

Earthquakes

Buildings and bridges are subject to many loads, including self-weight, wind, and snow. However, no load is as dramatic as ground shaking caused by earthquakes, rivalled only by tsunamis if that occurs with the earthquake. For nearly a century, structural engineers have explicitly designed against earthquakes. Since the 1990s, further efforts have been made to directly quantify the damage, sometimes labelled performance-based earthquake engineering. To understand earthquakes, we go back to 1963, when research concluded that sea floors and continents drift horizontally. Soon after, in 1968, the term “plate tectonics” was established. This represented a paradigm shift in geology and explained the main reason for earthquakes. Because the tectonic plates are always moving there are many earthquakes every day. The Geological Survey of Canada, via their Earthquakes Canada website, earthquakescanada.nrcan.gc.ca, and the Geological Survey of the United States (USGS), earthquake.usgs.gov, list these events. According to the Cascadia Region Earthquake Workgroup, www.crew.org, more than 1,000 earthquakes occur each year in western Canada and more than 100 earthquakes of magnitude 5 or greater have occurred in the last 70 years west of Vancouver Island. Near Vancouver the latest magnitude 7+ events are:

- Magnitude 9.0 on January 26, 1700 a distance 161km west of Vancouver
- Magnitude 7.4 on December 15, 1872 a distance 145km southeast of Vancouver
- Magnitude 7.0 on December 6 1918 a distance 207km northwest of Vancouver
- Magnitude 7.3 on June 23, 1946 a distance 170km northwest of Vancouver

The first in that list is a mega-thrust earthquake that was recorded as a tsunami in Japan. According to the CREW website these high-energy mega-ruptures occur in the Cascadia region on average every 500 to 600 years, with time between events as low as 100 to 300 years. It is now 318 years since the most recent January 1700 event so anyone building a structure in Vancouver is making high-stakes design decisions under substantial uncertainty.

Characterizing Earthquakes

Fault Geometry

Ground shaking, what we call an earthquake, occurs when strain energy is released in a rupture somewhere in the lithosphere, i.e., the Earth’s crust or upper-most solid mantle. Most earthquakes, but not all, occur in the boundary regions between tectonic plates. There are three types of tectonic boundaries:

- A boundary where crust is created by upwelling of the Earth’s mantle, called a spreading ridge or collisional boundary
- A boundary where one tectonic plate is pushed underneath another, thus decreasing the amount of crust, called a subduction zone boundary
- A boundary where there is relative movement, but where the amount of crust does not change, called a transform fault boundary

The geometry along tectonic boundaries is complicated. Seismologists are able to identify fault planes, but only as local approximations. The orientation of a fault plane is described by two angles:

- The vertical angle between the fault plane and a horizontal plane is called the dip angle. For example, a vertical fault has dip angle equal to 90°.
- The horizontal angle of the intersection line between the fault plane and a horizontal plane is called the strike angle, which essentially measures the deviation from the North-South direction.

Rupture Geometry

When a rupture occurs along a fault the movement is said to occur as dip slip or strike slip, or both. To understand the directions it is useful to think of two perpendicular vectors in the fault plane; the dip vector always has a component in the vertical direction and the strike vector is always in the horizontal plane. Consequently, **strike slip** motion occurs when one side of the fault moves horizontally relative to the other. Conversely, with **dip slip** the relative motion is vertical. Unless the dip angle is 90°, i.e., unless the fault plane is vertical, the slip is either normal, in which case the two sides of the fault move away from each other, or **reverse**, in which case the two sides are pushed towards each other. In summary, there are three types of ruptures:

