Basic Seismology and Seismic Hazard Assessment

Fawad Ahmed Najam, PhD
National University of Sciences and Technology (NUST) Islamabad, Pakistan

Pennung Warnitchai, PhD
Asian Institute of Technology (AIT), Bangkok, Thailand

January, 2020

Contents

Chapter 1

Basic Seismology

1.1. What is an Earthquake?

- Shaking and vibration at the surface of the earth resulting from underground movement along a fault plane or from volcanic activity
- An earthquake is the result of a sudden release of energy in the Earth's crust that creates seismic waves
- An earthquake is a sudden and sometimes catastrophic movement of a part of the Earth's surface.

1.2. Types of Earthquakes

- EQs can be classified by their mode of generation as follows:
    - Tectonic Earthquakes
        - The most common earthquakes
        - Produced when rocks break suddenly in response to the various geological (tectonic) forces
    - Volcanic Earthquakes
        - EQs that occurs in conjunction with volcanic activity
        - EQs induced by the movement (injection or withdrawal) of magma
    - Collapse Earthquakes
        - Small EQs occurring in regions of underground caverns and mines
        - Caused by the collapse of the roof of the mine or caverns
        - Sometimes produced by massive land sliding
    - Human cause explosion earthquakes
        - Produced by the explosion of chemical or nuclear devices

1.3. The Causes of Earthquakes

In 1891, a Japanese seismologist, Prof. B. Koto, after careful study of the Mino-Owari earthquake noted, "It can be confidently asserted that the sudden faulting was the actual cause (and not the effect) of the earthquake."

This finding was the start of common acceptance that fractures and faults were the actual mechanism of the earthquake and not its results, and was the basis of the development of the seismology.

In ancient Japanese folklore, a giant catfish (Namazu) lives in the mud beneath the earth. It is guarded by the god Kashima who restrains the fish with a stone. When Kashima let his guard fall, Namazu thrashes its body, causing violent earthquakes.

Ground Failure by Lateral Fault Movement

Surface rupture caused by Fault dislocation

- Shortly after the San Francisco earthquake of 1906, an American geologist, Harry Fielding Reid, investigated the geological aftermath.
- He noticed that a displacement of nearly 6 meters had occurred on certain parts of the San Andreas Fault which runs under San Francisco, and he proposed the theory that strain had been building up over a long period of time and suddenly released in the EQ.

“It is impossible for rock to rupture without first being subjected to elastic strains greater than it can endure. We concluded that the crust in many parts of the earth is being slowly displaced, and the difference between the displacements in neighboring regions set up elastic strains, which may become larger than the rock can endure. A rupture then take place, and the strained rock rebounds under its own elastic stresses, until the strain is largely or wholly relieved.

When a fault ruptures, the elastic energy stored in the rock is released, partly as heat and partly as elastic waves.

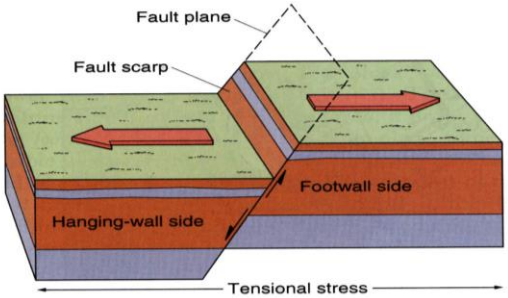
In the majority of cases, the elastic rebound on opposite sides of the fault are in opposite directions.

This is known as the elastic rebound theory.

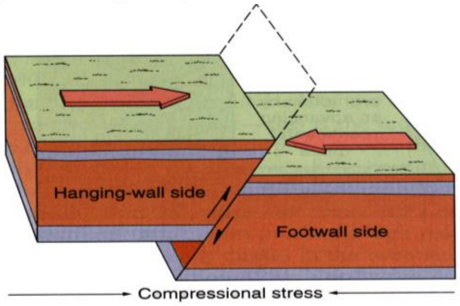
1.4. Types of Faults

Four Basic Types of Faults

Fault: A fault is a **fracture** along which the blocks of crust on either side have moved relative to one another parallel to the fracture.

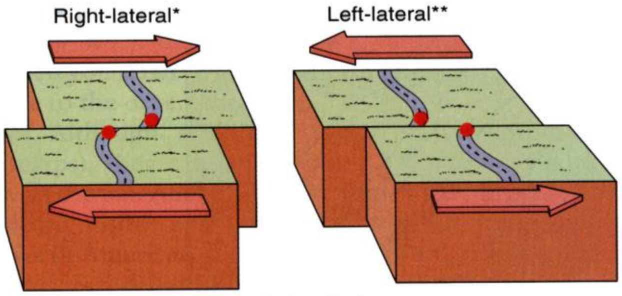


(a) Normal fault (tension)



(b) Thrust or reverse fault (compression)

Dip Slip (normal or thrust)



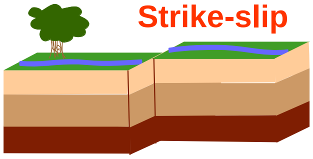
(c) Strike-slip fault (lateral shearing)

Strike Slip (right or left lateral)

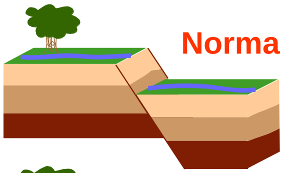
Strike-slip faults are vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral.

Dip-slip faults are inclined fractures where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed normal, whereas if the rock above the fault moves up, the fault is termed reverse (or thrust). Oblique-slip faults have significant components of both slip styles.

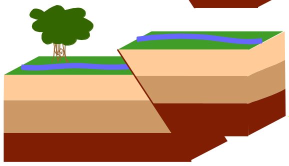
Oblique-slip faults: Oblique-slip faulting suggests both dip-slip faulting and strike-slip faulting. It is caused by a combination of shearing and tension or compressional forces, e.g., left-lateral normal fault.



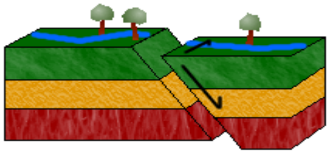
Strike-slip



Normal



Thrust



Oblique-slip

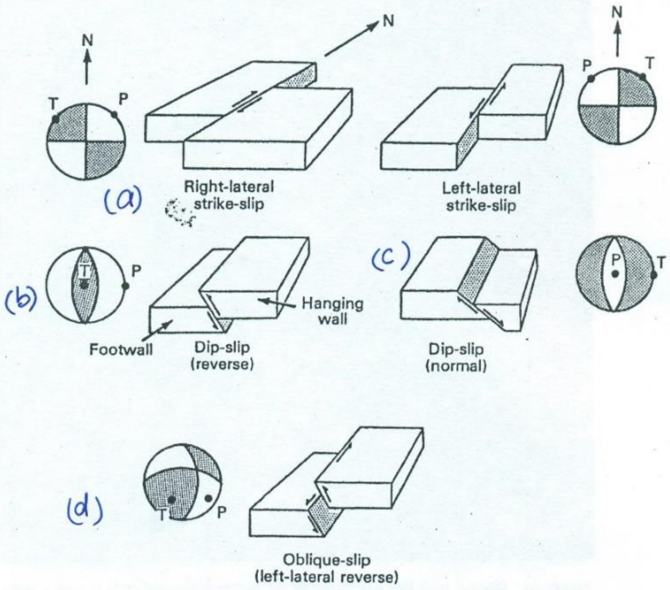


FIGURE 2.7 Different types of faults classified by the orientation of relative movement along the fault plane during an earthquake (after Clark and Hauge 1971; Wesson and others 1975; and Berlin 1980). Also shown are the corresponding focal mechanism solutions with pressure (T) and tension (T) axes.

horizontal movement — a = Strike slip → when crust is in Shear

vertical [b = Thrust (reverse) → " " " " Compression

c = Normal → " " " " Tension

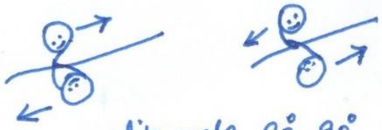
Combination of horizontal and vertical ← d = Combination of Shear and Tension/Comp.

Sometimes water in rupture zone turn into stream, and rock melt down. This makes the movement of rocks in rupture zone like liquid movement. So the rupture is not a dry and cool process, it is a wet and high-temperature process.

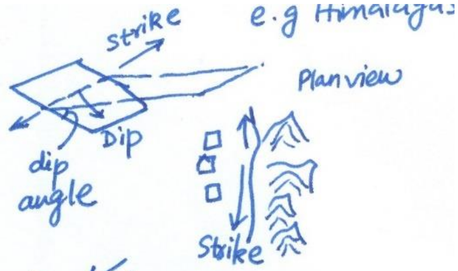
Crustal Faults

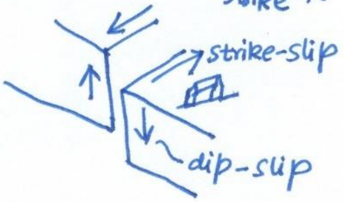
Strike-slip
(sliping in the direction of strike)

Right-lateral Left-lateral

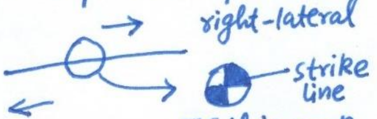


dip angle 80°-90°





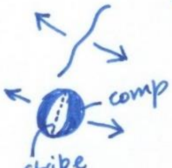
Beach Balls → Moment Tensors
describe the direction of strike and slip and dip.



■ Soil in comp
□ " " tension

Strike-slip Crustal Faults

Normal Fault
dip angle 50°-75°



Moment Tensor

Reverse/Thrust Fault (10°-55°)

Most powerful EQs.

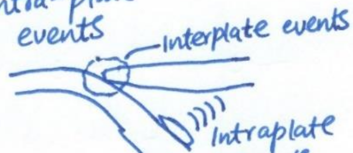
Oblique Fault
(Strike-slip and dip-slip)

Crustal Faults ≠ Plate Boundaries

Subduction Zones = Plate Boundaries

Interplate events
(Mega-thrust EQS)

Intra-plate events



Intraplate events
(v. deep)
but directly under cities

Moment Tensor

1.5. Earthquake Rupture

The rupture begins at the earthquake focus within the crustal rock and then spreads outward in all directions in the fault plane.

The boundary of the rupture does not spread out uniformly. Its progress is jerky and irregular because crustal rocks vary in their physical properties and overburden pressure from place to place.

If this rupture reaches the surface (as happens in a minority of shallow earthquakes), it produces a visible fault trace.

After shocks always spread along the fault line. So we can see the extent of rupture by checking the distribution of aftershocks.

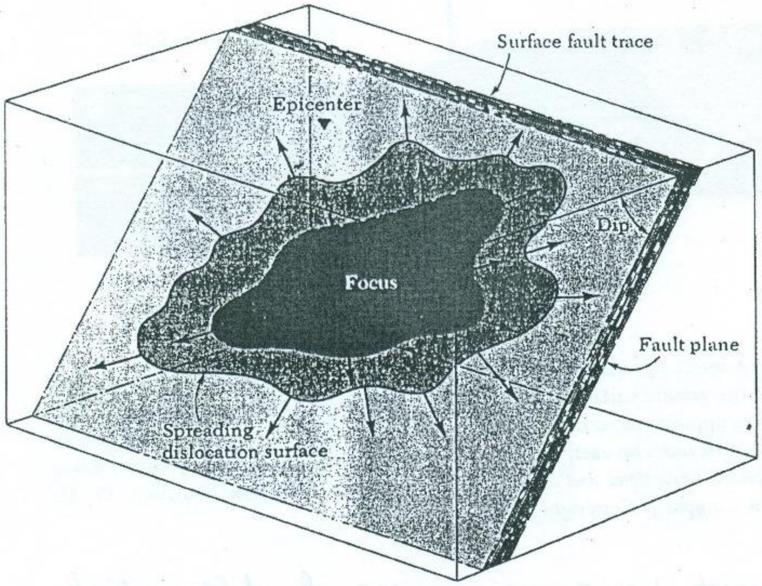


Figure 6.6 Side view into the Earth's crust showing rupture of the rocks spreading out from the focus of the earthquake along the dipping fault plane. Two stages of the rupture are shown. The arrows indicate the direction of the spreading rupture. (The epicenter is the point on the Earth's surface directly above the focus.) [From Bruce A. Bolt, *Nuclear Explosions and Earthquakes: The Parted Veil* (San Francisco: W. H. Freeman and Company, Copyright © 1976).]

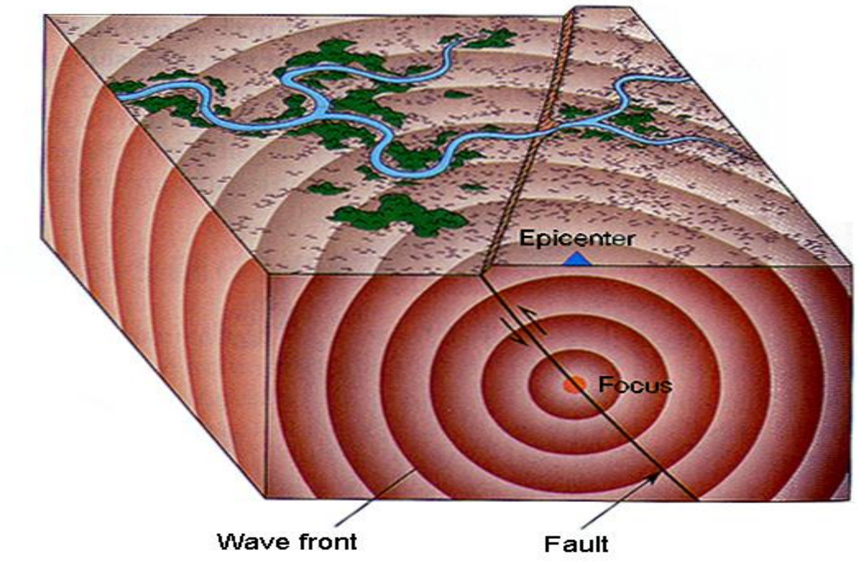
Progressive rupture

rupture at a point triggers the failure in surrounding rocks.

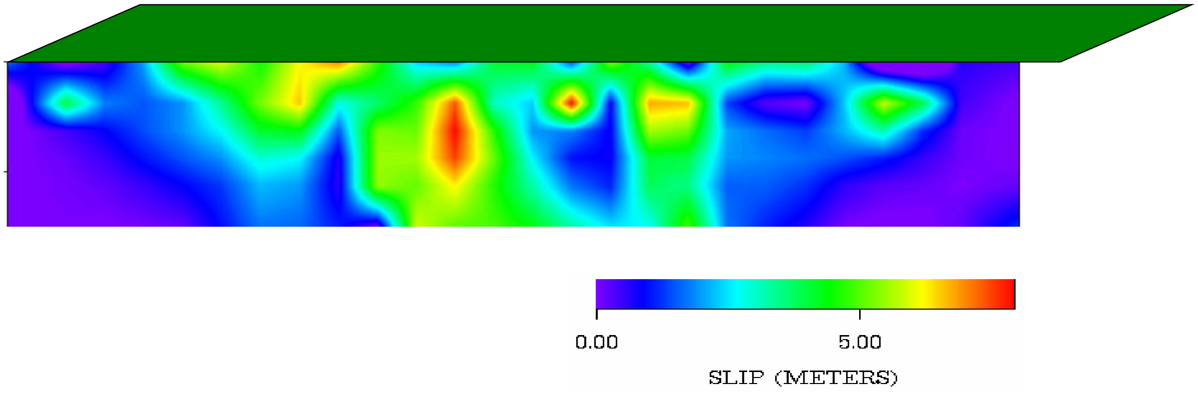
If Size of rupture
=1 Km => M5
10-20km => M6
40-70km => M7
200km => M8
200-1000km + => M9

Focus — from where the rock "starts" rupturing.

Amount of slip vary — material hetrogeneous along the rupture zone



Total Slip in the M7.3 Landers Earthquake



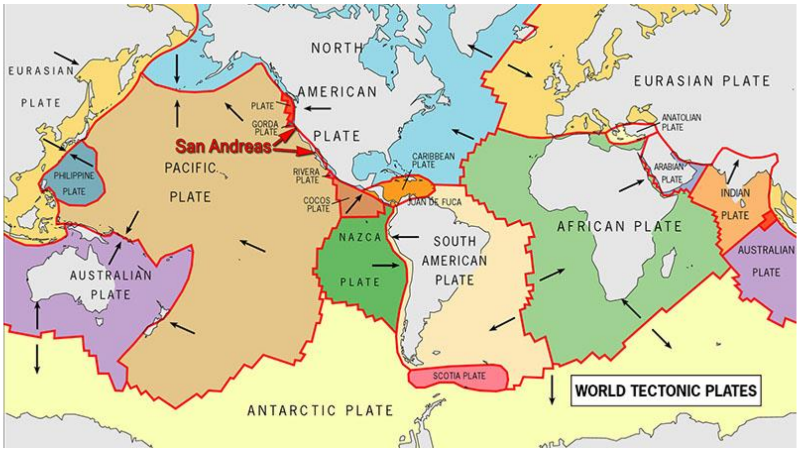
Rupture on a Fault

Surface Rupture: Strike-slip Fault Example

Surface Rupture: Normal Fault Example

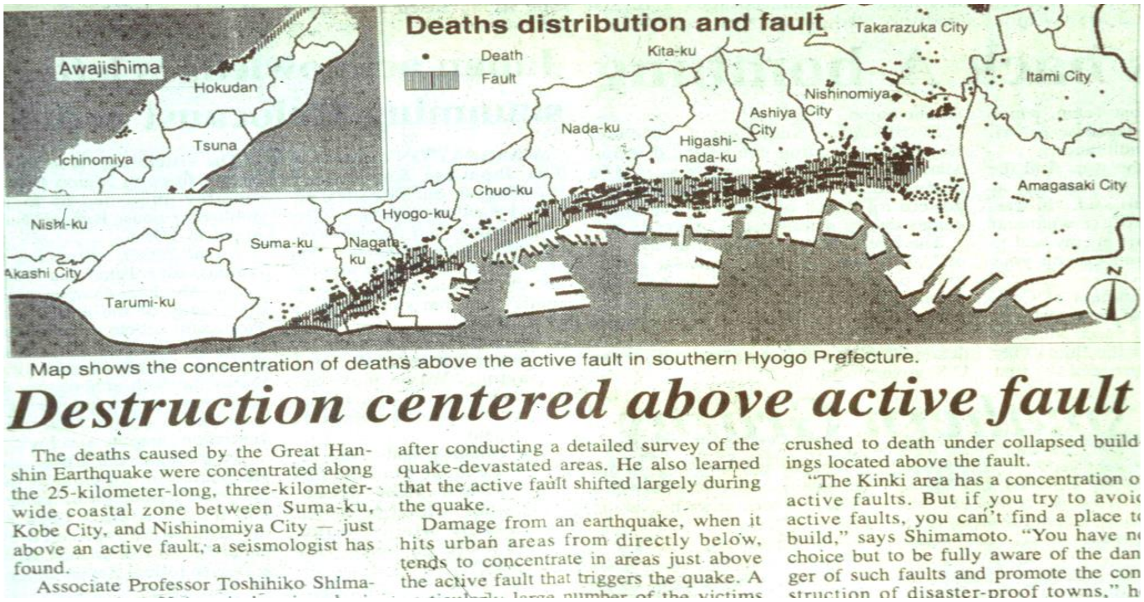
Dixie Valley-Fairview Peaks, Nevada earthquake. December 16, 1954

San Andreas Fault



Surface Rupture: Thrust Fault Example

Strong ground shaking above the rupture zone
The 1995 Kobe Earthquake



Map shows the concentration of deaths above the active fault in southern Hyogo Prefecture.

Destruction centered above active fault

The deaths caused by the Great Hanshin Earthquake were concentrated along the 25-kilometer-long, three-kilometer-wide coastal zone between Suma-ku, Kobe City, and Nishinomiya City — just above an active fault, a seismologist has found.

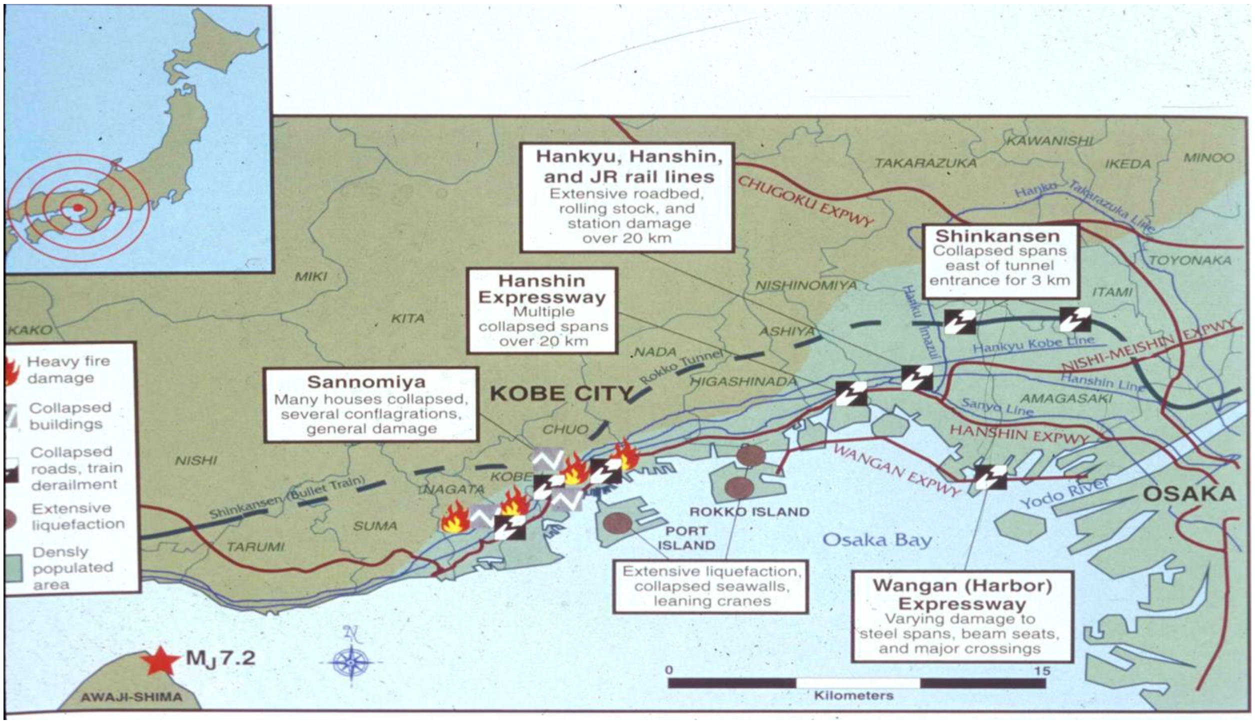
Associate Professor Toshihiko Shima-

after conducting a detailed survey of the quake-devastated areas. He also learned that the active fault shifted largely during the quake.

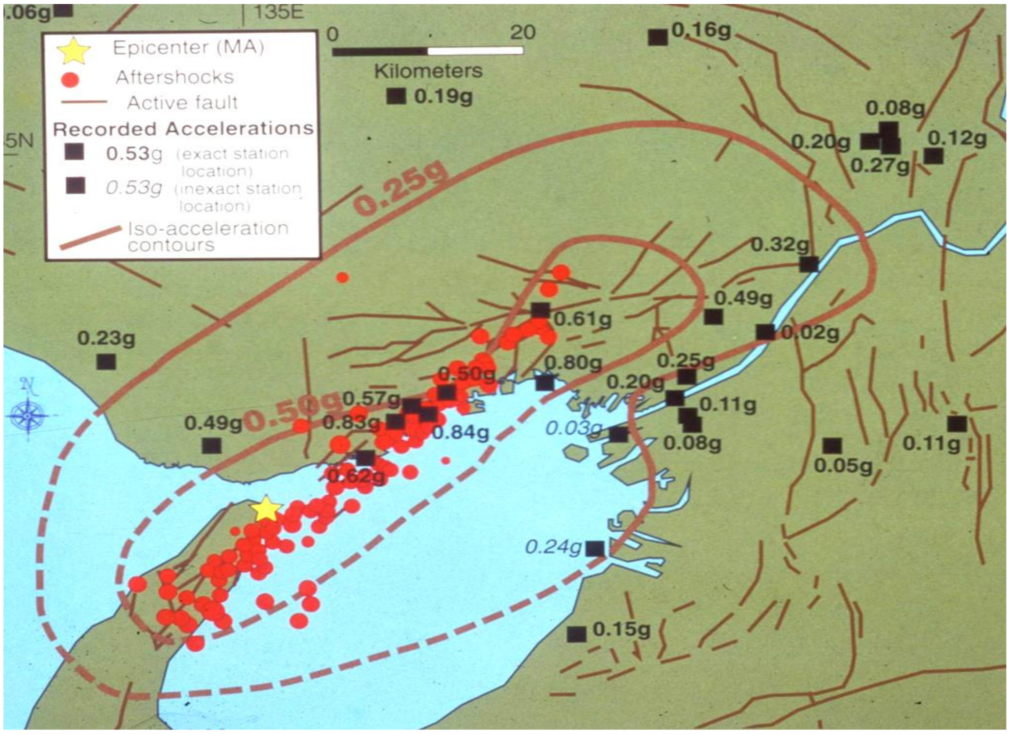
Damage from an earthquake, when it hits urban areas from directly below, tends to concentrate in areas just above the active fault that triggers the quake. A

crushed to death under collapsed buildings located above the fault.

"The Kinki area has a concentration o active faults. But if you try to avoi active faults, you can't find a place t build," says Shimamoto. "You have n choice but to be fully aware of the danger of such faults and promote the construction of disaster-proof towns," h

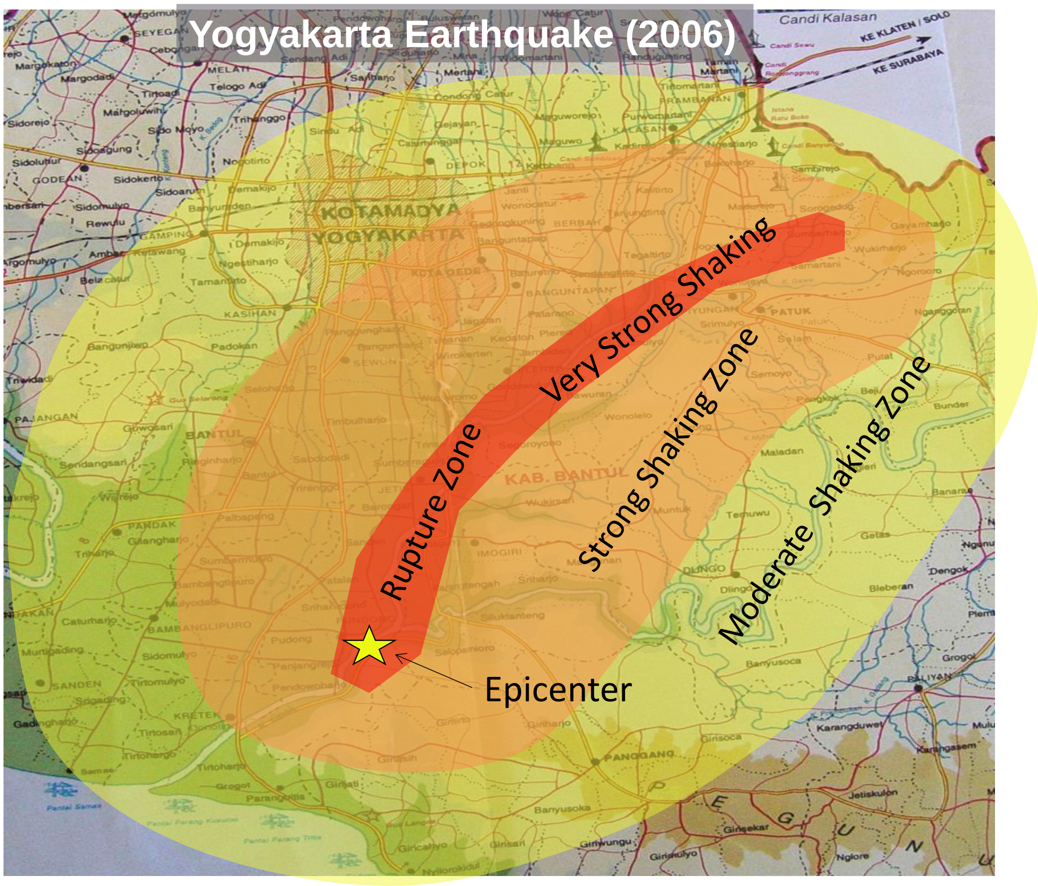


The 1995 Kobe Earthquake



The distance from your site to ruptre plane is more important than distance from site to epicenter. May be the rupture propagated towards your site.

Size of rupture is not predictable. Depends on the initial stress and rock type, which vary from place to place.


Yogyakarta Earthquake (2006)
Very Strong Shaking
Rupture Zone
Strong Shaking Zone
Moderate Shaking Zone
Epicenter

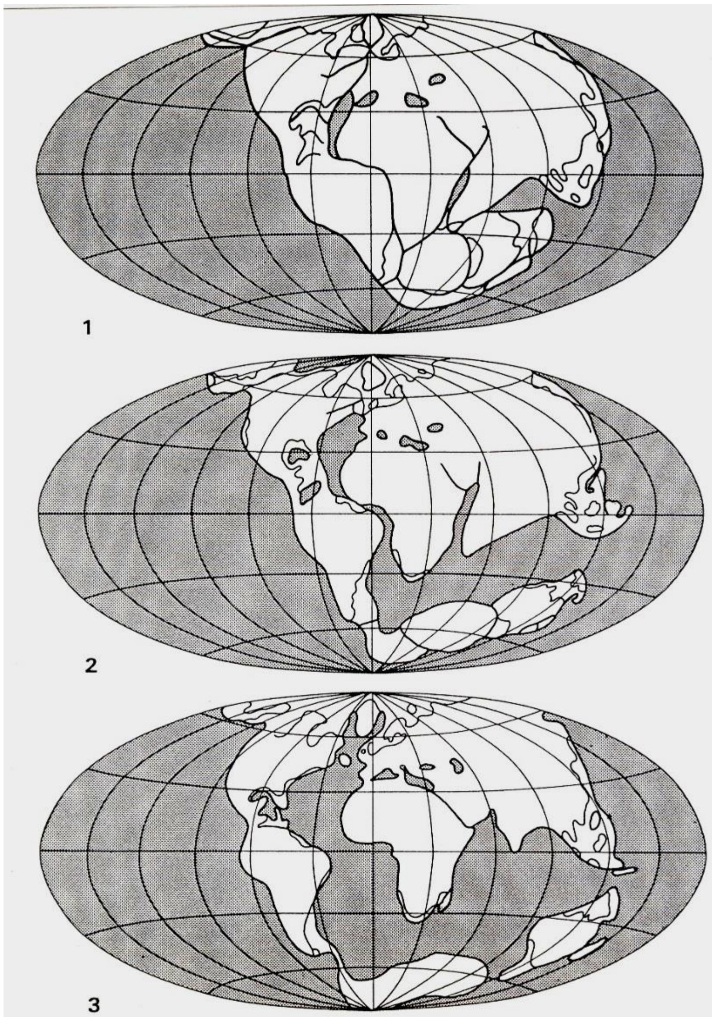

Bantul, Yogyakarta
Strong Ground Shaking + Unreinforced Masonry Houses
= A Major Disaster

1.6. Continental Drift

In 1910 a German meteorologist and astronomer, Alfred Wegener, put forward a theory:

At about 200 million years ago, the earth consisted of only one continent, which he called Pangaea (all lands), and one ocean, Panthalassa (all seas). Eventually, for reasons which Wegener could not explain, this mass of land broke up in mesozoic times—about 150 million years ago—and started to move; firstly into N-S devisions, and then into E-W ones.

He called the process continental drift.



Diagrams illustrating Wegener's theory of continental drift.

1 270 million years ago, the continents were united in a single block called Pangaea.
2 150 million years ago, Pangaea started to divide. North America and Europe were still united. It is now believed that North and South America were apart at this stage.
3 1 million years ago, the continents were beginning to assume the shapes and positions we know today.

Initially the Wegener theory was too fanciful for many, and at the existing level of scientific knowledge it could not be proved.

Wegener was roundly condemned.

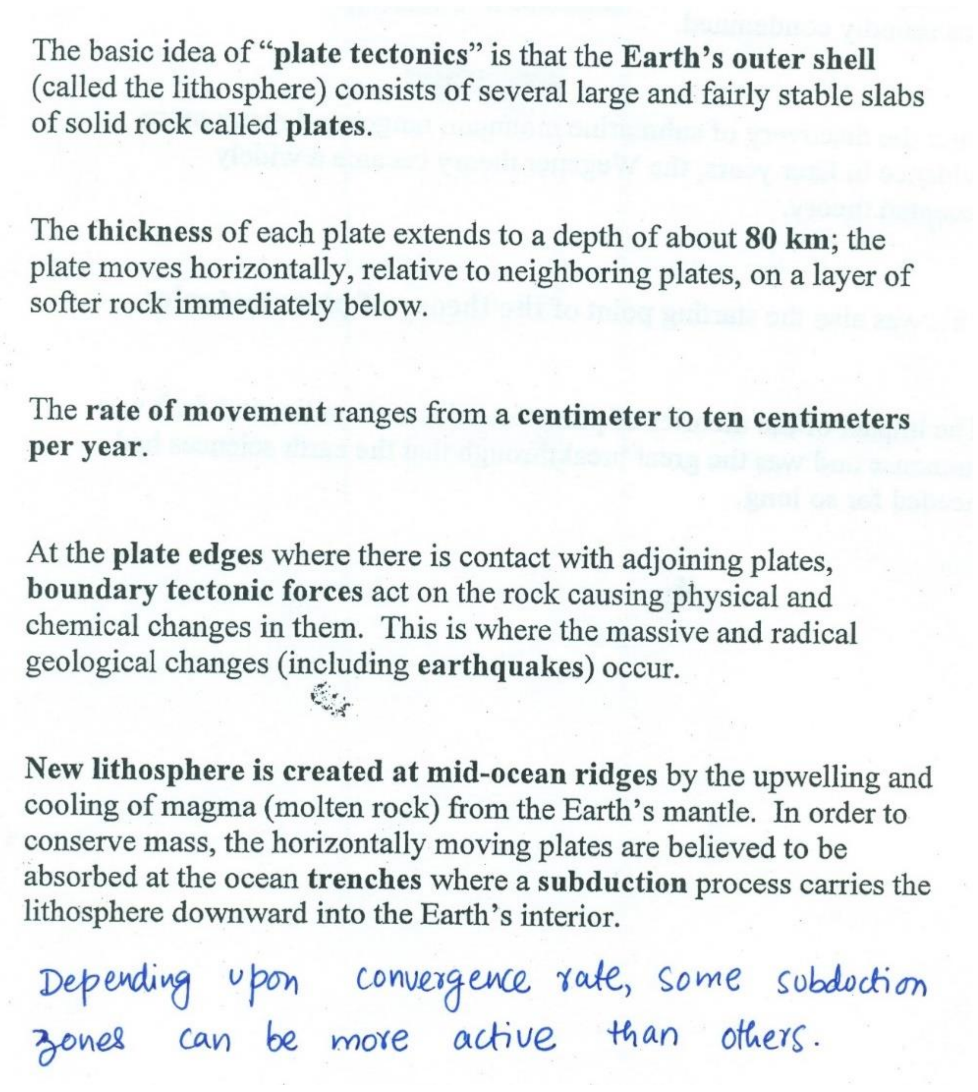
After the discovery of submarine mountain ranges and many more evidence in later years, the Wegener theory became a widely accepted theory.

This was also the starting point of the theory of plate tectonics.

The impact of the theories of plate tectonics and continental drift was immense and was the great breakthrough that the earth sciences had needed for so long.

1.7. Plate Tectonics

The basic idea of “plate tectonics” is that the earth’s outer shell (called the lithosphere) consists of several large and fairly stable slabs of solid rock called plates.



The basic idea of “**plate tectonics**” is that the **Earth’s outer shell** (called the lithosphere) consists of several large and fairly stable slabs of solid rock called **plates.**

The **thickness** of each plate extends to a depth of about **80 km**; the plate moves horizontally, relative to neighboring plates, on a layer of softer rock immediately below.

The **rate of movement** ranges from a **centimeter** to **ten centimeters per year**.

At the **plate edges** where there is contact with adjoining plates, **boundary tectonic forces** act on the rock causing physical and chemical changes in them. This is where the massive and radical geological changes (including **earthquakes**) occur.

New lithosphere is created at mid-ocean ridges by the upwelling and cooling of magma (molten rock) from the Earth’s mantle. In order to conserve mass, the horizontally moving plates are believed to be absorbed at the ocean **trenches** where a **subduction** process carries the lithosphere downward into the Earth’s interior.

Depending upon convergence rate, some subduction zones can be more active than others.

This general geological theory has a number of implications for our understanding of earthquakes.

First, many more earthquakes will occur along the edges of the interacting plates (**interplate earthquakes**) than within the plate **boundaries (intraplate earthquakes**).

Second, because the directions of forces on plates vary across them, the mechanism of the sources of earthquakes and their size differ in different parts of a plate.

Only about 10 percent of the world's earthquake occur along the ocean-ridge system. In contrast, earthquakes occurring where plate boundaries converge, such as at trenches, contribute about 90 percent.

Third, the grand scale of the plate pattern and the steady rate of plate spreading imply that along a plate edge the slip should, on average, be a constant value over many years.

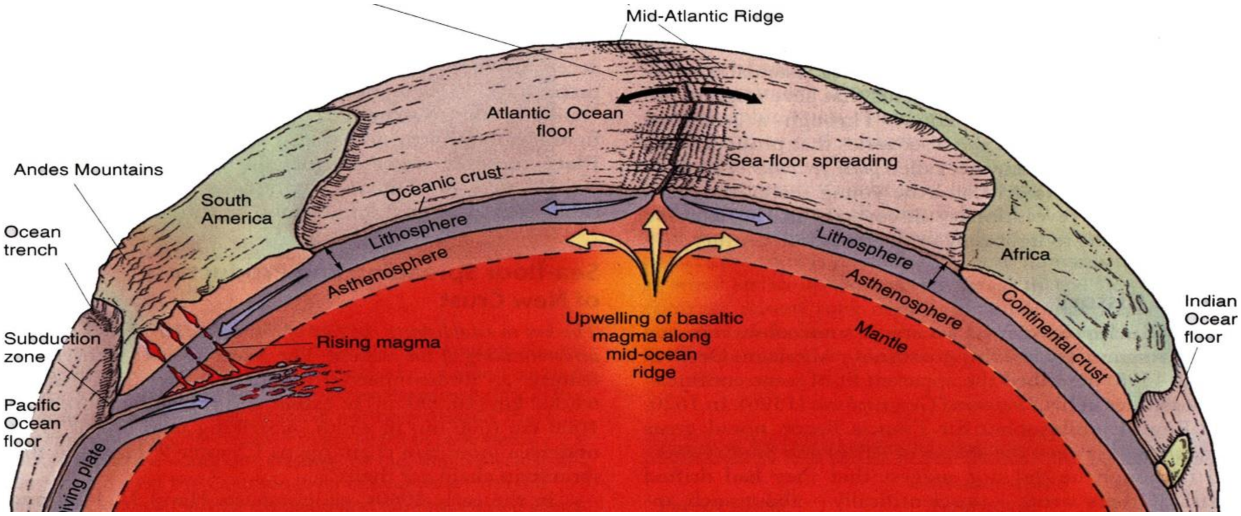
This idea suggests that the historical patterns of distance and time intervals between major earthquakes along major plate boundaries provide at least crude indication of places at which large earthquakes might occur.

Large and v.large EQs mostly produced in subduction zone (M8, M9 are very common)

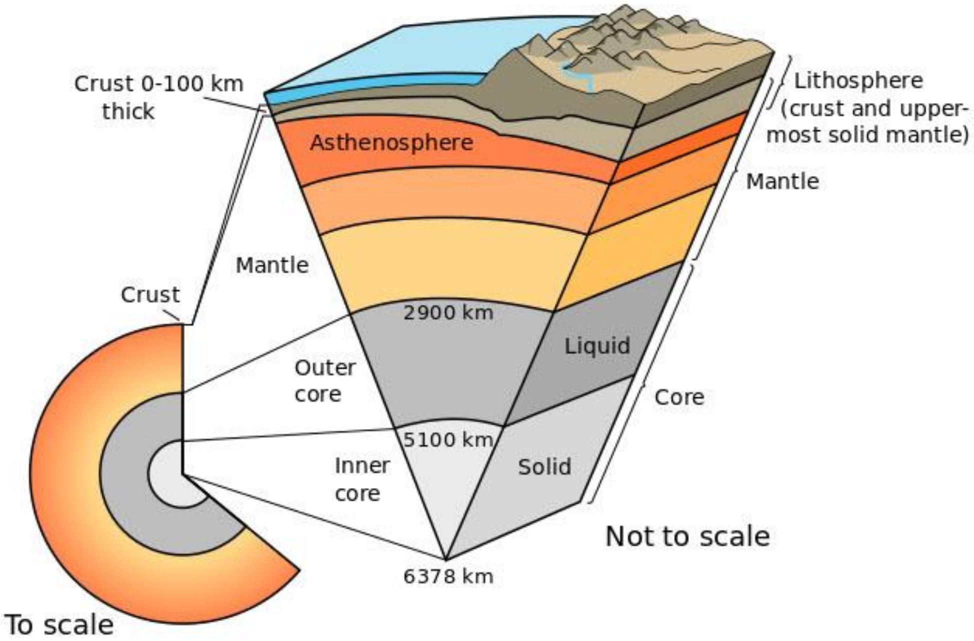
Less no. of EQs are at divergent Plate Boundaries (10 %)

Around 90% are at convergent plate boundaries.

1.8. Internal Structure of the Earth



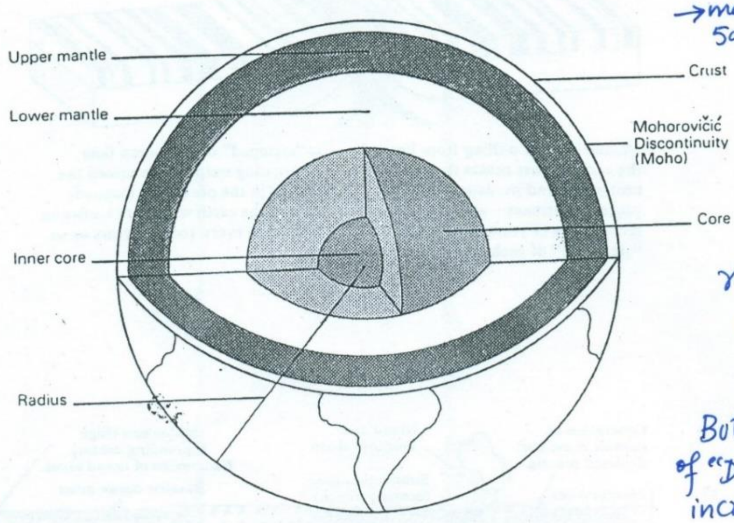
The thickness of each plate is about 80 km. The plate moves horizontally, relative to neighboring plates, on a layer of softer rock.



The process of divergence is continuous — Steady rate
but " " divergence is not continuous → Locking - releasing - locking - - - -
(not at regular rate) → random

so over a v. v. long period of Time → Convergence ≅ subduction

If you look long enough say 5000 yr
→ several last 5000 yrs
→ may be next 5000 yrs — Same

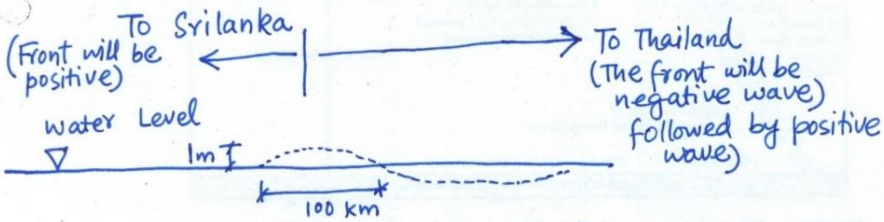


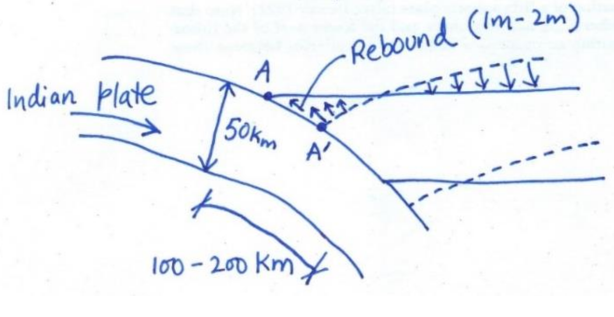
The interior of the earth.

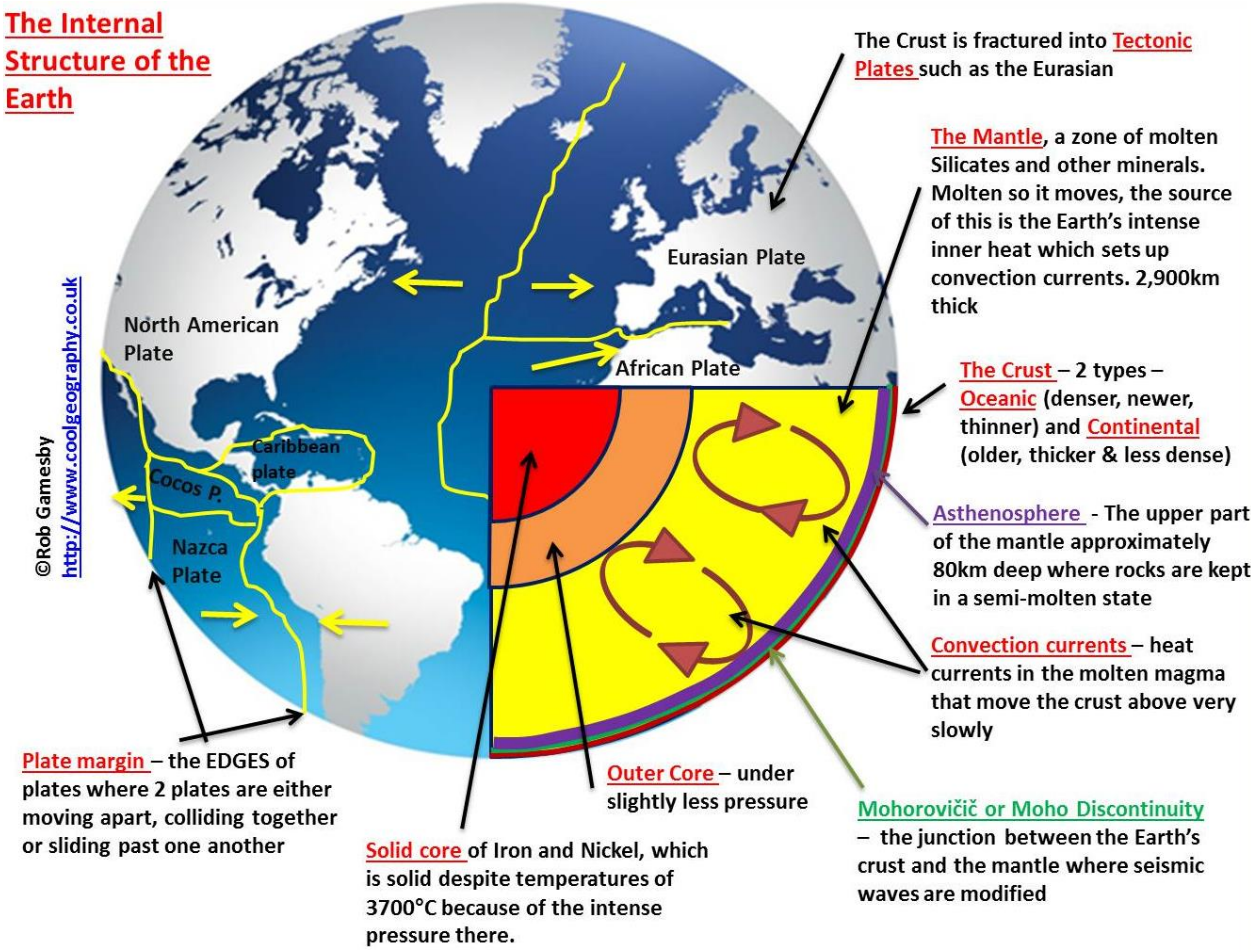
The rate of EQs is not increasing

But the number of "Disasters" is increasing

Population Density
more multi-story buildings







The Internal Structure of the Earth

The Crust is fractured into Tectonic Plates such as the Eurasian

The Mantle, a zone of molten Silicates and other minerals. Molten so it moves, the source of this is the Earth's intense inner heat which sets up convection currents. 2,900km thick

The Crust – 2 types – Oceanic (denser, newer, thinner) and Continental (older, thicker & less dense)

Asthenosphere - The upper part of the mantle approximately 80km deep where rocks are kept in a semi-molten state

Convection currents – heat currents in the molten magma that move the crust above very slowly

Mohorovičič or Moho Discontinuity – the junction between the Earth's crust and the mantle where seismic waves are modified

Outer Core – under slightly less pressure

Solid core of Iron and Nickel, which is solid despite temperatures of 3700°C because of the intense pressure there.

Plate margin – the EDGES of plates where 2 plates are either moving apart, colliding together or sliding past one another

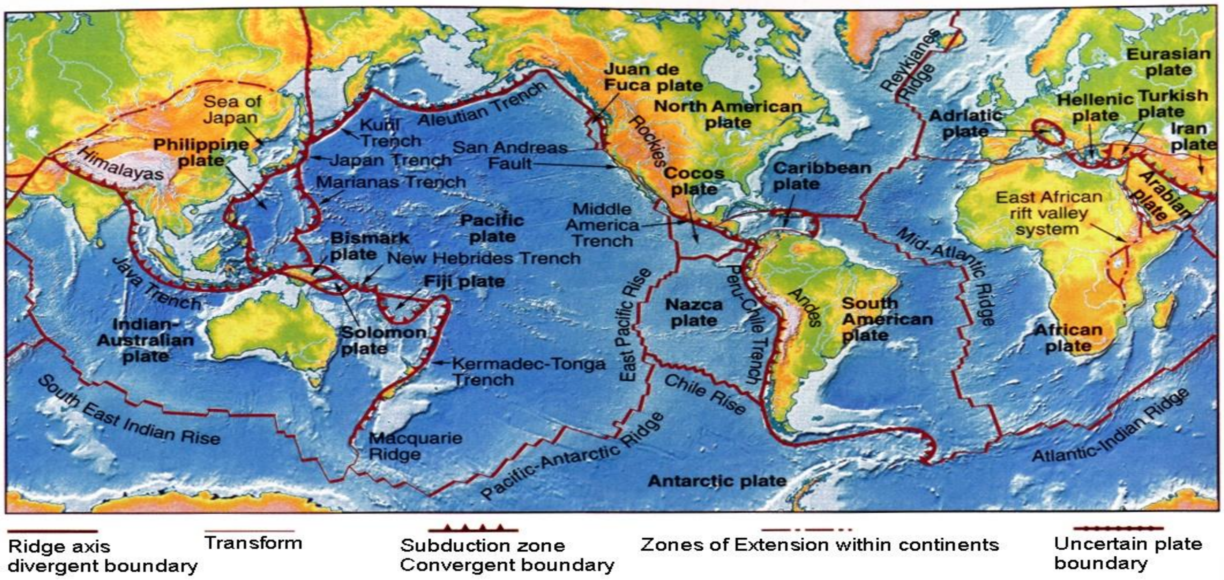
©Rob Gamesby http://www.coolgeography.co.uk

1.9. Earth's Tectonic Plates and their Movements

Convergence plate boundary: subduction zone etc.

