part we will discuss the application of probabilistic catastrophe models, their development, along with their strengths, limitations and areas of future development for earthquake risk modelling.

*"UNDERSTANDING THE BASIS OF WHAT TRIGGERS EARTHQUAKES AND WHERE THEY CAN OCCUR, AS WELL AS THE TERMINOLOGY AND METHODS OF MEASURING EARTHQUAKE SEVERITY ARE FUNDAMENTAL TO UNDERSTANDING THE RISK AND THE MODELS THAT WE USE."*

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