Magnitude

Several magnitude measures exist, but many are based on instruments that are less sensitive at higher magnitudes. This is called saturation and makes those magnitude measures unsuitable to assess the magnitude of severe earthquakes. A magnitude scale that does not saturate is the moment magnitude

$$M_w = \frac{\log_{10}(M_0)}{1.5} - 10.7 \quad (1)$$

It does not saturate because it is based on the seismic moment M_0 . The seismic moment is measured in dyne·cm (1dyn=10⁻⁵N). Rather than being defined directly by instrument measurements the seismic moment is

$$M_0 = G \cdot A \cdot D \quad (2)$$

where G =shear modulus measured in dyne/cm², typically around 30·10¹⁰, A =rupture area in cm², and D =average slip length in cm. In the aftermath of earthquakes the seismic moment is estimated from the long-period components of a seismogram. For historical events the geological information about shear modulus, rupture size, and rupture displacement is estimated. The bounded exponential probability density function

$$f(m) = \frac{\beta \cdot \exp[-b \cdot (m - M_{\min})]}{1 - \exp[-\beta \cdot (M_{\max} - M_{\min})]} \quad \text{for } M_{\min} \leq m \leq M_{\max} \quad (3)$$

where b and M_{\max} are distribution parameters, is sometimes used to predict the magnitude of future earthquakes (McGuire 2004).

Energy

The magnitude of an earthquake is an indicator of the potential energy that is released by the rupture. The energy, E , measured in ergs ($1\text{erg}=10^{-7}\text{J}$) is related to the moment magnitude by

$$\log_{10}(E) = 11.8 + 1.5 \cdot M_w \quad (4)$$

Combining Eqs. (1) and (4) suggests a linear relationship between energy and seismic moment:

$$E = 10^{-4.25} \cdot M_0 \quad (5)$$

Rate of Occurrence

The Gutenberg-Richter equation is well known in earthquake engineering. It postulates that small earthquakes occur more frequently than large ones. In particular, it states that the average annual rate of earthquakes that exceed a certain magnitude decreases exponentially with increasing magnitude:

$$\log_{10}(\lambda_M) = a - b \cdot M \quad (6)$$

where λ_M =mean annual number of earthquakes exceeding magnitude and M , a , and b are constants. Eq. (6) suggests that the annual rate of earthquakes that exceed $M=0$ is 10^a . In other words, 10^a is the annual rate of earthquakes of any magnitude. The probability distribution of the magnitude of these earthquakes is understood by first plotting λ_M (ordinate) versus M (abscissa) based on Eq. (6). If that curve is scaled by dividing all ordinate values by 10^a so that it equals unity at $M=0$ then this is a complementary CDF for the magnitude. Thus, the CDF is

$$F(m) = 1 - \frac{\lambda_M}{10^a} = 1 - \frac{10^{a-b \cdot m}}{10^a} = 1 - 10^{-b \cdot m} \quad (7)$$

where lower-case m is the outcome of the random variable M .

Occurrence Probability

Eq. (6) does not imply a Poisson occurrence model; λ_M simply counts the number of occurrences and presents the result as an average annual rate. As we know from the notes on the Poisson process the annual rate is NOT equal to the annual probability. Hence, one cannot multiply λ_M by number of years to get the probability of earthquakes in a time period. Some occurrence model, such as the Poisson process, is needed to calculate the probability of earthquakes in a time period. That step, and even the use of the Gutenberg-Richter relationship itself, may not be appropriate when individual earthquake sources are considered. For a single source, the accumulation and sudden release of strain energy may exhibit a periodic pattern in which characteristic earthquakes dominate the count.

Depth

The depth of a rupture is called shallow if it is less than 70km. A depth between 70km and 300km is referred to as intermediate. At the extreme, depths in the range of 300-700km occur in subduction zones. Ruptures do not occur deeper where the temperature of the Earth's mantle prevents brittle ruptures.

Occurrences near Vancouver

A quick search online will provide images showing the boundaries between the Earth's major tectonic plates. Thereafter it may be interesting to view the location of earthquakes on the websites of the Geological Surveys mentioned earlier. It soon becomes clear that earthquakes tend to be concentrated around the edges of the tectonic plates. To confirm, consider Figure 1, which shows the location of strong earthquakes in the last 100 years. Unfortunately, seismologists do not have models sufficient to simulate the build-up of stresses and subsequent ruptures. Hence, occurrence times, locations, and magnitudes remain uncertain. Historical data is the primary basis for models to predict the location of future earthquakes.