Divergence plate boundary: Plates diverges at mid-ocean ridges

Transform fault: Plates move laterally each other



Tectonic Plates

Earth's Changing Landscapes

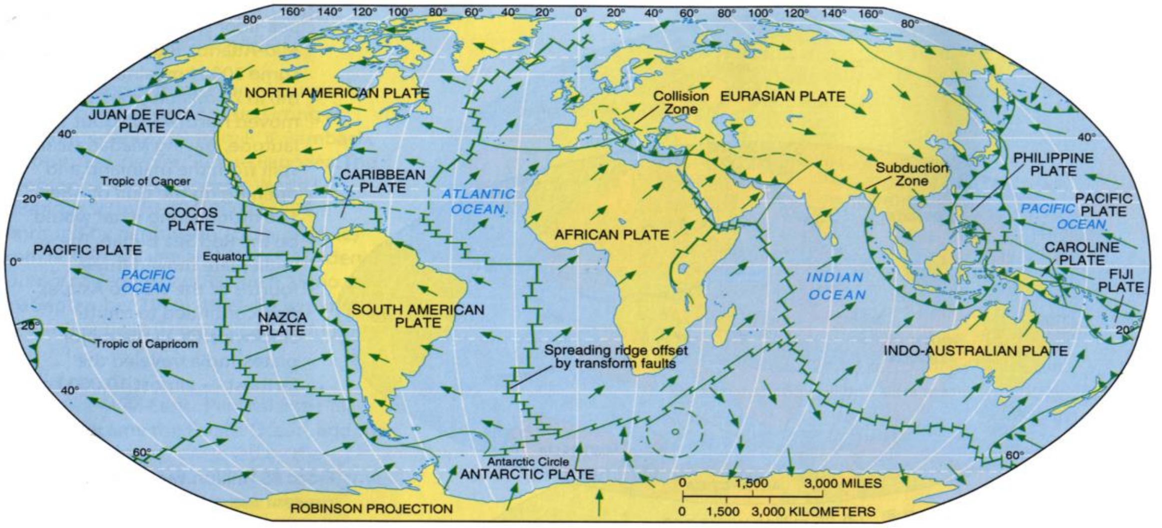
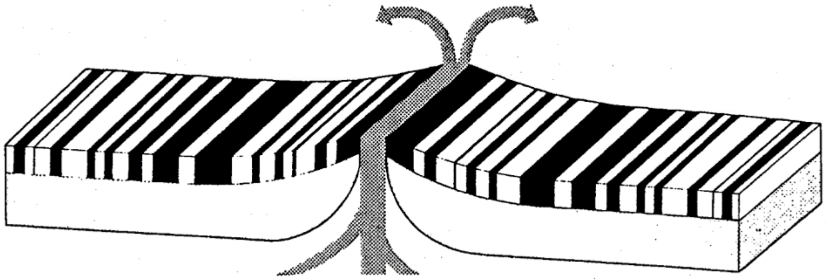


Figure 8-16 **Earth's 14 lithospheric plates and their movements.**
Each arrow represents 20 million years of movement, the longer arrows indicating that the Pacific and Nazca plates are moving more rapidly than the Atlantic plates. [Adapted from U.S. Geodynamics Committee.]



Molten magma welling from beneath the earth's crust passes through the central rift and hardens. As the process continues – as it has continued for millions of years – the magnetic "signature" of each long convulsion is "stamped" on the ocean floor. Alternating stripes then record the "flips" in the prevailing magnetic field of the earth which are known to take place every 100,000 years or so.

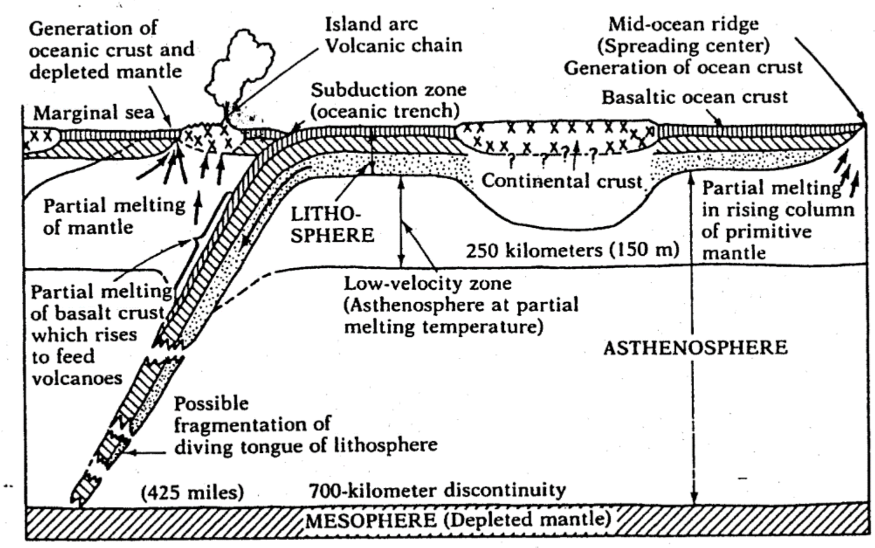


FIGURE 4.3 Schematic cross-section of a lithospheric plate (after Dewey 1972). Note that the mantle includes the mesosphere, the asthenosphere and the lower part of the lithosphere. Changes in rock composition or properties define the boundaries between these elements.

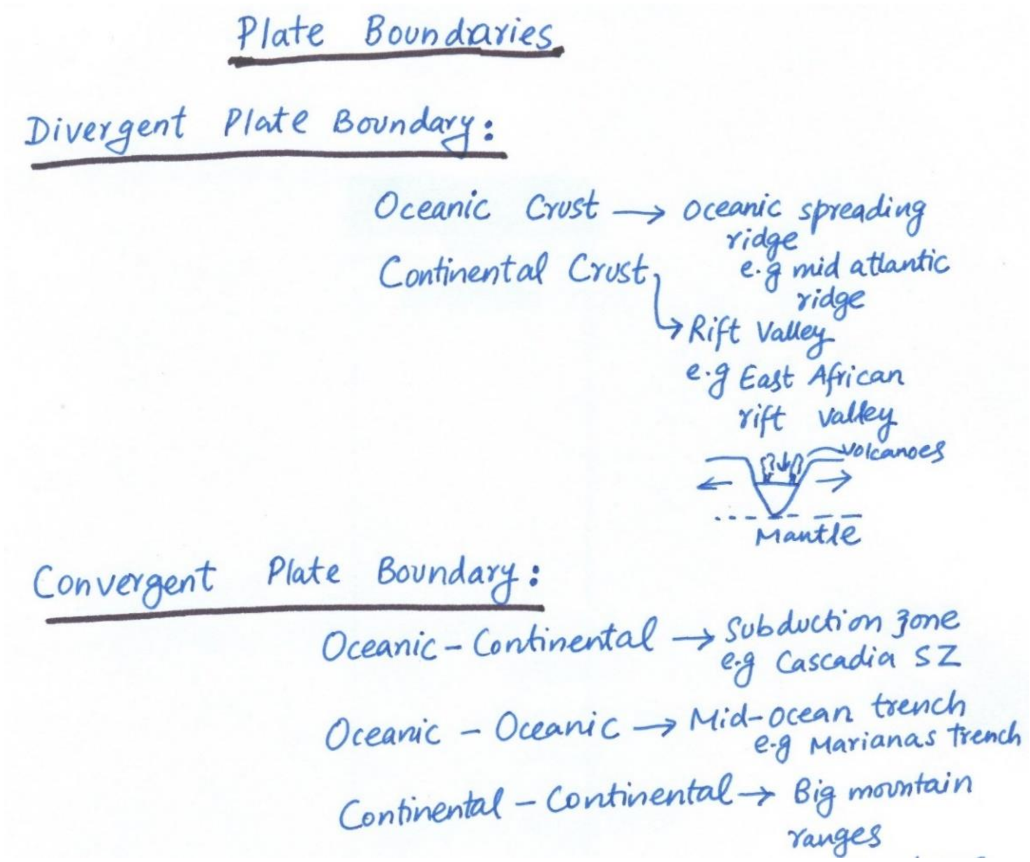


Plate Boundaries

Divergent Plate Boundary:

Oceanic Crust → oceanic spreading ridge
e.g mid atlantic ridge

Continental Crust → Rift Valley
e.g East African rift valley

Convergent Plate Boundary:

Oceanic - Continental → Subduction zone
e.g Cascadia SZ

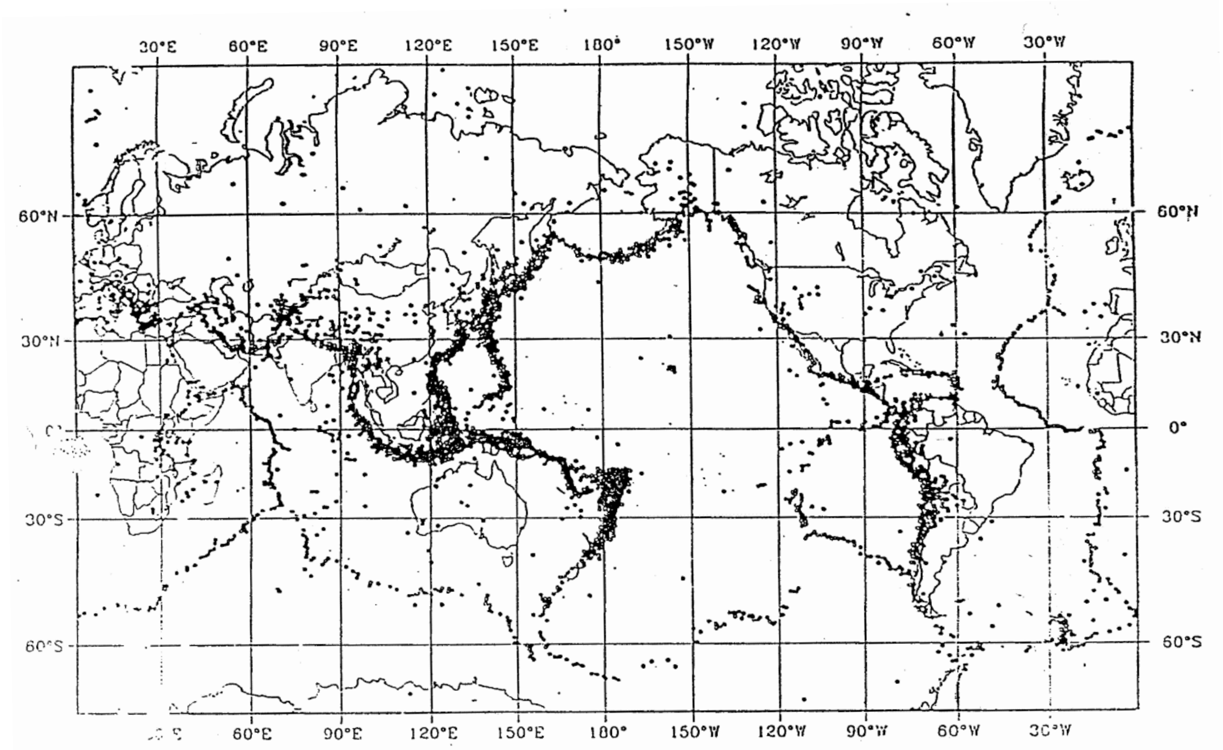
Oceanic - Oceanic → Mid-ocean trench
e.g Marianas trench

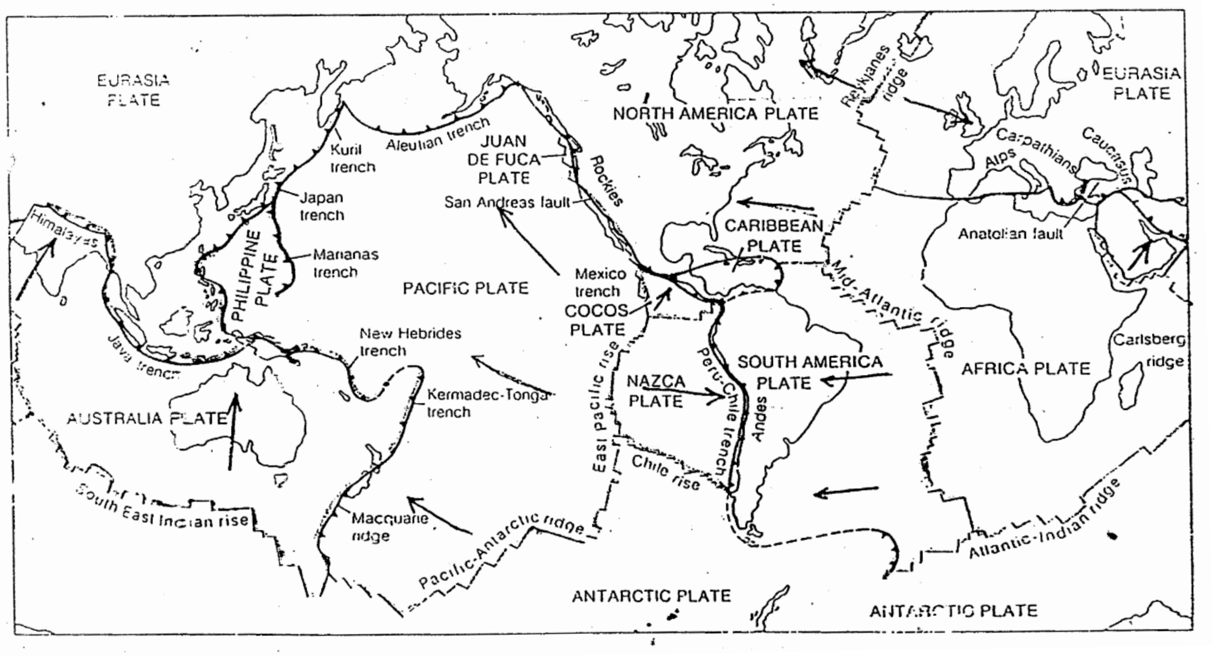
Continental - Continental → Big mountain ranges

The rate of plate movement ranges from 1 to 10 centimeters per year.

At the plate edges where there is contact with adjoining plates, boundary tectonic forces act on the rock causing physical and chemical changes in them.

This is where the massive and radical geological changes (including earthquakes) occur.





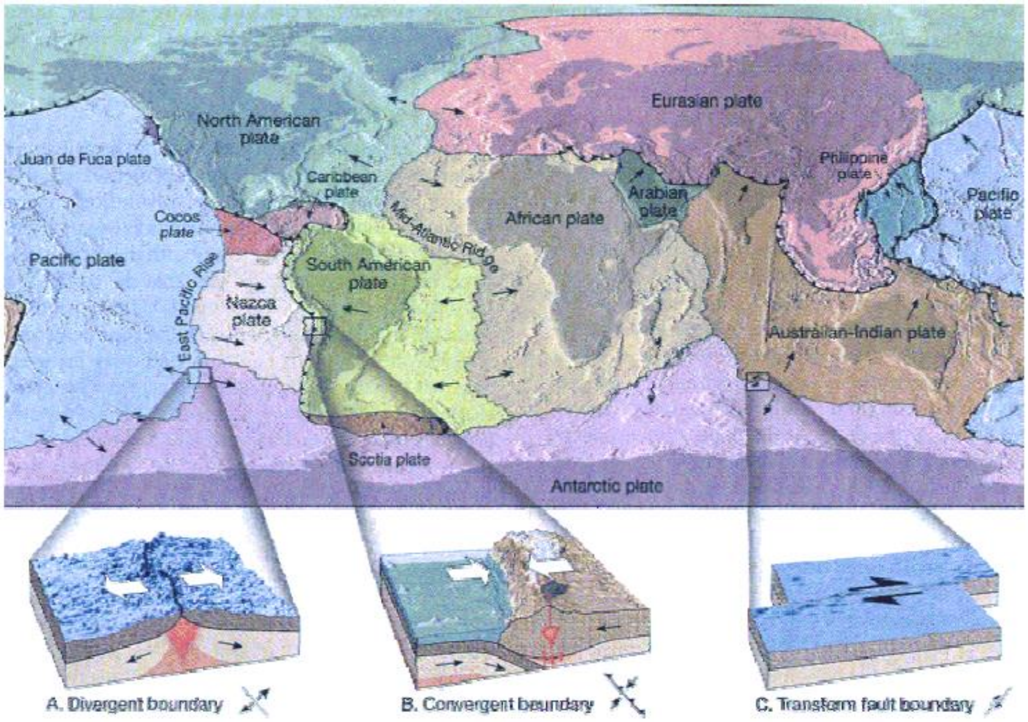
Where do earthquakes occur?

Three Main Types of Plate Boundaries:

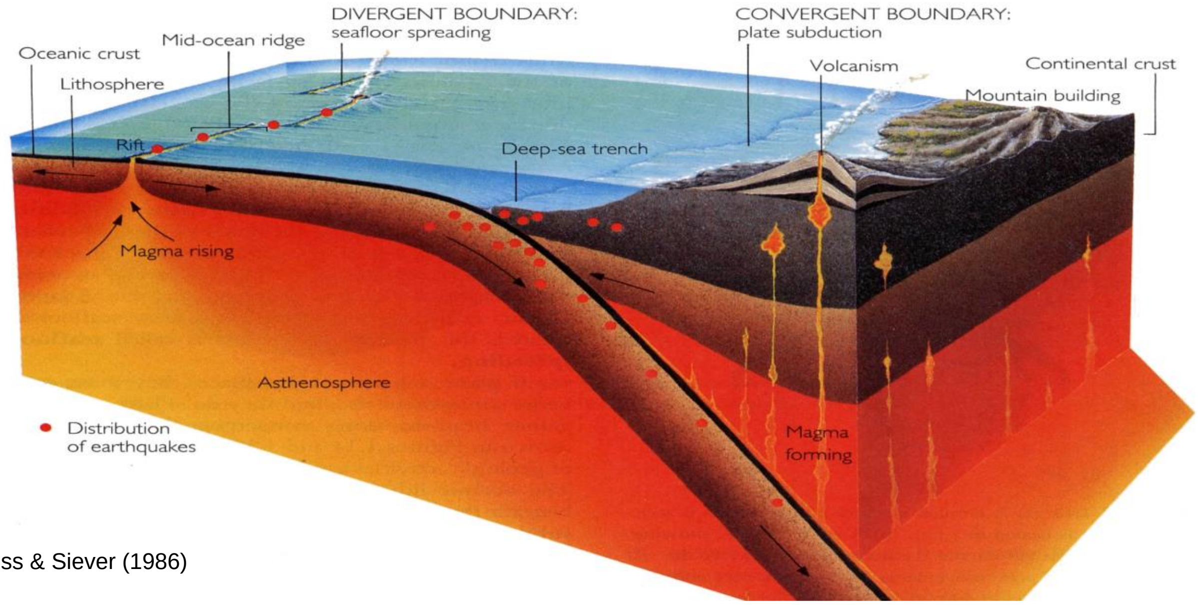
Convergent Plate Boundary: When the two plates "bump" into each other

Divergent Plate Boundary: When the two plates “pull away” from each other

Transform Plate Boundary: When the two plates “slide past” each other



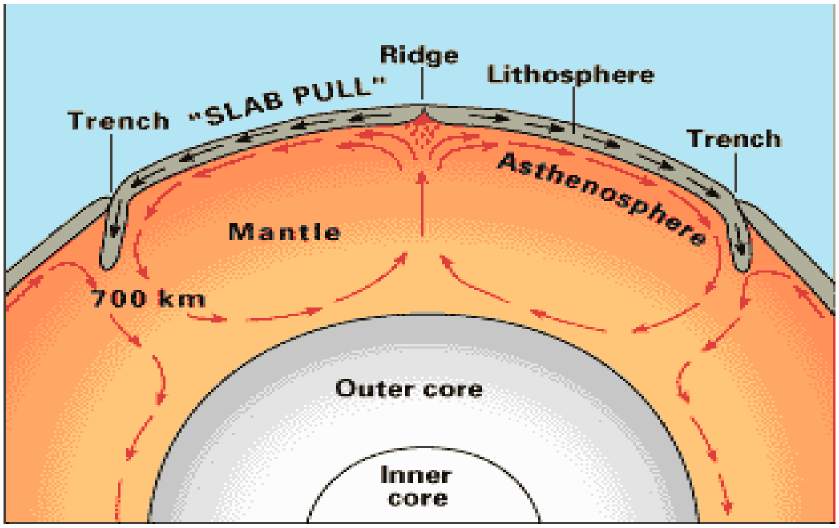
New tectonic plate is created at mid-ocean ridges by the upwelling and cooling of magma (molten rock) from the Earth’s mantle. In order to conserve mass, the horizontally moving plates are believed to be absorbed at the ocean trenches where a subduction process carries the tectonic plate downward into the Earth’s interior.



Press & Siever (1986)

An oceanic spreading ridge is the fracture zone along the ocean bottom where molten mantle material comes to the surface, thus creating new crust. This fracture can be seen beneath the ocean as a line of ridges that form as molten rock reaches the ocean bottom and solidifies.

An oceanic trench is a linear depression of the sea floor caused by the subduction of one plate under another.



This plate tectonics theory has a number of implications for our understanding of earthquakes.

First, many more earthquakes will occur along the edges of the interacting plates (interplate earthquakes) than within the plate boundaries (intraplate earthquakes).

Second, because the directions of forces on plates vary across them, the mechanism of the sources of earthquakes and their size differ in different parts of a plate.

Only about 10% of the world's earthquakes occur along the ocean ridge system. In contrast, earthquakes occurring where plate boundaries converge, such as trenches, contribute about 90 %.

Third, the grand scale of the plate pattern and the steady rate of plate spreading imply that along a plate edge the slip should, on average, be a constant value over many years.

This idea suggests that the historical patterns of distance and time intervals between major earthquakes along major plate boundaries provide at least crude indication of places at which large earthquakes might occur.

Earthquakes and Volcanoes

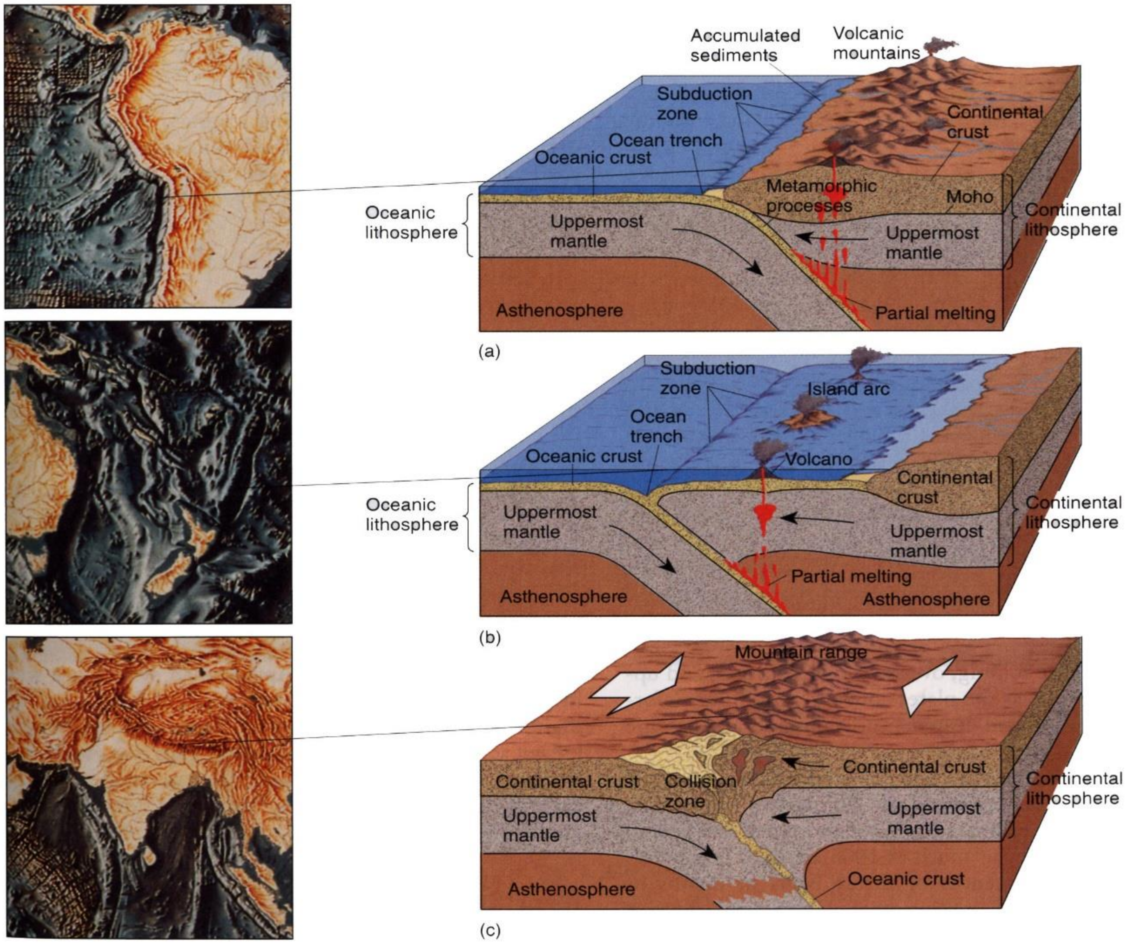


Figure 9-15 **Three types of plate convergence.**
Real-world examples illustrate three types of crustal collisions. Oceanic–continental (example: Nazca plate–South American plate collision and subduction) (a); oceanic–oceanic (example: New Hebrides Trench near Vanuatu, 16° S, 168° E) (b); and, continental–continental (example: India plate and Eurasian landmass collision and resulting Himalayan Mountains) (c). [Inset illustrations derived from *Floor of the Oceans,* 1975, by Bruce C. Heezen and Marie Tharp. © 1980 by Marie Tharp.]

Three types of plate convergence

- 12 plates. They move at diff but constant speeds. Most EQ happen along plate boundaries.
- Lquique EQ M 8.2 2014 Chile (1960 M9.5 Chile).

  ↓
- Oceanic plate sinks below Continental plate. When critical, stress releases.
  ↳ accumulates then.
- Land Movements → measured to determine accumulated stress. Whether fully lock or not.
- >10% of world EQ → Japan
- Seismic waves can be used to extract subterrenian features. Soft areas → move slow.

  Pacific plate → hard area.

  Blue area — soft — Where connection of boundaries is weak.
- EQs are triggered by plate movements.
- Plates become thicker as they move.

  Sea water cools the plate → Mantle part also cools and integrate with plate → increasing thickness and weight → sinks → so plate moves down.
- Fallen plates found → Sink fully in mantle → so this process is from hundreds of millions of years soon after earth solidify. 4 billion years. → earth life.

→ early earth → Plates start getting heavier and sinks in to mantle → Mantle part goes up → This is Dynamic circulation. The earth released its energy by this "Convection process".

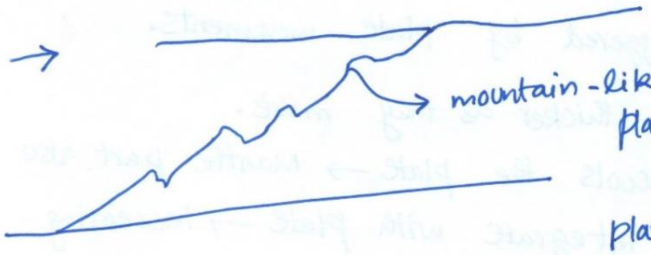
→ 6000 Km → tremor felt in MOSCOW (2013)
↳ Starting from Japan. (epicenter).
(M8 focus = 600 km deep in ground).

→ Most EQs under 50 Km deep.

(This case may be the seismic waves directly pass through mantle. b/c 600km is mantle starts).

reached russia ← 6000 km away.

→



→ mountain-like structures at plate boundaries.
↓
plate retains its roughness as it sinks.

At hypocenter → was one mountain-like structure.
Stress built for 6000 years → finally released.
After EQ → scientists found He-3 (helium-3) in water at location of hypocenter in sea.

→ They believe → mantle underneath have released tons of water in to sea during EQ. This water might have triggered the EQ. Water seap through the boundary, filled the gap, boundary slippery and that can cause triggering.

→ The timing and extent of EQ is dependent on how much stress level , amount of stored energy.

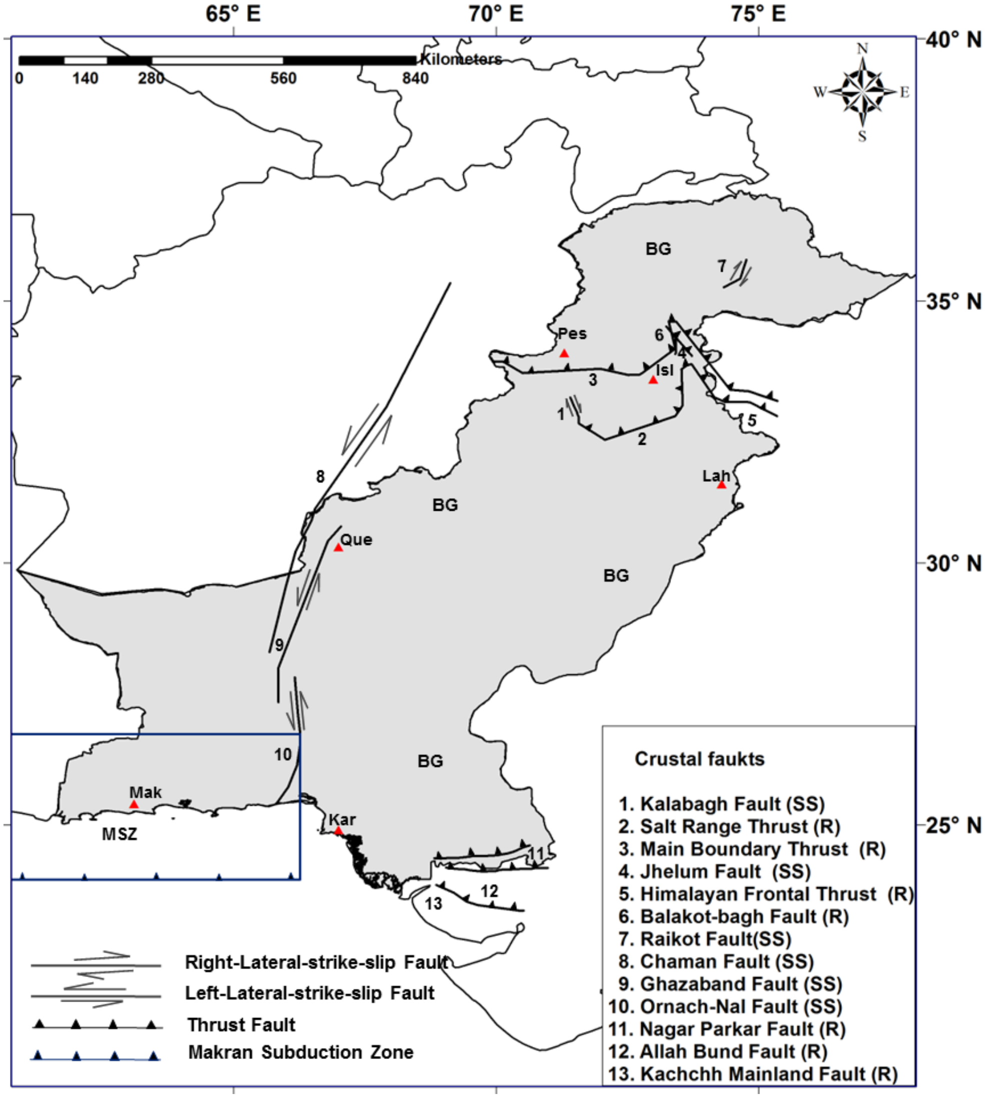
→ The mountain-like structures can be 3000 m or 3500 m.

→ San Andreas 1300 km. Pacific plate - ~~East~~ west.
North American plate → east

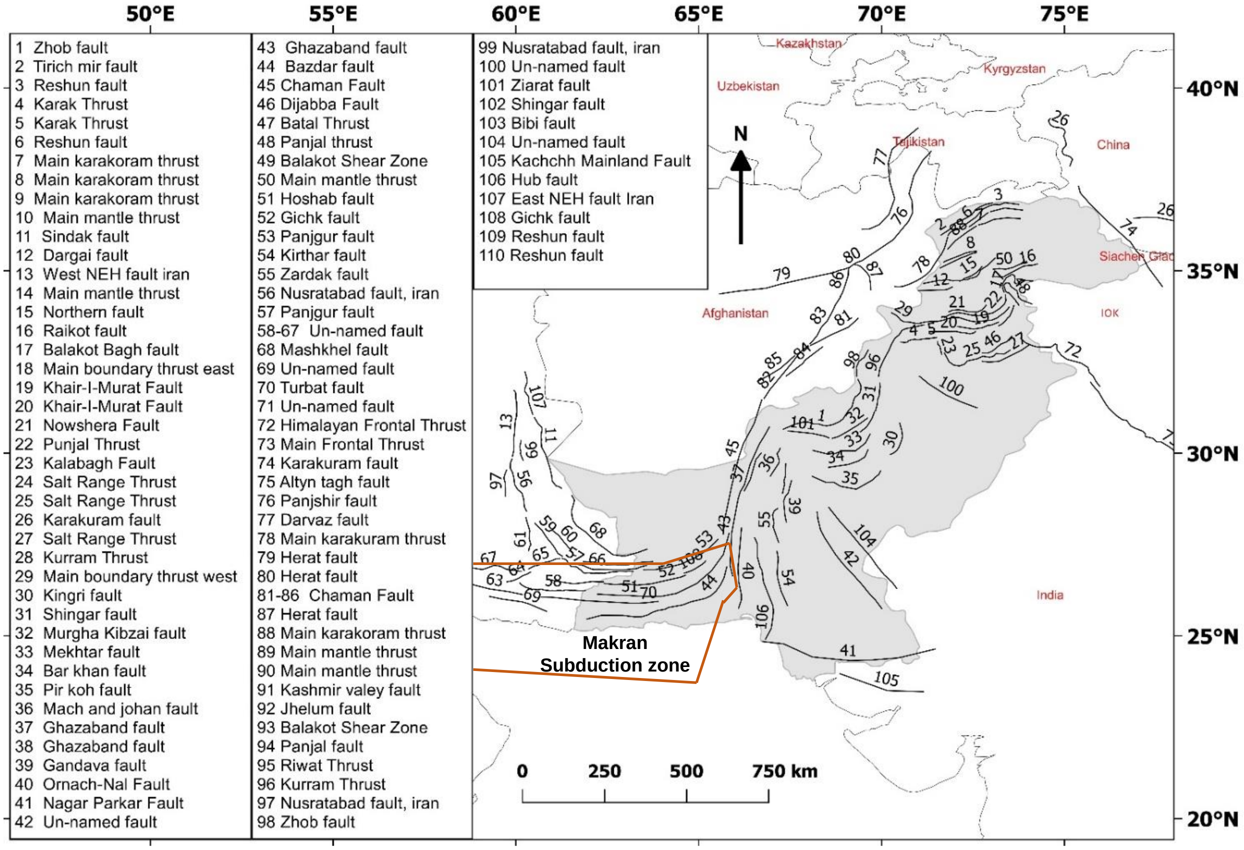
They slip parallel ↳ not sink.

→ M 9.5 Chile → largest ever recorded EQ

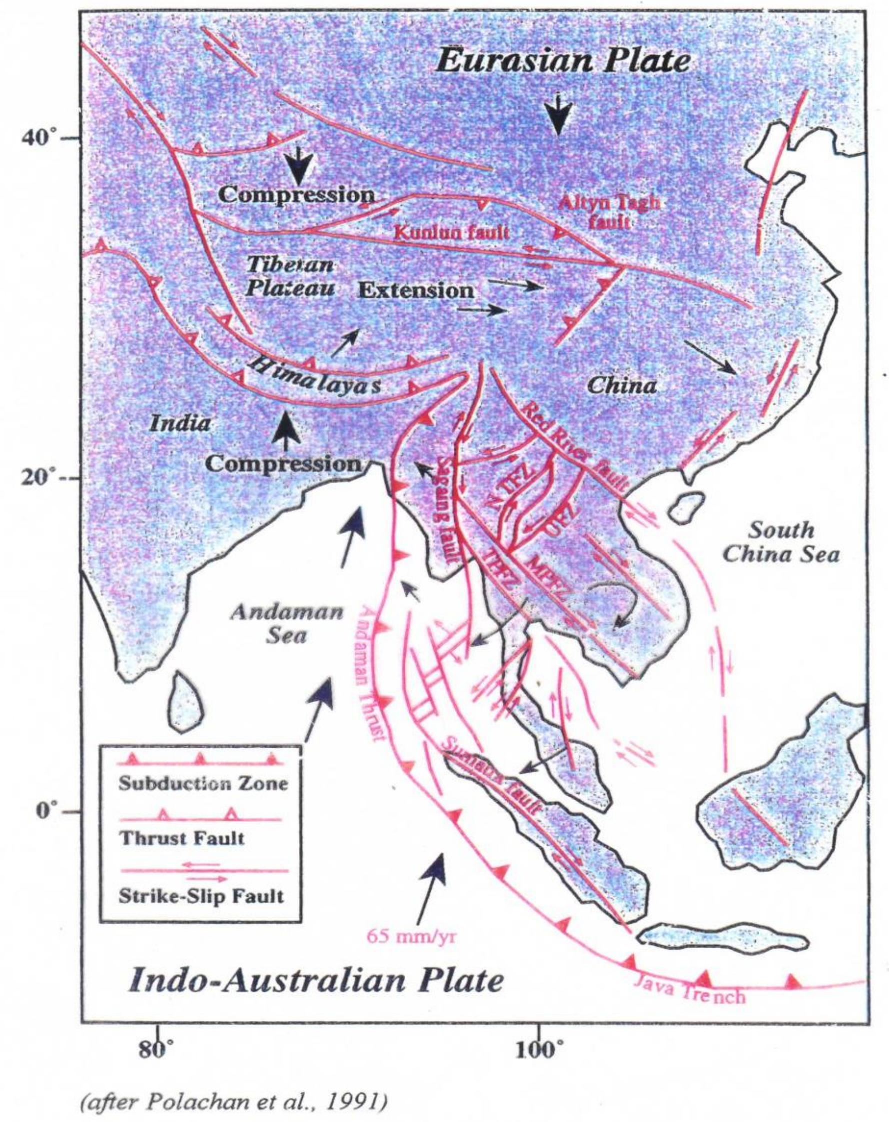
1.10. Tectonic Maps



Tectonic map of Pakistan



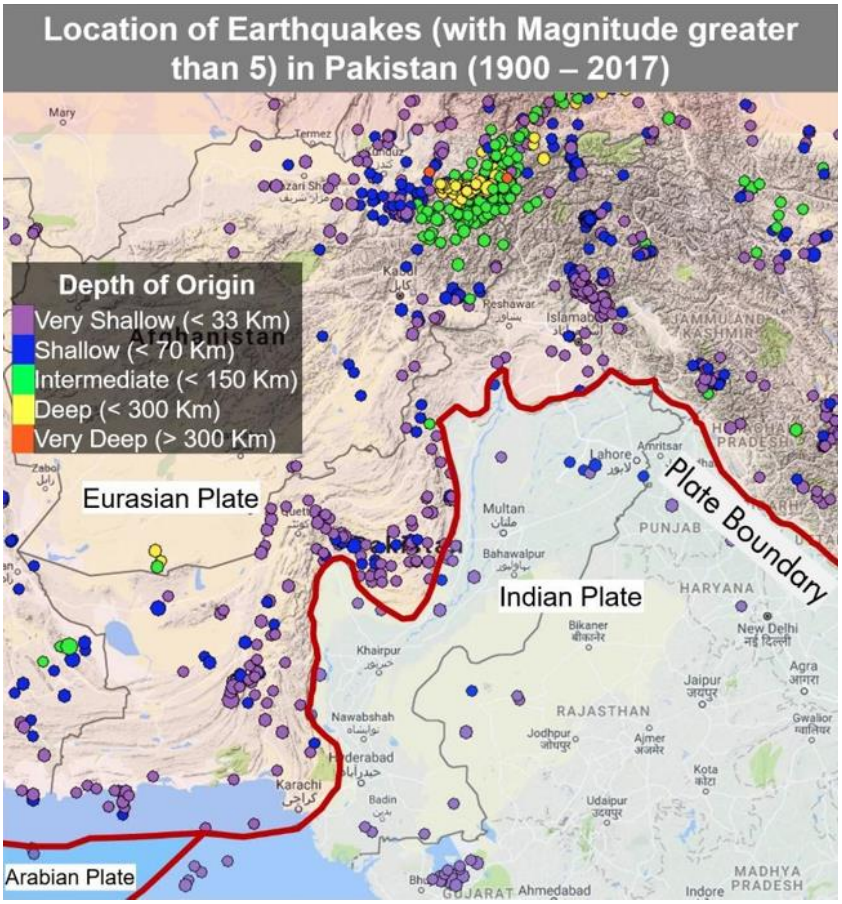
Tectonic map of Pakistan



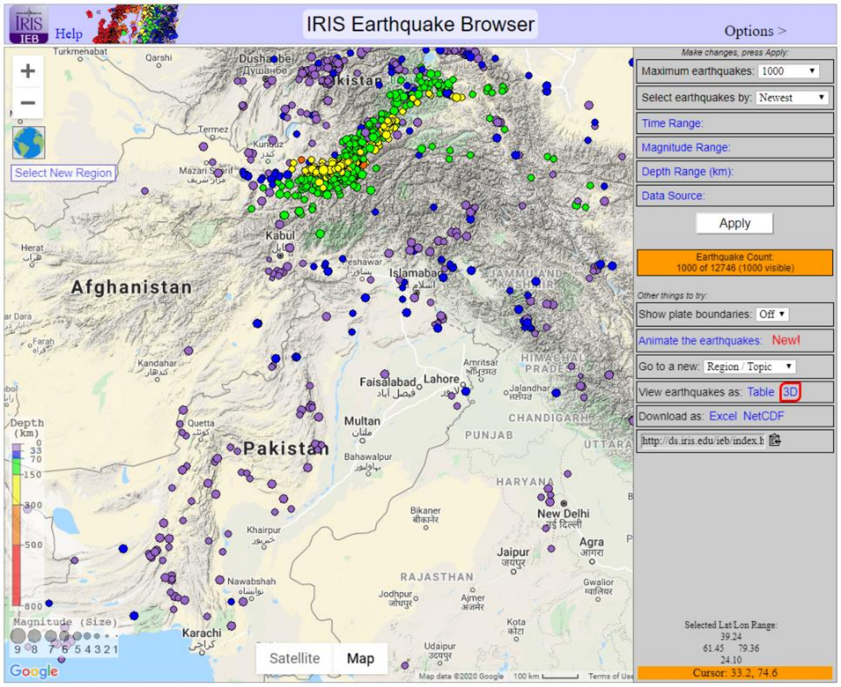
(after Polachan et al., 1991)

Tectonic Map of South-East Asia

1.11. Seismicity Maps



IRIS Earthquake Browser: http://ds.iris.edu/ieb/



Make changes, press Apply:

Maximum earthquakes: 1000 ▾

Select earthquakes by: Newest ▾

Time Range:

Magnitude Range:

Depth Range (km):

Data Source:

Apply

Earthquake Count:
1000 of 12746 (1000 visible)

Other things to try:

Show plate boundaries: Off ▾

Animate the earthquakes: New!

Go to a new: Region / Topic ▾

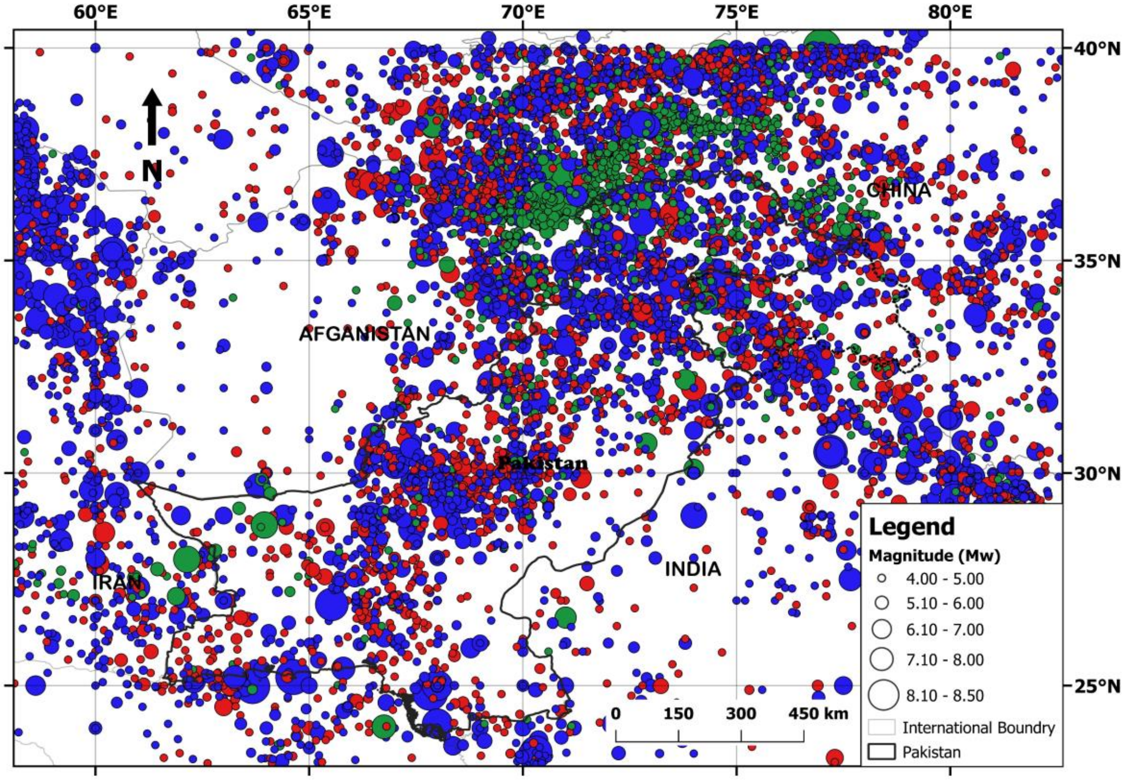
View earthquakes as: Table 3D

Download as: Excel NetCDF

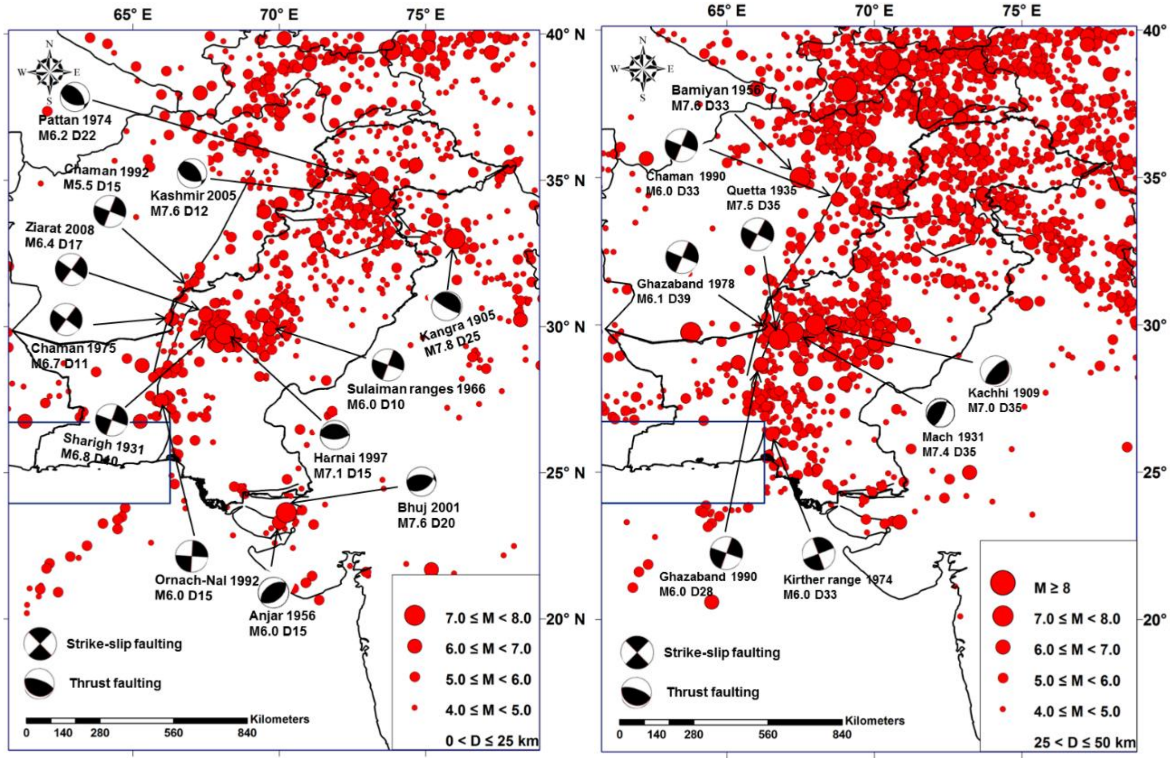
http://ds.iris.edu/ieb/index.h

Selected Lat/Lon Range:
39.24
61.45 79.36
24.10

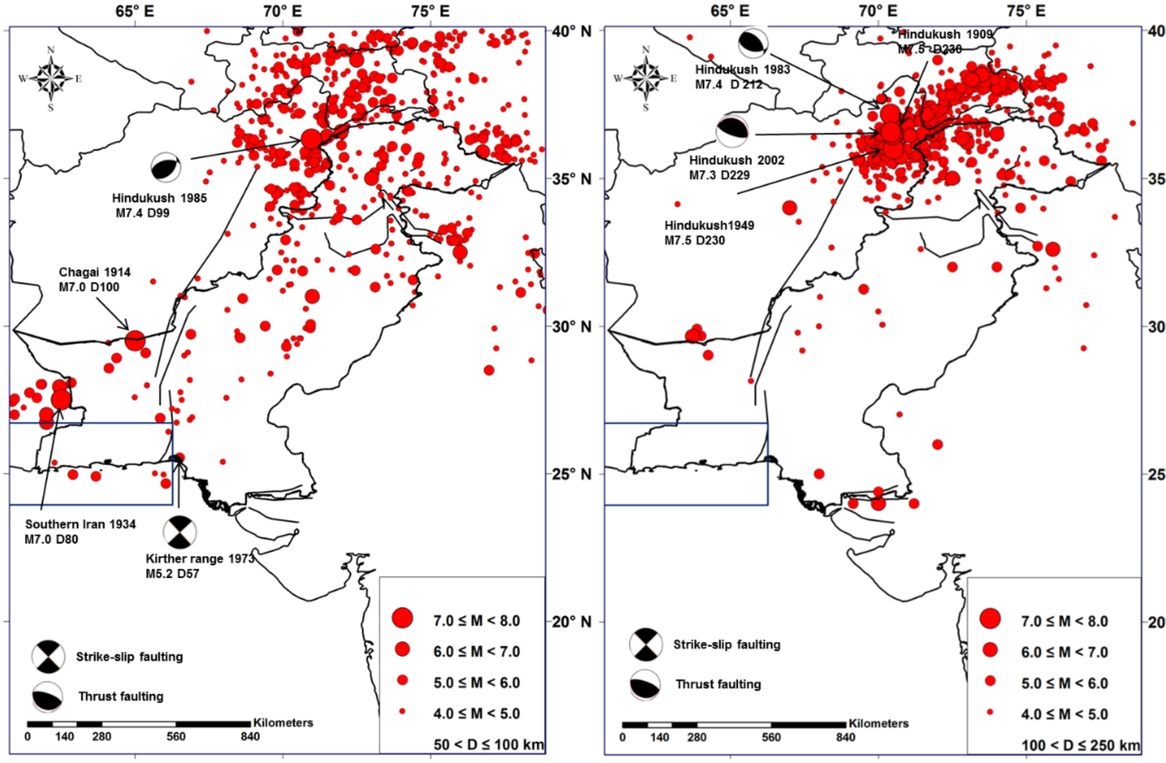
Cursor: 33.2, 74.6



Blue 0 – 25 km **Red** 25 – 50 km **Green** 50 – 250 km

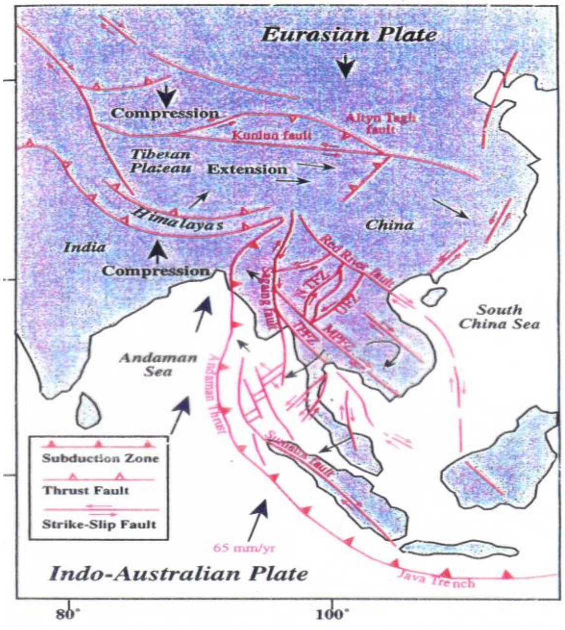


Seismicity (0-25 km depth, left), (25-50 km depth, right)

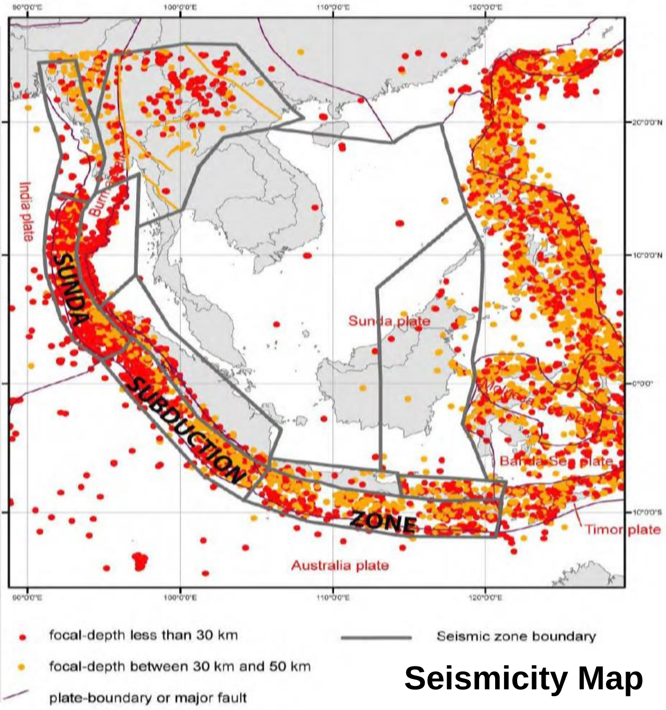


Seismicity (50-100 km depth, left), (100-250 km depth, right)

Tectonic Map

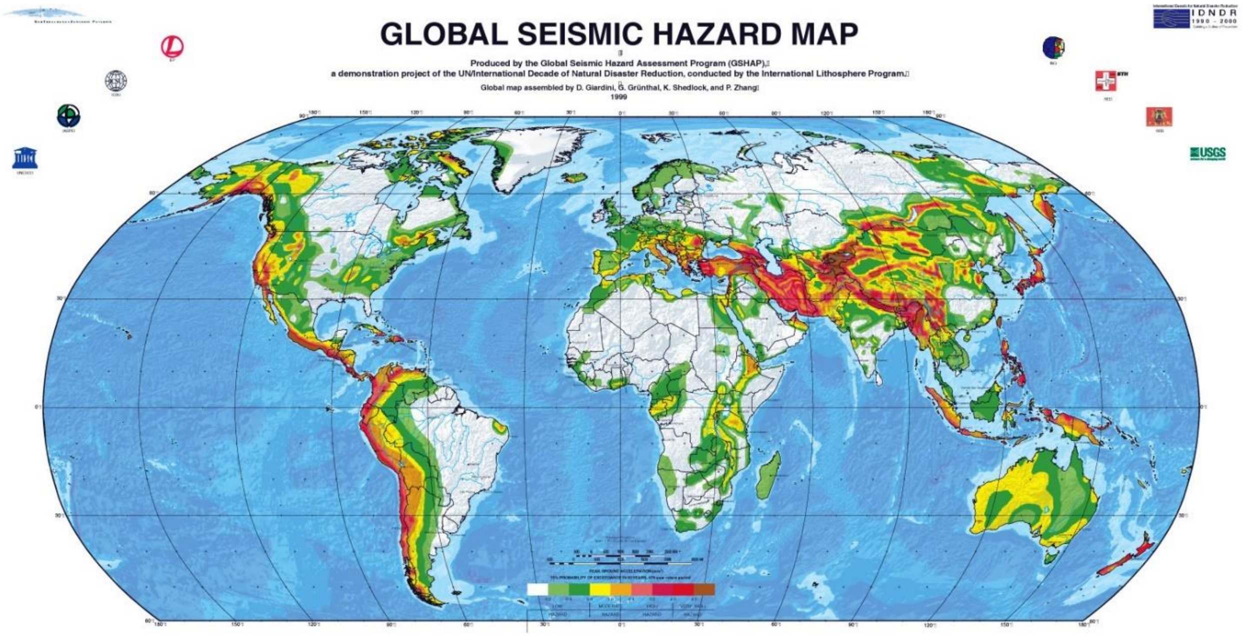


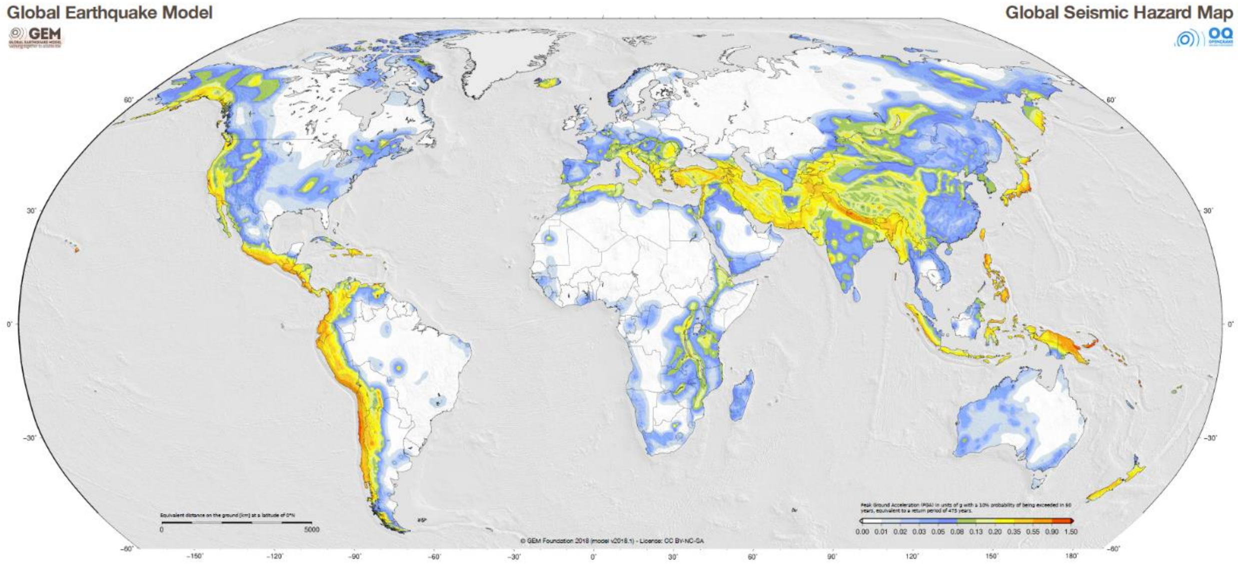
(after Polachan et al., 1991)

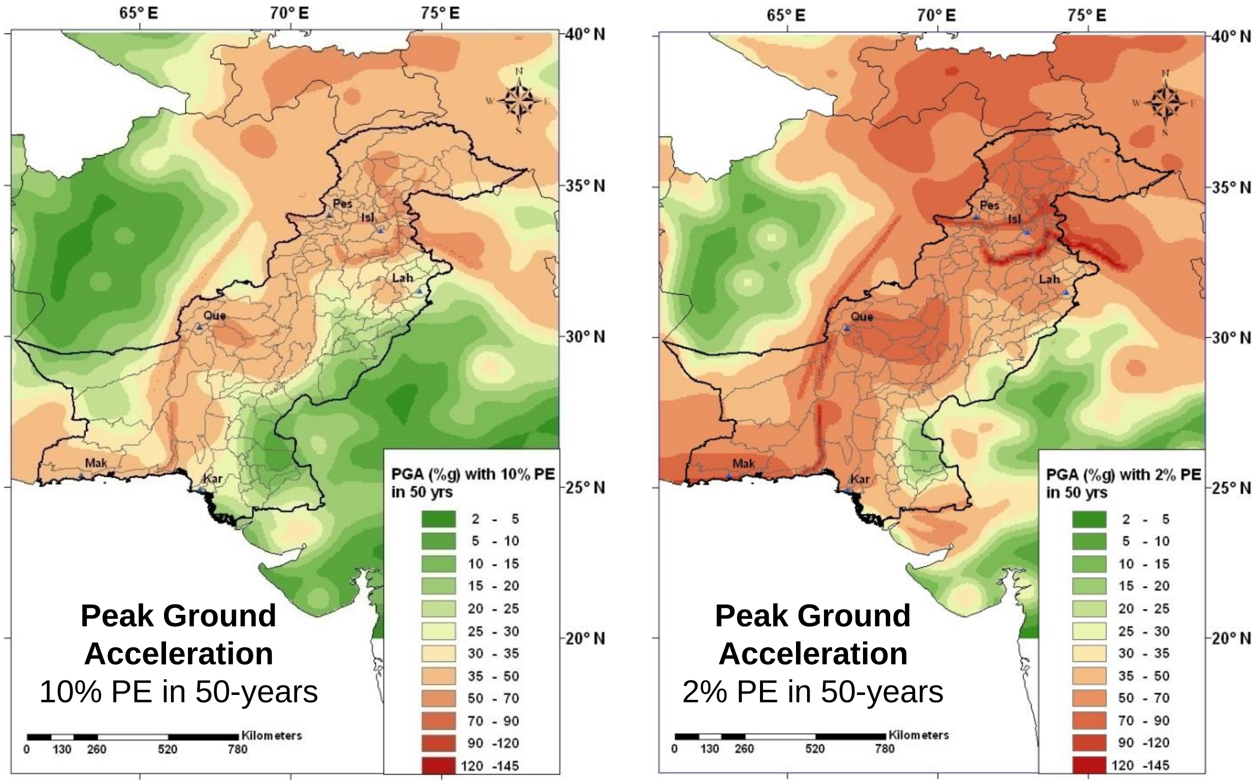


Seismicity Map

1.12. Hazard Maps

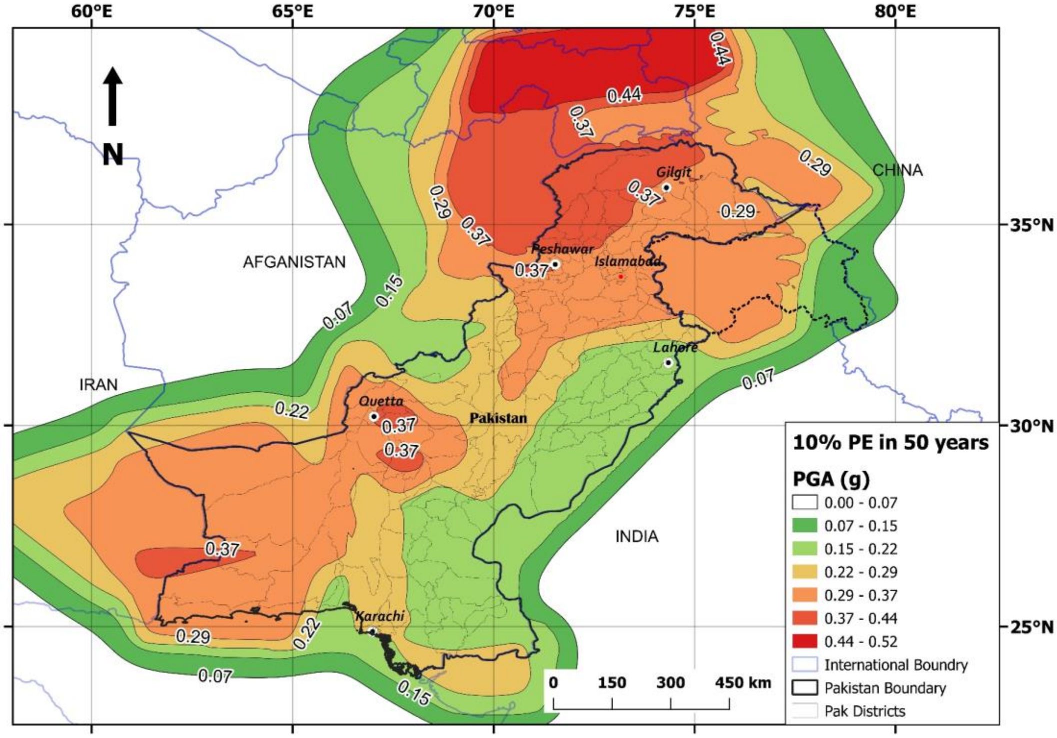


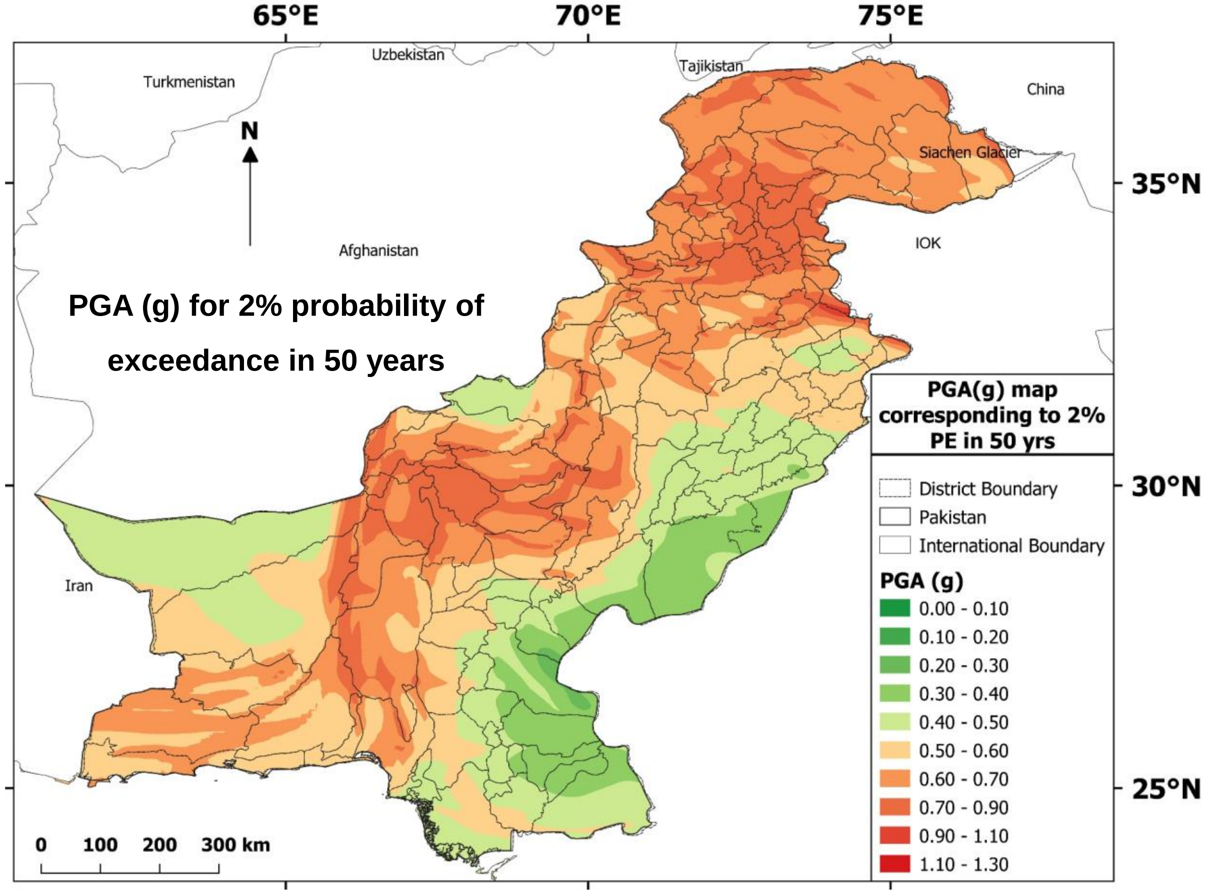




Source: Zaman S. (2016) Probabilistic Seismic Hazard Assessment and Site-Amplification Mapping for Pakistan

Peak Ground Acceleration (PGA) map for Design Basis Earthquake (DBE)



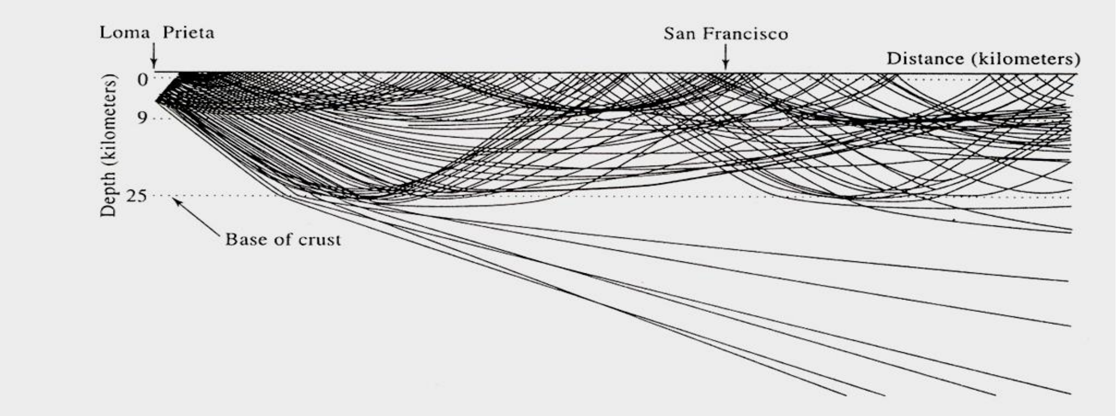


PGA (g) for 2% probability of exceedance in 50 years

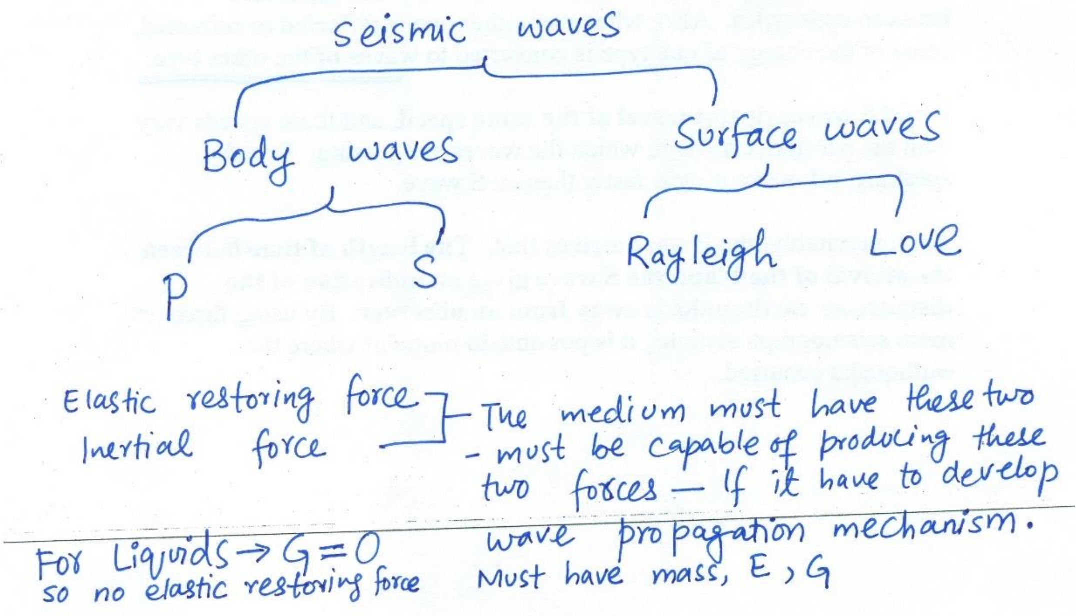
1.13. Seismic Waves

Earthquakes generate many types of seismic waves in complex patterns.

Some penetrate the earth and come to the surface in the same state, or slightly distorted. Others are reflected, or refracted, or bent by something or some zone of different density within the earth itself. Some travels round the circumference of the world and do not penetrate at all.



Rays of seismic shear waves from the focus of the 1989 Loma Prieta earthquake through the crust



Elastic restoring force
Inertial force

The medium must have these two - must be capable of producing these two forces — If it have to develop wave propagation mechanism.
Must have mass, E, G

For Liquids → $G = 0$
so no elastic restoring force

There are 3 basic types of seismic waves:

- The primary (P) waves
- The secondary (S) waves
- The surface waves

P waves are compressional waves which exert a pull-push force.

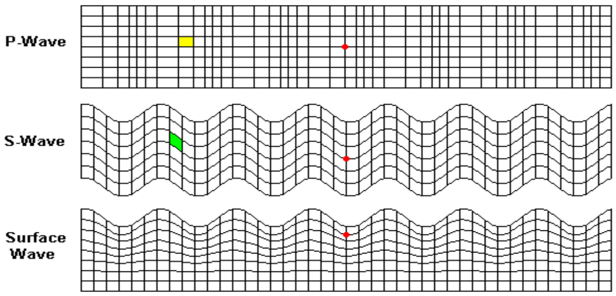
The motion of a P wave is the same as that of a sound wave—as it spreads out, it alternately pushes (compresses) and pulls (dilates) the rock.

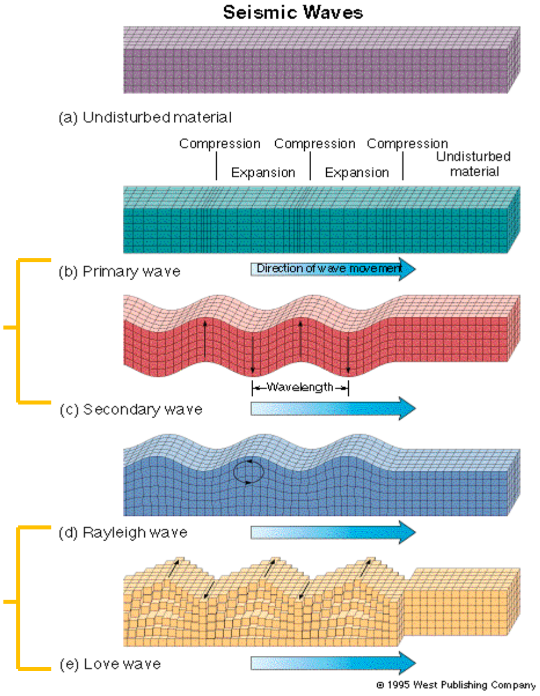
These P waves, just like sound waves, are able to travel through both solid rock and liquid material (such as volcanic magma or the oceans).

S waves are shear waves.

As it propagates through the body of rock, a shear wave shears the rock sideways at right angles to the direction of travel.

S waves cannot propagate in the liquid parts of the earth, such as the oceans or magma.





Body Waves

Surface Waves

Seismic Waves

Body Waves:

When the body waves (the P and S waves) move through the layers of the rock in the crust, they are reflected or refracted at the interfaces between rock types. Also, whenever either one is reflected or refracted, some of the energy of one type is converted to waves of the other type.

P and S waves do not travel at the same speed, and these speeds vary with the substance through which the waves are passing. Broadly speaking, a P wave travels faster than an S wave.

Thus at any site, the P wave arrives first, and the S wave arrives later.

The length of time between the arrival of the P and the S wave gives an indication of the distance an earthquake is away from an observer. By using 3 or more seismograph stations, it is possible to pinpoint where the earthquake occurred.

Surface Waves:

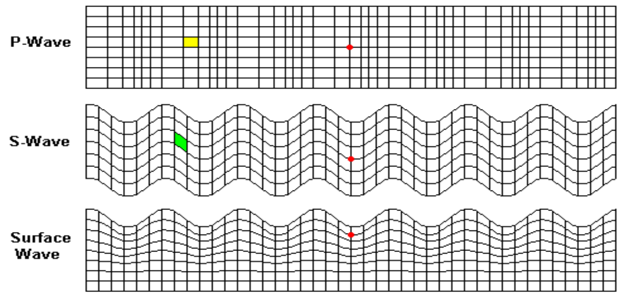
Surface waves have their motion restricted to near the ground surface. As the depth below this surface increases, wave displacements decrease.

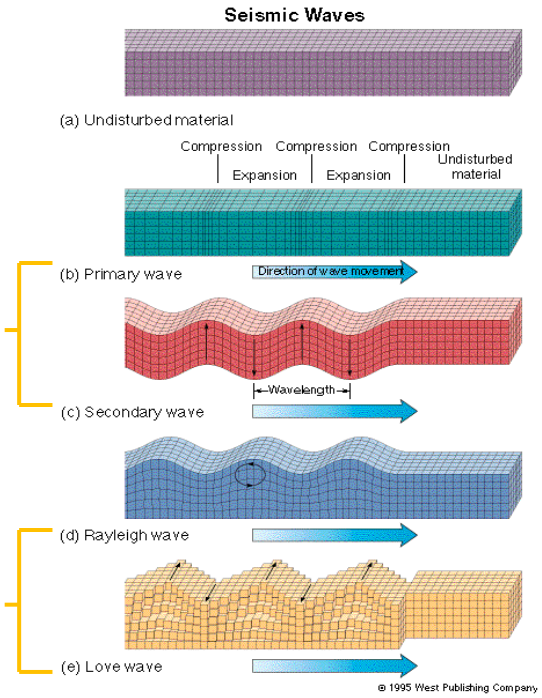
Surface waves travel more slowly than body waves.

Surface waves in earthquakes can be further divided into 2 types: Love waves and Rayleigh waves

The motion of a Love wave is essentially the same as that of S waves that have no vertical displacement. It moves the ground from side to side in a horizontal plane but at right angles to the direction of propagation. Love waves do not propagate through water.

Like rolling of ocean waves, the pieces of material disturbed by a Rayleigh wave move both vertically and horizontally in a vertical plane pointed in the direction in which the wave is travelling.





Seismic Waves

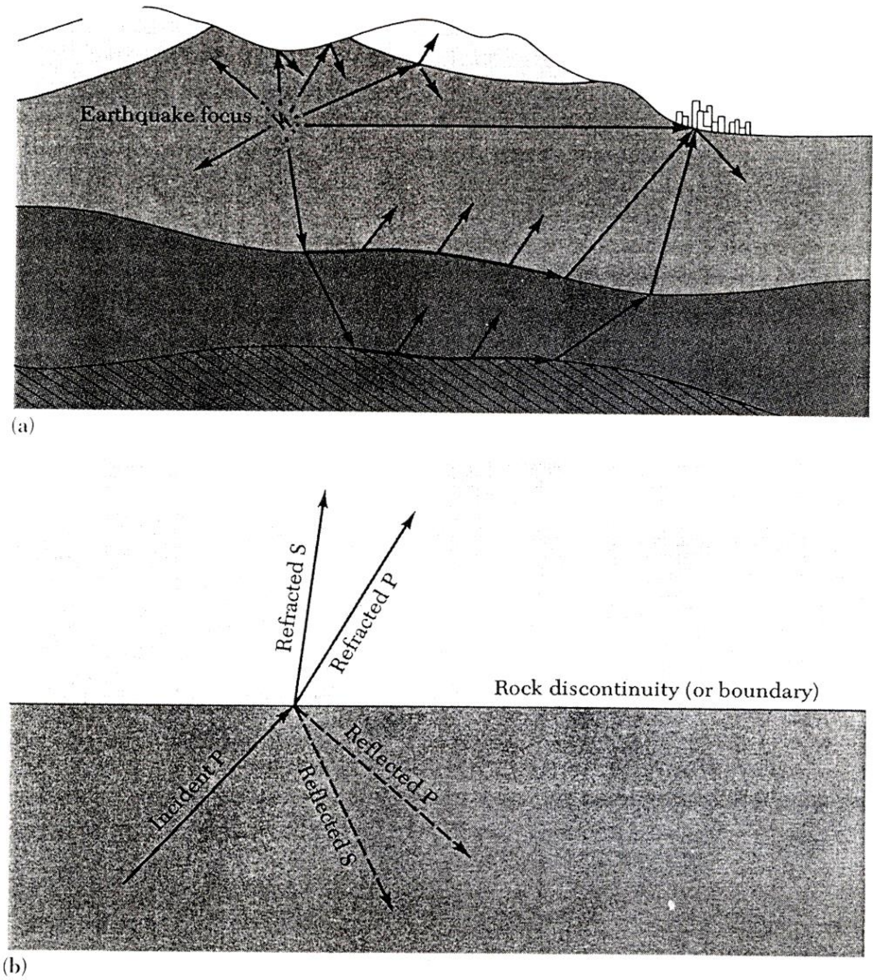
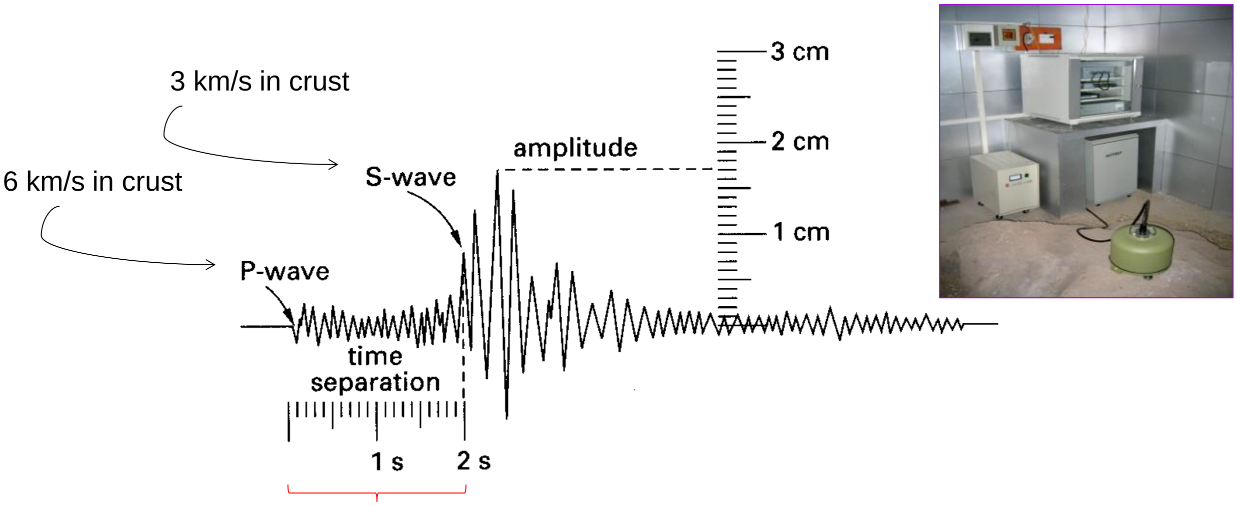


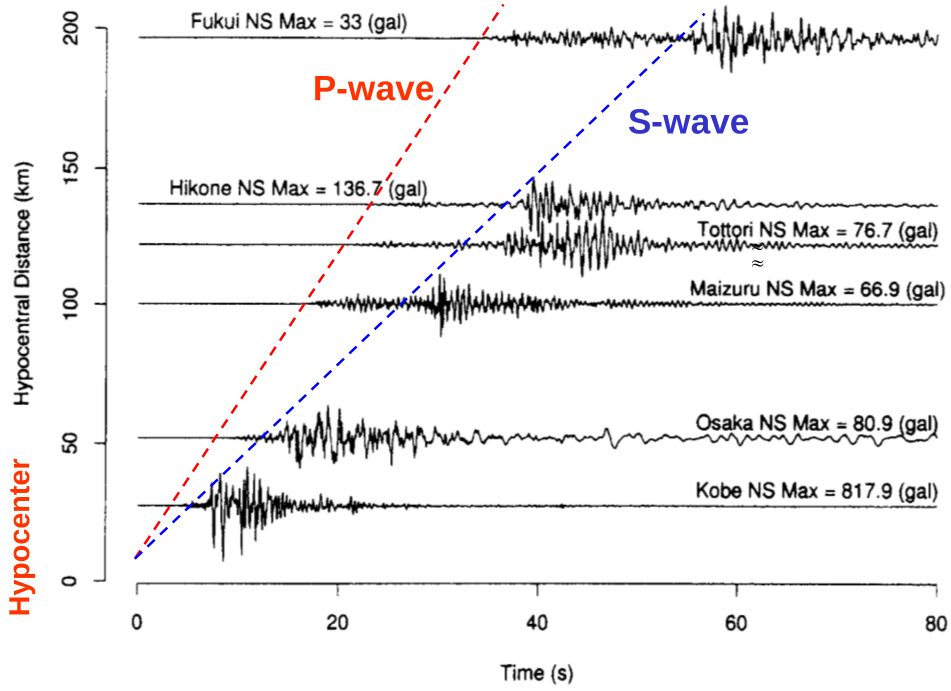
Figure 1.10 (a) A simplified picture of the paths of seismic P or S waves being reflected and refracted in rock structures of the Earth's crust. (b) The reflection and refraction of a longitudinal (P) wave in an earthquake after it hits a boundary between two types of rock. [From Bruce A. Bolt, *Nuclear Explosions and Earthquakes: The Parted Veil* (San Francisco: W. H. Freeman and Company. Copyright 1976).]

Instrumental Record at a Seismic Station

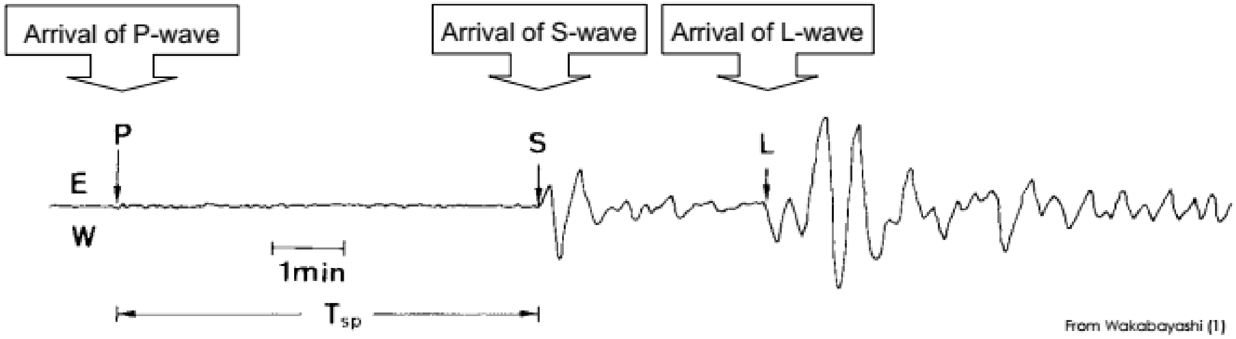


Difference in **arrival times between P and S waves**: measure of site-to-source distance

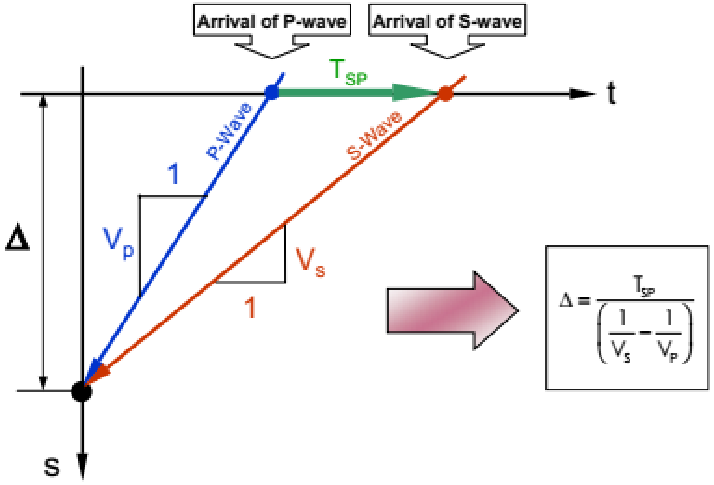
The 1995 Kobe Earthquake



Seismic Wave Records at Several Seismic Stations

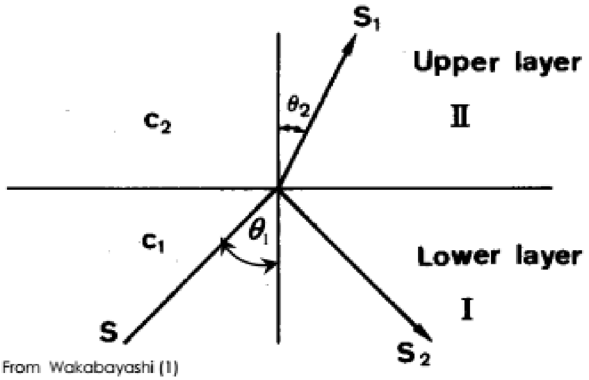


From Wakabayashi (1)



$$\Delta = \frac{T_{SP}}{\left(\frac{1}{V_S} - \frac{1}{V_P}\right)}$$

Reflection and refraction of waves



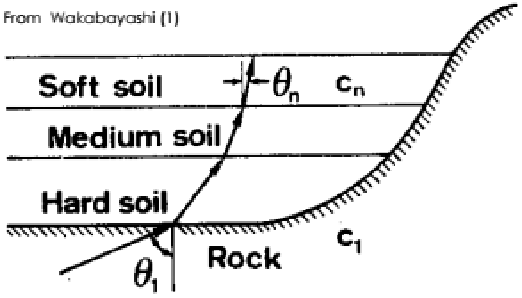
From Wakabayashi (1)

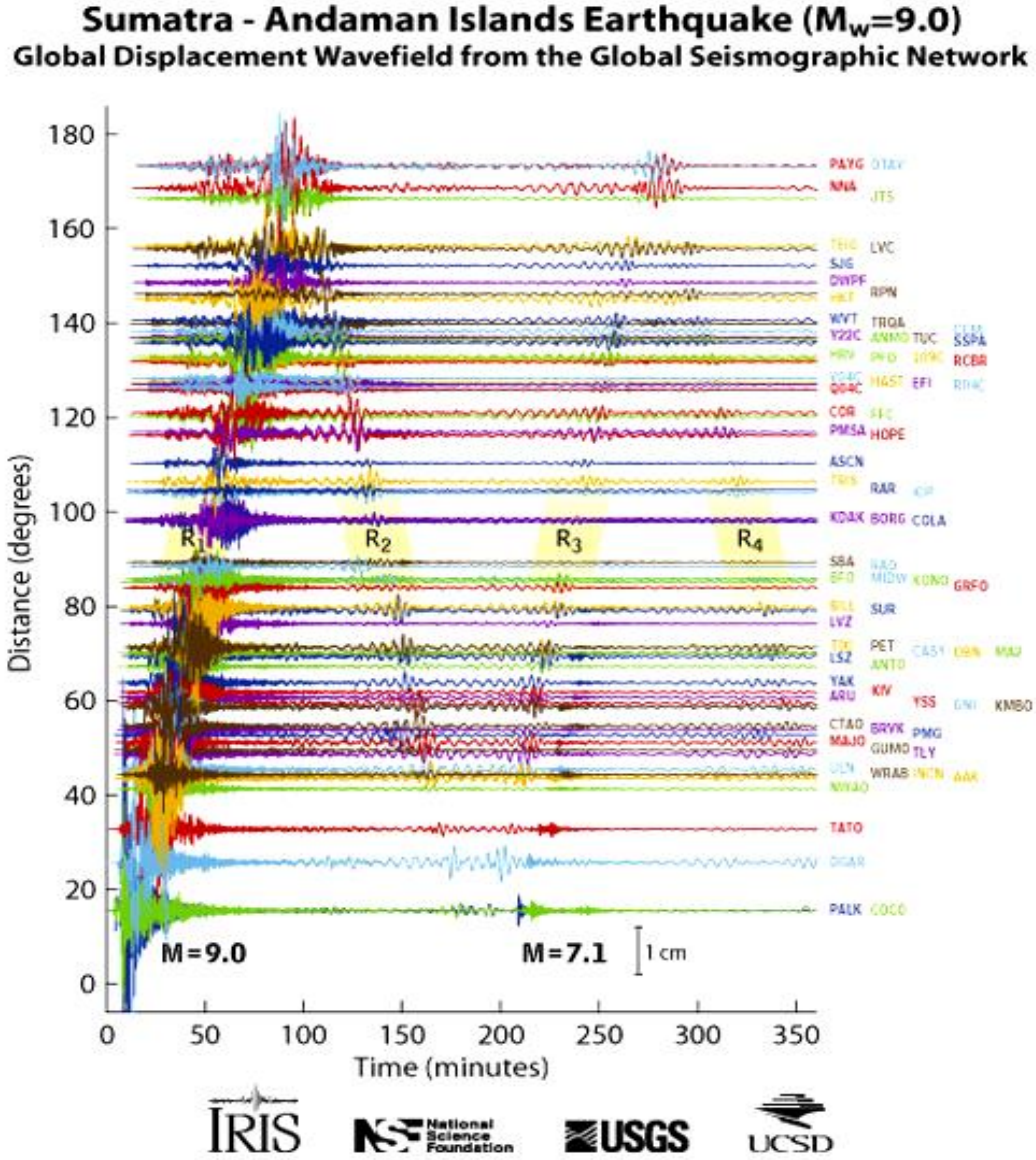
$$\frac{\sin\theta_1}{C_1} = \frac{\sin\theta_2}{C_2}$$

$$\sin\theta_n = \frac{C_n}{C_1} \cdot \sin\theta_1$$

Refraction of waves in the surface of layers

From Wakabayashi (1)



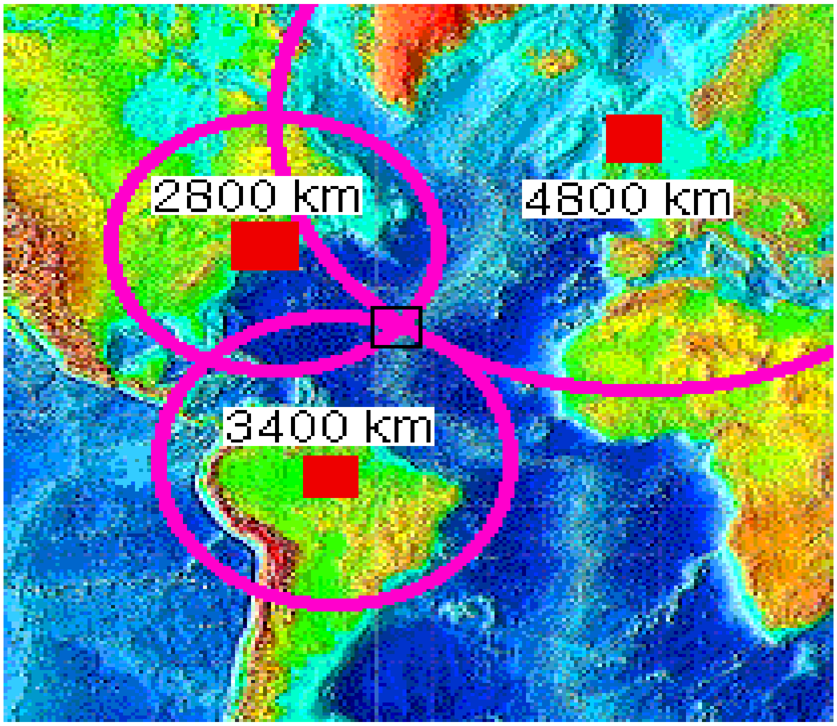


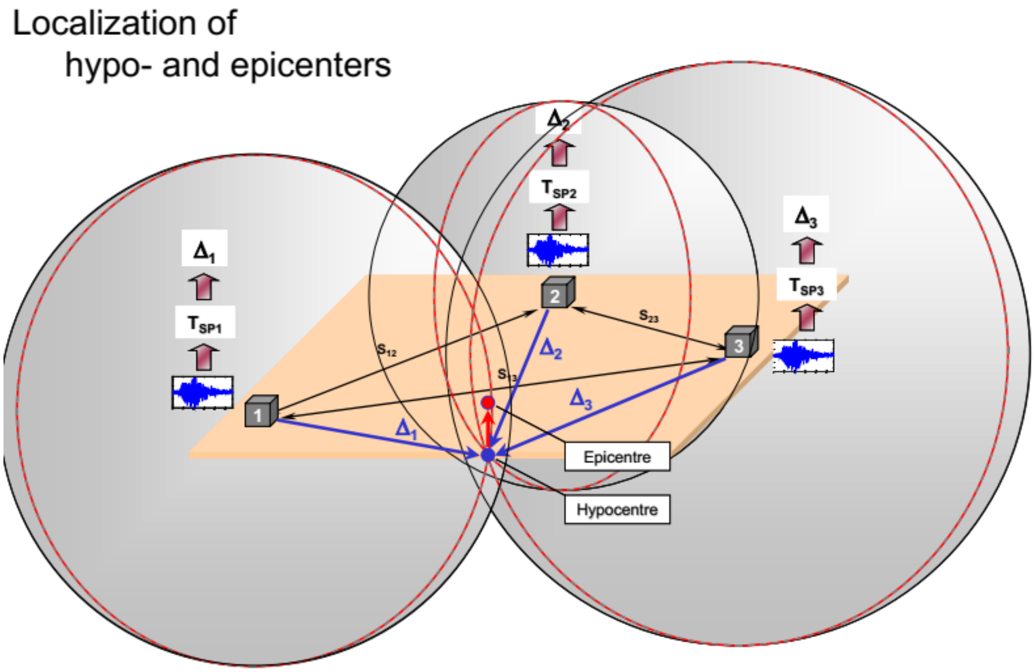
1.14. Locating Earthquakes

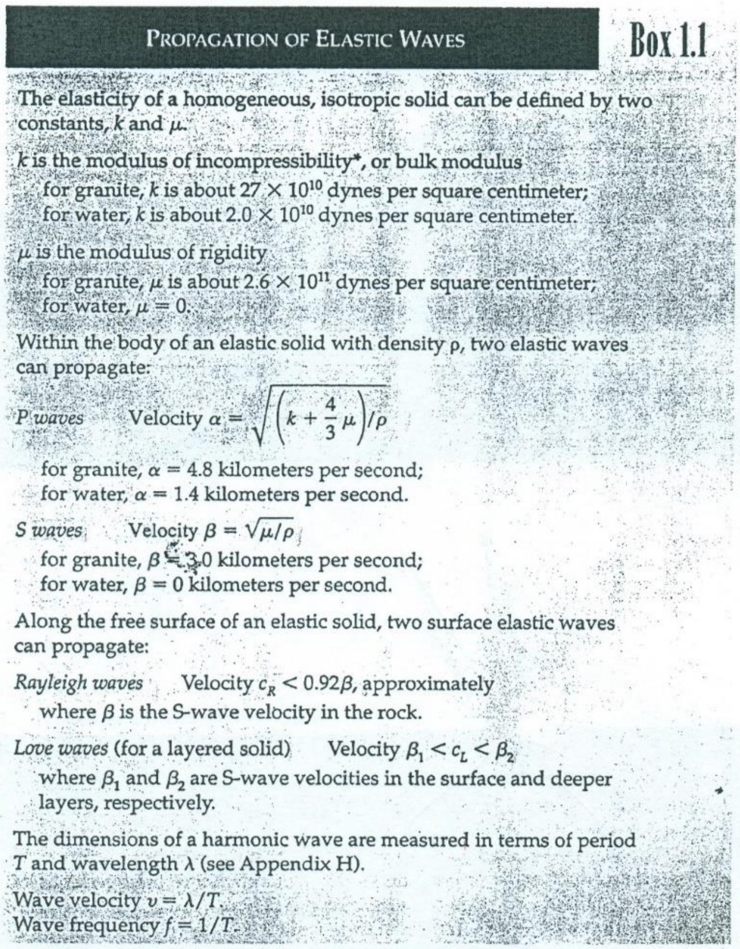
Although it is possible to infer a general location for an event from the records of a single station, it is most accurate to use three or more stations.

- A measurement of the P-S time at single station gives the distance between the station and the event.
- Drawing a circle on a map around the station's location, with a radius equal to the distance, shows all possible locations for the event.
- With the P-S time from a second station, the circle around that station will narrow the possible locations down to two points.

- It is only with a third station's P-S time that should identify which of the two previous possible points is the real one.







PROPAGATION OF ELASTIC WAVES **Box 1.1**

The elasticity of a homogeneous, isotropic solid can be defined by two constants, *k* and μ.

k is the modulus of incompressibility*, or bulk modulus
for granite, *k* is about 27×10^{10} dynes per square centimeter;
for water, *k* is about 2.0×10^{10} dynes per square centimeter.

μ is the modulus of rigidity
for granite, μ is about 2.6×10^{11} dynes per square centimeter;
for water, $\mu = 0$.

Within the body of an elastic solid with density ρ, two elastic waves can propagate:

P waves Velocity $\alpha = \sqrt{\left(k + \frac{4}{3}\mu\right)/\rho}$
for granite, $\alpha = 4.8$ kilometers per second;
for water, $\alpha = 1.4$ kilometers per second.

S waves Velocity $\beta = \sqrt{\mu/\rho}$
for granite, $\beta = 3.0$ kilometers per second;
for water, $\beta = 0$ kilometers per second.

Along the free surface of an elastic solid, two surface elastic waves can propagate:

Rayleigh waves Velocity $c_R < 0.92\beta$, approximately
where β is the S-wave velocity in the rock.

Love waves (for a layered solid) Velocity $\beta_1 < c_L < \beta_2$
where β_1 and β_2 are S-wave velocities in the surface and deeper layers, respectively.

The dimensions of a harmonic wave are measured in terms of period *T* and wavelength λ (see Appendix H).

Wave velocity $v = \lambda/T$.
Wave frequency $f = 1/T$.

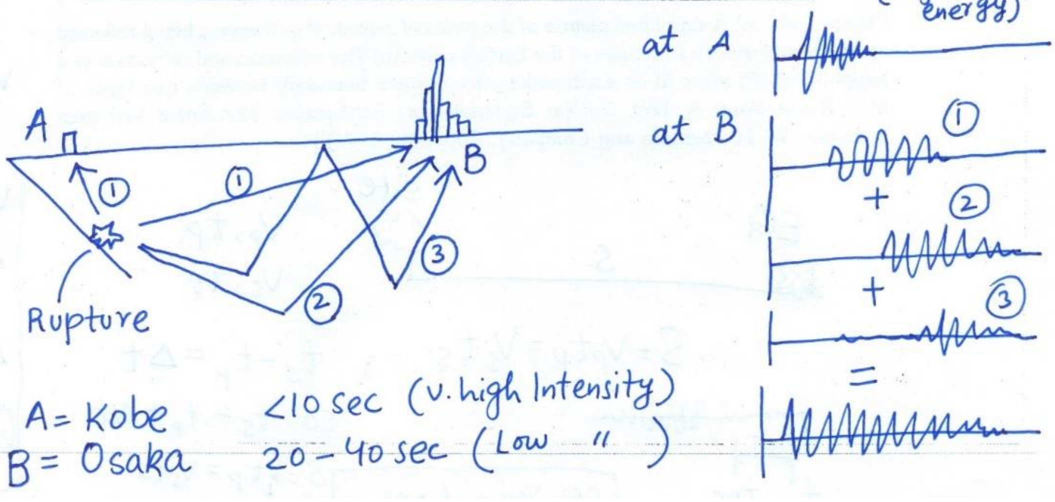
$V_P = \sqrt{\frac{E}{\rho}}$

$V_S = \sqrt{\frac{G}{\rho}}$

(P travels faster than S)

P will produce less shaking compared to S.