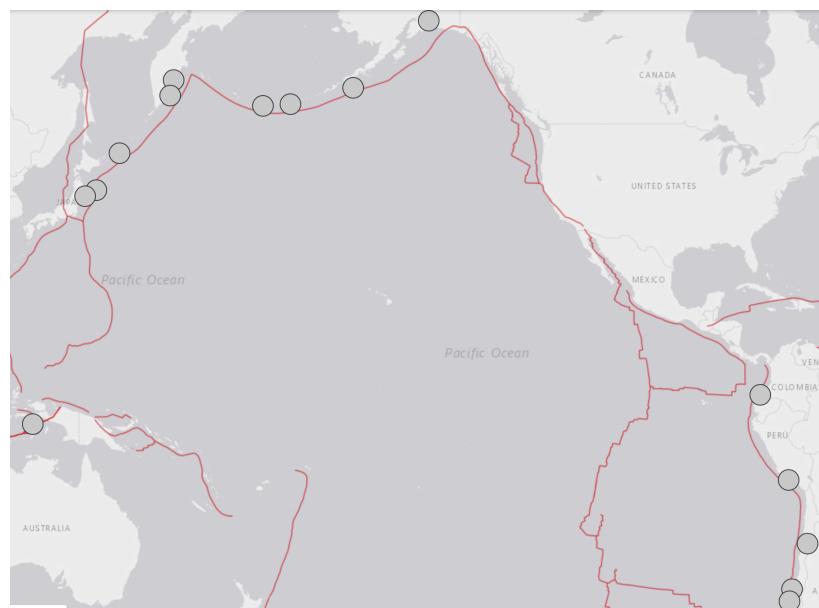


Figure 1: Earthquakes stronger than magnitude 8 since 1900 (USGS website).

The following list gives a vague sense of the earthquake sources near Vancouver, without any latitude-longitude pairs for the corner points of the area sources. Maximum magnitude of the crustal and subcrustal earthquakes are around 7.0 (Adams and Halchuk 2003; Mahsuli and Haukaas 2013):

- CASR: shallow crustal earthquakes with return period near 5 years
- JDFN: shallow crustal earthquakes with return period near 286 years
- JDFF: shallow crustal earthquakes with return period near 127 years
- GSP: deep subcrustal earthquakes with return period near 11 years

The Boore Atkinson 2008 attenuation relationship, mentioned later, is a possibility for the shallow earthquakes, while Atkinson Boore 2003 attenuation might be suitable for the deeper earthquakes, including the megathrust subduction earthquakes mentioned earlier, occurring with a return period near 300 years.

Attenuation

Shock waves are emitted when an earthquake rupture occurs. With time and distance the energy is ultimately absorbed, by damping in the material that the waves pass through. Naturally, this process of attenuation of the earthquake energy implies that the ground shaking diminishes, as a rule of thumb, with distance from the epicentre. However, even with known magnitude and location it is non-trivial to determine the level of ground shaking at a given site. In strong earthquakes the shock waves moves through the core of the Earth and can sometimes be felt on the other side of the Earth. Furthermore, the shock waves that travel at or near the surface of the Earth encounter different soil conditions that significantly affect the attenuation. Even the geometry and local evolution of the rupture can substantially affect how the energy is attenuated at distances away from the epicentre. It is perhaps possible to say that a strong earthquake, with magnitude near 7, does not cause damage beyond a **250-300km distance**.