(highest freq)
(Highest energy)



A= Kobe <10 sec (v. high Intensity)
B= Osaka 20–40 sec (Low ″)

1.15. Seismoscopes

It consisted of a spherically formed copper vessel (about 2.4 m in diameter). In the inner part of this instrument a column was so suspended that it can move in 8 directions.

When an earthquake occurs, the vessel is shaken, the dragon instantly drops the ball, and the frog which receives it vibrates vigoriously; anyone watching this instrument can easily observed earthquakes.

In the year A.D. 136, a Chinese called **Choko** (also called Chang Heng) invented an instrument for indicating earthquakes.

Once upon a time a dragon dropped its ball without any earthquake being observed, and people therefore thought the instrument of no use, but after 2 to 3 days a notice came saying that an earthquake had taken place in Rosei. Hearing of this, those who doubted the use of this instrument began to believe in it again.

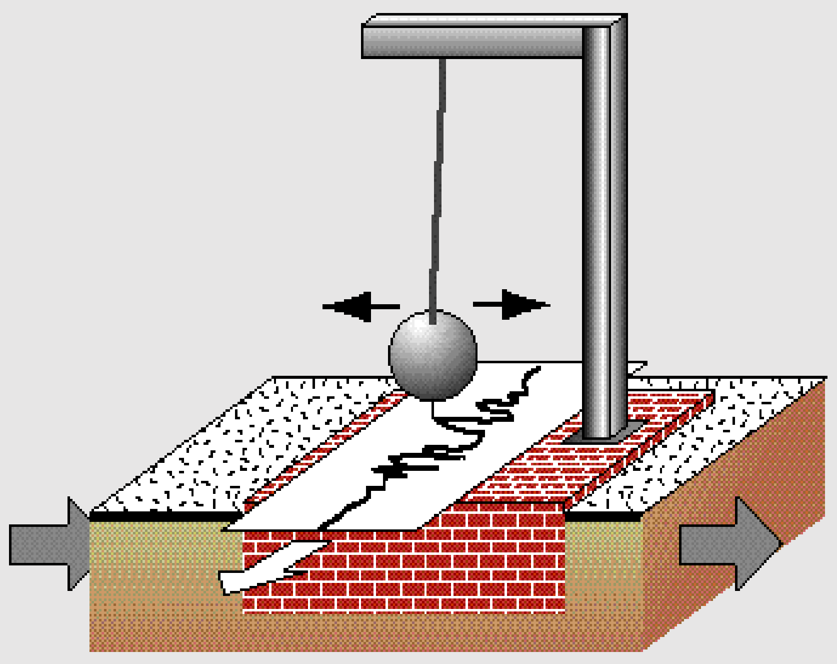
After this ingenious instrument had been invented by Choko, the Chinese government wisely appointed a secretary to make observations on earthquakes.

The earliest modern seismographs was invented by John Milne around 1880s during when he was Professor of Geology and Mining at the Imperial College of Engineering in Tokyo (University of Tokyo).

The principal problem for constructing precise earthquake measuring devices during that time was how to produce a body which would remain stationary, and detached from the world around in order to record the relative movement of the ground on which it actually rested.

They decided to make use of the mechanical principle of inertia—in essence the tendency of a heavy body to stay put.

Thus their seismographs relied on using a freely swinging pendulum whose movements were marked by pin or pen on a revolving drum of smoked glass, and later paper.



Mechanism of Seismograph:

An earthquake does not make the pendulum swing. Instead, the pendulum remains fixed as the ground moves beneath it.

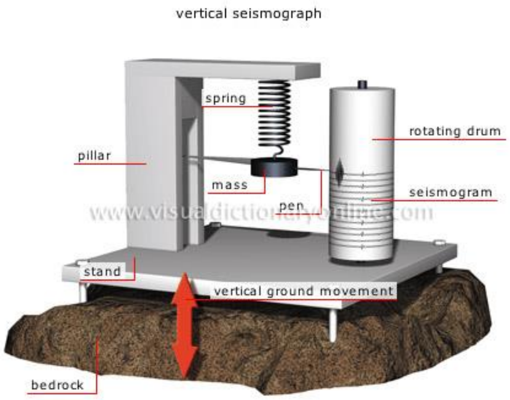
A pendulum with a short period (left) moves along with the support and registers no motion. A pendulum with a long period (right) tends to remain in place while the support moves.

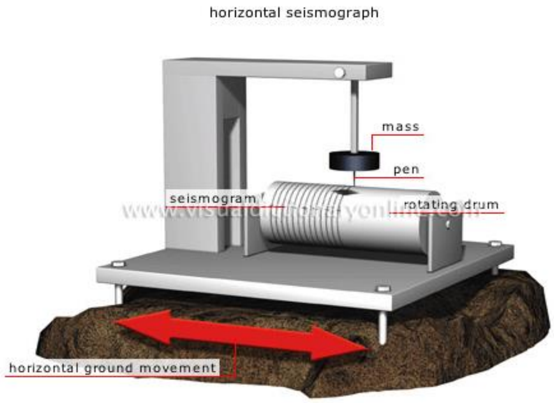
The boundary between the two types of behavior is the natural period of the pendulum. Only motions faster than the natural period will be detected; any motion slower will not.

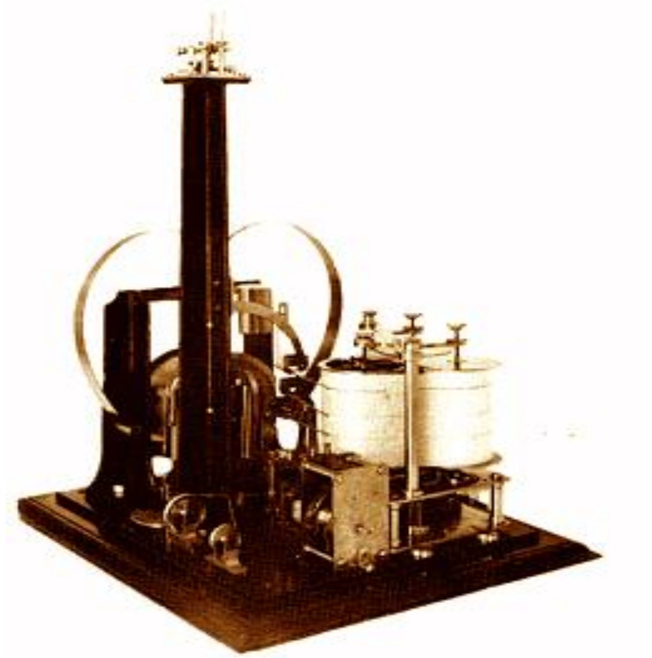
“Seismograph” usually refers a displacement-type seismometer.

The damping of the pendulum was also added to suppress the free vibration response and to improve the performance of the seismographs.

The Milne seismographs employed 3 devices, one for each component of ground motion (up-down, north-south, east-west components).







After his arrival in Japan, John Milne was responsible for the invention of a number of seismographs. This is one he produced with his colleague Gray.

Crown Copyright, Science Museum, London

but if the response of pendulum is in  This range. 24.

John Milne put damping (of ~0.7 = 70%.) to get 

So if we make a pendulum of f = 1 Hz — we can measure anything >1 Hz

Earthquakes normally —— 1 to 5 Hz.

Modern Seismographs:

The general principle behind the early seismographs is still the basic idea behind the designs of present-day seismographs.

In modern seismographs the relative motion between the pendulum and frame produces an electrical signal that is magnified electronically thousands or even hundreds of thousands of times before it is recorded.

The electrical signals can be recorded on to magnetic tapes, papers, or converted into equivalent digital signals and stored in computer memory.

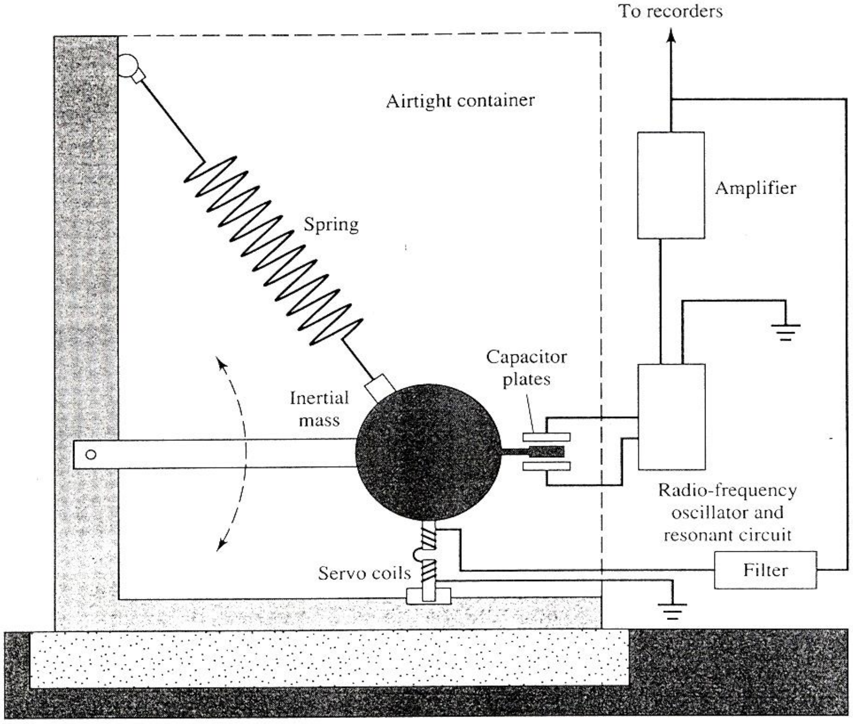


Figure 3.3 Principle of the vertical pendulum seismograph. The mass tends to remain stationary as the Earth moves. Relative motion at the capacitor plates generates an electrical signal that is fed to an analog or digital recorder. The filter feeds back spurious signals, representing undesirable ground motions, to coils that keep the mass centered. (From B. A. Bolt *Inside the Earth*.)

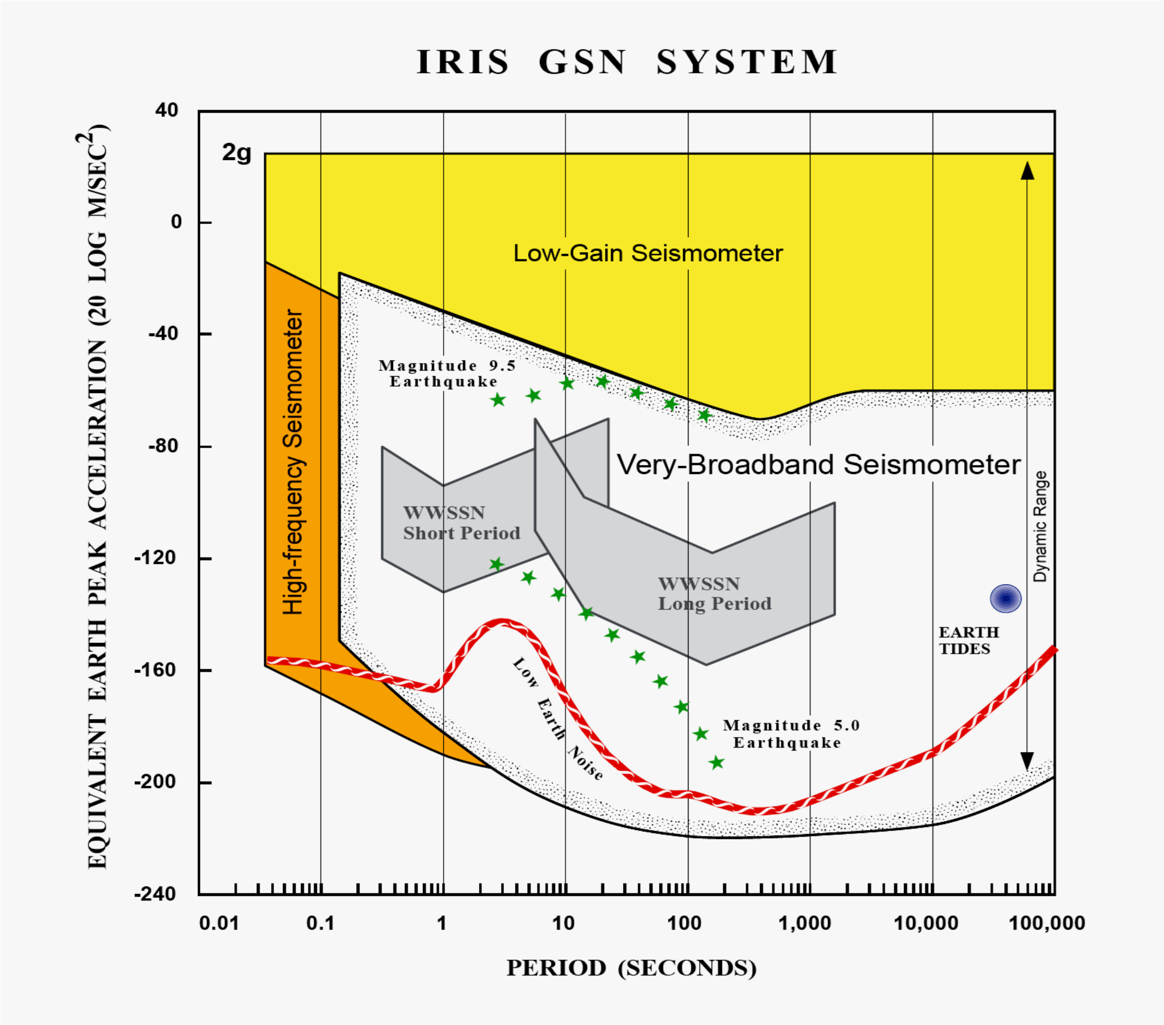
Most seismographs around the world are designed to detect small-amplitude motions (weak motions) and are very sensitive “ears on the world”. They can detect and record earthquakes of small size from very great distances (>1000 km).

Short-period Seismograph

Natural Period = 1 sec

Broadband Seismograph

Natural Period = 120 sec

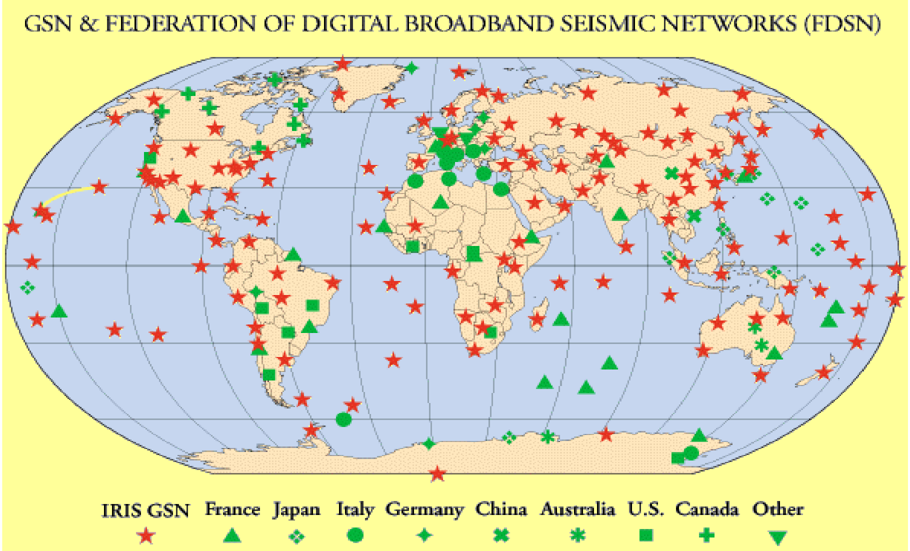


The IRIS Global Seismographic Network (GSN):

The goal of the GSN is to deploy 128 permanent seismic recording stations uniformly over the earth's surface.

IRIS: Incorporated Research Institutions for Seismology

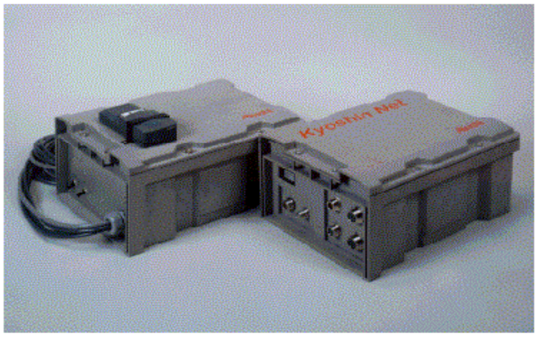
http://www.iris.edu/



Strong-motion Seismographs:

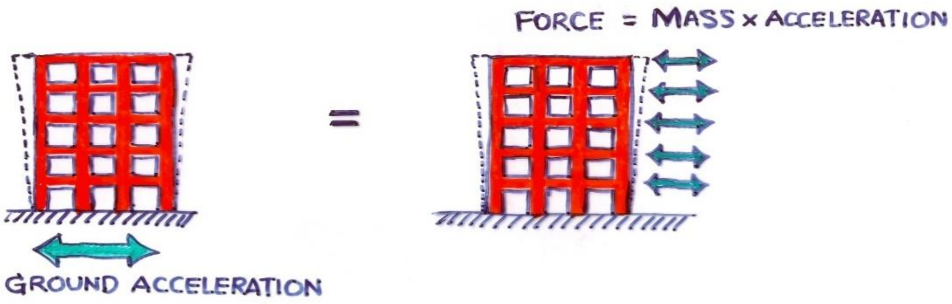
Strong-motion seismographs are specially designed to record the strong shaking of the ground in such a way that the records obtained can be directly read as acceleration of the ground.

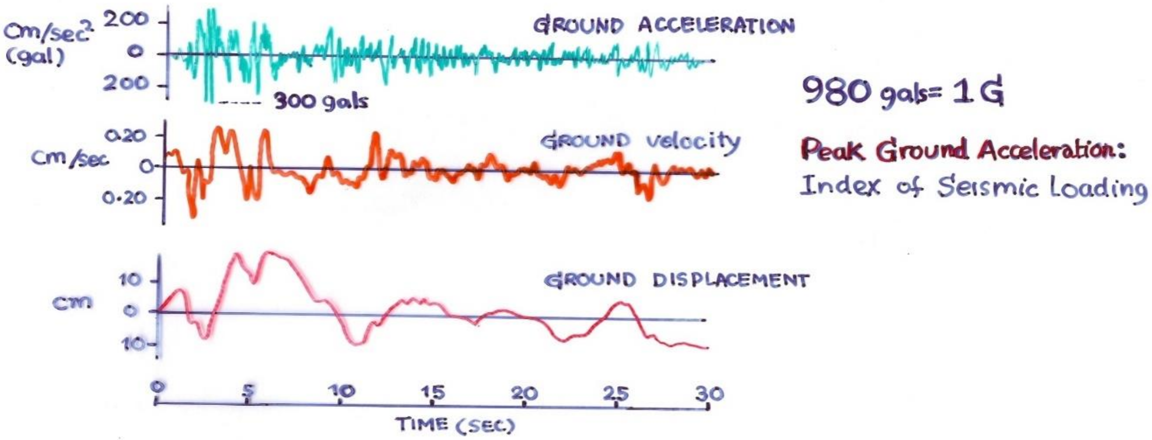
They are usually capable of recording acceleration of the ground greater than that of gravity.

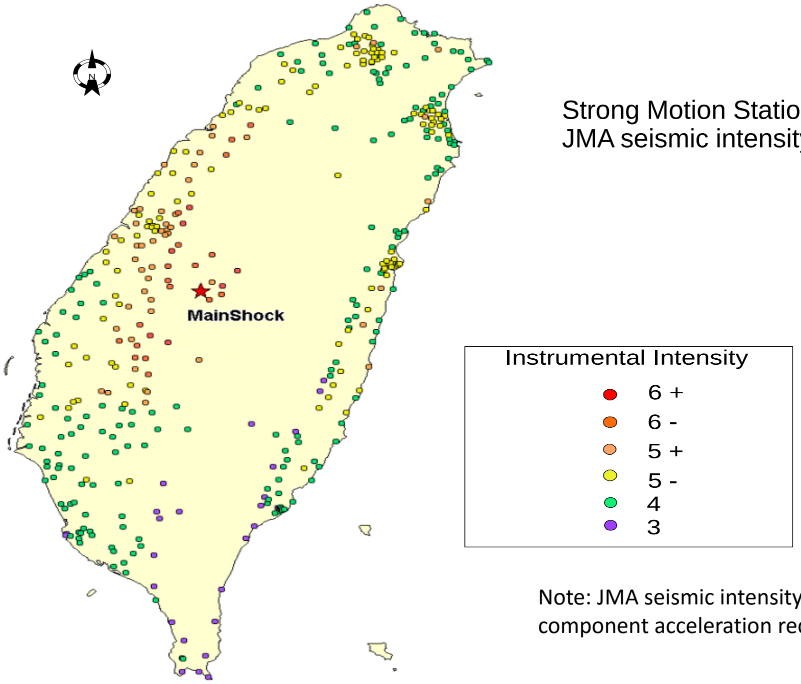


STRONG MOTION SEISMOGRAPH
Type K-NET95

Most strong-motion accelerometers do not record continuously but are triggered into motion by the first waves of the earthquake to arrive.

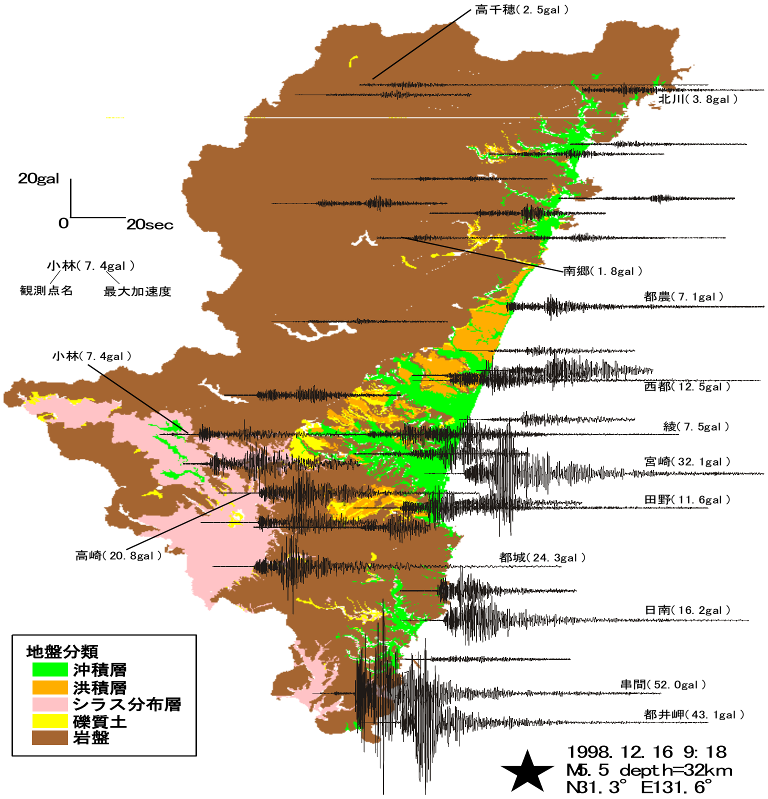






Strong Motion Stations in Taiwan and Distribution of the JMA seismic intensity for the 1999 Chi-Chi EQ

Note: JMA seismic intensity is calculated from a three-component acceleration record.



Strong-motion Records
In Yokohama, Japan

Magnitude-5 Earthquake
December 16, 1998
Depth 32 km

1.16. The Size of an Earthquake

The first scientific field study of the effects of a great earthquake was conducted by an Irish man, Robert Mallet, who was recognized as the first true seismologist.

In his assessment of the effects of the Neapolitan Earthquake of 1857 in southern Italy, Mallet was using the oldest instruments in the world: his eyes, a compass and a measuring stick.

Mallet's method included detailed mapping and tabulation of felt reports and damage to buildings and geological movements.

In this way he was able to measure the strength and distribution of the earthquake ground motion.

By drawing lines on a map between places of equal damage or of equal intensity (isoseismal lines), he determined the center of the earthquake shaking (the epicenter). Such maps are now called isoseismal maps.

Intensity is measured by means of *the degree of damage to structures of human origin, the amount of disturbances to the surface of the ground, and the extent of animal and human reaction to the shaking, not by measuring the ground motion with instruments.*

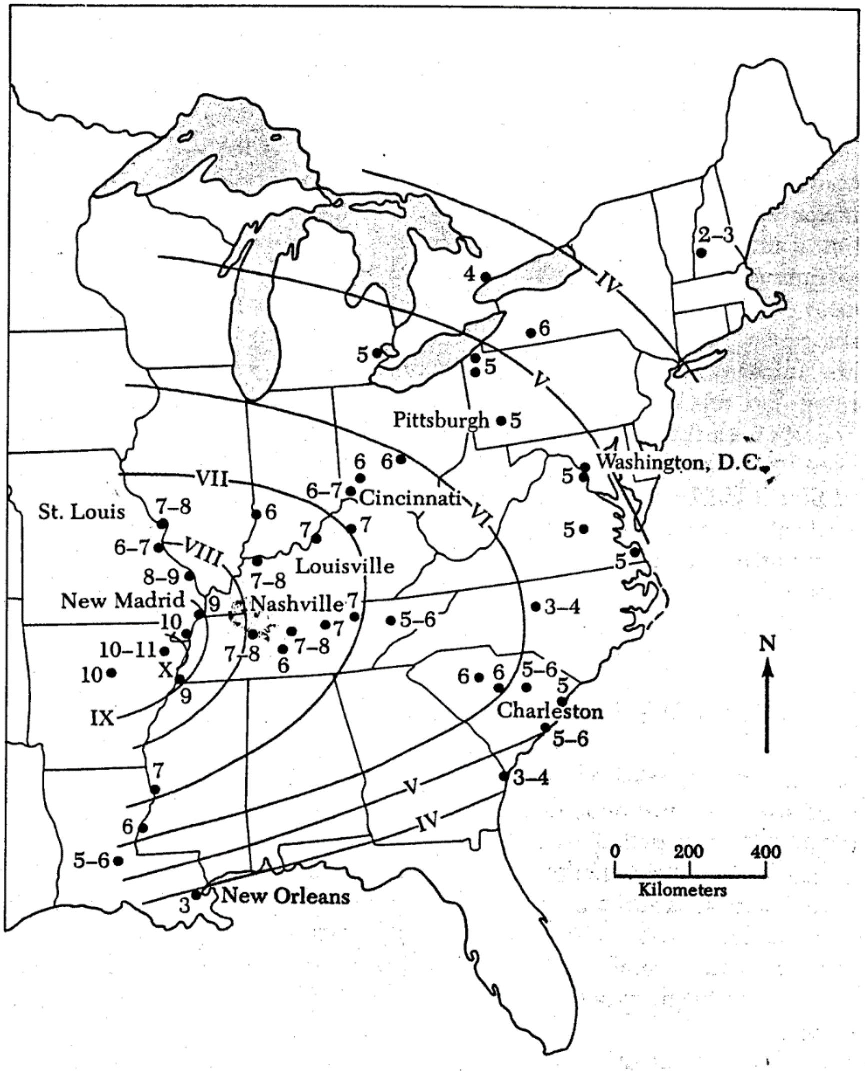
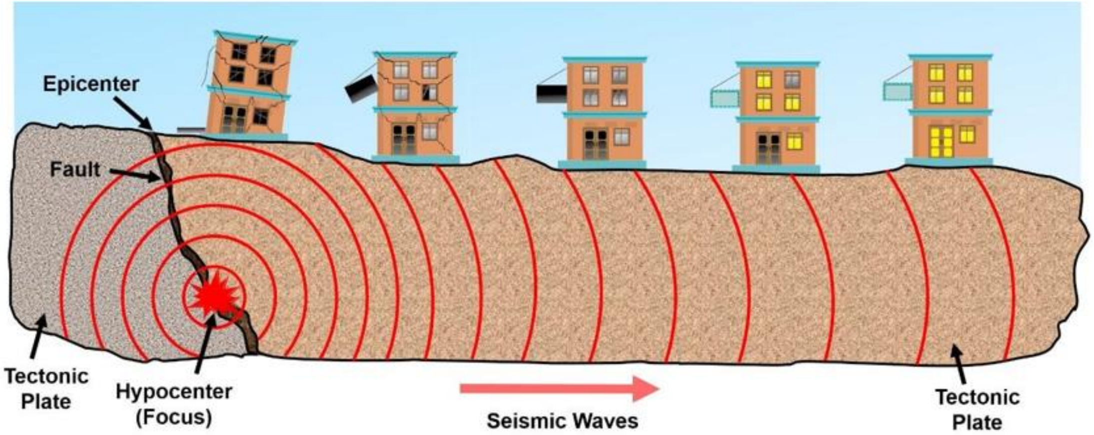


Figure 7.1 Isoseismal lines of intensity (Modified Mercalli scale) in the New Madrid, Missouri, earthquake on December 16, 1811. The felt radius of the earthquake extended to the East and Gulf coasts. Intensity in the then sparsely populated area west of the epicenter is unknown. Intensity values at specified points are given in Arabic numerals, and the isoseismals are labeled by Roman numerals. [Courtesy of O. Nuttli and *Bull. Seism. Soc. Am.*]



Felt Intensity	X+	IX	VIII	VII	VI	V	IV	II-III	I
Damage	Very Heavy	Heavy	Moderate to Heavy	Moderate	Light	Very Light	None	None	None
Shaking	Extreme	Violent	Sever	Very Strong	Strong	Moderate	Light	Weak	Not Felt

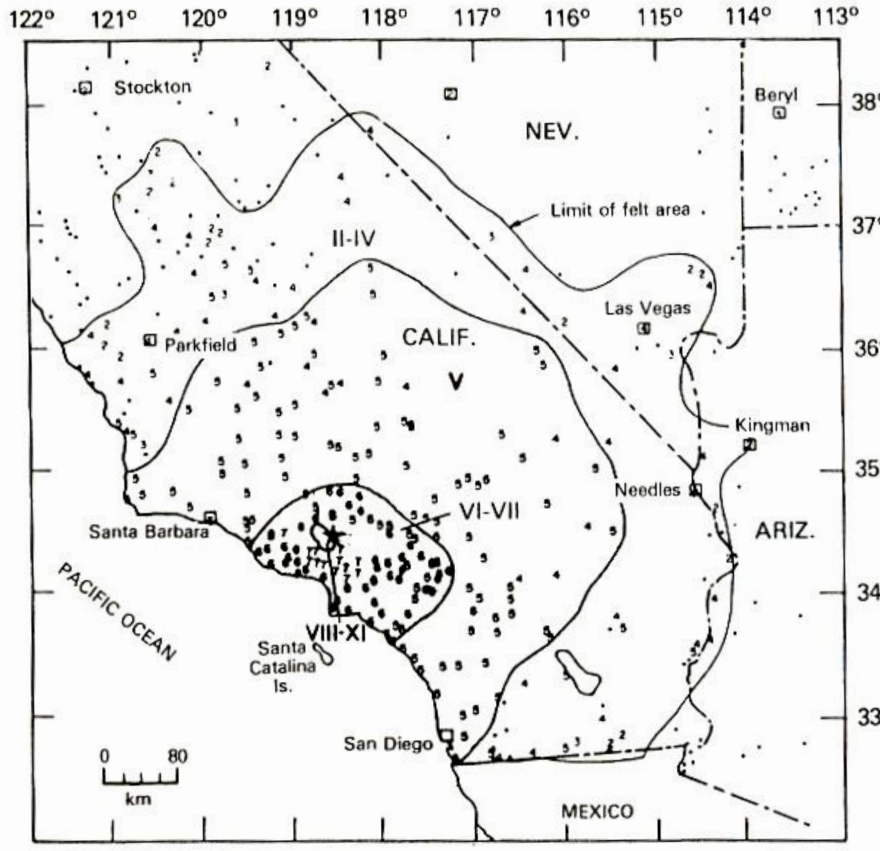


FIGURE 3.2 Generalized isoseismal map of the February 9, 1971 San Fernando, California earthquake. The epicenter is shown as a star. Roman numerals represent Modified Mercalli intensities between isoseismals. Arabic numerals represent Modified Mercalli intensities at specific cities. Dots represent locations where it was reported that the earthquake was not felt (after Coffman and Angel 1983).

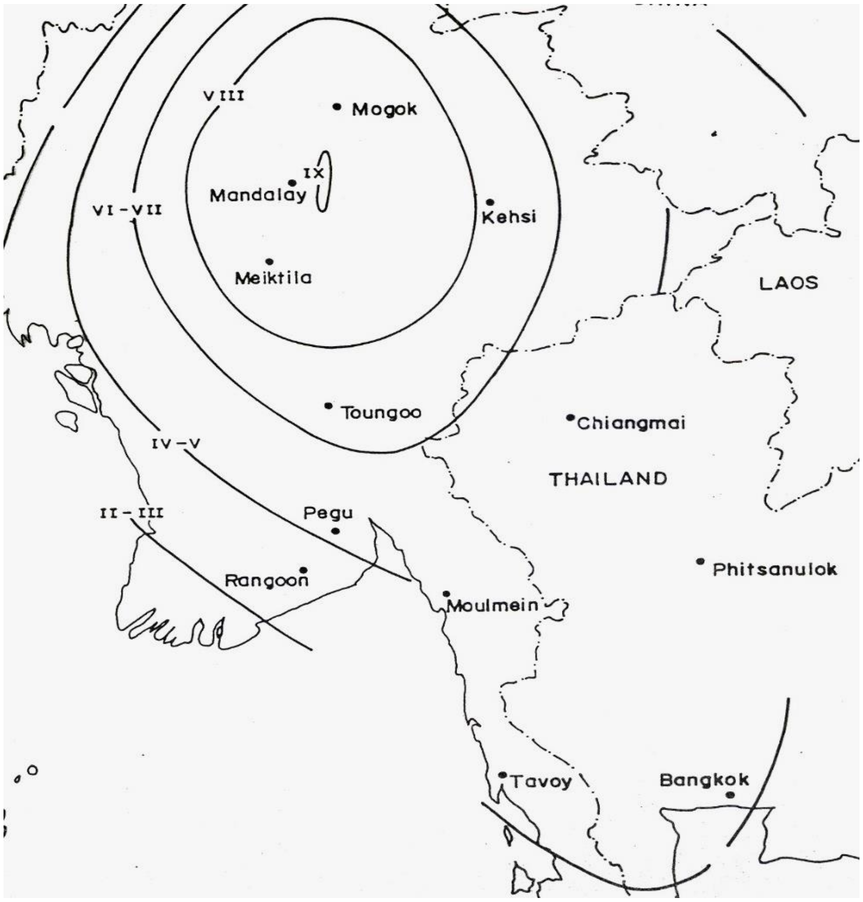
1.16.1. Intensity Scales

The first intensity scale of modern times was developed by M. S. de Rossi of Italy and Francois Forel of Switzerland in the 1880s. It was called the Rossi-Forel Intensity Scale (I — X).

A more refined scale, with 12 values, was constructed in 1902 by the Italian seismologist and volcanologist G. Mercalli.

A modified version of it, called the Modified Mercalli Intensity (MMI) Scale, was developed by H. O. Wood and Frank Neumann to fit construction conditions in California (and most of the United States).

Alternative intensity scales have been developed and are widely used in other countries, notably in Japan (the JMA Intensity Scale) and the central and eastern European countries (the Medvedev-Sponheuer-Karnik (MSK) Intensity Scale), where conditions differ from those in California.



Isoseismal Map of the Mandalay earthquake of 23 May 1912 (after Brown, 1914), Rossi-Forel Intensity Scale

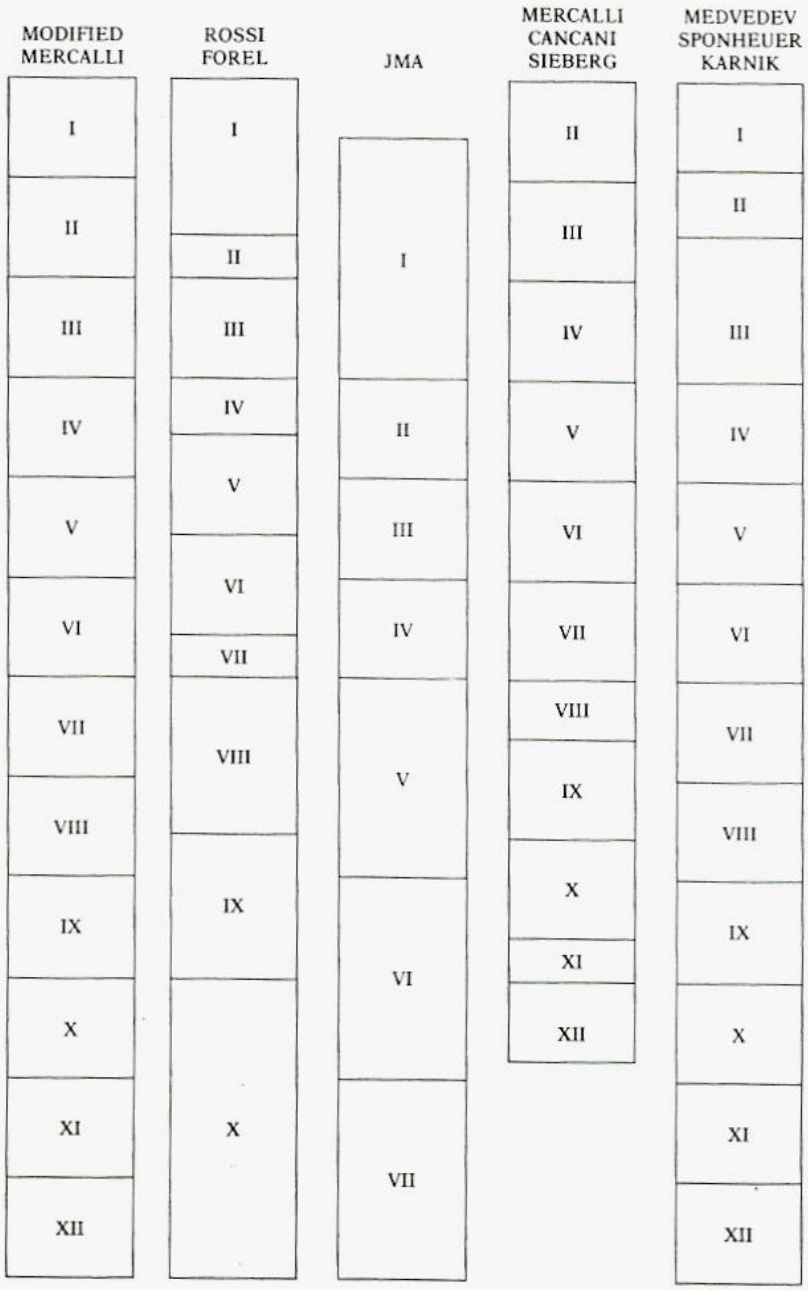
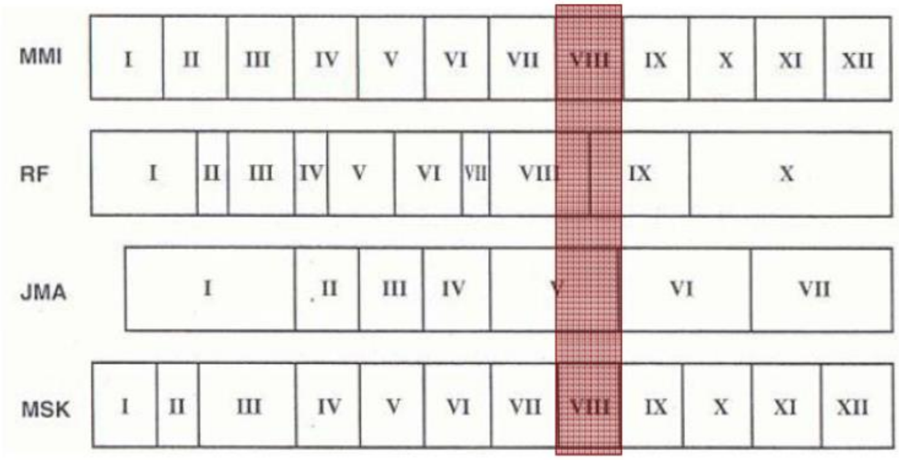
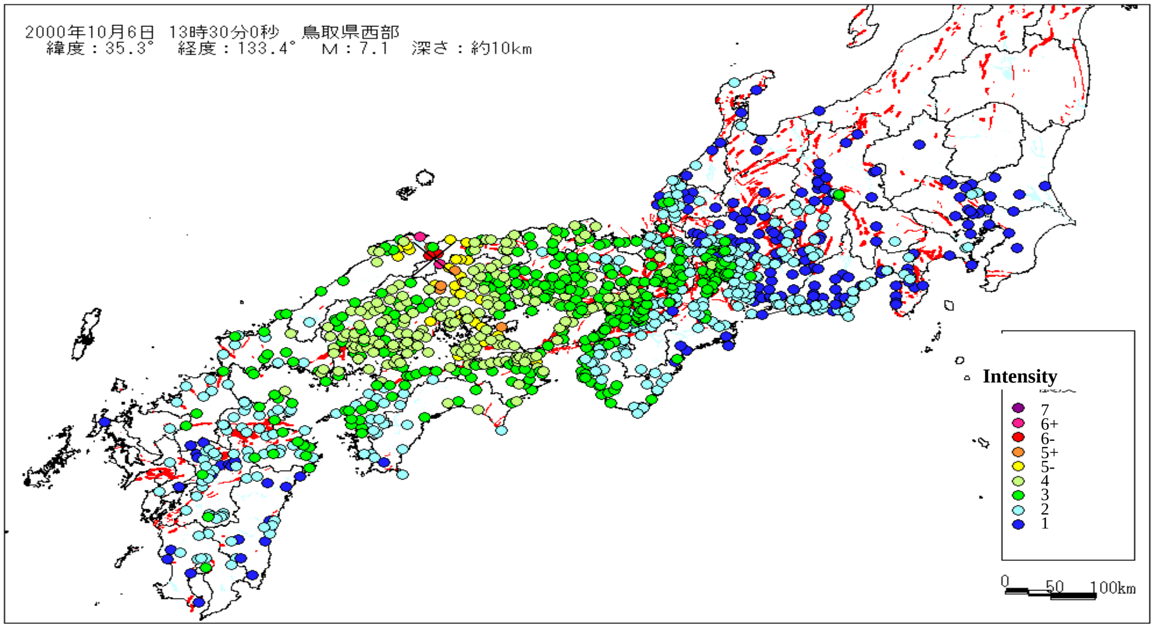


FIGURE 3.1 A comparison of seismic intensity scales (after Murphy and O'Brien 1977; and Richter,1958).

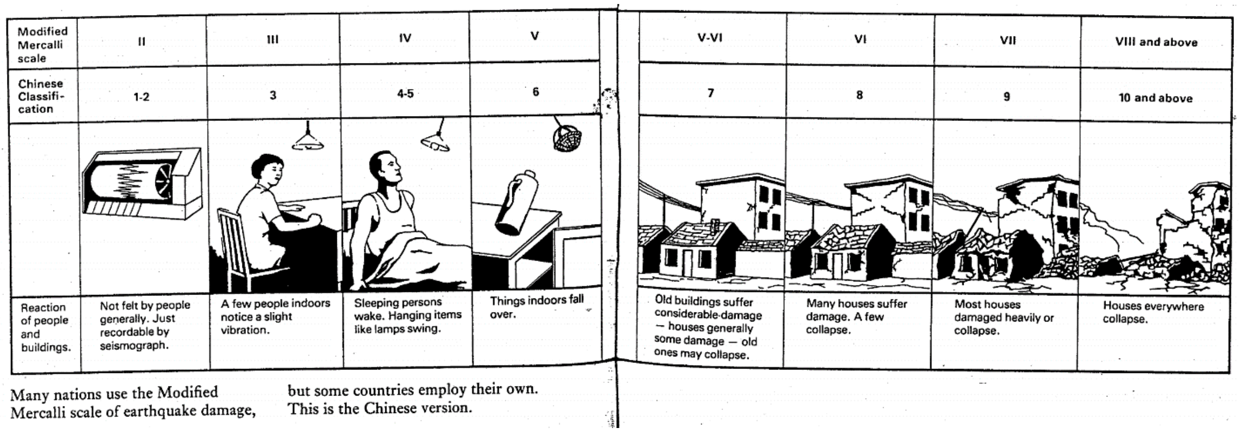
Comparison of different intensity scales

Comparison of the different intensity scales





JMA Instrumental Intensity in the 2000 Tottori EQ Measured by National Seismic Networks



Modified Mercalli scale	II	III	IV	V	V-VI	VI	VII	VIII and above
Chinese Classification	1-2	3	4-5	6	7	8	9	10 and above
Reaction of people and buildings.	Not felt by people generally. Just recordable by seismograph.	A few people indoors notice a slight vibration.	Sleeping persons wake. Hanging items like lamps swing.	Things indoors fall over.	Old buildings suffer considerable damage — houses generally some damage — old ones may collapse.	Many houses suffer damage. A few collapse.	Most houses damaged heavily or collapse.	Houses everywhere collapse.

Many nations use the Modified Mercalli scale of earthquake damage, but some countries employ their own. This is the Chinese version.

Chines Intensity scale

The Modified Mercalli Intensity Scale (Wood and Neumann, 1931)

I. Not felt—or, except rarely under especially favorable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, bodies of water, may sway—doors may swing, very slowly.

II. Felt indoors by few, especially on upper floors, or by sensitive, or nervous persons. Also, as in grade I, but often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water, may sway, doors may swing, very slowly; sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced.

III. Felt indoors by several, motion usually rapid vibration. Sometimes not recognized to be an earthquake at first. Duration estimated in some cases. Vibration like that due to passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of tall structures. Rocked standing motor cars slightly.

IV. Felt indoors by many, outdoors by few. Awakened few, especially light sleepers. Frightened no one, unless apprehensive from previous experience. Vibration like that due to passing of heavy or heavily loaded trucks. Sensation like heavy body striking building or falling of heavy objects inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Creaking of walls, frame, especially in the upper range of this grade. Hanging objects swung, in numerous instances. Disturbed liquids in open vessels slightly. Rocked standing motor cars noticeably.

V. Felt indoors by practically all, outdoors by many or most: outdoors direction estimated. Awakened many, or most. Frightened few—slight excitement, a few ran outdoors. Buildings trembled throughout. Broke dishes, glassware, to some extent. Cracked windows—in some cases, but not generally. Overturned vases, small or unstable objects, in many instances, with occasional fall. Hanging objects, doors, swing generally or considerably. Knocked pictures against walls, or swung them out of place. Opened, or closed, doors, shutters, abruptly. Pendulum clocks stopped, started, or ran fast, or slow. Moved small objects, furnishings, the latter to slight extent. Spilled liquids in small amounts from well-filled open containers. Trees, bushes, shaken slightly.

VI. Felt by all, indoors and outdoors. Frightened many, excitement general, some alarm, many ran outdoors. Awakened all. Persons made to move unsteadily. Trees, bushes, shaken slightly to moderately. Liquid set in strong motion. Small bells rang—church, chapel, school, etc. Damage slight in poorly built buildings. Fall of plaster in small amount. Cracked plaster somewhat, especially fine cracks, chimneys in some instances. Broke dishes, glassware, in considerable quantity, also some windows. Fall of knick-knacks, books, pictures. Overturned furniture in many instances. Moved furnishings of moderately heavy kind.

VII. Frightened all—general alarm, all ran outdoors. Some, or many, found it difficult to stand. Noticed by persons driving motor cars. Trees and bushes shaken moderately to strongly. Waves on ponds, lakes, and running water. Water turbid from mud stirred up. Incaving to some extent of sand or gravel stream banks. Rang large church bells, etc. Suspended objects made to quiver. Damage negligible in buildings of good design and construction, slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Cracked chimneys to considerable extent, walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Broke numerous windows, furniture to some extent. Shook down loosened brickwork and tiles. Broke weak chimneys at the roof-line (sometimes damaging roofs). Fall of cornices from towers and high buildings. Dislodged bricks and stones. Overturned heavy furniture, with damage from breaking. Damage considerable to concrete irrigation ditches.

VIII. Fright general—alarm approaches panic. Disturbed persons driving motor cars. Trees shaken strongly—branches, trunks, broken off, especially palm trees. Ejected sand and mud in small amounts. Changes: temporary, permanent; in flow of springs and wells; dry wells renewed flow; in temperature of spring and well waters. Damage slight in structures (brick) built especially to withstand earthquakes. Considerable in ordinary substantial buildings, partial collapse: racked, tumbled down, wooden houses in some cases; threw out panel walls in frame structures, broke off decayed piling. Fall of walls. Cracked, broke, solid stone walls seriously. Wet ground to some extent, also ground on steep slopes. Twisting, fall, of chimneys, columns, monuments, also factory stacks, towers. Moved conspicuously, overturned, very heavy furniture.

IX. Panic general. Cracked ground conspicuously. Damage considerable in (masonry) structures built especially to withstand earthquakes: threw out of plumb some wood-frame houses built especially to withstand earthquakes; great in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations, racked frames; serious to reservoirs; underground pipes sometimes broken.

X. Cracked ground, especially when loose and wet, up to widths of several inches; fissures up to a yard in width ran parallel to canal and stream banks. Landslides considerable from river banks and steep coasts. Shifted sand and mud horizontally on beaches and flat land. Changed level of water in wells. Threw water on banks of canals, lakes, rivers, etc. Damage serious to dams, dikes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Developed dangerous cracks in excellent brick walls. Destroyed most masonry and frame structures, also their foundations. Bent railroad rails slightly. Tore apart, or crushed endwise, pipe lines buried in earth. Open cracks and broad wavy folds in cement pavements and asphalt road surfaces.

XI. Disturbances in ground many and widespread, varying with ground material. Broad fissures, earth slumps, and land slips in soft wet ground. Ejected water in large amounts charged with sand and mud. Caused sea-waves ("tidal" waves) of significant magnitude. Damage severe to wood-frame structures, especially near shock centers. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Affected yielding wooden bridges less. Bent railroad rails greatly, and thrust them endwise. Put pipe lines buried in earth completely out of service.

XII. Damage total—practically all works of construction damaged greatly or destroyed. Disturbances in ground great and varied, numerous shearing cracks. Landslides, falls of rock of significant character, slumping of river banks, etc., numerous and extensive. Wrenched loose, tore off, large rock masses. Fault slips in firm rock, with notable horizontal and vertical offset displacements. Water channels, surface and underground, disturbed and modified greatly. Dammed lakes, produced waterfalls, deflected rivers, etc. Waves seen on ground surfaces (actually seen, probably, in some cases). Distorted lines of sight and level. Threw objects upward into the air.

1.16.2. Earthquake Magnitudes

If the magnitudes of earthquakes are to be compared worldwide, a measure is needed that does not depend (as does intensity) on the density of population and type of construction.