Wave Propagation

The waves that travel through the interior of the Earth are body waves, which in turn give rise to surface waves. The body waves are of two types:

- P-waves, which are the primary, faster, and longitudinal pressure waves that travel through solids as well as liquids, with a velocity near 5.5km/s in granite
- S-waves, which are secondary slower shear waves that travel only through solids, with a velocity 2.7km/s in granite

Particles subjected to P-waves moves along the axis of propagation of the waves. S-waves make the particles move perpendicular to the direction of the propagation of the waves. Surface waves appear when the body waves reach the Earth's surface. They are a result of interacting P and S waves. While body waves dominate the motion near the epicentre the surface waves dominate at distances more than approximately twice the thickness of the Earth's crust, i.e., twice 30-50km away from the epicentre. Two types of surface waves are identified in engineering considerations of ground motion:

- Rayleigh waves, which induce vertical motion, similar to waves emanating from a stone dropped in water
- Love waves, which induce horizontal motion perpendicular to the direction of the propagation of the wave

Distance Parameters

It is sometimes difficult to visualize the concept of a distance to an earthquake because the rupture itself has geometrical dimensions. In fact, the concept does indeed cease to be meaningful when the rupture stretches far along a fault line. Assuming the rupture location can be identified as a point, its location is called hypocentre. Sometimes the words focus and focal point are used instead. The hypocentre is usually at some depth from the Earth's surface; the location on the Earth's surface directly above it is called the epicentre. The distance from a site to the hypocentre and the epicentre is called hypocentral and epicentral distances, respectively. The following notation is common, with the latter three definitions applying to ruptures of significant size:

- R_1 : hypocentral distance
- R_2 : epicentral distance

- R_3 : distance to zone of highest energy release
- R_4 : closest distance to the rupture zone
- R_5 : closest distance to the surface projection of the rupture

Attenuation Relationships

Although one wishes to simulate ground motions from propagation of energy through soil and geography, resulting in 3D ground motions, only scalar intensities are used in design. Empirical attenuation relationships that take magnitude and distance as input and give scalar intensity as output are omnipresent seismic hazard analysis:

- Campbell and Duke (1974)
- McGuire & Hanks (1980)
- Hanks & McGuire (1981)
- Joyner and Boore (1981)
- Campbell (1981)
- Boore (1983)
- Joyner and Boore (1988)
- Wilson (1993)
- Campbell and Bozorgnia (1994)
- Atkinson (1997)
- Atkinson & Boore (2003)
- Boore & Atkinson (2008)

Intensity

The magnitude and intensity of an earthquake sound like similar concepts, but they are very different. The magnitude gives the energy of the rupture; the intensity is site-specific and typically attenuates with distance from the rupture. In other words, the intensity of an earthquake is site-specific. One intensity measure is referred to as the Modified Mercalli Intensity Scale. It was developed in 1931 by the American seismologists Harry Wood and Frank Neumann (<https://earthquake.usgs.gov/learn/topics/mercalli.php>). This intensity measure is based on observed effects: I) Not felt, II) Weak, III) Weak, IV) Light, V) Moderate, VI) Strong, VII) Very strong, VIII) Severe, IX) Violent, X) Extreme. Other intensity measures, still scalars, are used in engineering practice:

- Peak ground acceleration, PGA
- Peak ground velocity, PGV
- Spectral acceleration, $Sa(T)$, i.e., maximum acceleration response, including the ground acceleration, at some natural period, T , measured in seconds, of a single-degree-of-freedom system

Structural engineers typically use Sa to predict structural damage. Geotechnical engineers use PGA but also PGV, which relates to liquefaction. The building code provides design intensities that have a specified probability of being exceeded within a time period. The National Building Code of Canada provides values that have a 2% chance of being exceeded in 50 years, which according to the Poisson occurrence model corresponds to a

2,474.92-year return period and a 0.0404% annual chance. Table 1 shows those values for Downtown Vancouver.

Table 1: Intensities downtown Vancouver from Earthquakes Canada website.

Sa _{0.05}	Sa _{0.1}	Sa _{0.2}	Sa _{0.3}	Sa _{0.5}	Sa ₁	Sa ₂	Sa ₅	Sa ₁₀	PGA	PGV
0.445	0.677	0.836	0.840	0.743	0.420	0.254	0.080	0.028	0.363	0.545

Other intensity measures exist, including the “Arias intensity” proposed by the Chilean engineer Arturo Arias in 1970:

$$I_A = \frac{\pi}{2g} \int_0^{T_d} \ddot{u}_g(t)^2 dt \quad (8)$$

where I_A =Arias intensity in m/s, g =acceleration of gravity, T_d =earthquake duration, and \ddot{u}_g =ground acceleration. The integral is essentially the sum of the squared acceleration values from ground motion record.