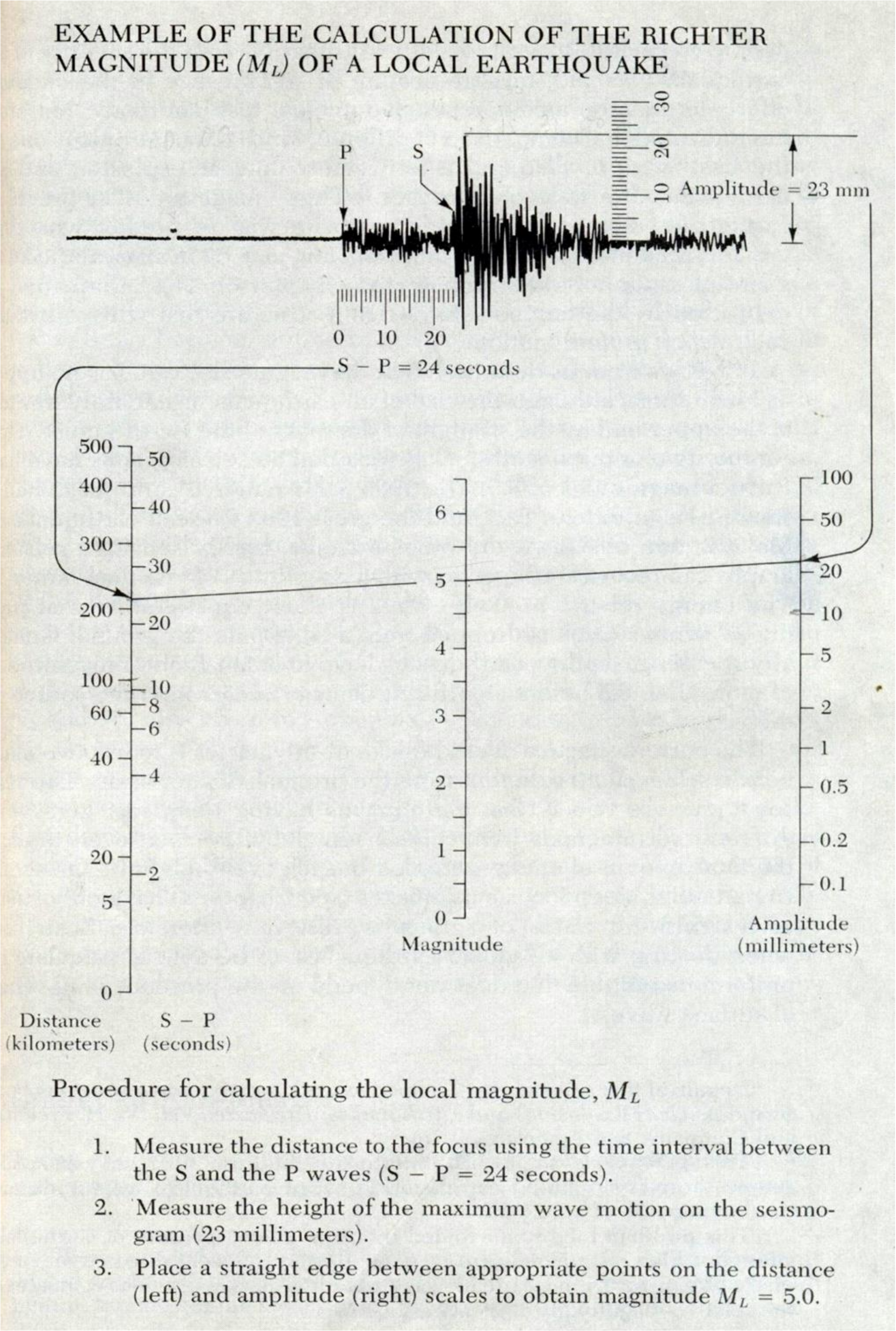
Such quantitative scale was originated in 1931 by Kiyoo Wadati in Japan and later on developed by Dr. Charles Richter in 1935 in California.

Richter defined the magnitude of an earthquake as *the logarithm to base 10 of the maximum seismic-wave amplitude (in micrometer) recorded on a standard Wood-Anderson short-period seismograph*[1] *at a distance of 100 km from the earthquake epicenter*.

Every time the magnitude goes up by 1 unit, the amplitude of the earthquake waves increases 10 times.

At first the scale was intended to deal with Californian earthquakes only, but with the cooperation of Professor Beno Gutenberg the scale was adapted to enable earthquakes to be classified worldwide.

The Richter magnitude scale is also called Local Magnitude (M_L).



EXAMPLE OF THE CALCULATION OF THE RICHTER MAGNITUDE (M_L) OF A LOCAL EARTHQUAKE

Procedure for calculating the local magnitude, M_L

1. Measure the distance to the focus using the time interval between the S and the P waves (S − P = 24 seconds).
2. Measure the height of the maximum wave motion on the seismogram (23 millimeters).
3. Place a straight edge between appropriate points on the distance (left) and amplitude (right) scales to obtain magnitude M_L = 5.0.

At the present time there are several magnitude scales. The most used magnitude scales are surface-wave magnitude (M_s), body-wave magnitude (m_b), and moment magnitude (M_w).

M_s is a world-wide scale determined from the maximum amplitude of Rayleigh waves with a period of about 20 seconds (between 18 s and 22 s) on a standard long-period seismograph[1]. It is most widely used magnitude scale for large damaging shallow earthquakes (less than 70 km deep).

It was developed in 1950s by the same researchers who developed M_L (Gutenberg and Richter) in order to improve resolution on larger earthquakes.

m_b is a world-wide scale determined from the maximum amplitude of the first few cycles of the P wave motion observed on the vertical component of seismogram. The waves measured typically have a period of about 1 second. It is widely used for characterizing deep earthquakes.

Saturation of Earthquake Magnitudes:

It must be noted that most magnitude scales saturate, or stop increasing with increasing earthquake size.

This occurs because each magnitude scale is determined using a seismic wave of a particular period and wave length, which at a certain level does not increase in amplitude as the earthquake source size and energy release increase.

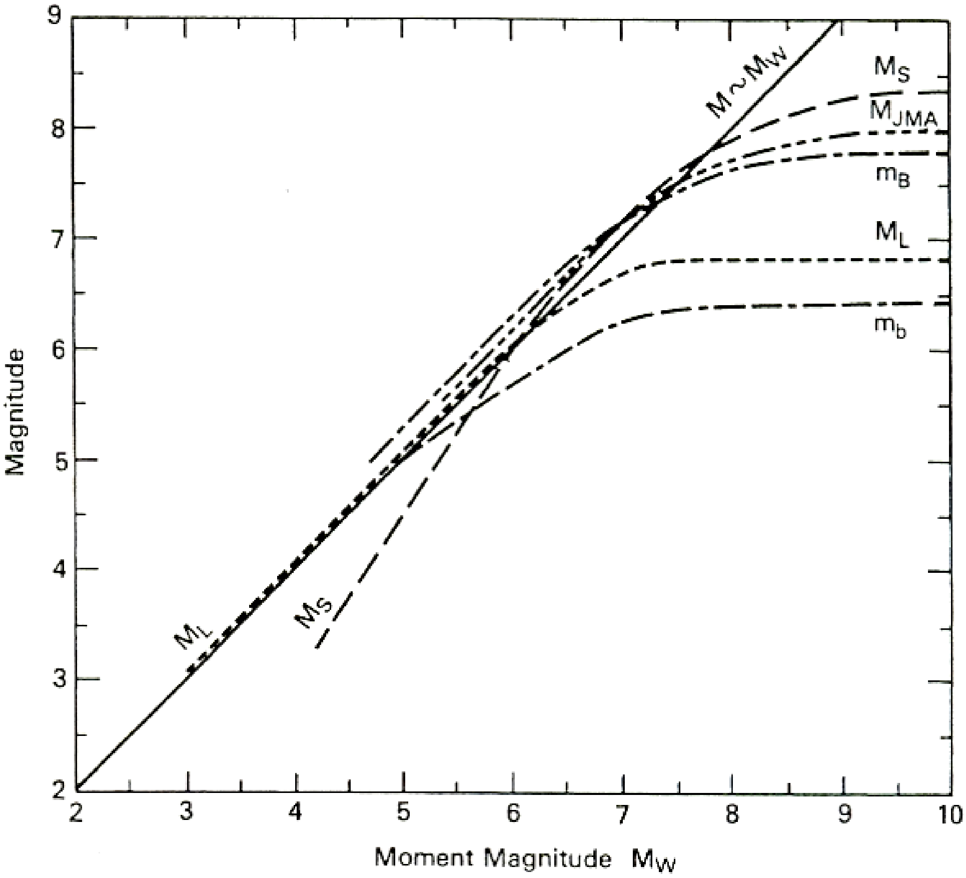


FIGURE 2.4 A comparison of moment magnitude with other magnitude scales (after Heaton, Tajima and Mori 1986).

Moment Magnitude Scale:

A more reliable and robust magnitude scale is moment magnitude (M_w). It was introduced by Hanks and Kanamori in 1979. It is based on the seismic moment (M_o), which is a measure of the whole dimension of the slipped fault:

$$M_W \quad = \quad (2/3).\,(\mathrm{Log}_{10}\, M_o\, -10.7)$$

Where M_o is seismic moment (in N.m). Geologically M_o is a description of the extent of deformation at the earthquake source. It is simply defined as:

$$M_o \quad = \quad m\,A\,D \quad = \quad 2\,m\,E_S\,/\,Ds$$

Where m is the shear modulus of the rock in the source region (typically 30 gigapascal)

A is the fault rupture area

D is the average dislocation or relative movement (slip) between the opposite sides of the fault.

E_S is radiated seismic energy

Ds is stress drop

The definition based on A D allows M_o to be derived from geological faulting parameters that can be easily observed in the field for large surface-rupturing earthquakes. The definition based on E_S / Ds allows M_o to be derived from seismological measurements.

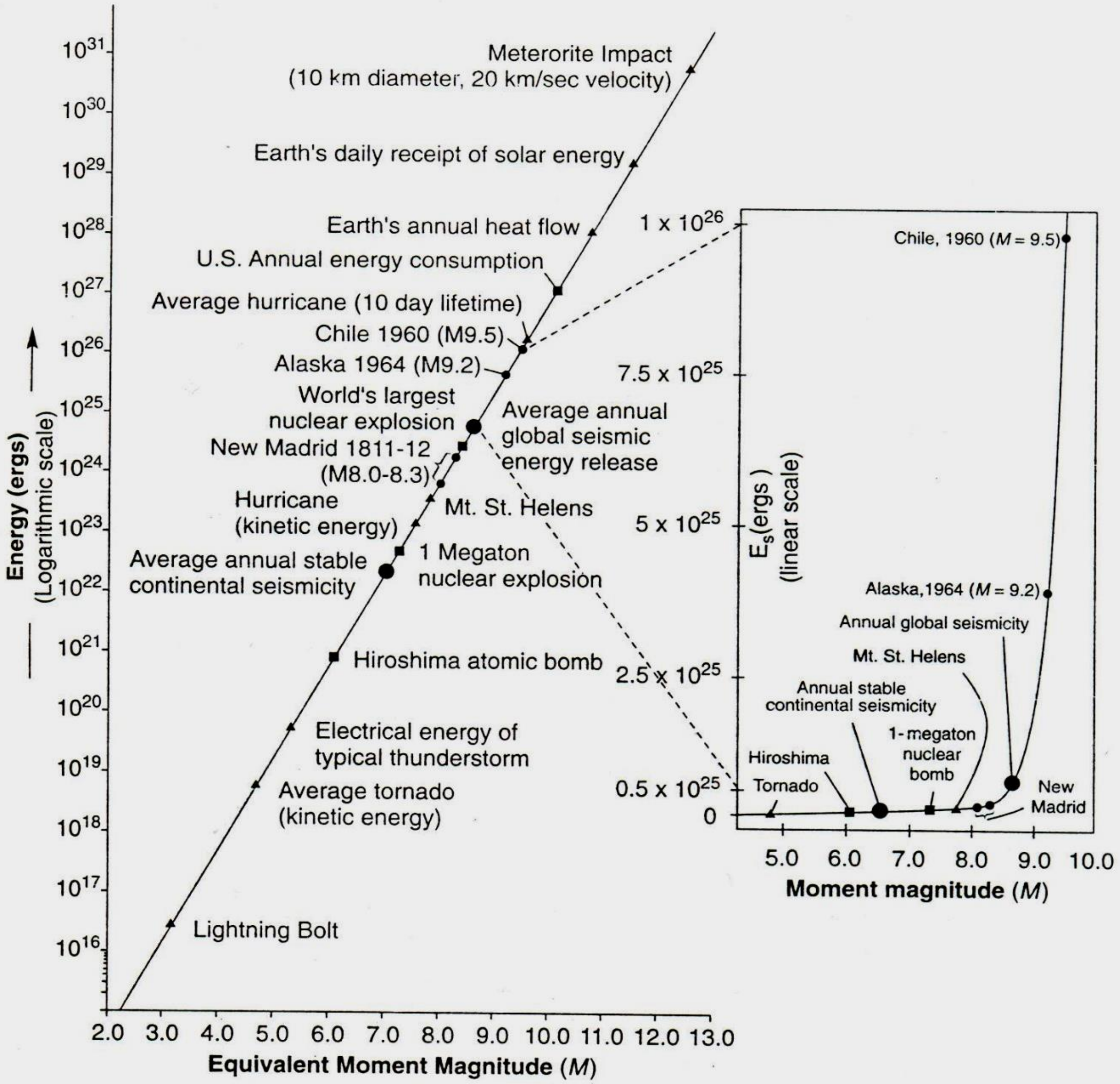


Figure 2.31 Relative energy of various natural and human-made phenomena. (After Johnston, 1990. Reprinted by permission of USGS.)

Earthquake Energy

Each unit change in magnitude corresponds to a 32 fold increase in earthquake energy.

1.17. USGS Earthquake Event Pages

An example of 24 September 2019 Mirpur Earthquake (M 5.4)

USGS Event Page:

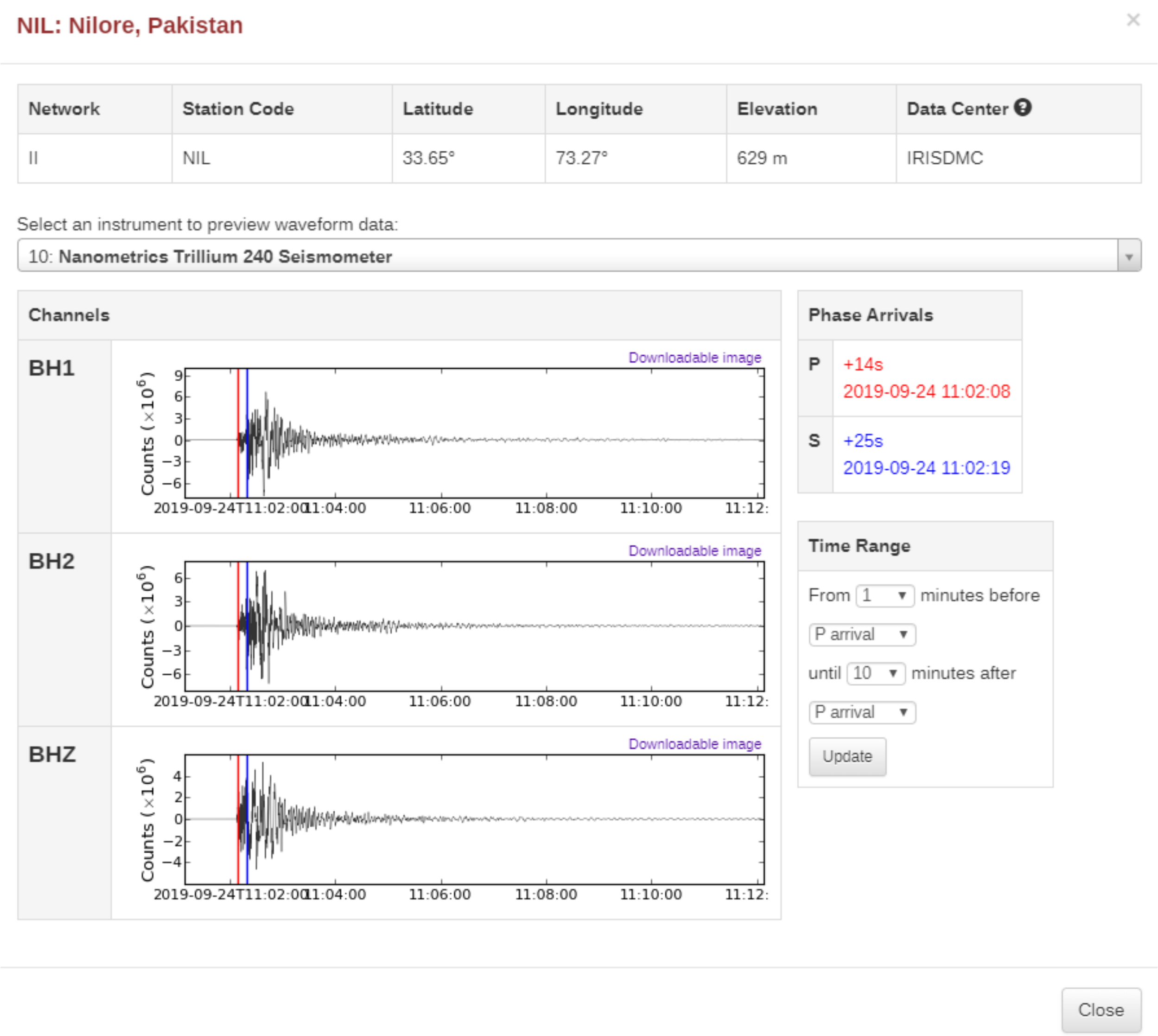
https://earthquake.usgs.gov/earthquakes/eventpage/us60005mqp/executive

IRIS Event Page:

http://ds.iris.edu/ds/nodes/dmc/tools/event/11121410

Time History Data from Wilber 3 (IRIS):

http://ds.iris.edu/wilber3/find_stations/11121410



NIL: Nilore, Pakistan

Network	Station Code	Latitude	Longitude	Elevation	Data Center
II	NIL	33.65°	73.27°	629 m	IRISDMC

Select an instrument to preview waveform data:
10: **Nanometrics Trillium 240 Seismometer**

Phase Arrivals	
P	+14s 2019-09-24 11:02:08
S	+25s 2019-09-24 11:02:19

Time Range

From 1 minutes before P arrival

until 10 minutes after P arrival

Chapter 2

Seismic Hazard Assessment

2.1. Earthquake Hazards

- Ground shaking
- Ground displacement along faults: surface rupture
- Ground failures: soil liquefaction, landslide, mud slide, differential soil settlement, etc.
- Tsunami
- Floods from dam and levee failures
- Fires resulting from earthquakes

Ground Shaking Hazard: Wenchuan Earthquake (2008), China (*Magnitude = 8.0)*

Ground Shaking Hazard: Kashmir Earthquake (2005), Balakot, Pakistan (*Magnitude* = *7.7)*

Ground Shaking Hazard: Yogyakarta Earthquake (2006), Indonesia (*Magnitude* = *6.2*)

Surface Rupture Hazard: The 1999 Chi-Chi earthquake, Taiwan

The 1999 Chi-Chi earthquake, Shih-Kang Dam

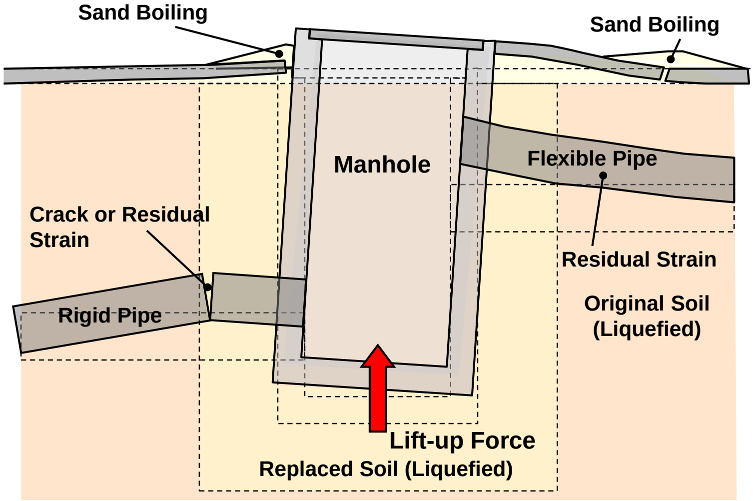
Soil Liquefaction Hazard

Loss of Bearing Capacity

A building in Dagupan, Philippines after the 1990 Luzon EQ

Overturned building in Adpazari, Turkey in the 1999 Kocaeli EQ

Damage to Sewers



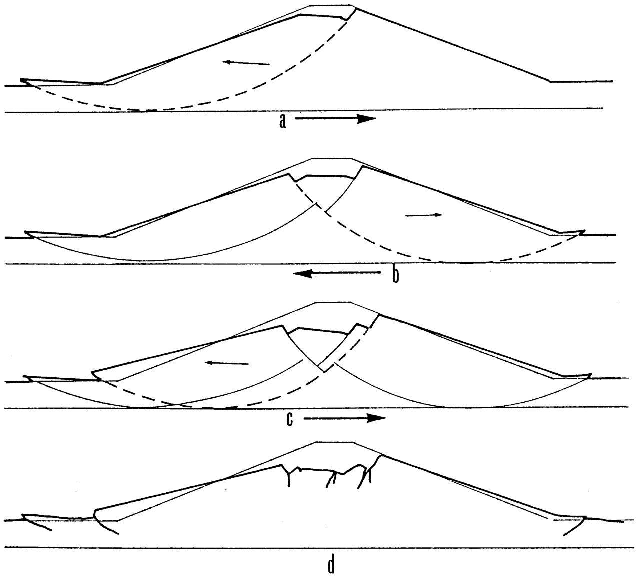
Tokachi-oki EQ, Hokkaido (2003)

Underground Pipe Failure in Baguio, Philippines *(Luzon Earthquake, 1990)*

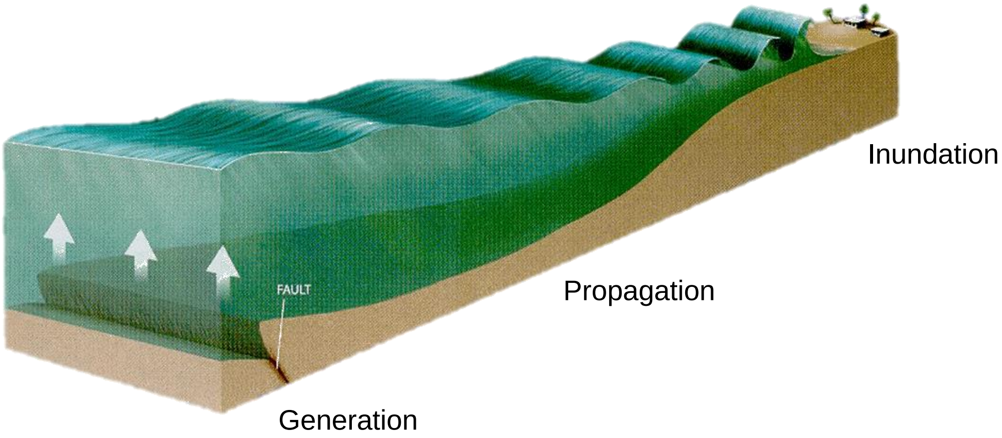
5

Earthquake-induced Landslide in Wenchuan County, China *(Wenchuan Earthquake, 2008)*

Dynamic Stability of Embankment



Bhuj earthquake 2001 Irrigation Dams



Tsunami generated by an earthquake

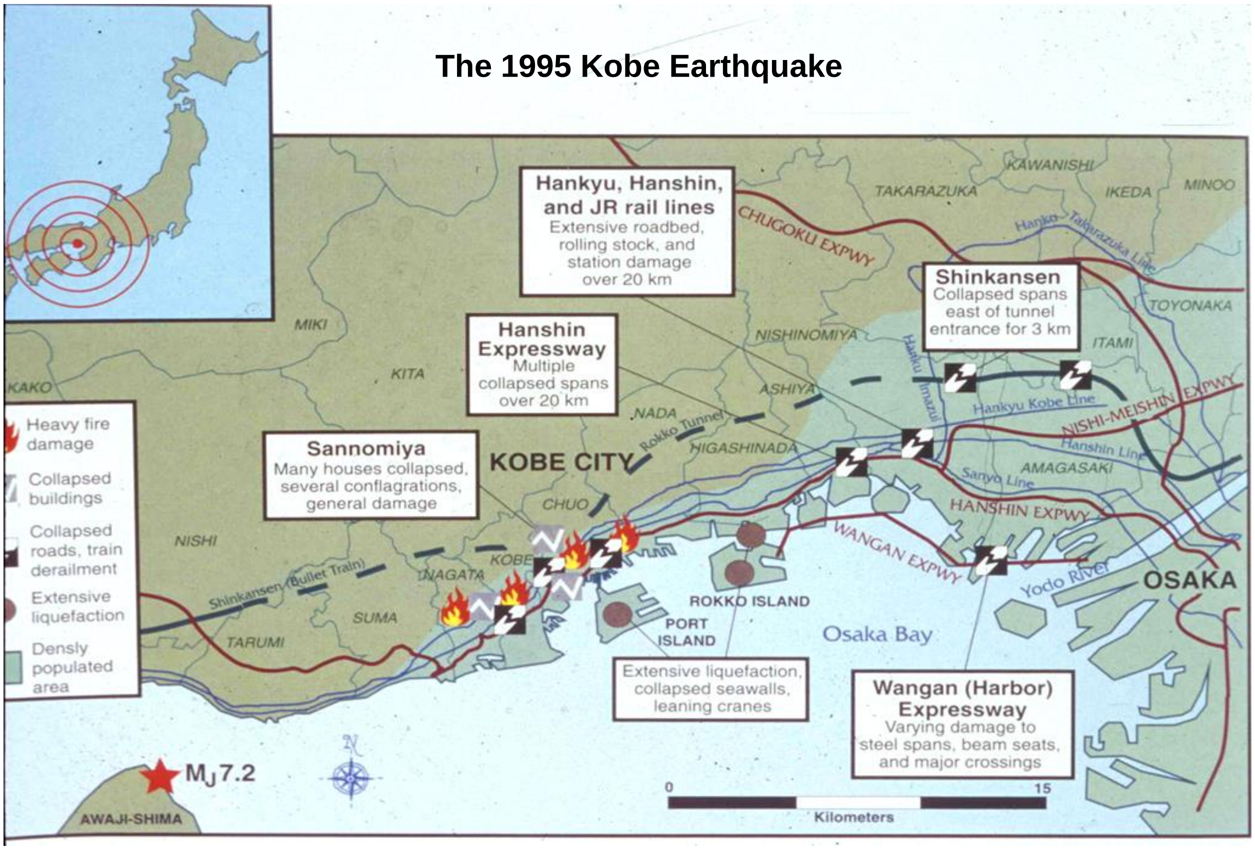
→ Normal Ocean waves — normally drive by wind — wavelength is 10s of meters. Period is low (freavency is high)

→ But ~~s~~tsunami waves — 100s of Km — Period is in order of 10min to several hours. The amplitude is very low in deep sea — when shallow zone, the amplitude can be amplified more than 10 times and it slows down.

Once EQ happen — the wave takes time to reach the shore — Thailand Tsunami — 2hours — warning System

There is no tsunamic-resistant design — You can run.

" " EQ - " " — " cannot " .



The 1995 Kobe Earthquake

Hankyu, Hanshin, and JR rail lines Extensive roadbed, rolling stock, and station damage over 20 km

Hanshin Expressway Multiple collapsed spans over 20 km

Sannomiya Many houses collapsed, several conflagrations, general damage

Shinkansen Collapsed spans east of tunnel entrance for 3 km

Extensive liquefaction, collapsed seawalls, leaning cranes

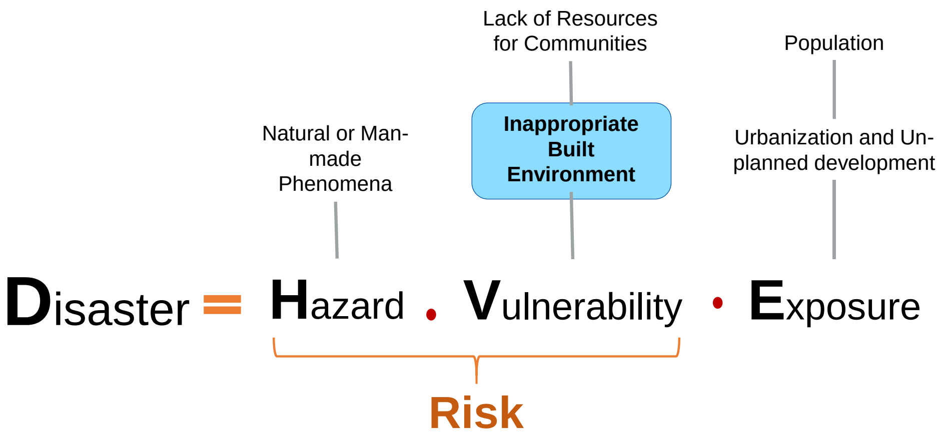
Wangan (Harbor) Expressway Varying damage to steel spans, beam seats, and major crossings

Fires resulting from the Earthquake (Kobe EQ, 1995)

Fires resulting from the Earthquake (Kobe EQ, 1995)

2.2. Basic Questions

- Where will future earthquakes occur?
- What will be their size?
- What will be their frequency of occurrence?
- What will be the ground shaking intensity at the site produced by earthquakes of different size, focal depth, and epicentral location?
- How will the ground motion be influenced by local soil conditions and geology?
- What will be the earthquake hazards (landslide, liquefaction, etc.) produced at the site?
- How about the susceptibility of buildings and structures to damage from the ground shaking and ground failures?



To reduce risk of disaster and increase safety,
we need to estimate hazard properly,
and Reduce **Vulnerability**

Seismic Hazard & Seismic risk

- It is not possible to predict when and where earthquakes will occur and how large they will be, therefore, seismic hazard must be described in terms of probabilities.
- Seismic hazard: the probability of occurrence of potentially destructive seismic ground shaking at given site within a given time interval.
- Seismic risk: the “risk” depends not only on “seismic hazard” but also on the susceptibility to damage of structure.

2.3. Seismic Hazard and Seismic Risk

SEISMIC HAZARD × SEISMIC VULNERABILITY = SEISMIC RISK

- In principle, Seismic Hazard Assessment (SHA) can address any natural hazard associated with earthquakes, including ground shaking, fault rupture, landslide, liquefaction, or tsunami.
- However, most interest is in the estimation of ground-shaking hazard, since it causes the largest economic losses in most earthquakes.
- Moreover, of all the seismic hazards, ground motion is the predominant cause of damage from earthquakes; building collapses, dam failures, landslides, and liquefactions are all the direct result of ground motion.
- *The Chapter, therefore, is restricted to the estimation of the earthquake ground motion hazard*.

Seismic Zone: A seismic zone is generally a large region within which, for practical purposes, the seismic hazard may be taken to be approximately uniform.

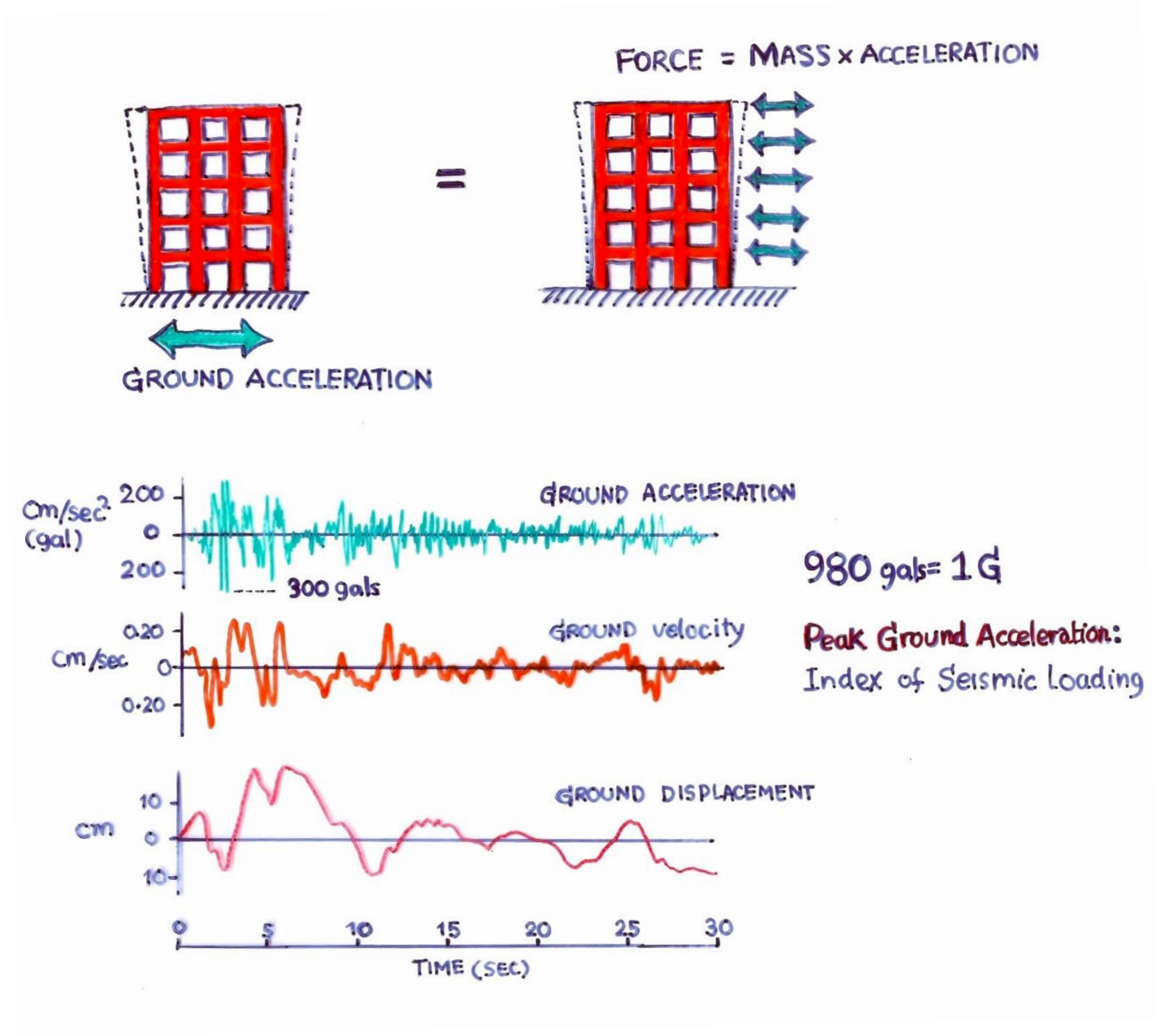
A seismic microzone is a small area within a region that has variations in hazard due to local soil conditions, topography, proximity to faults, etc. (the microzonation is not included in the scope of this lecture).

2.4. Ground Motion Parameters

There are many different ground motion parameters—displacement, velocity, acceleration, or MMI.

Usually Peak Ground Acceleration (PGA) is considered to be the preferred ground motion parameter.

Seismic Hazard = Ground-shaking Hazard = the probability of occurrence of potentially destructive seismic ground shaking at a given site within a given time interval.



Ground Motion Parameters

Baseline Correction:

A common source of error → Triggering acceleration

results in a Linear errors in velocity. → quadratic error in displacement

Correct using baseline correction → subtract the constant acceleration.

If linear error in acceleration → quadratic error in velocity.

Removing Noise:

To overcome, we apply filters.

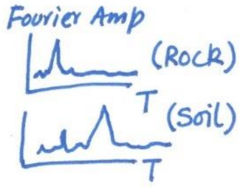
High pass filter → Removes all low frequency noise (usually below 0.1 Hz) e.g thunderstorms very far away.
Allow high freq to pass

Low pass filter → Removes all high freq noise (usually above 25 Hz). e.g from machinery.

Band pass filter → Removes both high and low freq noise.
(Butterworth filter)

Ground Motion Parameters:

- a) Amplitude
    - PGA
    - PGV
    - PGD
- b) Freq. content
    - Fourier spectrum ↑ e.g
    - Response spectrum
    - T_P (Period at which max SA occurs in RS (5% damping))
    - Bandwidth (the range of freq over which some level of fourier amplitude is exceeded (usually $1/\sqrt{2}$ X max amplitude).
    - Mean Period
    - $\frac{V_{max}}{A_{max}}$
    - Shape factor
    - Central Freq
- c) Duration
    - Bracketed duration
    - eq. No. of cycles



Bracketed Duration (Td)**:** the length of time between first and last threshold acceleration (usually 0.05g).

Equivalent No. of cycles: Conversion between EQ magnitude and the number of equivalent laboratory uniform harmonic stress cycles it would take to produce the same effects in soil. (Related to the amount of energy input to the soil)

Parameters Considering Amplitude, Freq Content and Duration

Arias Intensity (I_a)

quantifies the amount of energy from a strong ground motion record by Integrating the acceleration time history.

$$I_a = \frac{\pi}{2g} \int_0^{\infty} [a(t)]^2 \, dt$$

"Significant time" is the amount of time it takes to Integrate from $I_a = 5\%$ to $I_a = 95\%$ of the maximum value.

Cumulative Abs Velocity (CAV)

Simple integration of the area under the absolute accelerogram.

$$CAV = \int_0^{T_d} |a(t)| \, dt$$

2.5. Seismic Hazard Assessment

Seismic Hazard Analysis (SHA) has been widely used by engineers, regulators, and planners to mitigate earthquake losses:

- ✓ Specifying seismic design levels for individual structures and building codes
- ✓ Evaluating the seismic safety of existing facilities
- ✓ Planning for societal and economic emergencies (emergency preparedness)
- ✓ Setting priorities for the mitigation of seismic risk
- ✓ Insurance analysis

Information for Seismic Hazard Analysis:

a) Seismic Sources

- Location, shape, activity of seismic source zones (or faults)
- Historical earthquake record (date, time, epicenter co-or, M. focal depth)
- Magnitude—recurrence relationship for each source zone (or fault)

b) Ground motion Characteristics

- Accelerogrärms at many sites, observed intensities of shaking
- Related geological information
- Attenuation relationship

The determination of probabilistic ground acceleration should be rationally based on all available information.

2.6. Probabilistic vs. Deterministic

DSHA considers the effect at a site of either a single scenario earthquake, or a relatively small number of individual earthquakes.

Difficulties surrounded the selection of a representative earthquake on which the hazard assessment would be based.

PSHA quantifies the hazard at a site from all earthquakes of all possible magnitudes, at all significant distances from the site of interest, as a probability by taking into account their frequency of occurrence.

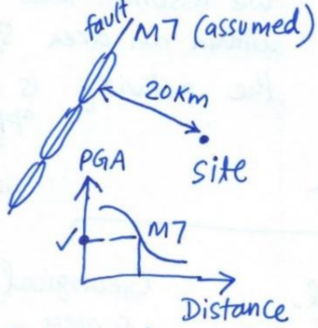
Deterministic earthquake scenarios, therefore, are a subset of the probabilistic methodology.

Seismic Hazard Analysis (SHA)

(Evaluating design parameters of EQ ground motions at a particular site)

Deterministic Approach (DSHA)

(Quantitative estimate of EQ hazard based on single EQ magnitude assumed to occur at a fixed distance from site and a specified GM probability level)



You consider only the worst "Scenario"

✓ used for design

- The attenuation relation have uncertainity.

- If more than one source — then critical scenario ???
- If fault can produce M7 in 50 or 500 years ⟶ Same Answer ???

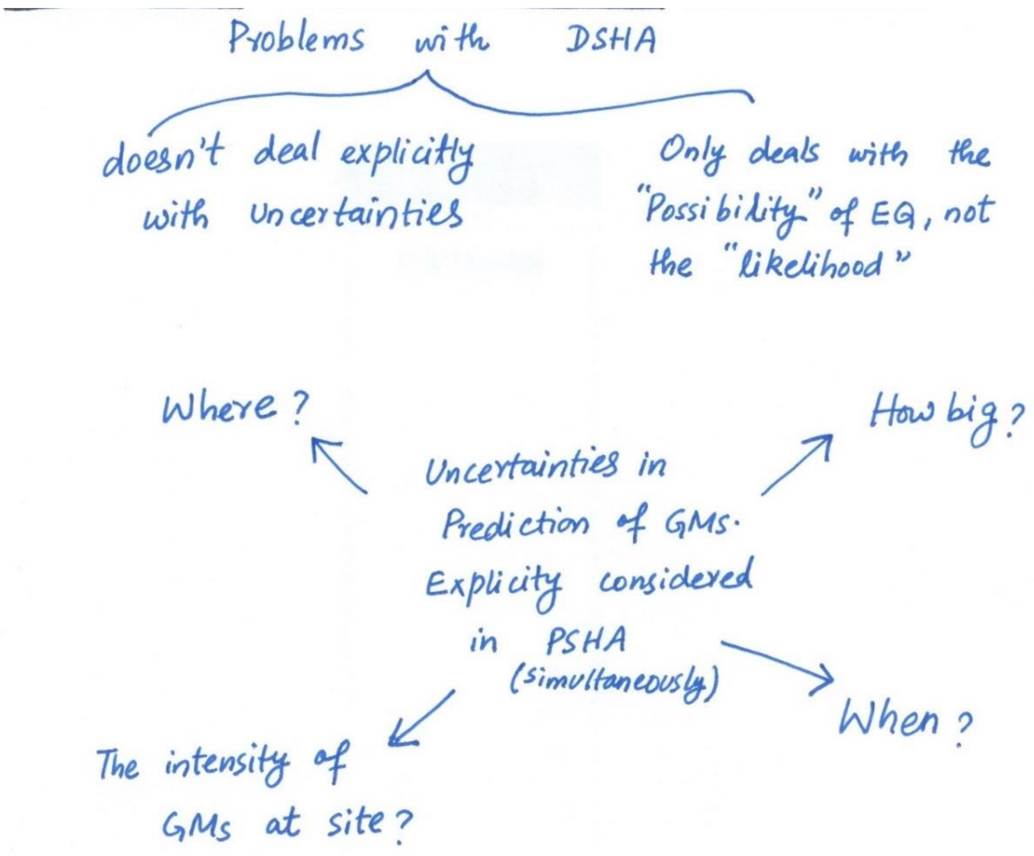
Probabilistic Seismic Hazard Analysis (PSHA)

(Quantitative estimate of EQ hazard considering all possible EQs from all possible sources and probability of these occurances; An Integrated approach Covering all uncertainities

↓

Seismic Risk Analysis (SRA)

The estimation of damage arising from EQ hazard and evaluating its socio-economic impact; SRA would be preceded by PSHA.



2.7. The Probabilistic Seismic Hazard Assessment (PSHA)

Probabilities are useful in characterizing seismic hazard since earthquakes and their effects are random phenomena.

Probabilistic seismic hazard analysis(PSHA) takes into account the seismic potential of the seismic sources, the random nature of earthquake occurrences, the random nature of the ground motion produced by these earthquakes, the damage potential of these ground motions, and the uncertainties involved at all levels of the process .

Prior to the widespread use of PSHA for assessing earthquake hazards, Deterministic methods (DSHA) dominated such assessments.

2.8. The PSHA Procedure

1) Selection of site(s)
2) Identification of all critical tectonic features (e.g. active faults, seismic source zones) likely to generate significant earthquakes—seismic sources
3) Defining the seismicity of these seismic sources

4) Selection of a suitable attenuation relationship—an equation that estimates ground-motion parameters from earthquake magnitude and source-to-site distance for various site conditions
5) Computation of the ground motion parameters at the site.

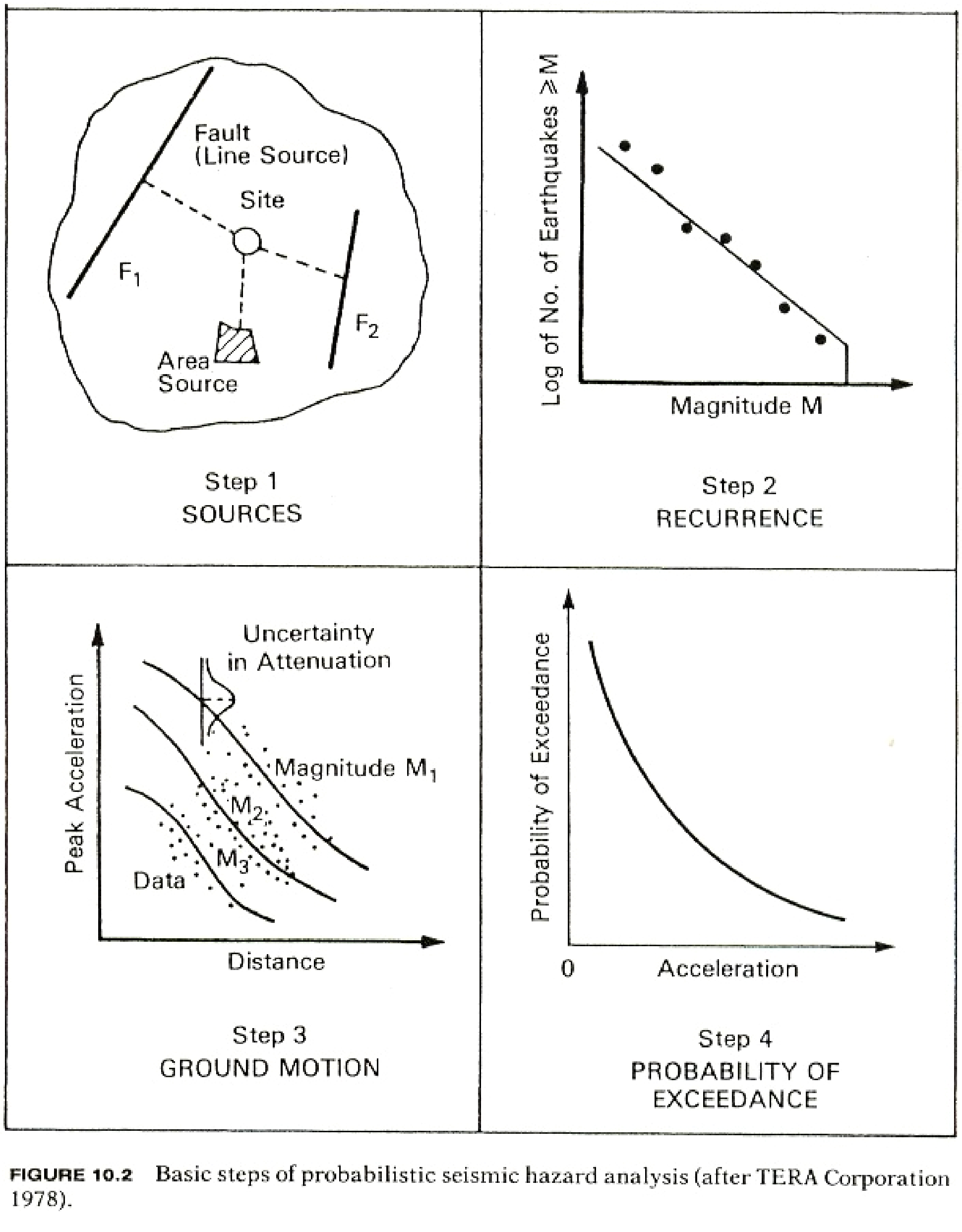


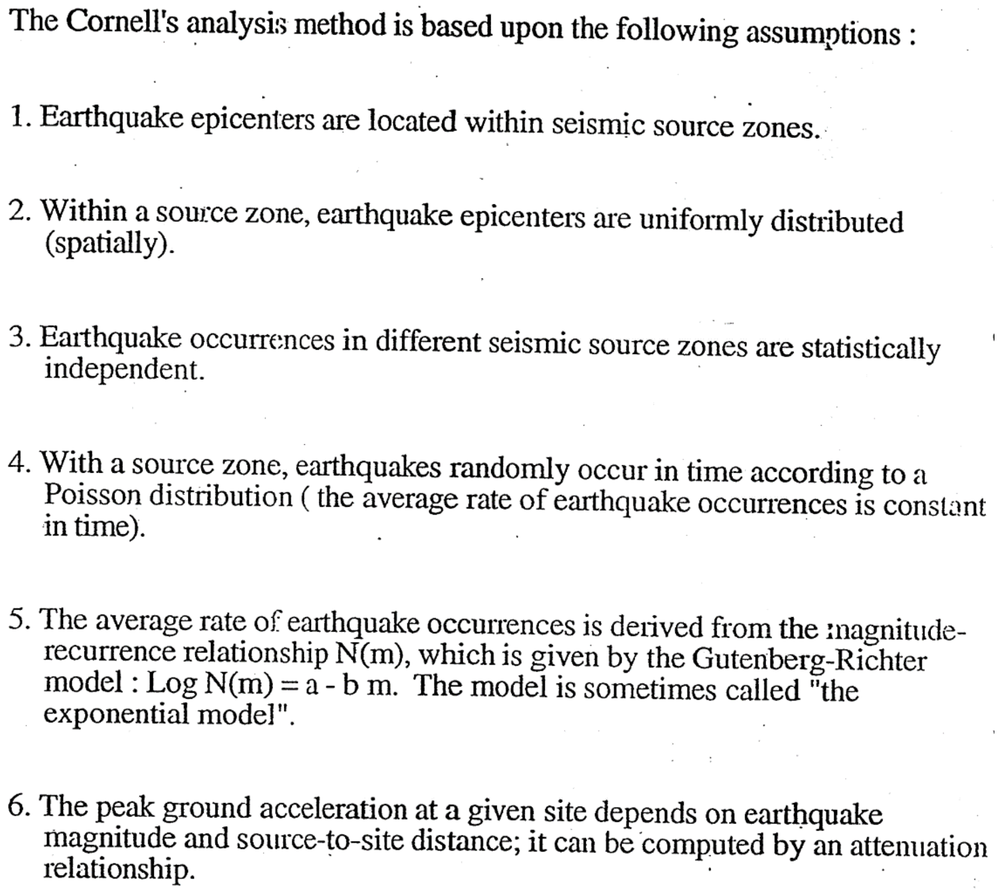
FIGURE 10.2 Basic steps of probabilistic seismic hazard analysis (after TERA Corporation 1978).

- The analytical approach of PSHA was first developed by C.A. Cornell in 1968.
- It was used by S.T. Algermissen et.al. (USGS) for developing a probabilistic seismic hazard map of US in 1976.

- The map was later on used as a basis for developing the US seismic zone map in the Uniform Building Code (US) in 1988.
- The analysis procedure is currently widely accepted and used all over the world.

The Key Assumptions in Calculating Probabilistic Ground Motions

1) Earthquakes occur within the defined seismic source zones or along the defined active faults.
2) Within each defined seismic source zone (or active fault), earthquakes occur randomly at any location with an equal chance (probability).
3) Within each defined seismic source zone (or active fault), earthquakes randomly occur in time, in which the average rate of occurrence is defined by its magnitude-recurrence relation. This random occurrence in time is modeled as a Possion process.
4) The occurrence of an earthquake is statistically independent of the occurrence of other earthquakes.
5) In any earthquake event, the ground motion parameter (e.g. PGA, SA) at the site of interest can be estimated from the earthquake magnitude, source-to-site distance, and other earthquake parameters by using the selected attenuation relationship.



The Cornell's analysis method is based upon the following assumptions :

1. Earthquake epicenters are located within seismic source zones.
2. Within a source zone, earthquake epicenters are uniformly distributed (spatially).
3. Earthquake occurrences in different seismic source zones are statistically independent.
4. With a source zone, earthquakes randomly occur in time according to a Poisson distribution (the average rate of earthquake occurrences is constant in time).
5. The average rate of earthquake occurrences is derived from the magnitude-recurrence relationship N(m), which is given by the Gutenberg-Richter model : Log N(m) = a - b m. The model is sometimes called "the exponential model".
6. The peak ground acceleration at a given site depends on earthquake magnitude and source-to-site distance; it can be computed by an attenuation relationship.

2.9. Identification of Seismic Sources

Where active faults have been identified and mapped, they become the sources of future earthquakes.

Where specific faults have not been identified or their characteristics are not well understood, it is common to define ‘seismic source zone’.

Within the seismic source zone, earthquakes are typically modeled either as a single point of energy release (a point source) or as a rupture on a fault (a finite-size source) with a random location or orientation.

In such cases, the challenge of the analyst is to identify source zones in which the seismicity is relatively uniform.

Even in areas where faults are well defined, a source zone may be needed to model the random occurrence of small and moderate earthquakes (M < 6.5)—background seismicity.

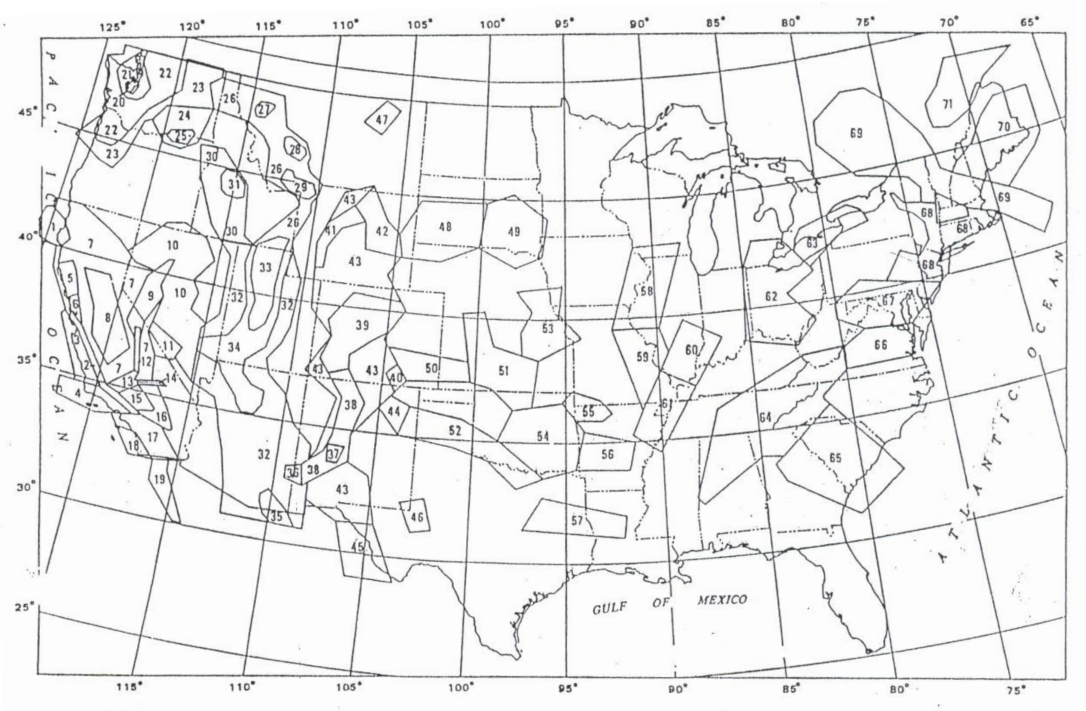
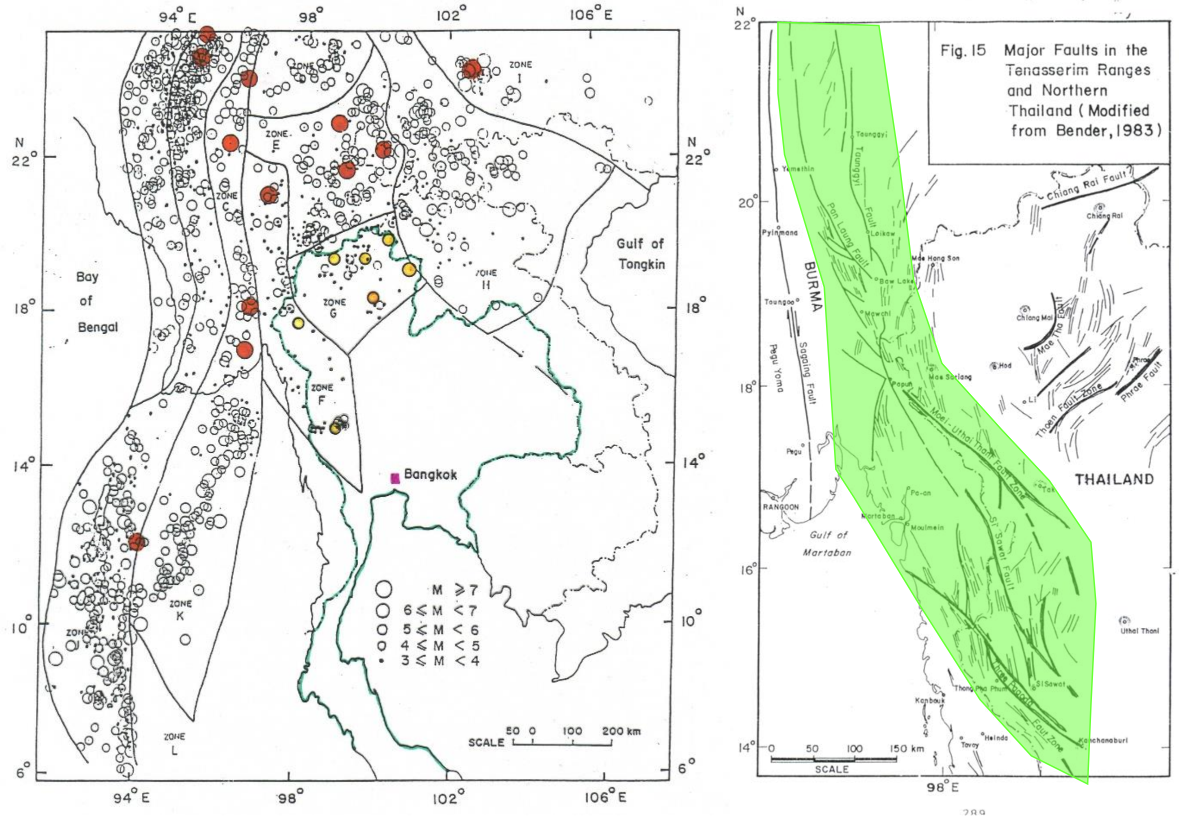
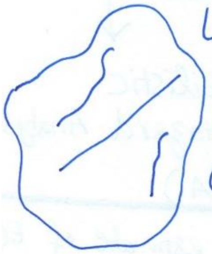


FIGURE 4.—Seismic source zones within the conterminous United States (from Algermissen and Perkins, 1976). Zone numbers correspond to those in table 4.



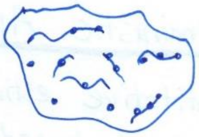
Earthquakes in Thailand-Burma-Indochina Region (1910-2000)

Seismic Sources



Line Sources
↓
Active faults
(explicit modeling)

Area source



many faults
|
we dont know much

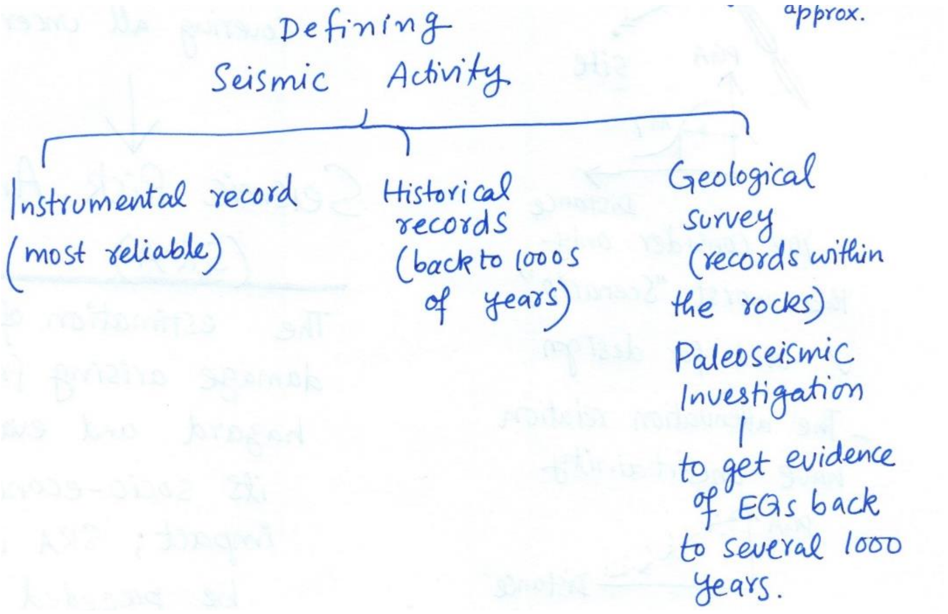
So we lump them into an area source ←
|
we assume that within an area source, the activity is uniform.
approx.

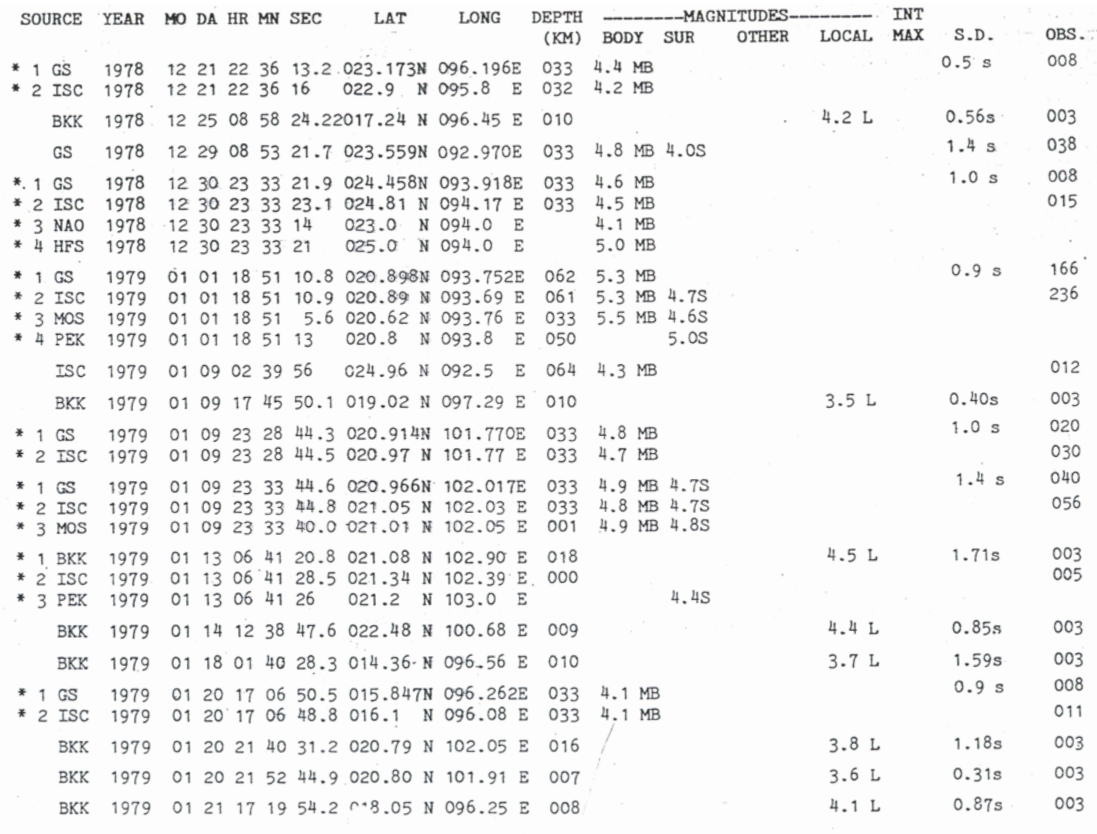
2.10. Defining the Seismicity of Seismic Sources

One commonly used parameter for defining the seismicity:

The rate of occurrence of earthquakes larger than some lower-bound magnitude $m_o = \nu$

- m_o is defined as the smallest earthquake expected to produce damage.
- Typically $m_o = 4.0$
- In traditional applications of PSHA, n is simply estimated from the historical rate of occurrence of earthquakes exceeding m_o
- The estimate requires historical and instrumental records of earthquakes
- Another relatively new technique—paleoseismic investigation—has been successful in providing information on prehistoric fault movements and seismicity of active faults.





SOURCE	YEAR	MO	DA	HR	MN	SEC	LAT	LONG	DEPTH	--------MAGNITUDES--------				INT	S.D.	OBS.
									(KM)	BODY	SUR	OTHER	LOCAL	MAX		
* 1 GS	1978	12	21	22	36	13.2	023.173N	096.196E	033	4.4 MB					0.5 s	008
* 2 ISC	1978	12	21	22	36	16	022.9 N	095.8 E	032	4.2 MB						
BKK	1978	12	25	08	58	24.22	017.24 N	096.45 E	010				4.2 L		0.56s	003
GS	1978	12	29	08	53	21.7	023.559N	092.970E	033	4.8 MB	4.0S				1.4 s	038
* 1 GS	1978	12	30	23	33	21.9	024.458N	093.918E	033	4.6 MB					1.0 s	008
* 2 ISC	1978	12	30	23	33	23.1	024.81 N	094.17 E	033	4.5 MB						015
* 3 NAO	1978	12	30	23	33	14	023.0 N	094.0 E		4.1 MB						
* 4 HFS	1978	12	30	23	33	21	025.0 N	094.0 E		5.0 MB						
* 1 GS	1979	01	01	18	51	10.8	020.898N	093.752E	062	5.3 MB					0.9 s	166
* 2 ISC	1979	01	01	18	51	10.9	020.89 N	093.69 E	061	5.3 MB	4.7S					236
* 3 MOS	1979	01	01	18	51	5.6	020.62 N	093.76 E	033	5.5 MB	4.6S					
* 4 PEK	1979	01	01	18	51	13	020.8 N	093.8 E	050		5.0S					
ISC	1979	01	09	02	39	56	024.96 N	092.5 E	064	4.3 MB						012
BKK	1979	01	09	17	45	50.1	019.02 N	097.29 E	010				3.5 L		0.40s	003
* 1 GS	1979	01	09	23	28	44.3	020.914N	101.770E	033	4.8 MB					1.0 s	020
* 2 ISC	1979	01	09	23	28	44.5	020.97 N	101.77 E	033	4.7 MB						030
* 1 GS	1979	01	09	23	33	44.6	020.966N	102.017E	033	4.9 MB	4.7S				1.4 s	040
* 2 ISC	1979	01	09	23	33	44.8	021.05 N	102.03 E	033	4.8 MB	4.7S					056
* 3 MOS	1979	01	09	23	33	40.0	021.01 N	102.05 E	001	4.9 MB	4.8S					
* 1 BKK	1979	01	13	06	41	20.8	021.08 N	102.90 E	018				4.5 L		1.71s	003
* 2 ISC	1979	01	13	06	41	28.5	021.34 N	102.39 E	000							005
* 3 PEK	1979	01	13	06	41	26	021.2 N	103.0 E			4.4S					
BKK	1979	01	14	12	38	47.6	022.48 N	100.68 E	009				4.4 L		0.85s	003
BKK	1979	01	18	01	40	28.3	014.36 N	096.56 E	010				3.7 L		1.59s	003
* 1 GS	1979	01	20	17	06	50.5	015.847N	096.262E	033	4.1 MB					0.9 s	008
* 2 ISC	1979	01	20	17	06	48.8	016.1 N	096.08 E	033	4.1 MB						011
BKK	1979	01	20	21	40	31.2	020.79 N	102.05 E	016				3.8 L		1.18s	003
BKK	1979	01	20	21	52	44.9	020.80 N	101.91 E	007				3.6 L		0.31s	003
BKK	1979	01	21	17	19	54.2	018.05 N	096.25 E	008				4.1 L		0.87s	003

Instrumental earthquake data of Myanmar, Thailand and Indonesia

Investigation of Active Faults: Fault Trenching in Taiwan

Geological Record found in a Fault Trench in Taiwan

Fault Trenching in Kanchanaburi, Thailand

2.10.1. Magnitude-Recurrence Relationship

The most commonly used equation (model) to describe the occurrence of earthquakes is the well-known Gutenberg-Richter relationship:

$$Log_{10} N(m) = a - b.m$$

N(m) is the average number per year of earthquakes having magnitudes greater than m. *a* and *b* are constants; they are conventionally obtained from an appropriate statistical analysis of historical earthquakes.

10^a is the average number per year of earthquakes above magnitude zero.

b describes the relative rate of occurrence of different magnitudes. *b* is typically 1.0 ± 0.3.

The form of this relationship has been verified from observations of seismicity throughout the world.

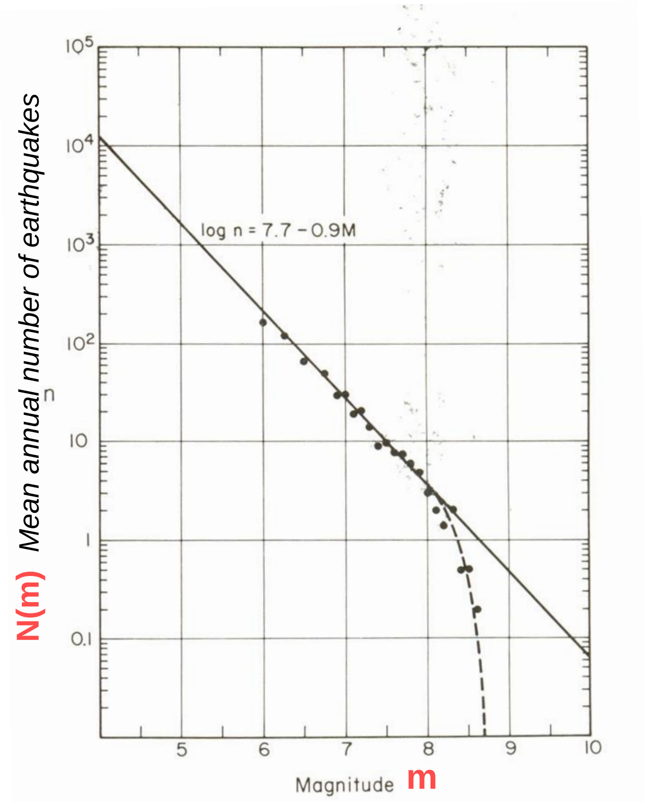


Fig. 5.5. Mean annual frequency distribution of world earthquakes, 1904–1946; *ndM* is the mean annual number of shocks having magnitudes lying between *M* and *M* + *dM*.

m	N(m)
8.0	2
7.0	20
6.0	100
5.0	3,000
4.0	15,000

The Gutenberg-Richter (exponential) model

Fault Sources

- For some faults, the occurrence rate of large earthquakes deviates from that predicted by Gutenberg-Richter relationship.
- For these faults, a characteristic earthquake model is thought to represent more accurately the seismicity of the fault.

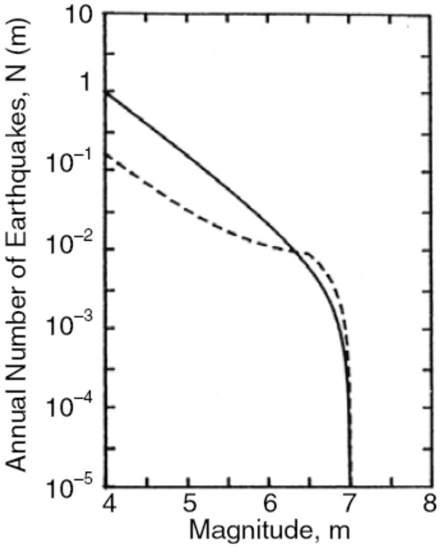
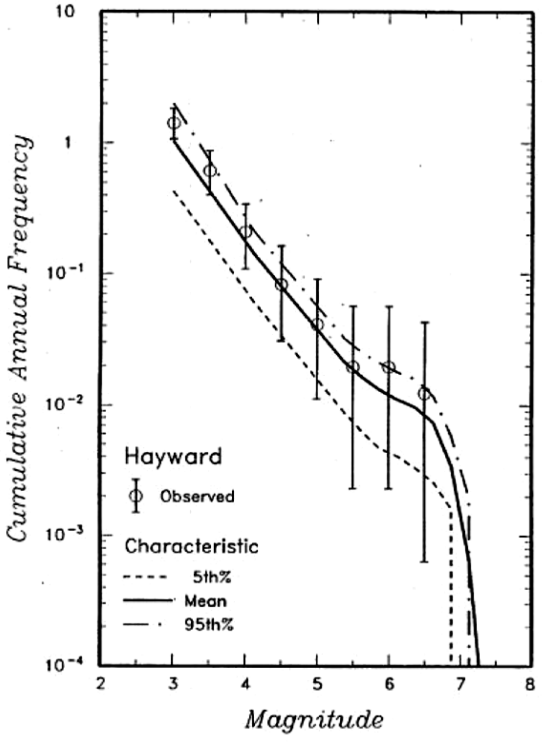
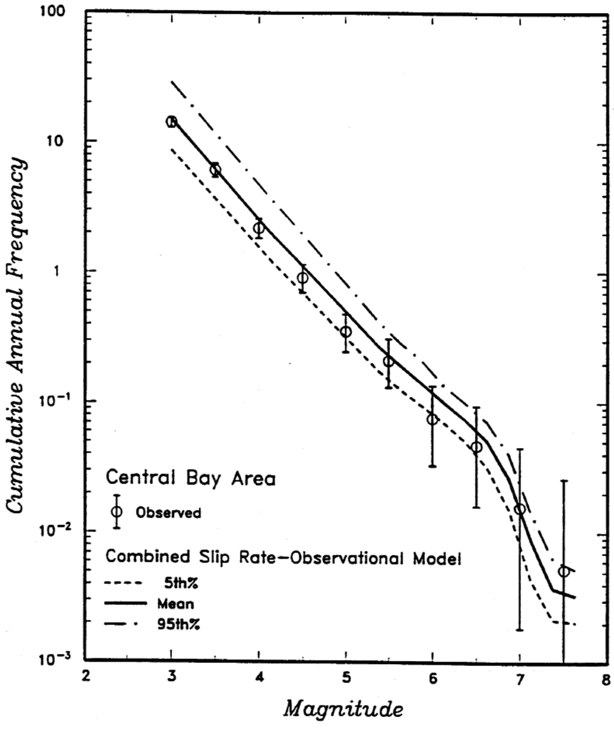


FIGURE 8.7 Comparison of the exponential (solid line) and characteristic recurrence (dashed line) frequency curves. (From Youngs, R.R. and Coppersmith, K.J., *Bull. Seismol. Soc. Am.*, 75, 939–964, 1985.)





2.10.2. Magnitude-scaling relationships

Provides M_w as a function of rupture area or rupture length (or vice versa).

Area → km^2
Length → km

Wells and Coppersmith (1994, Bulletin of SSA)

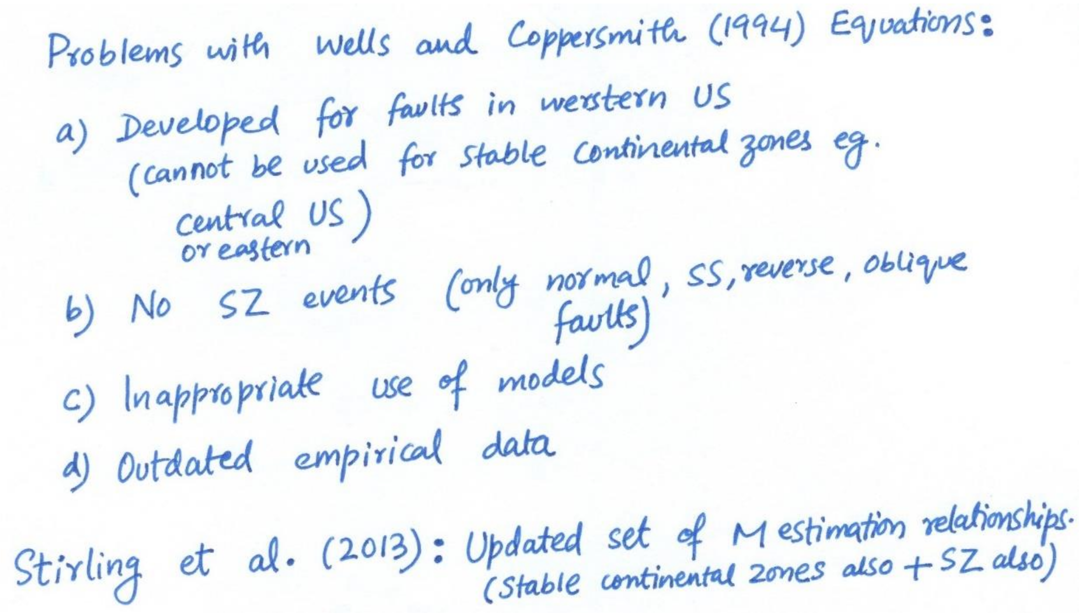
$$M_w = 4.07 + 0.98 \log(\text{Area}) \quad (\text{All rupture types})$$

$$M_w = 5.08 + 1.16 \log(\text{Length}) \quad (\text{All rupture types})$$

Wells and Coppersmith (1994) empirical relationships → $M = f(\text{geometry of fault})$

Surface rupture Length
width
rupture area
suface disp

$$\underset{\text{dependent variable (e.g M)}}{y} = \underbrace{a + b}_{\text{regression coefficients}}\,(\overset{\text{Independent variable}}{x}) + \underbrace{\underset{\text{Prob. of not exceeding a certain SD}}{\overset{\text{Students t-distribution}}{t_{(1-\alpha)}}} \cdot \underset{\text{SD}}{S} \cdot \left[\frac{1}{\underset{\text{no. of events/data points in the model}}{n}} + 1\right]^{1/2}}_{\text{Poobabilistic part}}$$



Problems with Wells and Coppersmith (1994) Equations:

a) Developed for faults in western US
(cannot be used for stable continental zones eg.
central US)
or eastern

b) No SZ events (only normal, SS, reverse, oblique faults)

c) Inappropriate use of models

d) Outdated empirical data

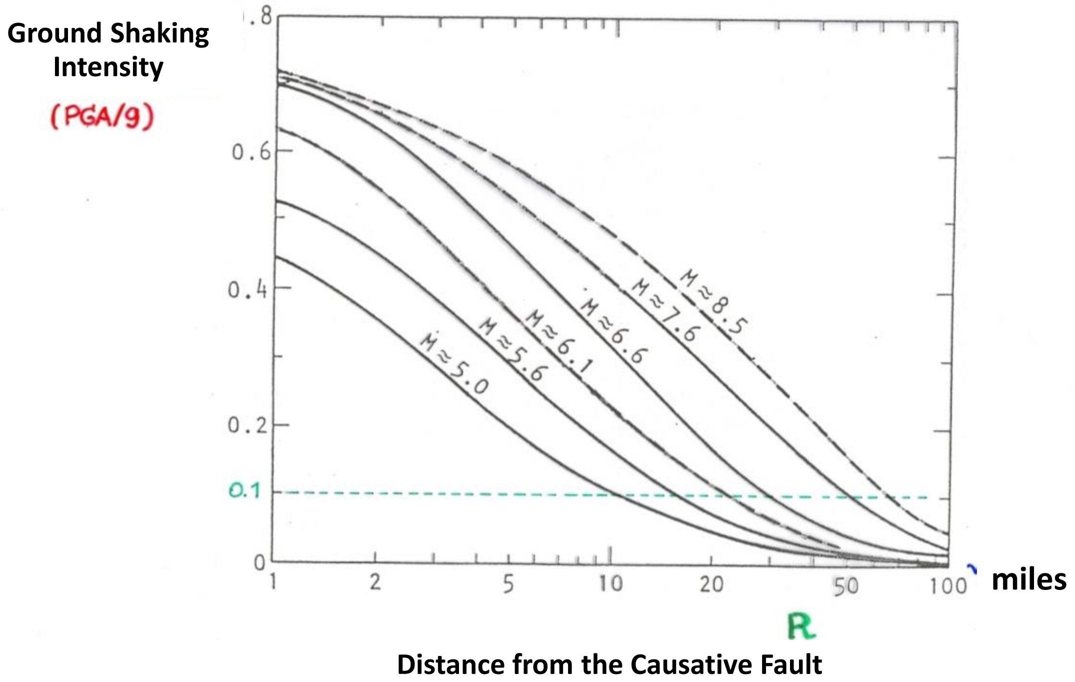
Stirling et al. (2013): Updated set of M estimation relationships.
(Stable continental zones also + SZ also)

2.11. Attenuation Relationships

The ground motion attenuation relationships provide the means of estimating a strong-ground-motion parameter of interest from parameters of the earthquake, such as magnitude, source-to-site distance, fault mechanism, local site conditions, etc.

A wide variety of empirical ground motion attenuation relationships is available for application in PSHA.

The choice of an appropriate relationship is governed by the regional tectonic setting of site of interest, whether it is located within a stable continental region, or an active tectonic region, or whether the site is in proximity to a subduction zone tectonic environment.



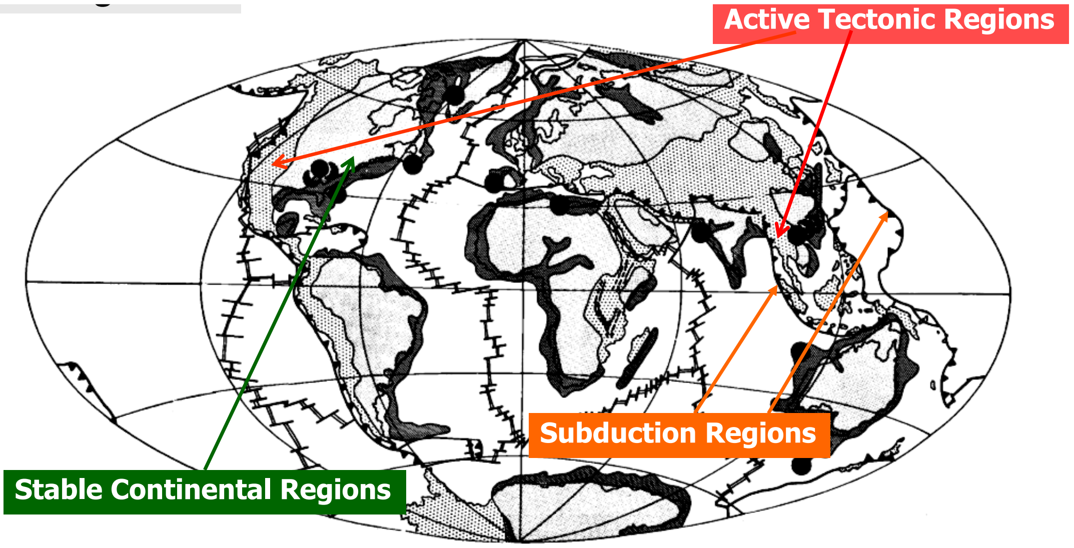


FIGURE 5.6 Geographic distribution of active and stable continental tectonic regions worldwide. (From Johnston, A.C. 1994. "Seismotectonic Interpretations and Conclusions from the Stable Continental Region Seismicity Database," in *The Earthquake of Stable Continental Regions, Vol. 1, Assessment of Large Earthquake Potential*, Electric Power Research Institute, Palo Alto, CA, pp. 1–103. With permission.)

TABLE 5.3 List of Selected Attenuation Relations

Region	Tectonic Environment	Attenuation Relation
Western North America	Shallow active crust	Abrahamson and Silva [1997] Boore et al. [1997] Campbell and Bozorgnia [in press] Sadigh et al. [1993, 1997]
Eastern North America	Shallow stable crust	Atkinson and Boore [1995, 1997] Toro et al. [1997] Campbell [in press]
Europe	Shallow active crust	Ambraseys et al. [1996]
	Shallow stable crust	Dahle et al. [1990]
Japan	All types undivided	Molas and Yamazaki [1995, 1996]
Worldwide	Shallow extended crust	Spudich et al. [1999]
	Subduction interface	Youngs et al. [1997]
	Subduction intraslab	Youngs et al. [1997]
	Subduction undivided	Crouse [1991a, 1991b]

Ground motion attenuation is often represented by the form:

$$Log_{10}Y = c_1 + c_2.M + c_3.Log_{10} R + c_4.R + c_5.F + c_6.S + e$$

Y is the ground motion parameter of interest (i.e. PGA, PGV, SA, SD)

M is earthquake magnitude

R is source-to-site distance

F is the faulting mechanism of the earthquake

S is a description of the local site conditions

e is a random error term with a mean of zero and a standard deviation of s (a Gaussian probability distribution); this term describes the variability in ground motion.

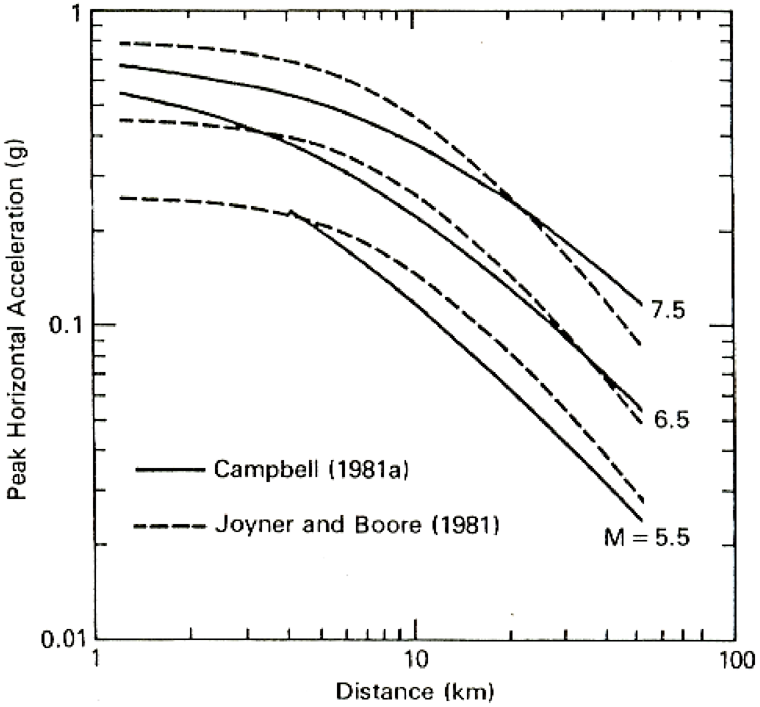
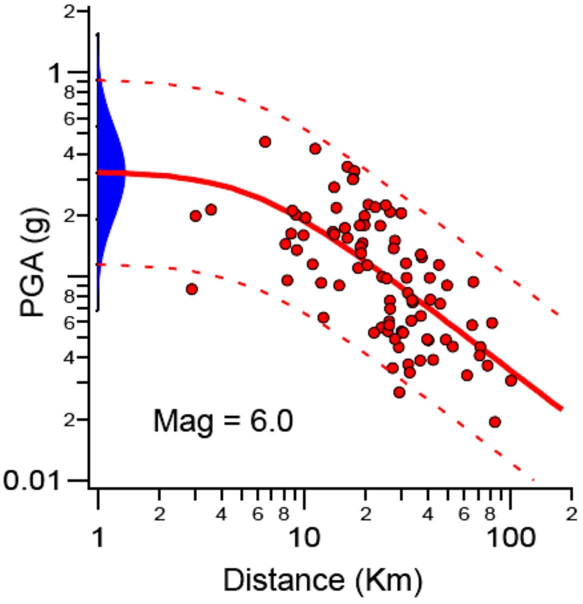


FIGURE 7.4 Median (50th percentile) estimates for peak horizontal acceleration from Campbell (1981a) and Joyner and Boore (1981). Joyner and Boore (1981) estimates of the maximum horizontal component have been reduced by 12% so that they may be compared with the (Campbell 1981a) estimates of the mean horizontal component (after Campbell 1981a).



Random error of attenuation model

$$\log SA_{(M,R,soil)} = \underbrace{\overline{\log SA}_{(M,R,soil)} + \varepsilon\sigma}_{\text{Come from GMPE}}$$

What are GMPEs?

GMPEs or attenuation relationships provide a means of predicting the level of ground shaking and its associated uncertainity at any given site or location, based on an EQ magnitude, source-to-site distance, local soil conditions, fault mechanism etc.

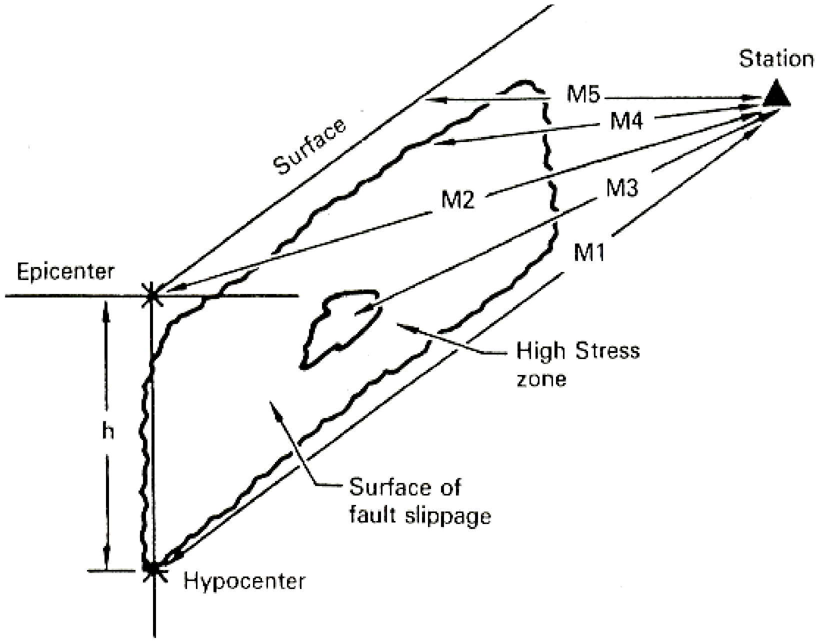


FIGURE 7.3 Schematic illustration of methods of distance measurement used in the determination of the distance value to be associated with a ground motion observation. M1 is the hypocentral distance (focal depth is h), M2 is the epicentral distance. M3 is the distance to the center of high-energy release (or high localized stress drop), M4 is the closest distance to the slipped fault, in this case, the fault rupture does not extend to the surface, and M5 is the closest distance to the surface projection of the fault rupture (after Shakal and Bernreuter 1981).

Source-to-site distance

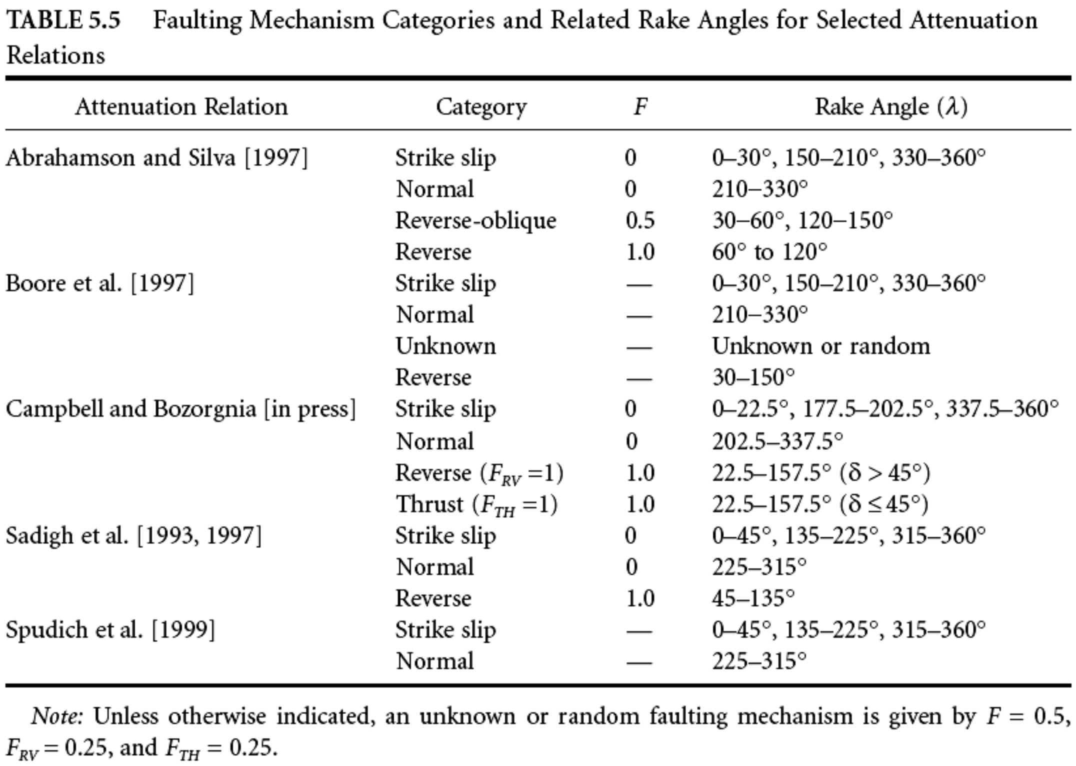


TABLE 5.5 Faulting Mechanism Categories and Related Rake Angles for Selected Attenuation Relations

Attenuation Relation	Category	F	Rake Angle (λ)
Abrahamson and Silva [1997]	Strike slip	0	0–30°, 150–210°, 330–360°
	Normal	0	210–330°
	Reverse-oblique	0.5	30–60°, 120–150°
	Reverse	1.0	60° to 120°
Boore et al. [1997]	Strike slip	—	0–30°, 150–210°, 330–360°
	Normal	—	210–330°
	Unknown	—	Unknown or random
	Reverse	—	30–150°
Campbell and Bozorgnia [in press]	Strike slip	0	0–22.5°, 177.5–202.5°, 337.5–360°
	Normal	0	202.5–337.5°
	Reverse ($F_{RV}=1$)	1.0	22.5–157.5° ($\delta > 45°$)
	Thrust ($F_{TH}=1$)	1.0	22.5–157.5° ($\delta \leq 45°$)
Sadigh et al. [1993, 1997]	Strike slip	0	0–45°, 135–225°, 315–360°
	Normal	0	225–315°
	Reverse	1.0	45–135°
Spudich et al. [1999]	Strike slip	—	0–45°, 135–225°, 315–360°
	Normal	—	225–315°

Note: Unless otherwise indicated, an unknown or random faulting mechanism is given by $F = 0.5$, $F_{RV} = 0.25$, and $F_{TH} = 0.25$.

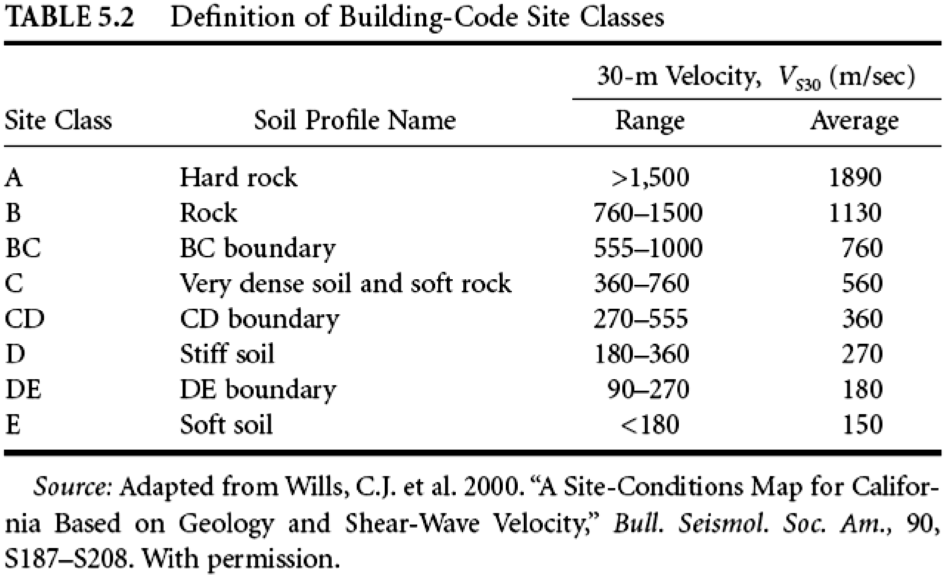


TABLE 5.2 Definition of Building-Code Site Classes

Site Class	Soil Profile Name	30-m Velocity, V_{S30} (m/sec) Range	Average
A	Hard rock	>1,500	1890
B	Rock	760–1500	1130
BC	BC boundary	555–1000	760
C	Very dense soil and soft rock	360–760	560
CD	CD boundary	270–555	360
D	Stiff soil	180–360	270
DE	DE boundary	90–270	180
E	Soft soil	<180	150

Source: Adapted from Wills, C.J. et al. 2000. "A Site-Conditions Map for California Based on Geology and Shear-Wave Velocity," *Bull. Seismol. Soc. Am.*, 90, S187–S208. With permission.

$$\log_{10} Y = c_1 + c_2 . M + c_3 . \log_{10} R + c_4 . R + c_5 . F + c_6 . S + e$$

Coefficients c_1, c_2, c_3, c_4, c_5, and c_6 are normally determined by fitting the equation to actual ground motion data (applying statistical regression analyses).

The term $c_3 . \log_{10} R$ represents the geometric attenuation of the seismic wave front as it propagates away from the earthquake source.

The term **$c_4.R$** represents the anelastic attenuation that results from the material damping and scattering as the seismic waves propagate through the crust.

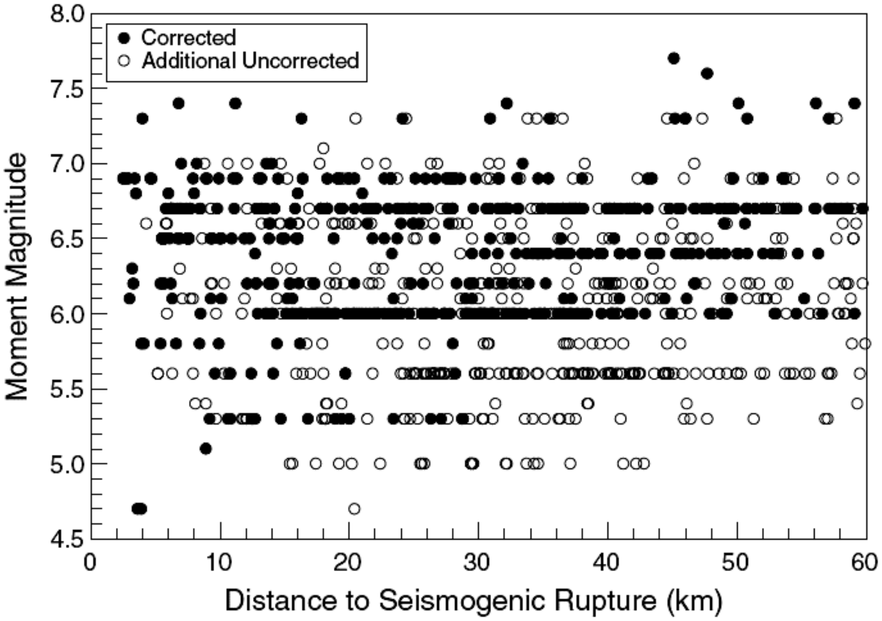


FIGURE 5.1 Example PGA attenuation relation (top) and its associated database (bottom). Uncorrected recordings are analog or digital acceleration time histories that have not been processed and, therefore, can provide only estimates of PGA. Corrected recordings are acceleration times histories that have been processed to derive velocity and displacement time histories, response spectra, and Fourier amplitude spectra. (From Campbell, K.W. and Bozorgnia, Y. 1999. "Vertical Ground Motion: Characteristics, Relationship with Horizontal Component, and Building-Code Implications," in *Proc. SMIP99 Seminar on Utilization of Strong-Motion Data*, M. Huang, Ed., Sept. 15, San Francisco, pp. 23–49. California Strong Motion Instrumentation Program, Sacramento. With permission.)

Ground motion database used for developing an attenuation relationship

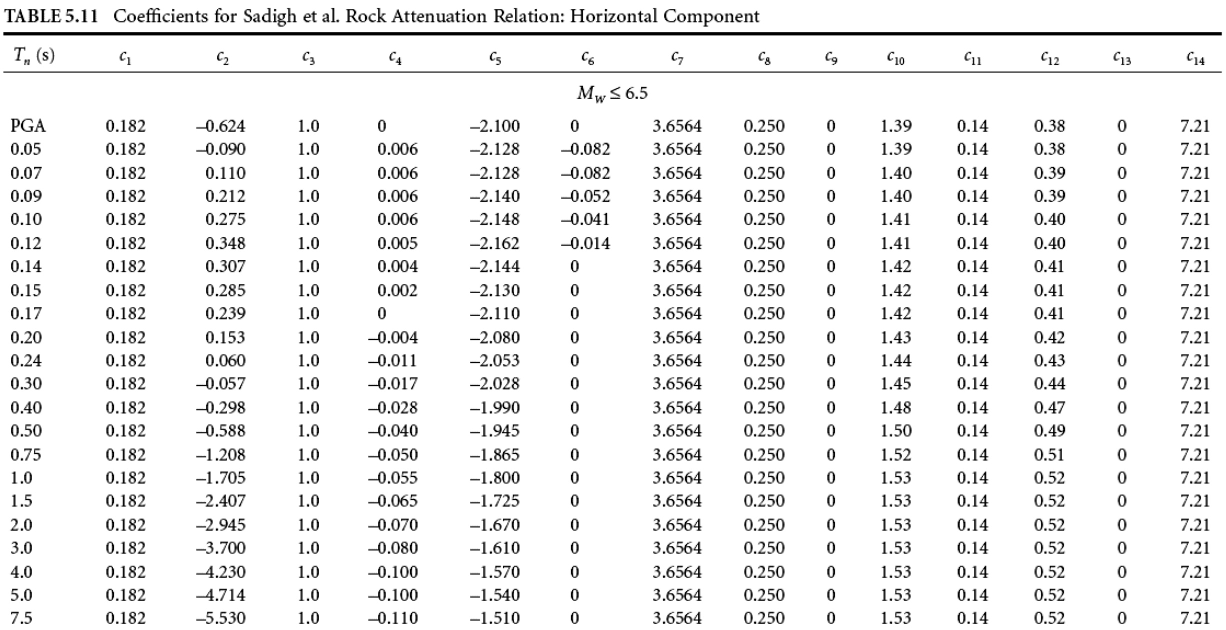
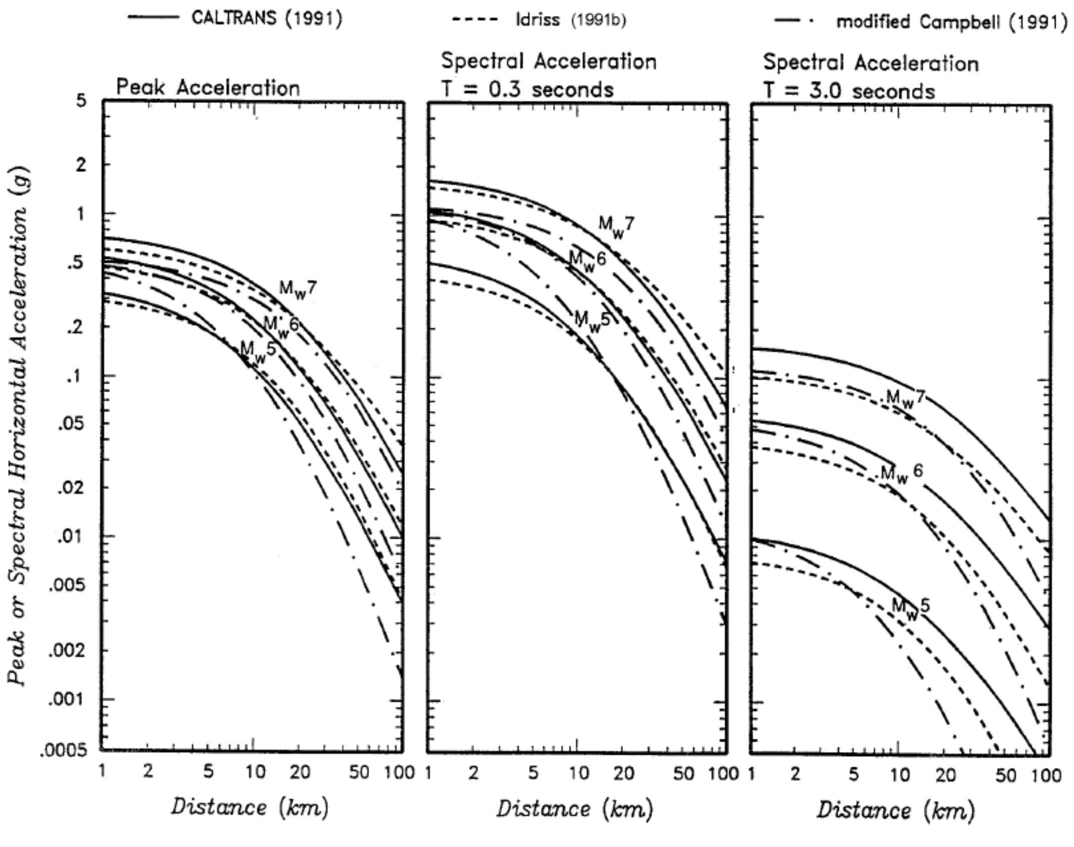


TABLE 5.11 Coefficients for Sadigh et al. Rock Attenuation Relation: Horizontal Component

T_n (s)	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	c_{11}	c_{12}	c_{13}	c_{14}
							$M_W \leq 6.5$							
PGA	0.182	–0.624	1.0	0	–2.100	0	3.6564	0.250	0	1.39	0.14	0.38	0	7.21
0.05	0.182	–0.090	1.0	0.006	–2.128	–0.082	3.6564	0.250	0	1.39	0.14	0.38	0	7.21
0.07	0.182	0.110	1.0	0.006	–2.128	–0.082	3.6564	0.250	0	1.40	0.14	0.39	0	7.21
0.09	0.182	0.212	1.0	0.006	–2.140	–0.052	3.6564	0.250	0	1.40	0.14	0.39	0	7.21
0.10	0.182	0.275	1.0	0.006	–2.148	–0.041	3.6564	0.250	0	1.41	0.14	0.40	0	7.21
0.12	0.182	0.348	1.0	0.005	–2.162	–0.014	3.6564	0.250	0	1.41	0.14	0.40	0	7.21
0.14	0.182	0.307	1.0	0.004	–2.144	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.15	0.182	0.285	1.0	0.002	–2.130	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.17	0.182	0.239	1.0	0	–2.110	0	3.6564	0.250	0	1.42	0.14	0.41	0	7.21
0.20	0.182	0.153	1.0	–0.004	–2.080	0	3.6564	0.250	0	1.43	0.14	0.42	0	7.21
0.24	0.182	0.060	1.0	–0.011	–2.053	0	3.6564	0.250	0	1.44	0.14	0.43	0	7.21
0.30	0.182	–0.057	1.0	–0.017	–2.028	0	3.6564	0.250	0	1.45	0.14	0.44	0	7.21
0.40	0.182	–0.298	1.0	–0.028	–1.990	0	3.6564	0.250	0	1.48	0.14	0.47	0	7.21
0.50	0.182	–0.588	1.0	–0.040	–1.945	0	3.6564	0.250	0	1.50	0.14	0.49	0	7.21
0.75	0.182	–1.208	1.0	–0.050	–1.865	0	3.6564	0.250	0	1.52	0.14	0.51	0	7.21
1.0	0.182	–1.705	1.0	–0.055	–1.800	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
1.5	0.182	–2.407	1.0	–0.065	–1.725	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
2.0	0.182	–2.945	1.0	–0.070	–1.670	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
3.0	0.182	–3.700	1.0	–0.080	–1.610	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
4.0	0.182	–4.230	1.0	–0.100	–1.570	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
5.0	0.182	–4.714	1.0	–0.100	–1.540	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21
7.5	0.182	–5.530	1.0	–0.110	–1.510	0	3.6564	0.250	0	1.53	0.14	0.52	0	7.21

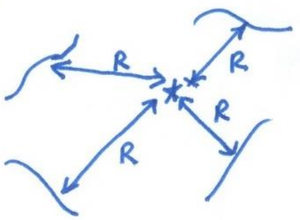
Coefficients of an attenuation relationship



Attenuation models for SA

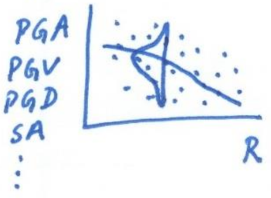
Ground Motion Prediction Equations

GMPEs: use the data that we have collected so far and fit equations to them for predicting future grond motions.