Ground Motions

For those who believe that an equation of motion is needed to commit earthquake engineering, ground motions are needed. They come in three versions: recorded, scaled, and synthetic. Scaled ground motions are essentially recorded ground accelerations multiplied by some constant.

Recorded Ground Motions

Databases with recorded ground motions include <https://ngawest2.berkeley.edu> and <https://www.strongmotioncenter.org>. The start of a file downloaded from such a website may look like this:

```
PEER NGA STRONG MOTION DATABASE RECORD
Imperial Valley-06, 10/15/1979, Aeropuerto Mexicali, 45
ACCELERATION TIME SERIES IN UNITS OF G
NPTS= 1477, DT= .0100 SEC,
-.2901591E-02 -.2847179E-02 -.1804664E-02 -.3052730E-02 -.2686451E-02
-.2586473E-03 -.4729786E-02 -.4293959E-02 .1627709E-02 -.4946286E-02
-.4361103E-02 .5604519E-02 .9292657E-02 .7670052E-02 -.5229579E-03
-.8405083E-02 -.6926060E-02 -.1202189E-02 -.5874317E-02 .1572419E-03
.1065928E-01 -.5091980E-02 -.1386355E-01 .3992940E-02 .5716927E-02
.3811437E-02 -.1122310E-04 -.1314702E-01 -.3653687E-02 .1111602E-01
```

The file would continue with line-after-line of acceleration values, read line-by-line and NOT column-by-column. Such files are read and analysed in an example posted on this website: Figure 2 shows one of the horizontal ground acceleration records of this Imperial Valley earthquake. After reading x , y , and z -accelerations, and integrating them each twice to obtain displacements, the 3D view of the ground displacement shown in Figure 3 is obtained. It is observed that the ground moves back-and-forth, up-and-down, but less in the vertical direction and most in a particular horizontal direction. Another important engineering view of a ground motion is shown in Figure 4. It shows the maximum acceleration, including the ground acceleration, of a single-degree-of-freedom

system at different natural periods of vibration, in units of g, the acceleration of gravity, near 9.81m/s^2 . It is observed that the acceleration, and hence the force, according to Isaac Newton, diminishes with increasing natural period of vibration.

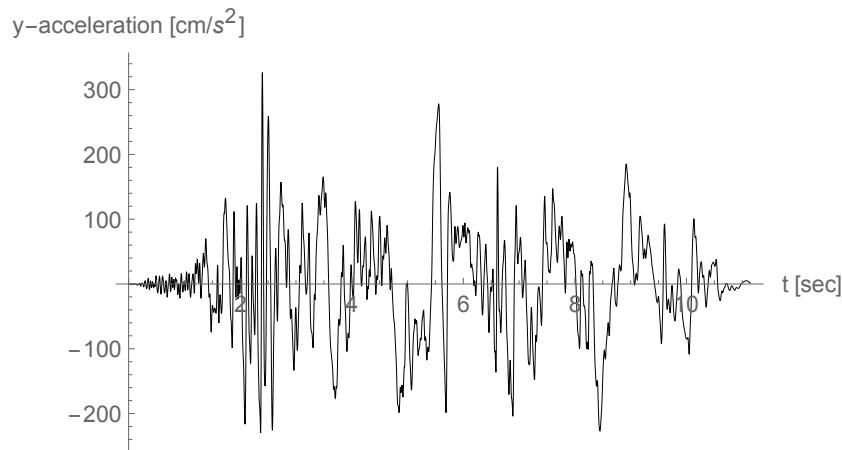


Figure 2: Imperial Valley, Aeropuerto Mexicali, ground acceleration.