We don't know many things about future grond motions. But may be (just may be) we do know Rs for each source.

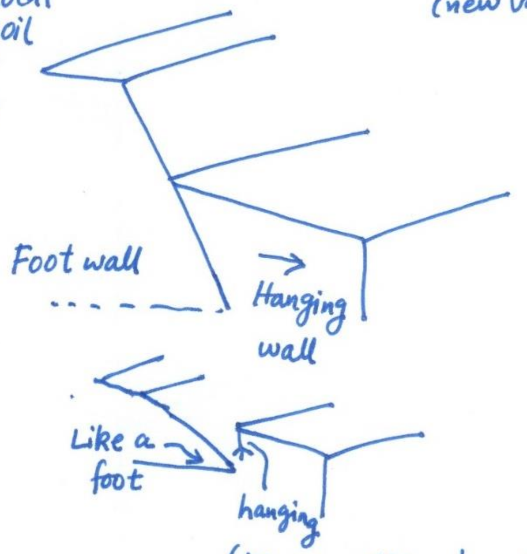
So if 1000s of recordings available



f(M, R)
↓ but
more complex eqs as we try to minimize scatter. (new variables)

Modern GMPEs → SA at different Ts.

- Fault type
- Fault Geometry
- Hanging wall / foot wall
- Site response effects — Local soil
  - Filter
  - Amplify
  - Deamplify
- Basin effect (reflections of seismic waves)
- Main Shock vs. after shock effects



(like something hanging)

If you are on hanging wall your GMs are much higher than if you are on footwall.

Ideally → All geographic areas should have their own set of GMPEs
↓
but not enough recorded data

So, we start combining earthquake records from geographically different areas with the assumption that the GMS should be similar despite the differences in location ⟶ Ergodic Assumption

Next Generation Attenuation Relationships (NGAs)

5 separate research teams were given the same set of GM data and were asked to develop relationships to fit the data. They could have used it in whatever way they want (exclude some, consider just a subset of data etc. etc.).

"For crustal faults in the Western US and other high- to moderate-seismicity areas" [Mainly administered and funded by PEER]

Their results published in 2008. (NGA West 1)

Updated " " " 2014 (NGA West 2)

Journal → Earthquake Spectra

a) Abrahamson, Silva and Kamai

b) Chiou and Youngs

c) Campbell and Bozorgnia

d) Boore, Stewart, Seyhan and Atkinson

e) Idriss

a – d → Used all data (recorded on rock or soil)

Idriss → used data recorded on stiff soil and rock only. (so shouldn't be used for soils or soft soils).

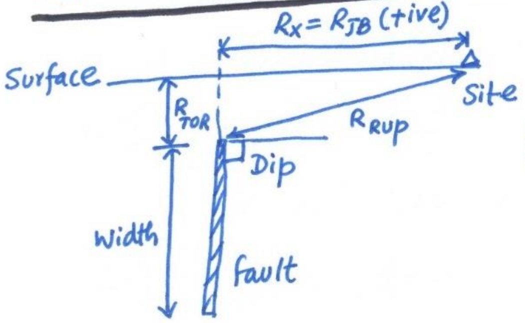
a) Pre-NGA GMPES → mostly from Abrahamson and Silva's work.

b) NGA West 1 → Recorded data is doubled (2 × a)

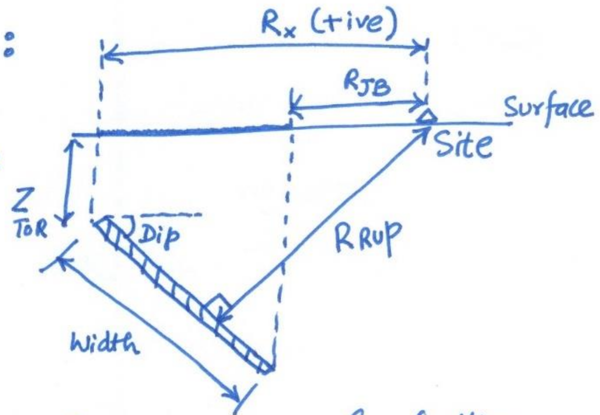
c) NGA West 2 → " " " 3 times. (3 × a)

[There are no subduction zone GMs in NGA West GMPES. Only crustal faults.]

NGA Distance Notations :



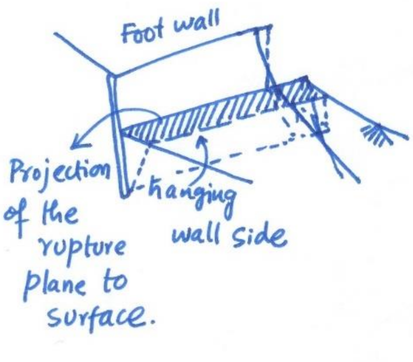
Strike slip faulting

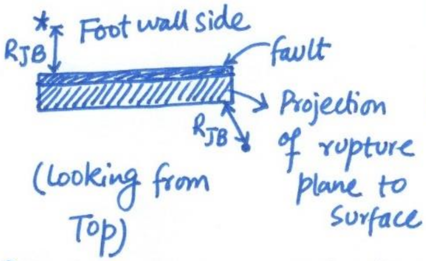


Reverse or normal faulting (hanging wall site)

a) R_{RUP} = Closest distance to rupturing fault plane

b) R_{JB} = Joyner-Boore distance

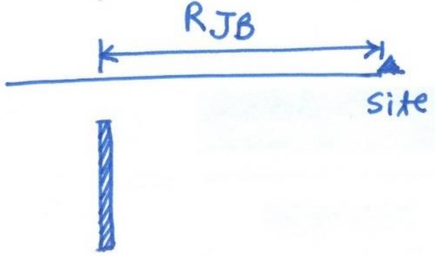




[If the site is inside projection then $R_{JB} = 0$

R_{JB} is the closest horizontal distance from site to the projection of the surface rupture.

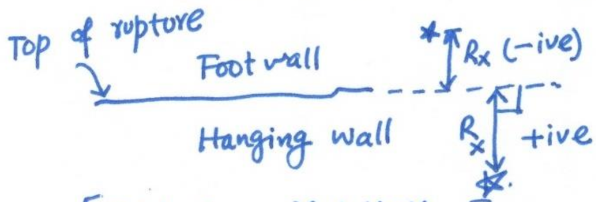
In case of Strike-slip fault, [closest distance to the surface projection of coseismic rupture]

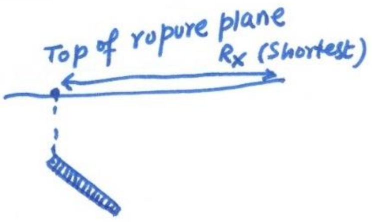


c) R_x = closest horizontal distance to the extension line of the top of rupture plane. [$\perp$ to fault strike]

+ if you are on hanging wall.

− " " " " foot wall.

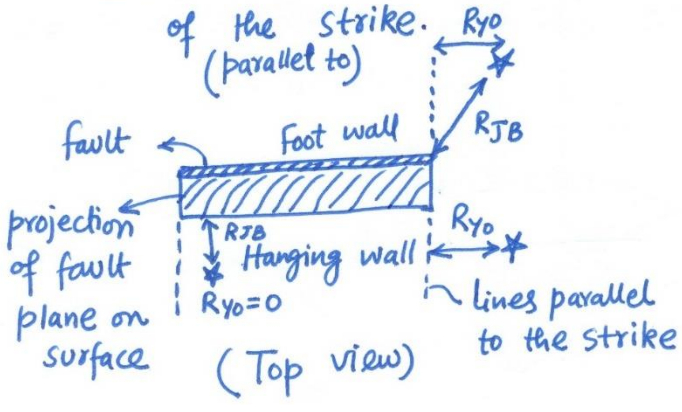




[Rupture menifest itself up to top of surface]

d) R_{Y_0} (used in NGA West 2)

= distance to the surface projection in the direction of the strike. (parallel to)



NGA soil vs. Rock

NGA eqs dont have a "trigger" for soil or rock. They rely on V_{s30} (Av. Shear wave velocity in the upper 30 m soil).

GMPEs for Subduction Zones:

[Do not use NGA GMPEs]

These GMs have their own seismic signature.

The following relationships can be used to predict either inter-plate or intra-plate SZ GMs.

a) Youngs et al. (1997)
b) Atkinson and Boore (2003)
c) Zhao et al. (2006)
d) NGA Subduction zone Project (still ongoing at this time)

GMPEs for Continental Seismic Sources: (eg central and eastern US)

- Little data
- GMs attenuate differently in fractured rocks (as in high seismicity area) than (in low seismicity areas) in solid rocks. So NGA West cannot be used.
- USGS used 9 GMPEs in 2014 update of NSHMs (National seismic Hazard Maps).

  Frankel and others (1996), Toro and others (1997) + Toro (2002), Silva and others (2002), Campbell (2003), Tavakoli and Pezeshk (2005), Atkinson and Boore (2006), Pezeshk and others (2011), Atkinson (2008), Somerville and others (2011)

- NGA Central US project is going on. The results will replace all previously used GMPEs.
  based on
  (Agreed upon data)

- Older GMPE's → check section 3.4 of Kramer book. Still valuable, provide gut-check, back-of-the envelop calculations.

NGA West 2 GMPE Spreadsheet: (by Emel Seyhan

Main — All calculations of 5 GMPES

Model Applicability → Check e.g Idriss not applicable to soft soils.

- GMPE Averaging → Geometric mean → $(X_1 \cdot X_2 \cdot X_3 \cdots X_n)^{1/n}$
  → Arithmetic mean
- GMPE Weights → Sum = 1
- # of SDS → for plotting Spectra
- Damping ξ
- $U \rightarrow = 1$ if you dont know/want to specify fault mechanism

F_{RV}, F_{NM}, F_{HW} (Triggers for reverse fault, normal fault and hanging wall site)

Default = Strike Slip fault

Dip Angle
- $SS \cong 90^\circ$
- $NF \cong 70^\circ - 80^\circ$
- $Rev\ F \cong 45^\circ$ or less

Z_{TOR} => for faults rup up to surface → $Z_{TOR} = 0$
Top of Rupture

If you have few (2,3) points in the data which you think can skew the data, then you use GM to minimize this effect. (Most professionals use)

- Region → Global

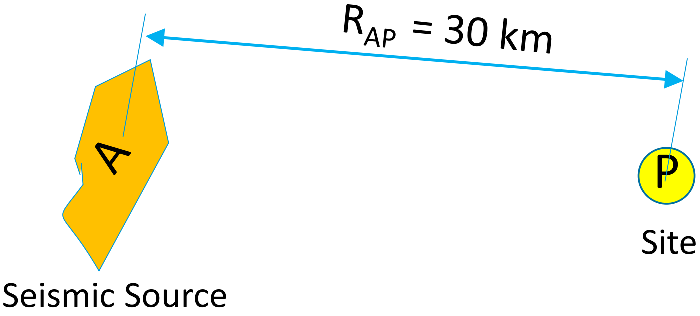
2.12. The Simplified PSHA for Beginners

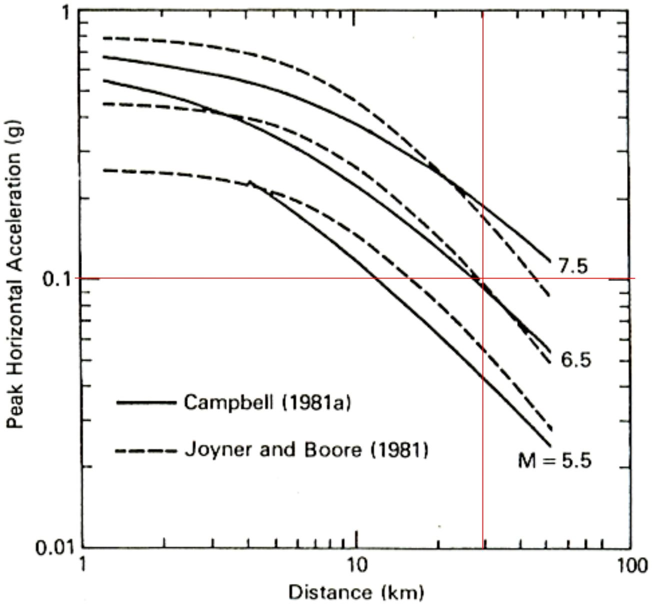
To demonstrate on how probabilistic ground motion is estimated, a simplified calculation of probabilistic ground motion is presented as follows:

Let’s consider a simple case where only one seismic source (A) is located near the site of interest (P).

Let’s set the PGA level of interest at the site to, say, 0.10 g.

According to the selected attenuation relationship, earthquakes with magnitude greater than 6.6 will produce PGA at the site equal to or greater than 0.10 g.



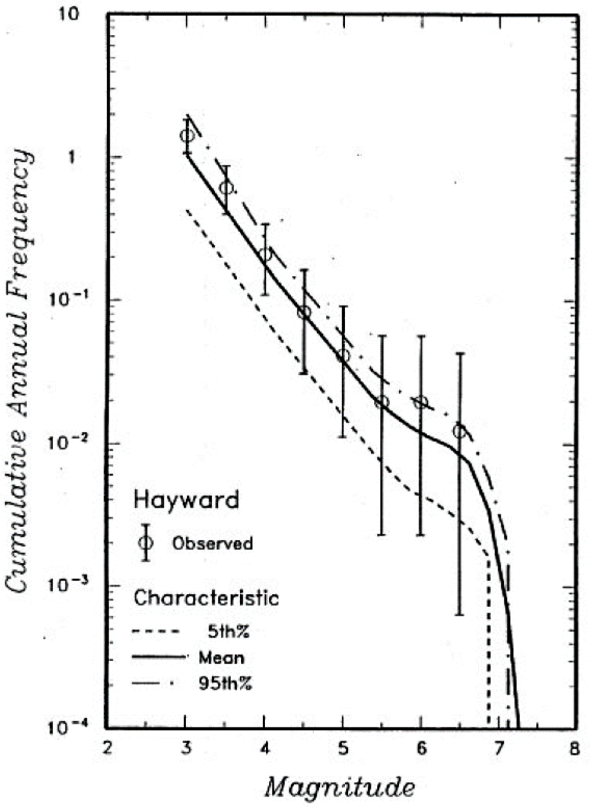


According to the magnitude-recurrence relationship of the source zone A, the annual occurrence rate of earthquakes with M > 6.6 = N(M=6.6) = 0.007 event per year

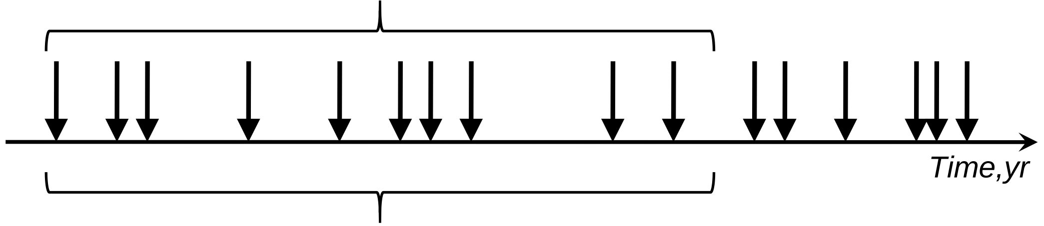
Hence, the annual occurrence rate of having PGA at the site exceeding 0.10 g = 0.007 (event per year)

= annual exceedance rate.

In the other words, the return period for PGA > 0.10 g = 1/0.007 = 143 years.



Random Occurrence of Earthquakes in Time: Poisson Process



Annual exceedance rate = total number of events/time period = 0.007

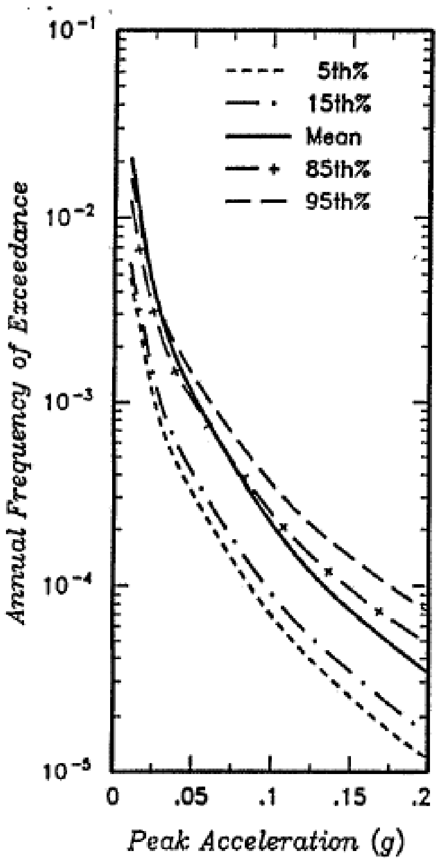
Return Period = time period/total number of events = 143 yr

↓ = *Earthquake Event with PGA > 0.10 g at the site*

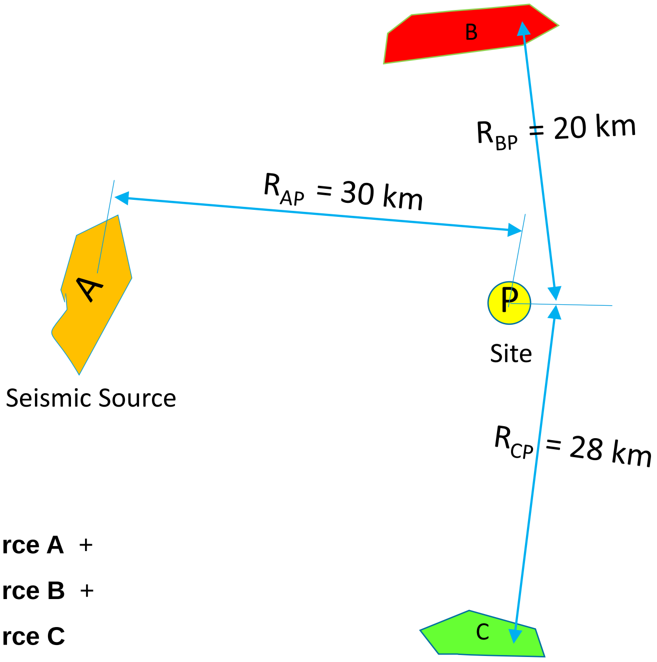
Given a time period of 10 years,
the chance of having such event in this time period
= 0.007 x 10 = 0.07 = 7 %, or
= 10/147 = 0.07 = 7 %

- Repeat the calculation process for many other PGA levels (0.01g, 0.05g, 0.20g, etc.).

- Draw the relationship between PGA and the corresponding annual exceedance rate.
- Then, determine the PGA level with annual exceedance rate of 0.002.
- This PGA level is equal to, say, 0.22 g.
- The exceedance rate in one year = 0.002. The exceedance rate in a 50-yr period = 0.002x50 = 0.10.
- The chance of exceeding PGA of 0.22g in a 50-yr period = 10%.
- Hence, the PGA level with 10% chance of being exceeded in a 50-yr period is 0.22g.



Multiple Sources



Annual exceedance rate at the site P =

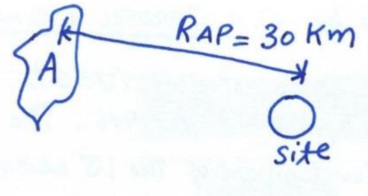
Annual exceedance rate caused by EQs in **source A** +

Annual exceedance rate caused by EQs in **source B** +

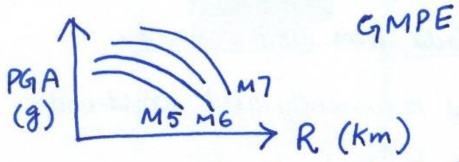
Annual exceedance rate caused by EQs in **source C**

Simplified PSHA

①



②



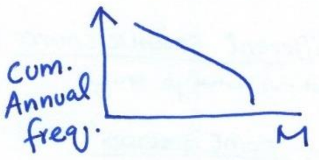
For PGA = 0.1g (say) and R = 30 Km

Pick M

Say M = 6.6

(EQs with M6.6+ at this source A will produce a PGA of 0.1g or higher)

③



M-R Relationship

Cum. Annual freq = Annual occurrance rate

$$\left(RP = \frac{1}{\text{annual occurrance rate}}\right)$$

M	N(M)
5	5000
6	500
7	50

} In say 1000^{0} years

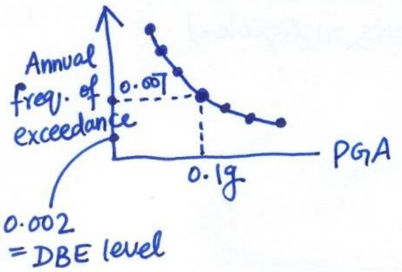
so $\frac{N(M)}{10{,}000}$ = Annual occurrance rate = Annual exceedance rate

= 0.007 (say)

So using M6.6 ⟶ Pick ⟶ ↑

so RP of PGA > 0.1g = $\frac{1}{0.007}$ = 143 years

④



Annual exceedance rate X 50 = Exceedance rate in 50 years

If PE in 50 years = 10%.

⟹ DBE

For DBE, Annual Exceedance rate = $\frac{10\%}{50}$

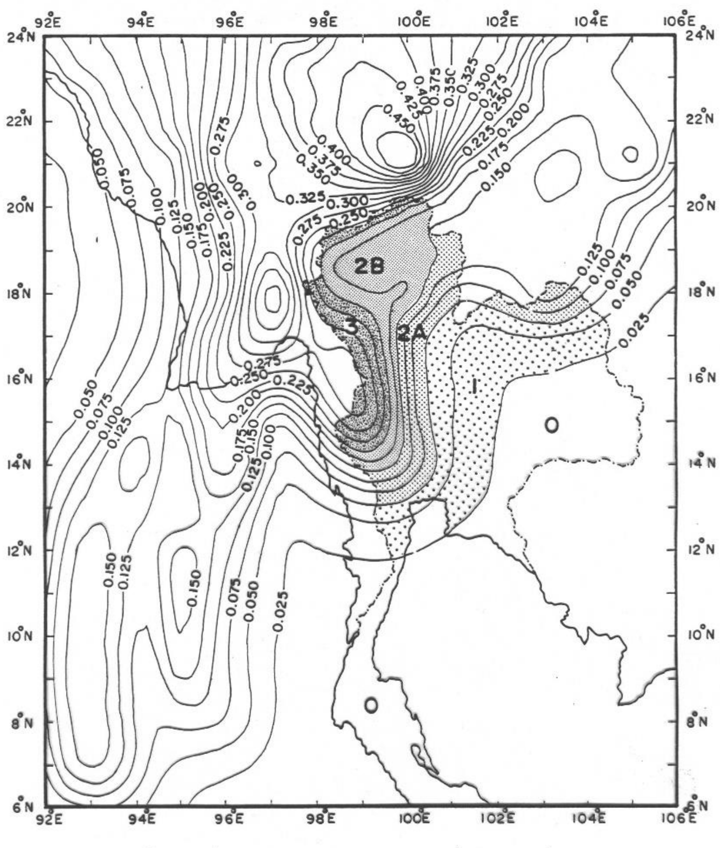
= 0.002

2.13. Hazard Maps Developed using the PSHA

Seismic hazard probability map is usually presented by a map showing contour lines of peak ground acceleration having a 10% probability of being exceeded in a 50-years period (which is equivalent to, approximately, 500-yr return period).

The probabilistic acceleration and velocity maps are multiple-use maps: -

- building code applications,
- regional land use planning,
- emergency preparedness,
- insurance analysis,
- Preliminary investigations of sites for critical facilities, etc.



Seismic Hazard Map of Thailand: This map shows contours of PGA (in unit of *g*) with 10% probability of exceedance in a 50-year exposure period.

DETERMINE LOCAL GROUND RESPONSE

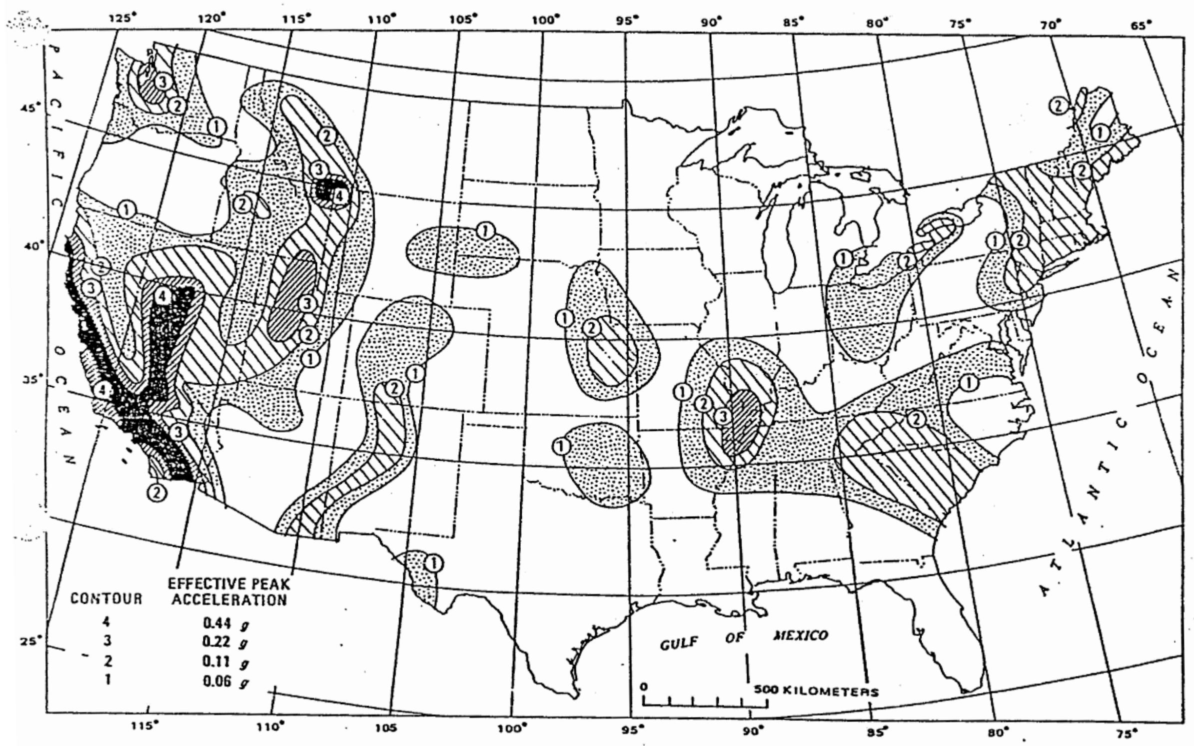


FIGURE 66.—Preliminary design regionalization proposed for 1976 Uniform Building Code (from Applied Technology Council, 1976).

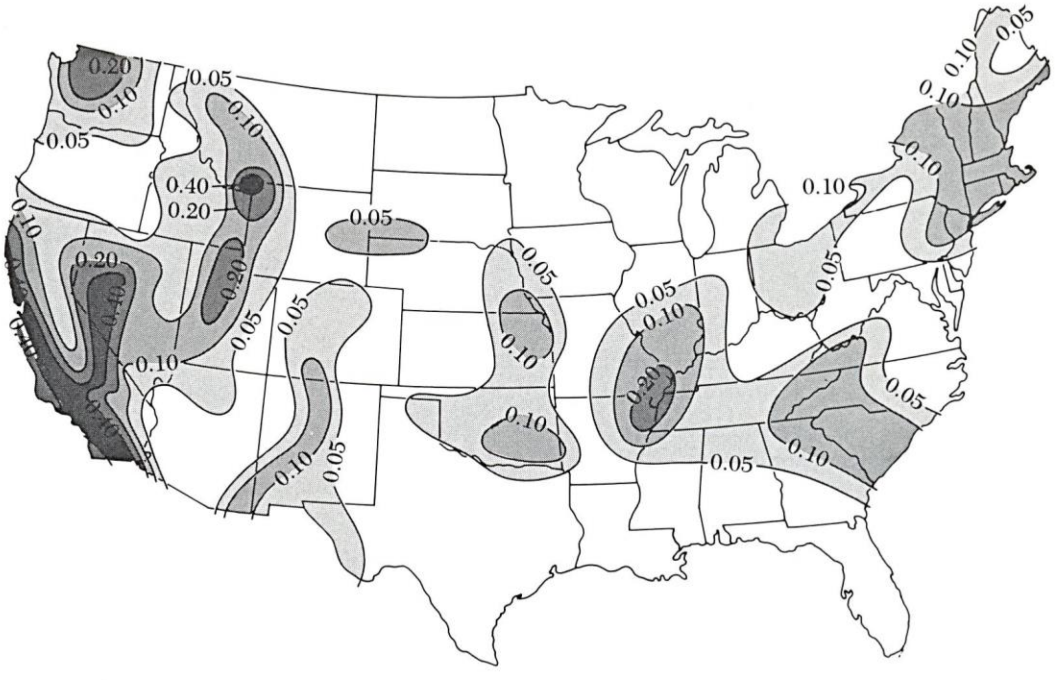


FIGURE 1

A new seismic risk map for the United States, prepared for the Applied Technology Council in 1976–77. The contours indicate effective peak, or maximum, acceleration levels (values are in decimal fractions of gravity) that might be expected (with odds of only 1 in 10) to be exceeded during a 50-year period.

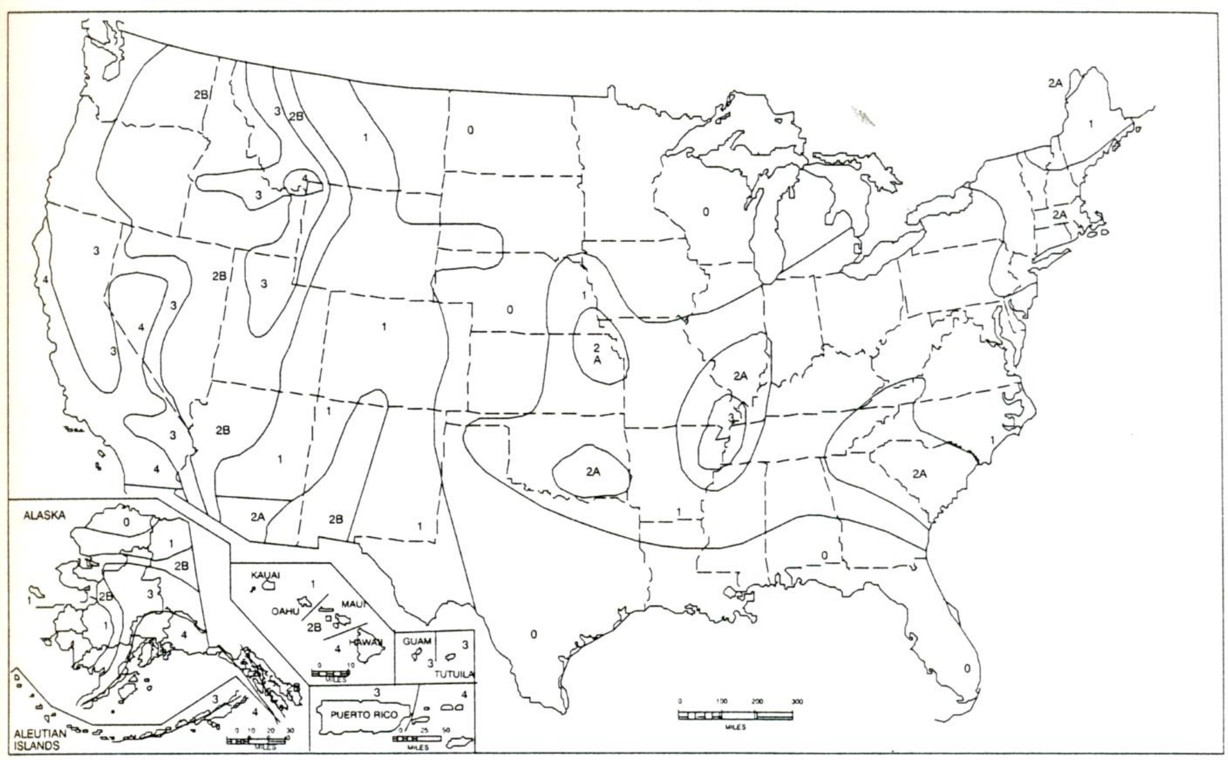
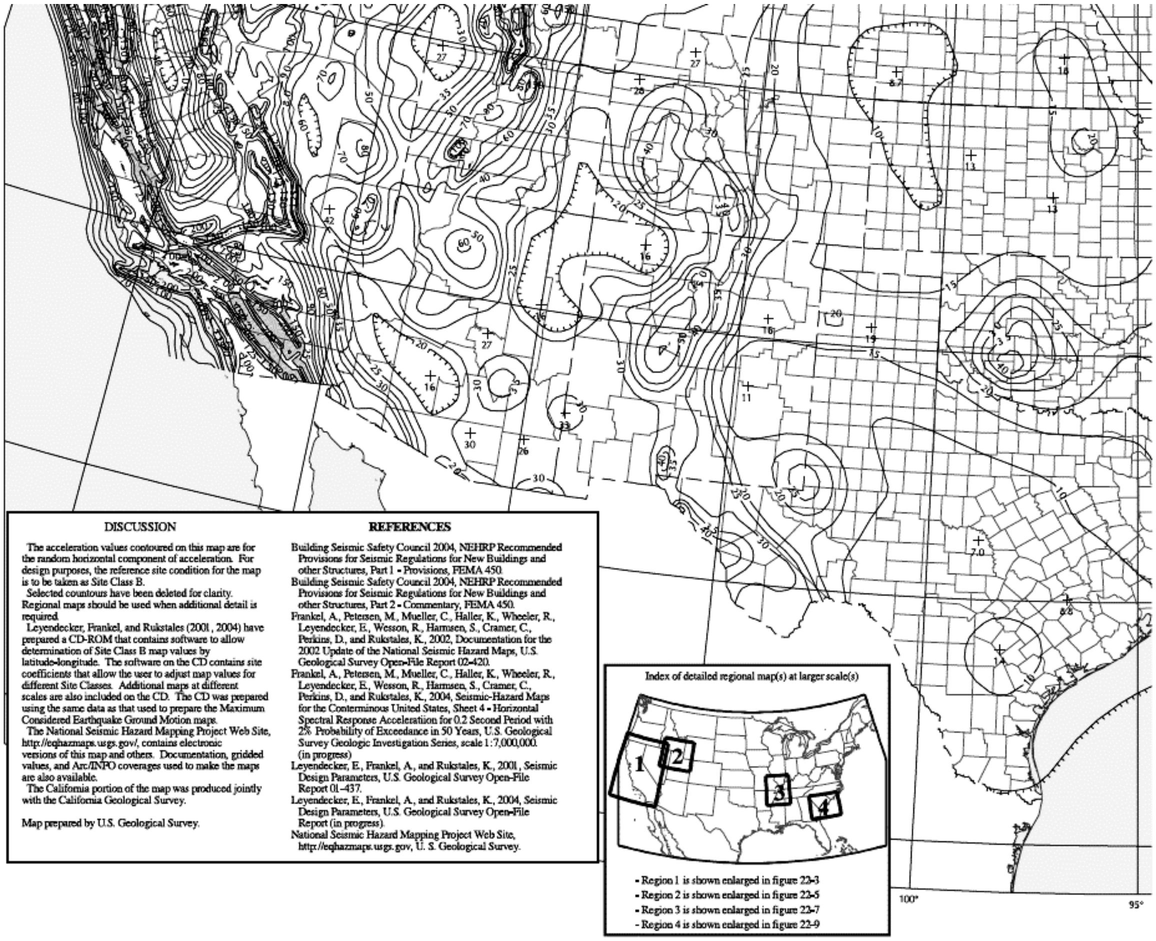


FIGURE 16-2—SEISMIC ZONE MAP OF THE UNITED STATES
For areas outside of the United States, see Appendix Chapter 16.



DISCUSSION

The acceleration values contoured on this map are for the random horizontal component of acceleration. For design purposes, the reference site condition for the map is to be taken as Site Class B.

Selected countours have been deleted for clarity. Regional maps should be used when additional detail is required.

Leyendecker, Frankel, and Rukstales (2001, 2004) have prepared a CD-ROM that contains software to allow determination of Site Class B map values by latitude-longitude. The software on the CD contains site coefficients that allow the user to adjust map values for different Site Classes. Additional maps at different scales are also included on the CD. The CD was prepared using the same data as that used to prepare the Maximum Considered Earthquake Ground Motion maps.

The National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov/, contains electronic versions of this map and others. Documentation, gridded values, and Arc/INPO coverages used to make the maps are also available.

The California portion of the map was produced jointly with the California Geological Survey.

Map prepared by U.S. Geological Survey.

REFERENCES

Building Seismic Safety Council 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures, Part 1 - Provisions, FEMA 450.

Building Seismic Safety Council 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures, Part 2 - Commentary, FEMA 450.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps, U.S. Geological Survey Open-File Report 02-420.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2004, Seismic-Hazard Maps for the Conterminous United States, Sheet 4 - Horizontal Spectral Response Acceleratiion for 0.2 Second Period with 2% Probability of Exceedance in 50 Years, U.S. Geological Survey Geologic Investigation Series, scale 1:7,000,000. (in progress)

Leyendecker, E., Frankel, A., and Rukstales, K., 2001, Seismic Design Parameters, U.S. Geological Survey Open-File Report 01-437.

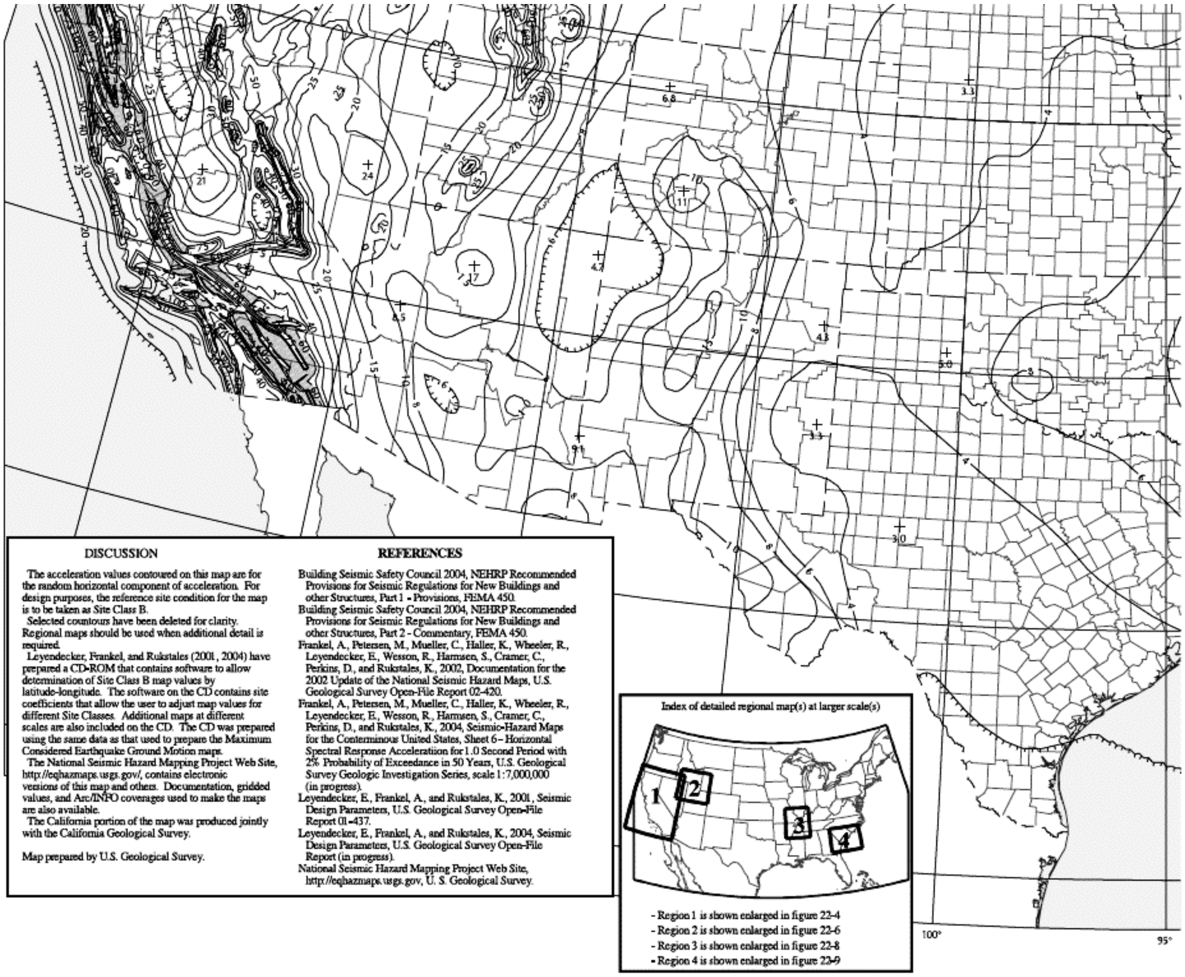
Leyendecker, E., Frankel, A., and Rukstales, K., 2004, Seismic Design Parameters, U.S. Geological Survey Open-File Report (in progress).

National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov, U. S. Geological Survey.

Index of detailed regional map(s) at larger scale(s)

- Region 1 is shown enlarged in figure 22-3
- Region 2 is shown enlarged in figure 22-5
- Region 3 is shown enlarged in figure 22-7
- Region 4 is shown enlarged in figure 22-9

FIGURE 22-1 MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION FOR THE CONTERMINOUS UNITED STATES OF 0.2 SEC SPECTRAL RESPONSE ACCELERATION (5% OF CRITICAL DAMPING), SITE CLASS B



DISCUSSION

The acceleration values contoured on this map are for the random horizontal component of acceleration. For design purposes, the reference site condition for the map is to be taken as Site Class B.

Selected countours have been deleted for clarity. Regional maps should be used when additional detail is required.

Leyendecker, Frankel, and Rukstales (2001, 2004) have prepared a CD-ROM that contains software to allow determination of Site Class B map values by latitude-longitude. The software on the CD contains site coefficients that allow the user to adjust map values for different Site Classes. Additional maps at different scales are also included on the CD. The CD was prepared using the same data as that used to prepare the Maximum Considered Earthquake Ground Motion maps.

The National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov/, contains electronic versions of this map and others. Documentation, gridded values, and Arc/INFO coverages used to make the maps are also available.

The California portion of the map was produced jointly with the California Geological Survey.

Map prepared by U.S. Geological Survey.

REFERENCES

Building Seismic Safety Council 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures, Part 1 - Provisions, FEMA 450.

Building Seismic Safety Council 2004, NEHRP Recommended Provisions for Seismic Regulations for New Buildings and other Structures, Part 2 - Commentary, FEMA 450.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2002, Documentation for the 2002 Update of the National Seismic Hazard Maps, U.S. Geological Survey Open-File Report 02-420.

Frankel, A., Petersen, M., Mueller, C., Haller, K., Wheeler, R., Leyendecker, E., Wesson, R., Harmsen, S., Cramer, C., Perkins, D., and Rukstales, K., 2004, Seismic-Hazard Maps for the Conterminous United States, Sheet 6 – Horizontal Spectral Response Accelerattiion for 1.0 Second Period with 2% Probability of Exceedance in 50 Years, U.S. Geological Survey Geologic Investigation Series, scale 1:7,000,000 (in progress).

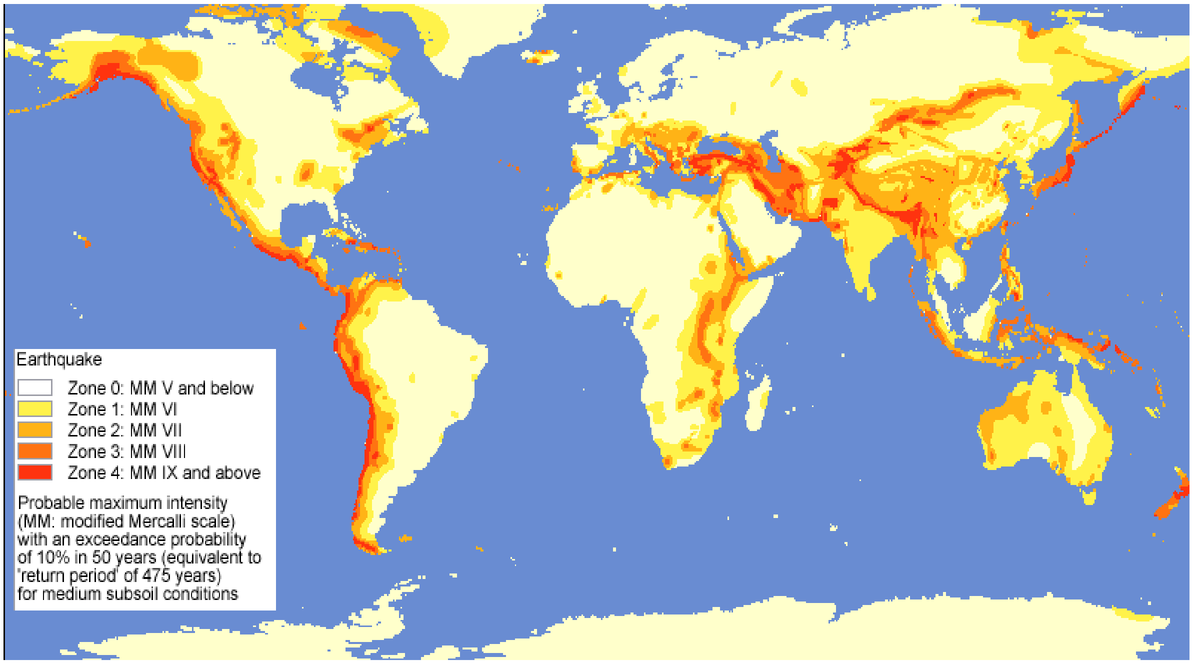
Leyendecker, E., Frankel, A., and Rukstales, K., 2001, Seismic Design Parameters, U.S. Geological Survey Open-File Report 01-437.

Leyendecker, E., Frankel, A., and Rukstales, K., 2004, Seismic Design Parameters, U.S. Geological Survey Open-File Report (in progress).

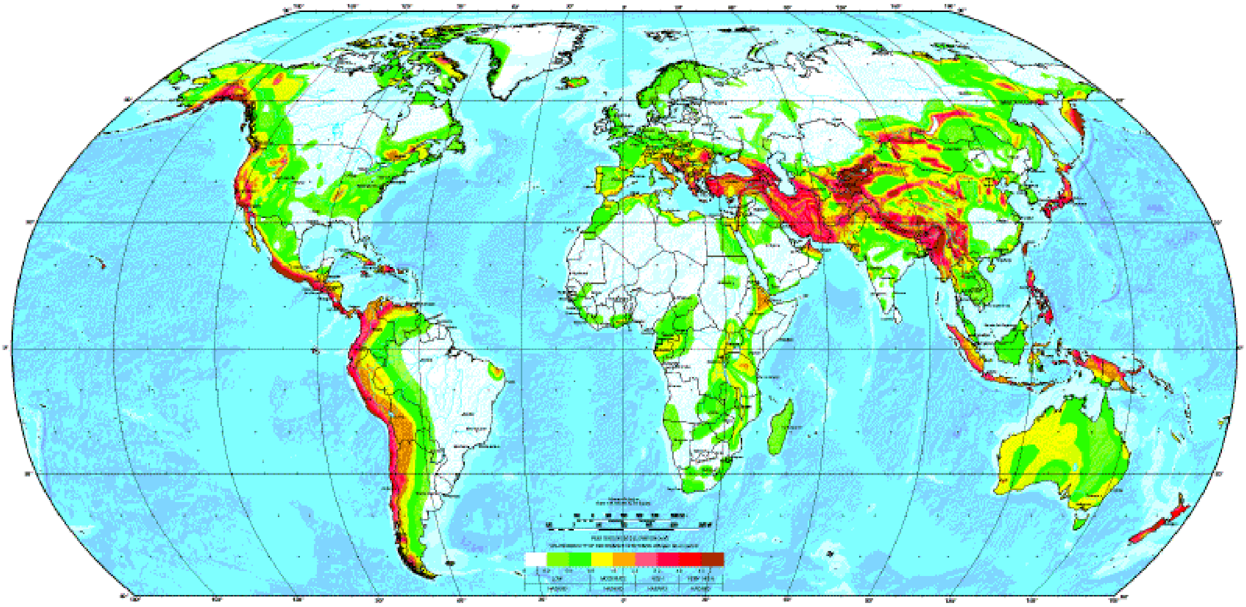
National Seismic Hazard Mapping Project Web Site, http://eqhazmaps.usgs.gov, U. S. Geological Survey.