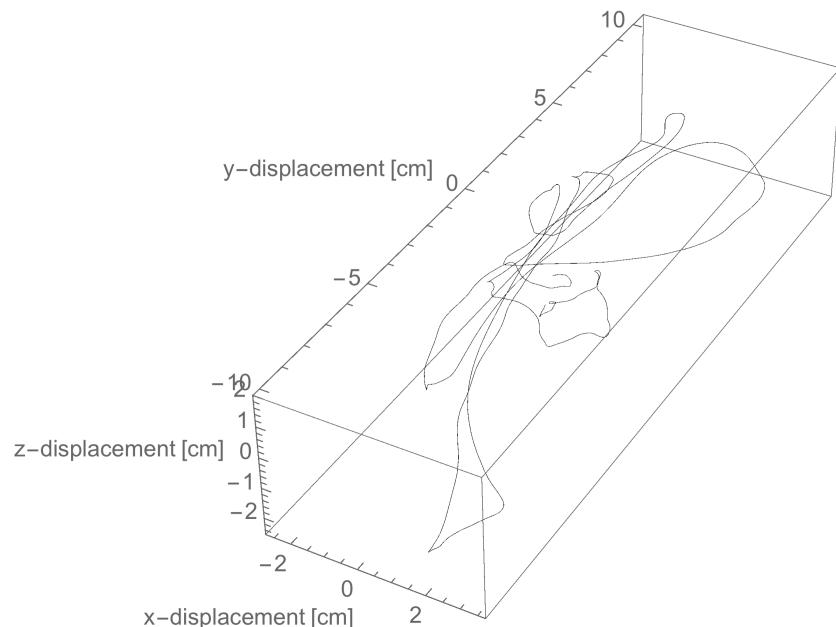


Figure 3: Imperial Valley earthquake, Aeropuerto Mexicali, 3D ground displacement.

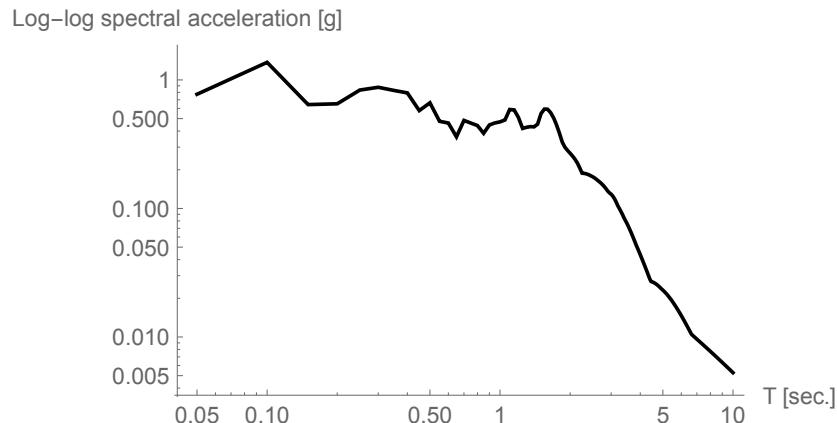


Figure 4: Imperial Valley, Aeropuerto Mexicali, spectral acceleration in one direction.

Synthetic Ground Motions

The holy grail of earthquake engineering is to simulate 3D ground motions of realistic future earthquakes at a site, covering the entire possible outcome space. For the purposes of engineering practice this goal is not within reach. Instead, engineers use recorded ground motions. There are several efforts to create workable synthetic ground motion approaches. Two leaders in the field are former University of California Berkeley professor Armen Der Kiuregian and Columbia University professor George Deodatis. Together with students Sanaz Rezaeian, Christos Vlachos, and Konstantinos Papakonstantinou they provide pedagogical exposures of the state-of-the-art in recent journal papers and ICASP/ICOSSAR conference papers. These evolving ground motion models provide realistic simulations of future earthquakes but are often calibrated towards recorded ground motion records, not magnitude and distance and specific geography and wave propagation. Perhaps the numerical simulation of wave propagation through 3D basins will be more productive in the long run; see for example efforts like the SCEC initiative (<https://www.scec.org/research/gmp>).

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