- Region 1 is shown enlarged in figure 22-4
- Region 2 is shown enlarged in figure 22-6
- Region 3 is shown enlarged in figure 22-8
- Region 4 is shown enlarged in figure 22-9

FIGURE 22-2 MAXIMUM CONSIDERED EARTHQUAKE GROUND MOTION FOR THE CONTERMINOUS UNITED STATES OF 1.0 SEC SPECTRAL RESPONSE ACCELERATION (5% OF CRITICAL DAMPING), SITE CLASS B



Global seismic hazard map

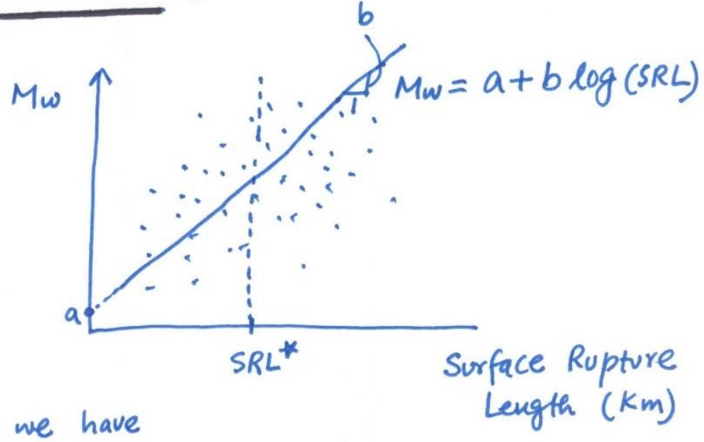


Global Seismic Hazard Map

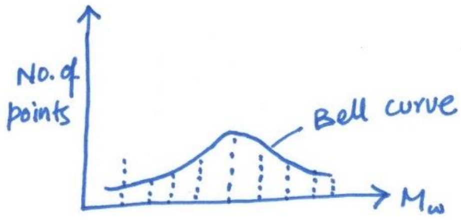
2.14. Pre-requisite Mathematical Concepts for the PSHA Process

2.14.1. Basics on Earthquake Statistics

Earthquake Statistics :

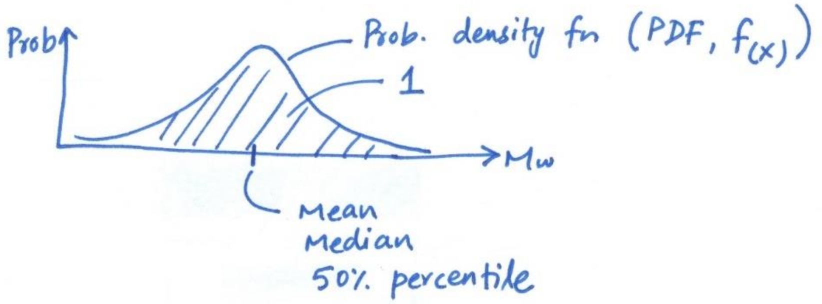


Lets say we have at a particular site of interest → SRL*

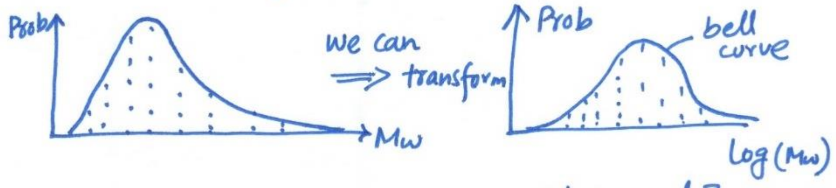


$$\frac{\text{No. of points for a Particular } M_w}{\text{Total No. of points}} = \text{Prob. of that } M_w .$$

So

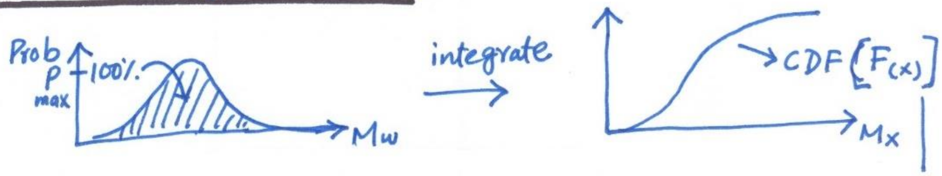


Sometimes the EQ data may also look like this



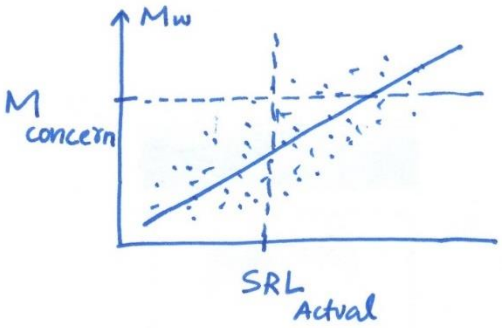
[Lognormal PDF]
mean ≠ median

Cumulative Density Function:

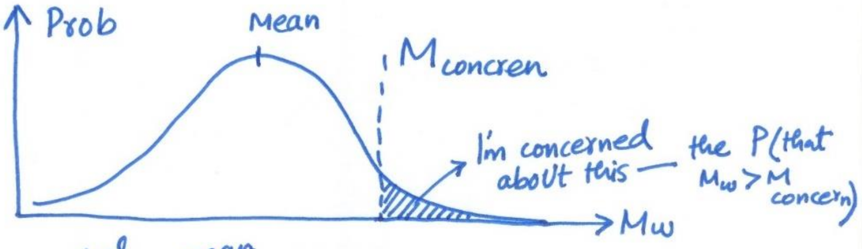


In EQ we mostly not interested in probability when a particular parameter is = some number, but we mostly care about when a parameter "exceeds" or "doesn't exceeds" a number. So CDF helps us in this.

Now,



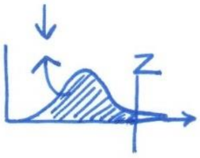
The mean Mw coresponding to SRL_{Actual} is $< M_{concern}$, so one may think that its OK. But if we consider the PDF, (the spread of actual data)



Z-score: $\dfrac{\overset{\text{actual}}{X} - \overset{\text{mean}}{\bar{X}}}{SD}$ so in this case, $\dfrac{M_{concern} - M_{mean}}{SD}$

CDF gives prob $(M < M_{concerned})$ → Prob. of non exceedance.

so Prob. of exceedance = 1 − CDF(Z)



2.14.2. Logarithms

if $a^p = N$ where $a \neq 0 \; or \; 1$, then $p = log_a N$

"p" is called the logarithm of N to the base a.

Laws of Logarithms

$$Log_a MN = Log_a M + Log_a N$$

$$Log_a {}^{M}/_{N} = Log_a M - Log_a N$$

$$Log_a M^p = p\ Log_a M$$

Change of base of Logarithms

$$Log_a N = \frac{Log_b N}{Log_b a}$$

Some useful relations:

$$10^{Log_{10} N} = N$$

$$Exp[Log_e N] = N$$

$$Log_{10} e = \frac{1}{Log_e 10}$$

2.14.3. Probability Theory

Probability: a nonnegative measure which is associated with an event

$$0\ \leq Probability\ \leq 1$$

$P\big($impossible event$\big) = 0$; i.e., no chance that the event will occur.

$P\big($certain event$\big) = 1$; i.e., 100% sure that the event will occur.

Conditional probability: The probability of an event may depend on the occurrence of another event.

The conditional probability of $E1$, assuming $E2$ has occurred is denoted by

It can be shown that

$$P\big[E_1 \text{and } E_2\big] = P\ [E_1/E_2]\ .\ P\ [E_2]$$

Statistical independence: If the occurrence of one event does not affect the probability of occurrence of another event, the two events are statistically independent.

Therefore, if $E1$, and $E2$ are statistically independent,

$$P[E_1/E_2] = P\ [E_1]$$

Then

$$P\ \big[E_1 \text{and } E_2\big] = P\ [E_1]\ .\ P\ [E_2]$$

Let X be a random variable

Suppose that we have N sample values of X: $\{x_1, x_2, x_3, \ldots\ldots x_N\}$

Sample mean $\bar{X} = \frac{1}{N}\sum_{i=1}^{N} x_i \xrightarrow{N\to\infty} E[X]$ the expected value of X

Sample variation $S_x^2 = \frac{1}{N-1}\ \sum_{i=1}^{N}(x_i - \bar{X})^2 \xrightarrow{N\to\infty} Var[X]$ the variance of X

$$E[X] = \sum_{all\,x} x\,.\,P[X = x]$$

$$Var[X] = \sum_{all\,x} (\,x - E[X])^2\,.\,P[X = x]$$

In this case, all x means all possible numerical values of X

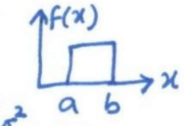
Total Probability Theorem: Total Prob of a system = Sum of individual probabilities from each contributing part.

$$P[Y] = \sum_{i=1}^{n} P[Y/X_i]\,P[X_i]$$

Prob. of $Y = \sum$(Prob. of Y such that Some X value is equal to X_i $\times$ (multipy) the prob. of $X = X_i$)

How to compute individual Probabilities? → PDF

PDFs
- Uniform Distribution, $f(x) = \frac{1}{b-a}$
- Normal ", $f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/2\sigma^2}$
- Lognormal "$f(x) = \frac{1}{x\sqrt{2\pi}\,\sigma_{\ln x}} \times \exp\left[-\frac{1}{2}\left(\frac{\ln x - \overline{\ln x}}{\sigma_{\ln x}}\right)^2\right]$



If we interested in P(exceeding or not exceeding), → CDF

$$F(x) = \int f(x)\,dx = \Phi\left(\frac{x-\mu_x}{\sigma_x}\right) \qquad \frac{x-\mu_x}{\sigma_x} = Z$$

$P(X < x_1) \rightarrow$ CDF

$P(X > x_1) = 1 - F(x)$

Φ = Standard normal CDF

2.14.4. The Poisson Process and Poisson Distribution

Suitable for the probabilistic modelling of many physical problems which involve the possible occurrences of events at any point in time (or space).

Earthquake occurrences, Traffic accidents on a given highway, etc.

The Poisson process is based on the following assumptions:

a) An event can occur at random at any time

b) The occurrence of an event in a given time interval is independent of that in any other non-overlapping intervals.

c) The probability of occurrence of an event in a small interval Δt is proportional to Δt, and can be given by $\nu\Delta t$, where ν is the mean rate of occurrence of the event (assumed to be constant); and the probability of two or more occurrences in Δt is negligible (of higher orders of Δt).

On the basis of these assumptions, the number of occurrences of the event in t is given by the Poisson Distribution:

$$P[N_t = n] = \frac{(\nu t)^n}{n!}\, e^{-\nu t}$$

Where

N_t is the number of occurrences in time interval t

ν is the mean occurrence rate; that is, the average number of occurrences of the event per unit time interval.

Therefore

$$P\big[\text{no event occur in } t\big] = P[N_t = 0] = e^{-\nu t}$$

Also, it can be proved that

$$E[N_t] = \nu t$$

$$Var[N_t] = \nu t$$

Detailed Derivation of the Poisson Distribution:

$$[N_{t+dt} = n] = [N_t = n \qquad \text{and no occurrence in} \qquad \big(t,\ t\ + dt\big)] \quad \text{or}$$

$$= [N_t = n - 1 \qquad \text{and one event occurs in} \qquad \big(t,\ t\ + dt\big)] \quad \text{or}$$

$$= [N_t = n - 2 \qquad \text{and two events occur in} \qquad \big(t,\ t\ + dt\big)] \quad \text{or}$$

$$P[N_{t-dt} = n] = P[N_t = n]\, P[N_{dt} = 0] + P[N_t = n - 1]\, P[N_{dt} = 1]$$

$$+ P[N_t = n - 2]\, P[N_{dt} = 2] + \cdots$$

On the basis of assumption (c), we obtain

$$P[N_{dt} = 1] = \nu\, dt$$

$$P[N_{dt} = 2] \cong 0$$

$$P[N_{dt} = 3] \cong 0$$

Hence,

$$P[N_{dt} = 0] = 1 - P[N_{dt} = 1] = 1 - \nu\, t$$

(since there are only two possibilities: either $N_{td} = 0$ or 1)

Introducing (c7) and (c6) into (c5) yields

$$P[N_{t+dt} = n] = P[N_t = n] - \nu\, dt\, .\, P[N_t = n] + \nu\, dt\, .\, P[N_t = n - 1]$$

Using the notation $P[N_t = n] \equiv p_n(t)$, Eq. (C8) becomes

$$p_n(t + dt) = p_n(t) - \nu\, dt\, .\, p_n(t) + \nu dt\, .\, p_{n-1}(t)$$

$$\frac{p_n(t+dt) = \ p_n(t)}{dt} = \nu \ . \ \left(p_{n-1}(t) - p_n(t)\right)$$

Therefore, in the limit as $dt \to 0$, we obtain the following differential equation for $p_n(t)$:

$$\frac{d\left(p_n(t)\right)}{dt} = \ \nu \left\{p_{n-1}(t) - \ p_n(t)\right\}$$

It should be noted here that the Eq. (c10) applies for any $n \geq 1$

For $= 0$, the preceding derivation leads to

$$\frac{dp_o(t)}{dt} = -\nu \, p_o$$

The general solution:

$$p_0(t) = \ c_0 \ e^{-\nu t}$$

The initial condition:

$$p_0(0) = 1.0$$

Therefore,

$$p_0(t) = e^{-\nu t}$$

For $n = 1$, the Eq. (c10) leads to

$$\frac{d}{dt} p_1 t = \nu \left\{p_0(t) - p_1(t)\right\}$$

$$\frac{d}{dt} p_1 t = \nu \, e^{-\nu t} - \nu \, p_1(t)$$

The initial condition in this case is

$$p_1(0) = 0$$

The solution for (c13) and its associated initial condition (c14) is

$$p_1 t = \nu \, t \, e^{-\nu t}$$

Repeating the process for $n = 2{,}3, \dots\dots$, we obtain

$$p_n(t) = \ \frac{(\nu \, t)^n}{n!} \ e^{-\nu t}$$

$$E[N_t] = \ \sum_{n=0}^{\infty} n \ P[N_t = n] = \ \sum_{n=0}^{\infty} n \ . \ p_n(t)$$

$$= \sum_{n=0}^{\infty} \frac{n \, . \, (\nu t)^n}{n!} e^{-\nu t}$$

$$= e^{-\nu t}\{0 \times 1 + 1 \times \nu t + \frac{2 \times (\nu t)^2}{2!} + \frac{3 \times (\nu t)^3}{3!} + \cdots\}$$

$$= e^{-\nu t} \times \nu t\,\{1 + \nu t + \frac{(\nu t)^2}{2!} + \frac{(\nu t)^3}{3!} + \cdots\}$$

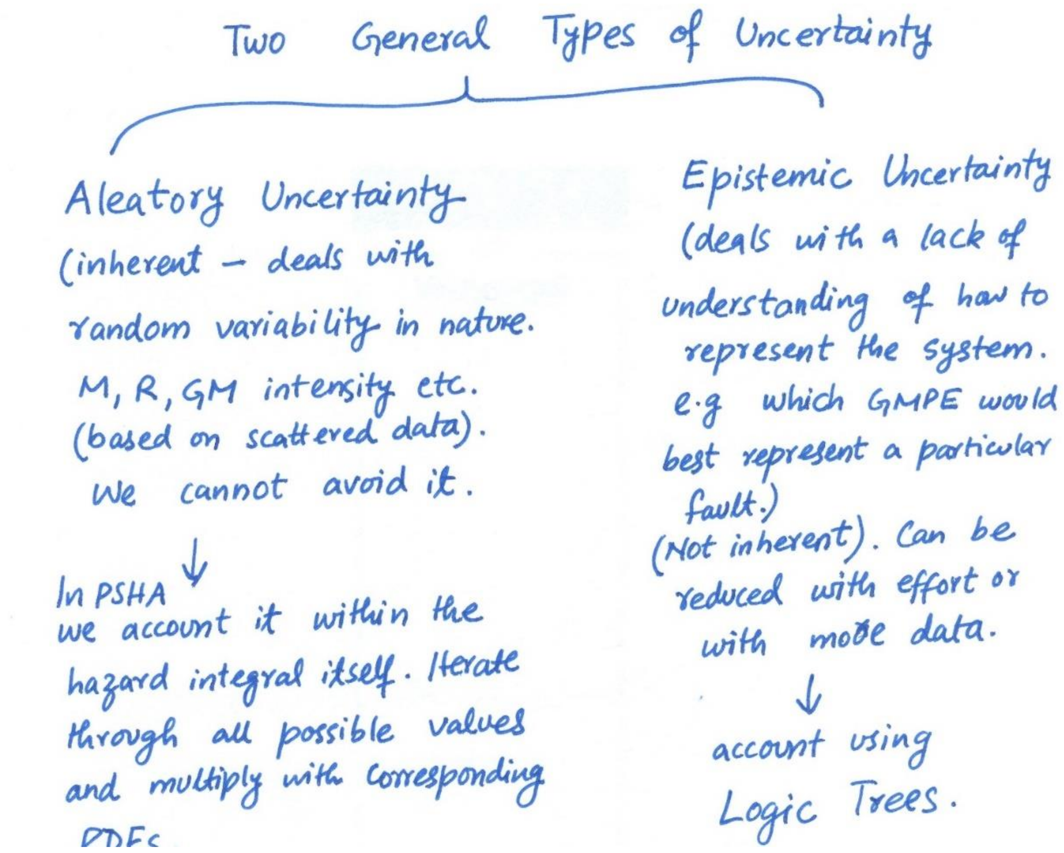
$$= e^{-\nu t}\,.\,e^{\nu t}\,.\,\nu t = \nu t$$

$$E[N_t] = \nu t$$

$$Var[N_t] = \sum_{n=0}^{\infty}\{n - E[N_t]\}^2\,.\,P[N_t = n] = \sum_{n=0}^{\infty}(n - \nu t)^2.\,p_n(t)$$

$$Var[N_t] = \nu t$$

2.15. Uncertainties in the PSHA Methodology



Two General Types of Uncertainty

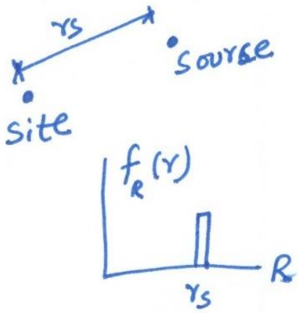
Aleatory Uncertainty
(inherent – deals with
random variability in nature.
M, R, GM intensity etc.
(based on scattered data).
We cannot avoid it.
↓
In PSHA
we account it within the
hazard integral itself. Iterate
through all possible values
and multiply with corresponding
PDFs

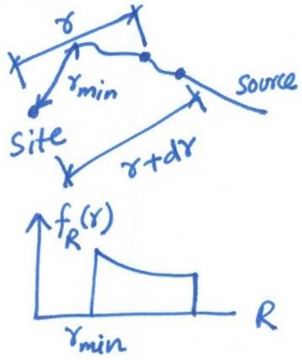
Epistemic Uncertainty
(deals with a lack of
understanding of how to
represent the system.
e.g which GMPE would
best represent a particular
fault.)
(Not inherent). Can be
reduced with effort or
with more data.
↓
account using
Logic Trees.

2.16. The Treatment of Aleatory Uncertainties in the PSHA

1) Spatial Uncertainty: The first uncertainty we experience in PSHA. Where will the EQ occur?

We divide the source into small segments and compute the likelihood that EQ could come from each segment.





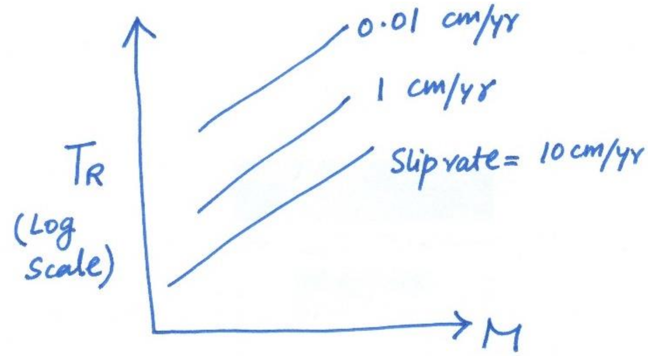
2) Size Uncertainty: How big the EQ will be? handled using "recurrence laws".
(2nd source of uncertainty)
(How often an EQ magnitude repeats itself)

Recurrence Laws
- Slip-dependent laws
- Gutenberg-Richter laws
- Characteristic Laws

λ_m = Annual rate of exceedance
The number of EQs larger than a specified magnitude that occurs each year on average.

$$T_R = \text{Return period} = \frac{1}{\lambda_m}$$

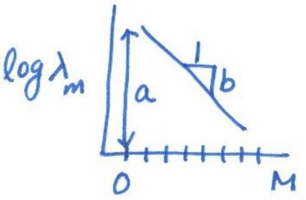
a) Slip-dependent Recurrence laws :- Typically assigned to faults that are known to have an approximate "average annual slip rate".



Using a given average slip ⟶ we get M using relationships like Wells and Coppersmith (1994) and then can determine T_R.

b) Gutenberg - Richter Recurrance Law : (sometimes called time dependent models)

"No. of EQs occurring anually from a given source is Log-linear fn of M_w."



$$\log \lambda_m = a - bm$$

$$\lambda_m = 10^{a-bm}$$

Also

$$\ln \lambda_m = \alpha - \beta m$$

$$\lambda_m = e^{\alpha-\beta m}$$

$$\alpha = 2.303a$$

$$\beta = 2.303b$$

Bounded G-R Recurrance law:

m_{min} , m_{max}

m_{min} ↓ we not interested in m_3 or m_4.

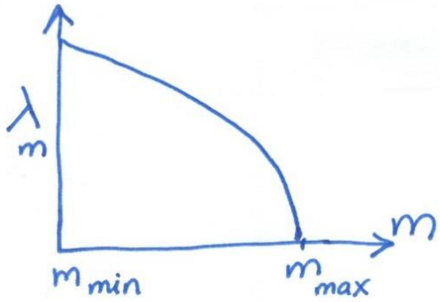
m_{max} ↓ b/w we know that certain sources cannot physically produce an $m > m_{max}$.

So we adjust the original equation. (to work within m_{min} and m_{max})

$$\lambda_m = \nu\left[\frac{e^{-\beta(m-m_{min})} - e^{-\beta(m_{max}-m_{min})}}{1-e^{-\beta(m_{max}-m_{min})}}\right], \quad m_{min}\le m\le m_{max}$$

Where $\nu = e^{\alpha-\beta m_{min}} = 10^{a-b m_{min}}$

so



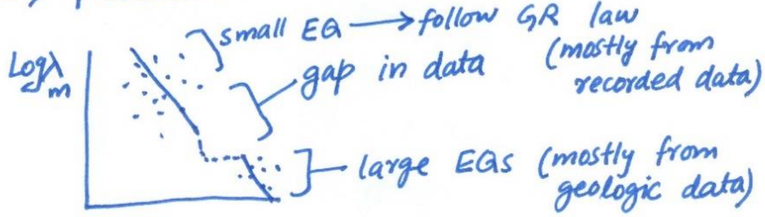
$$PDF = f_M(m) = P(M=m) = \frac{\beta e^{-\beta(m-m_{min})}}{1-e^{-\beta(m_{max}-m_{min})}}$$

$$CDF = F_M(m) = P[M<m] = \frac{1-e^{-\beta(m-m_{min})}}{1-e^{-\beta(m_{max}-m_{min})}}$$

c) Characteristic EQ Recurrance Laws:

Some faults tend to rupture with same Mw over and over again. → Paleoseismic studies.

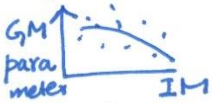
e.g



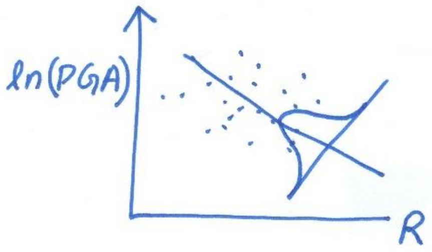
Small ones are linearly distributed → large ones are not.

3) GM Parameter Uncertainty: Uncertainty in GMPE

(3rd source of uncertainty)



We can go with e.g 84th percentile line etc, but lets account for all possible GMs and weigh accordingly.
in PSHA



e.g. if $PGA_{mean} = 0.162g$ (from mean line of GMPE)

$\sigma_{PGA} = 0.39$

$P(PGA > 0.25g) = ?$

So,

$$Z = \frac{X - \bar{X}}{\sigma} = \frac{\ln(0.25) - \ln(0.162)}{0.39} = 1.1128$$

$$P(PGA > 0.25g) = 1 - \underbrace{F}_{\substack{\downarrow \\ \text{Standard CDF}}}(Z) = 0.1329 = 13.29\%$$

Although the mean PGA from GMPE < PGA of interest, still there is a 13.29% chance that our actual PGA from future EQ will increase from the PGA of interest (0.25g).

But this mean PGA = 0.162g was computed for one M, R pair (one scenario). What about spatial uncertainty (R) and size uncertainty (M)? How we combine all three uncertainties?

↓

Total Probability Theorem

As long as we track our individual conditional probabilities, we can compute the final overal probability.

Step 1 Compute $P(PGA > 0.25g)$ for all possible combinations of M and R.

Step 2 Multiply it by the probability of having those particular values of M and R (separately)

Step 3 Sum it all together.

$$\underbrace{\lambda_{PGA=0.25g}}_{\text{mean annual rate of } PGA=0.25g} = \underbrace{\lambda_{m=m_{min}}}_{\substack{\text{mean annual rate of } m_{min} \\ \text{(also denote } \nu)}} \underbrace{\sum_{j=1}^{Nm} \sum_{k=1}^{NR} P[PGA>0.25g \mid m_j, r_k] \times P[M=m_j]\, P[R=r_k]}_{\text{Total Prob.} = \text{sum of all}}$$

Probability that PGA will be greater than 0.25g for a given m_j and r_K × Probability that $M = m_j$ × Probability that my $R = r_K$

$$\lambda_{M=m_{min}} = \nu = e^{\alpha - \beta m_{min}} = 10^{a - b m_{min}}$$

If we have more than 1 seismic sources, repeat the process.

$$\lambda_{PGA=0.25g} = \sum_{i=1}^{Ns} \nu_i \sum_{j=1}^{Nm} \sum_{K=1}^{NR} P[PGA>0.25g \mid m_j, r_k] \times P[M=m_j] \times P[R=r_k]$$

for any $SA = y^*$, we can write,

$$\boxed{\lambda_{Y>y^*} = \sum_{i=1}^{N_s} \nu_i \sum_{j=1}^{N_m} \sum_{k=1}^{N_R} P[Y>y^* | m_j, r_k]\, P[M=m_j]\, P[R=r_k]}$$

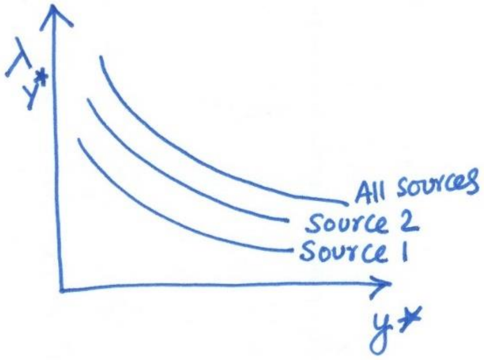
If we compute a wide range of λ_y^* and plot them against their corresponding $y^* \rightarrow$ Hazard Curve.

$$\underbrace{\lambda_{Y>y^*}}_{} = \sum_{i=1}^{N_s} \nu_i \int_{M=m_{min}}^{m_{max}} \int_R P[Y>y^* | m, r] \cdot \underset{\swarrow \text{ PDF of } M}{f_M(m)} \cdot \underset{\searrow \text{ PDF of } R}{f_R(r)}\, dr\, dm$$

Annual freq that GM at a site exceeds the chosen level $Y=y^*$

annual freq of exceeding m_{min}

$\rightarrow$ for any ith source $\rightarrow$ based on all $M > m_{min}$



4) **Temporal Uncertainty:** When an EQ of a given size will occur??

(4th and Final Source of uncertainty)

Since EQ occur infrequently relative to the lifetime of our designs, we can treat them as "randam" and "independent" processes.

i-e we can apply the "poisson probability model." $\rightarrow$ Same model that applies to rolling dice. $\rightarrow$ No memory
Same chance everyday.

(mean Annual.....)
from seismic hazard curve

Poisson Probability model:

$$\underbrace{P[Y_T > y^*]}_{\text{Probability of exceeding } y^* \text{ in a specified time frame } T.} = 1 - e^{-\lambda_{y^*} T}$$

(Years)

e.g we performed PSHA and $\lambda_{PGA=0.3g} = 0.0013$

$$T_R = \frac{1}{\lambda} = 770 \text{ years}$$

Compute the Probability of exceeding $PGA = 0.3g$ at the site in 50 years.

$$P[PGA > 0.3g] = 1 - e^{-(0.0013)(50)} = 0.0629 = 6.29\%$$

Q) Is the Poisson assumption about random occurrence Valid??? Seismic gaps??? Elastic Rebound Theory???

A) Error is negligible in majority of cases. The lifetime of our structures $<< T_R$.

But be careful using Poisson model if,

a) The structure has an unusuall long design life nuclear structures → 10 000 Yrs → use more advanced temporal uncertainty model.

b) Previous seismicity shows strong time-dependence between events. (more confidence on prediction)

c) One or more of the significant sources is well overdue.

Seismic Hazard Analysis

$$\lambda[X \geq x] \approx \sum_{\text{Sources } i} \nu_i \int_{M_0}^{M_{Max}} \int_{R/M} P[X \geq x/M,R] . f_M(m) . f_{R/M}(r/m) dr dm \qquad (1)$$

where

$\lambda[X \geq x]$ is the annual frequency that ground motion at a site exceeds the chosen level $X = x$;

ν_i is the annual rate of earthquakes on seismic source i, having magnitudes between M_0 and M_{max} $(= N_i(M_0))$

M_0 is the minimum magnitude of engineering significance

M_{max} is the max. magnitude assumed to occur on the source

$P[X \geq x/M,R]$ is the conditional probability that the chosen ground motion level is exceeded for a given magnitude and distance

$f_M(m)$ is the probability density function of earthquake magnitude

$f_{R/M}(r/m)$ is the probability density function of distance from the earthquake source to the site of interest.

$$\underset{\uparrow}{P[X \geq x]} = 1 - \exp(-t\lambda[X \geq x]) \qquad (2)$$

the probability that an observed ground motion parameter X will be greater than or equal to the value x in the next t years (the exposure period)

$$\underset{\uparrow}{R_X(x)} = \frac{1}{\lambda[X \geq x]} = \frac{-t}{\ln(1 - P[X \geq x])} \qquad (3)$$

Return Period

Ex: $R_X(x) = \dfrac{-50 \leftarrow \text{Exposure Period} = 50\text{yrs}}{\ln(1 - 0.1)} = 475$ years

$\nwarrow P_e = 10\%$

[The Basics of Seismic Risk Analysis: EERI 1989] S-2

For the well-known Gutenberg-Richter relationship

$$\log N(m) = a - bm \qquad (4)$$

where $N(m)$ is the number of earthquakes per year having magnitudes greater than m,

10^a is the number of earthquakes above magnitude zero,

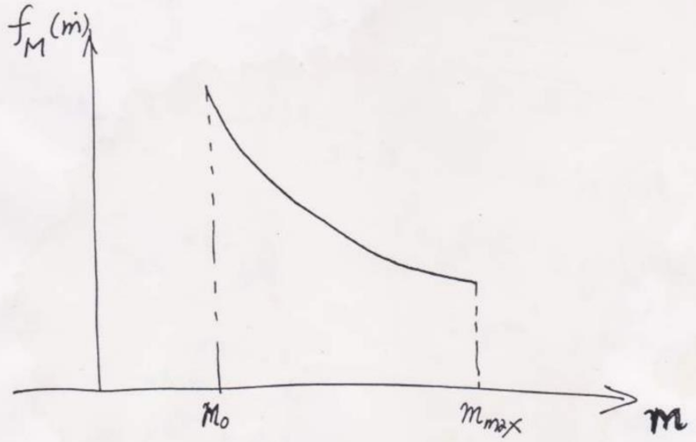
b describes the relative rate of occurrance of earthquakes with different magnitudes.

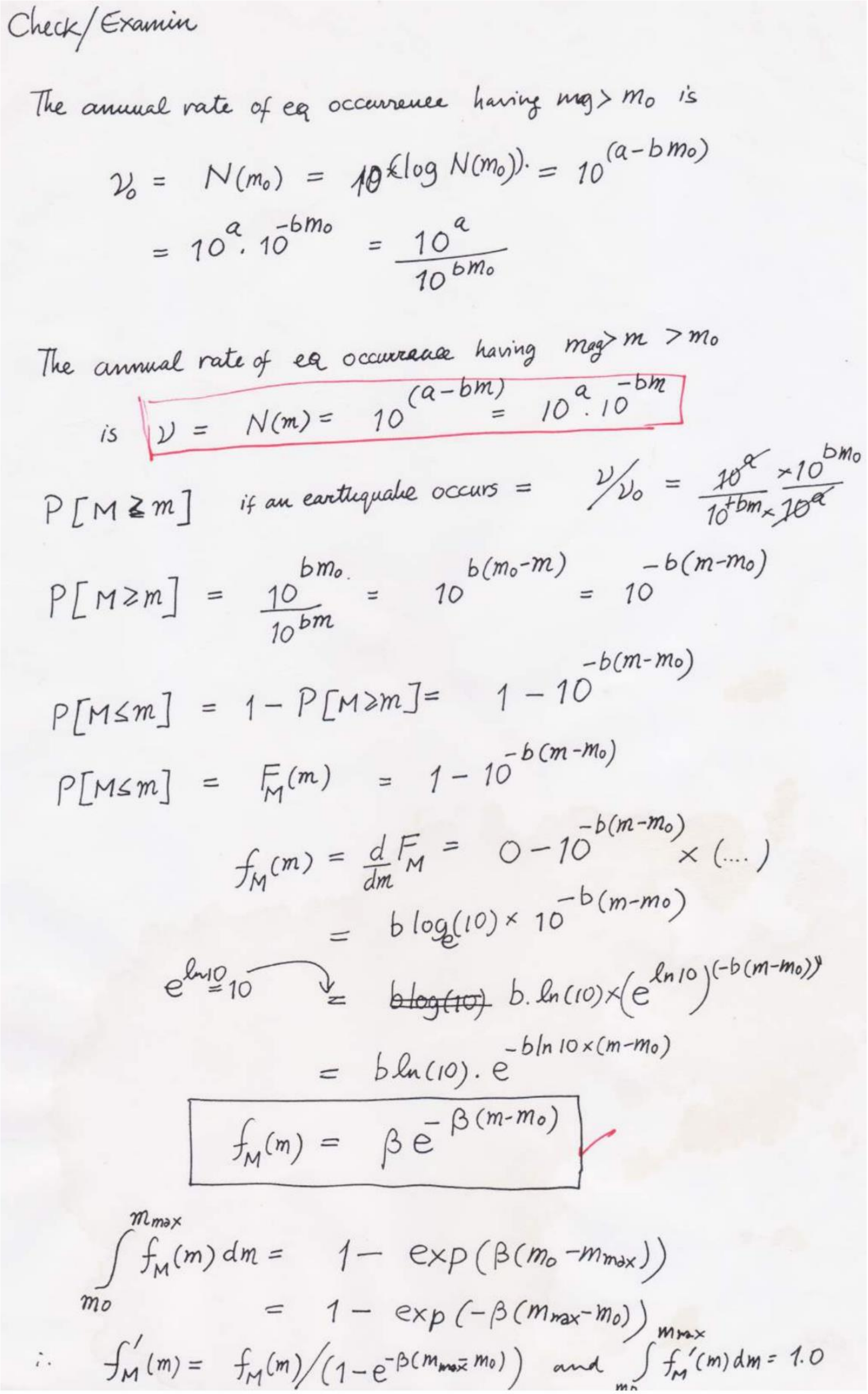
Incorporating minimum and maximum magnitudes m_0 and m_{max}, we can derive a probability density function that gives the probability that, if an earthquake occurs, it will be of magnitude m:

$$f_M(m) = k\beta \exp(-\beta(m-m_0)) \;,\quad m_0 < m < m_{max} \qquad (5)$$

where $\beta = b \ln(10)$

k is a normalizing constant $= \dfrac{1}{1-\exp(-\beta(m_{max}-m_0))}$ (6)





Check/Examin

The annual rate of eq occurrence having mag > m_0 is

$$\nu_0 = N(m_0) = 10^{(\log N(m_0))} = 10^{(a-bm_0)}$$

$$= 10^{a} \cdot 10^{-bm_0} = \frac{10^{a}}{10^{bm_0}}$$

The annual rate of eq occurrence having mag > m > m_0

is $\boxed{\nu = N(m) = 10^{(a-bm)} = 10^{a} \cdot 10^{-bm}}$

$P[M \geq m]$ if an earthquake occurs = $\nu/\nu_0 = \dfrac{\cancel{10^{a}}\times 10^{bm_0}}{10^{+bm}\times \cancel{10^{a}}}$

$$P[M \geq m] = \frac{10^{bm_0}}{10^{bm}} = 10^{b(m_0-m)} = 10^{-b(m-m_0)}$$

$$P[M \leq m] = 1 - P[M \geq m] = 1 - 10^{-b(m-m_0)}$$

$$P[M \leq m] = F_M(m) = 1 - 10^{-b(m-m_0)}$$

$$f_M(m) = \frac{d}{dm}F_M = 0 - 10^{-b(m-m_0)} \times (\dots)$$

$$= b\log_e(10) \times 10^{-b(m-m_0)}$$

$$e^{\ln 10} = 10 \curvearrowright = \cancel{b\log(10)}\; b.\ln(10) \times \left(e^{\ln 10}\right)^{(-b(m-m_0))}$$

$$= b\ln(10) . e^{-b\ln 10 \times (m-m_0)}$$

$$\boxed{f_M(m) = \beta e^{-\beta(m-m_0)}} \checkmark$$

$$\int_{m_0}^{m_{max}} f_M(m)\,dm = 1 - \exp(\beta(m_0 - m_{max}))$$

$$= 1 - \exp(-\beta(m_{max} - m_0))$$

$\therefore \quad f'_M(m) = f_M(m)/(1 - e^{-\beta(m_{max}-m_0)})$ and $\int_{m_0}^{m_{max}} f'_M(m)\,dm = 1.0$

$$f_M(m) = \frac{\beta\, e^{-\beta(m-m_0)}}{1-e^{-\beta(m_{max}-m_0)}} \qquad (19)$$

Where $$\int_{m_0}^{m_{max}} f_M(m)\,dm = 1.0 \qquad (20)$$

Hence $$N(m) = N(m_0) \cdot \int_{m}^{m_{max}} f_M(m)\,dm$$

$$= N(m_0) \cdot \int_{m}^{m_{max}} \frac{\beta . e^{-\beta(m-m_0)}}{1-e^{-\beta(m_{max}-m_0)}}\,dm$$

$$\boxed{N(m) = N(m_0) \cdot \frac{e^{-\beta(m-m_0)} - e^{-\beta(m_{max}-m_0)}}{1-e^{-\beta(m_{max}-m_0)}}} \qquad (21)$$

~~$= N(m_0)$~~ $$e^{-\beta(m-m_0)} = e^{-b\ln 10\,(m-m_0)}$$

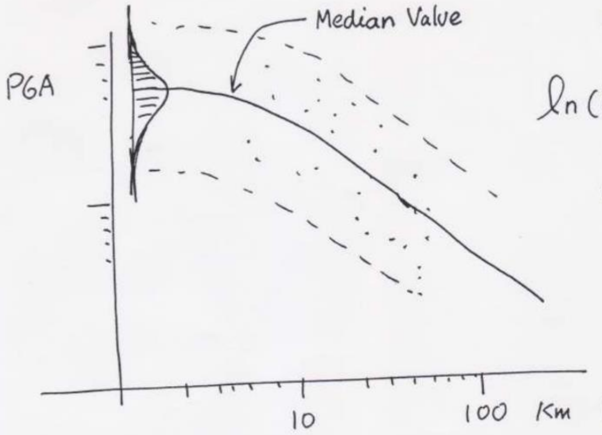
$$= e^{\ln 10 . (-b(m-m_0))}$$

$$= \left(e^{\ln 10}\right)^{-b(m-m_0)}$$

$$= 10^{-b(m-m_0)}$$

$$\boxed{N(m) = N(m_0) \cdot \frac{10^{-b(m-m_0)} - 10^{-b(m_{max}-m_0)}}{1-10^{-b(m_{max}-m_0)}}} \qquad (22)$$

Ground Motion Model:



Example:

$$\ln(\widehat{PGA}) = 0.53(M-6) - 0.39\ln(R^2+31) + 0.25$$

$\uparrow$ median

The observations scatter significantly about the (median) predicted values.

The uncertainty has a log-normal distribution!

$\ln(PGA)$ has a normal distribution.

The standard deviation of $\ln(PGA)$ is typically 0.5

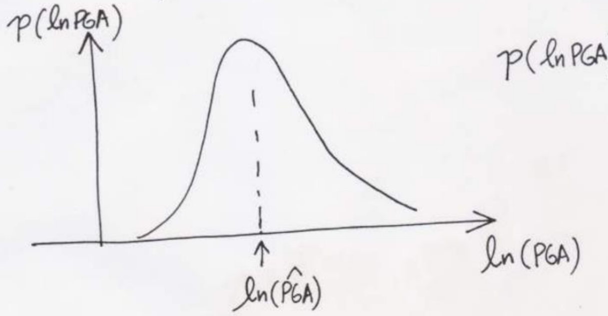
(95% of observations will fall within a factor of ≈ 2.7 ($e^{1.98 \times 0.5}$) of the median predicted PGA)

$y = \ln PGA + \sigma$

$e^y = e^{\ln PGA} \cdot e^{\sigma}$

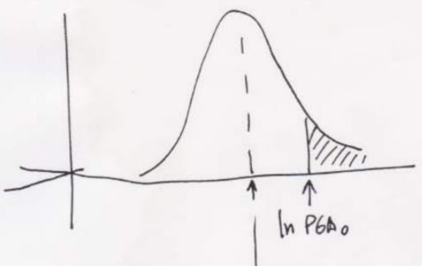
$= 1.648\ PGA\ (\sigma+)$

$= 0.606\ PGA\ (\sigma-)$



$$p(\ln PGA) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(\ln PGA - \ln\widehat{PGA})^2}{2\sigma}}$$

$$\underline{P}(\text{Ground shaking } PGA > PGA_0) = \frac{1}{\sigma\sqrt{2\pi}} \int_{\ln PGA_0}^{\infty} e^{-\frac{(\ln PGA - \ln\widehat{PGA})^2}{2\sigma}} \, d\ln PGA$$



The probability is usually evaluated assuming that ground motion values are log-normally distributed about the median value.

$$P[X \geqslant x/M,R] = \int_{x}^{\infty} p_X(X,M,R)\,dX \qquad (7)$$

Ground shaking Parameter of interest (e.g. PGA, SA, ...)

The probability density function for the Ground motion.

$\hat{X} = f(M,R)$

$$= \int_{x}^{\infty} \frac{1}{\sigma_{\ln X}\sqrt{2\pi}}\, e^{-\frac{(\ln X - \ln \hat{X})^2}{2\sigma_{\ln X}}}\, d\ln X \qquad (8)$$

We can the above eq. in the following normalized form:

$$P[X \geqslant x/M,R] = \int_{\varepsilon^*(M,R,x)}^{\infty} f_\varepsilon(\varepsilon)\,d\varepsilon \qquad (9)$$

where ε is the number of standard deviations of the ground motion (above the median ground motion)

$f_\varepsilon(\varepsilon)$ is the probability density function for the number of standard deviations (a standard normal distribution with mean 0 and varience 1)

ε^* is given by

$\hat{X} = f(M,R)$

$$\varepsilon^*(x;M,R) = \frac{\ln x - \ln \hat{X}}{\sigma_{\ln X}} \qquad (10)$$

a function of M, $\hat{X}$, ~~site~~ R

$$\therefore \quad P[X \geq x/M,R] = \int_{\varepsilon^*}^{\infty} f_\varepsilon(\varepsilon)\,d\varepsilon = 1 - \Phi(\varepsilon^*) \qquad (11)$$

Cumulative Standard normal distribution

For Multiple Sources

$$\lambda[X \geq x] = \sum_{i=1}^{N_{source}} \lambda_i[X \geq x] \qquad (12)$$

where N_{source} is the total number of fault and areal sources.

For a Poisson process,

$$\underline{P}[X \geq x/T] = 1 - \exp(-\lambda[X \geq x].T) \qquad (13) \text{ (same as (2))}$$

For $T = 50$ years, $P = 0.1$ (10%), the $\lambda = 0.0021/yr$

$1/\lambda = 475$ years

(This is to find $\lambda[X \geq x] = 0.0021/yr.$)

For $T = 50$ years, $P = 0.02$ (2%),

$$0.02 = 1 - e^{-50\times\lambda}$$

$$e^{-50\lambda} = 1 - 0.02 = 0.98$$

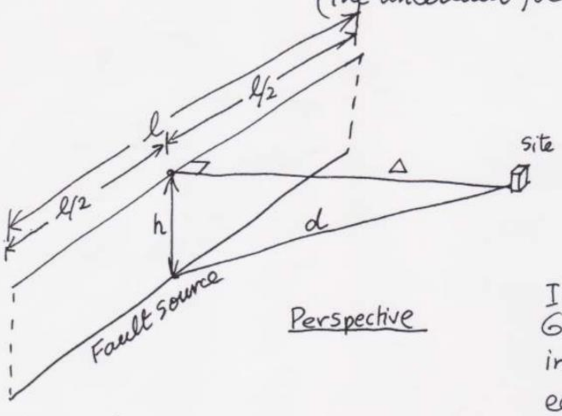
$$\ln e^{-50\lambda} = -50\lambda = \ln 0.98 = -0.0202$$

$$\underline{\lambda = 4.0405\times10^{-4}/yr.}$$

$$\underline{1/\lambda = 2475 \text{ yrs.}}$$

C. Allin Cornell 1968. Bull. Seis. Soc. Amer. Vol. 58 No. 5 S-~~4~~

$f_{R/M}(r/m) \Longrightarrow f_R(r)$ is the probability density function of R (the uncertain focal distance)

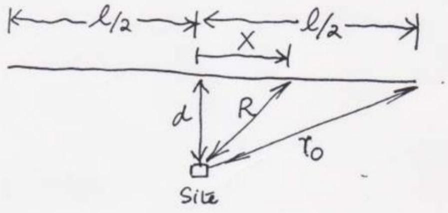


$$d = \sqrt{h^2+\Delta^2}$$

$$R = \sqrt{d^2+X^2}$$

$$r_0 = \sqrt{d^2 + \ell^2/4}$$

It is assumed that,
Given an occurrence of an event of interest along the fault, it is equally likely to occur anywhere along the fault.



: The location variable X is assumed to be uniformly distributed on the interval $(-\ell/2, \ell/2)$.

∴ The absolute Mag. of X, |X|, is uniformly distributed on the interval $(0, \ell/2)$

Cumulative prob. distri.

$$F_R(r) = P[R \le r] = P[R^2 \le r^2] = P[X^2+d^2 \le r^2]$$

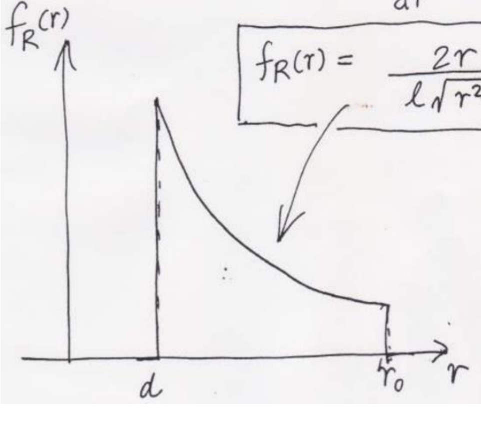
$$= P[X^2 \le r^2-d^2] = P[|X| \le \sqrt{r^2-d^2}]$$

uniform prob.

$$= \frac{\sqrt{r^2-d^2}}{\ell/2}, \quad d \le r \le r_0$$

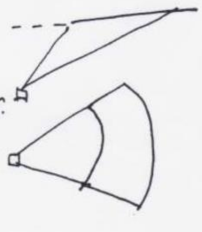
$$\therefore \quad f_R(r) = \frac{dF_R(r)}{dr} = \frac{d}{dr}\left(\frac{2\times\sqrt{r^2-d^2}}{\ell}\right)$$

$$\boxed{f_R(r) = \frac{2r}{\ell\sqrt{r^2-d^2}} \quad \text{for } d \le r \le r_0} \qquad (14)$$



For Other Cases

See Cornell's paper.



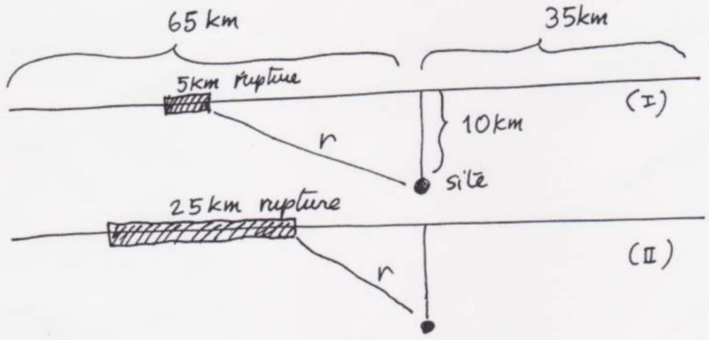
Distance Probability Distribution

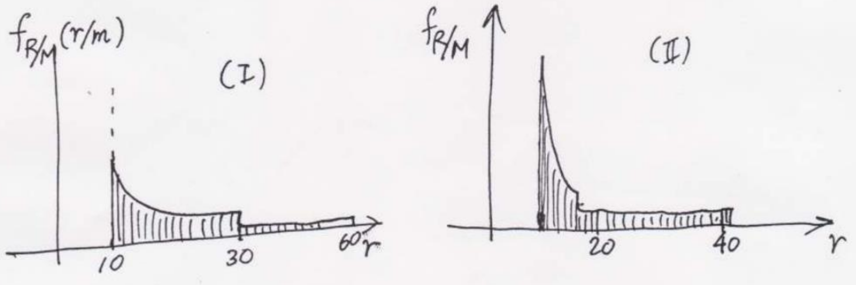
- The distance probability distribution depends on the geometry of earthquake sources and their distance from the site.

  An assumption is usually made that earthquakes occur with equal likelyhood on different parts of a source.

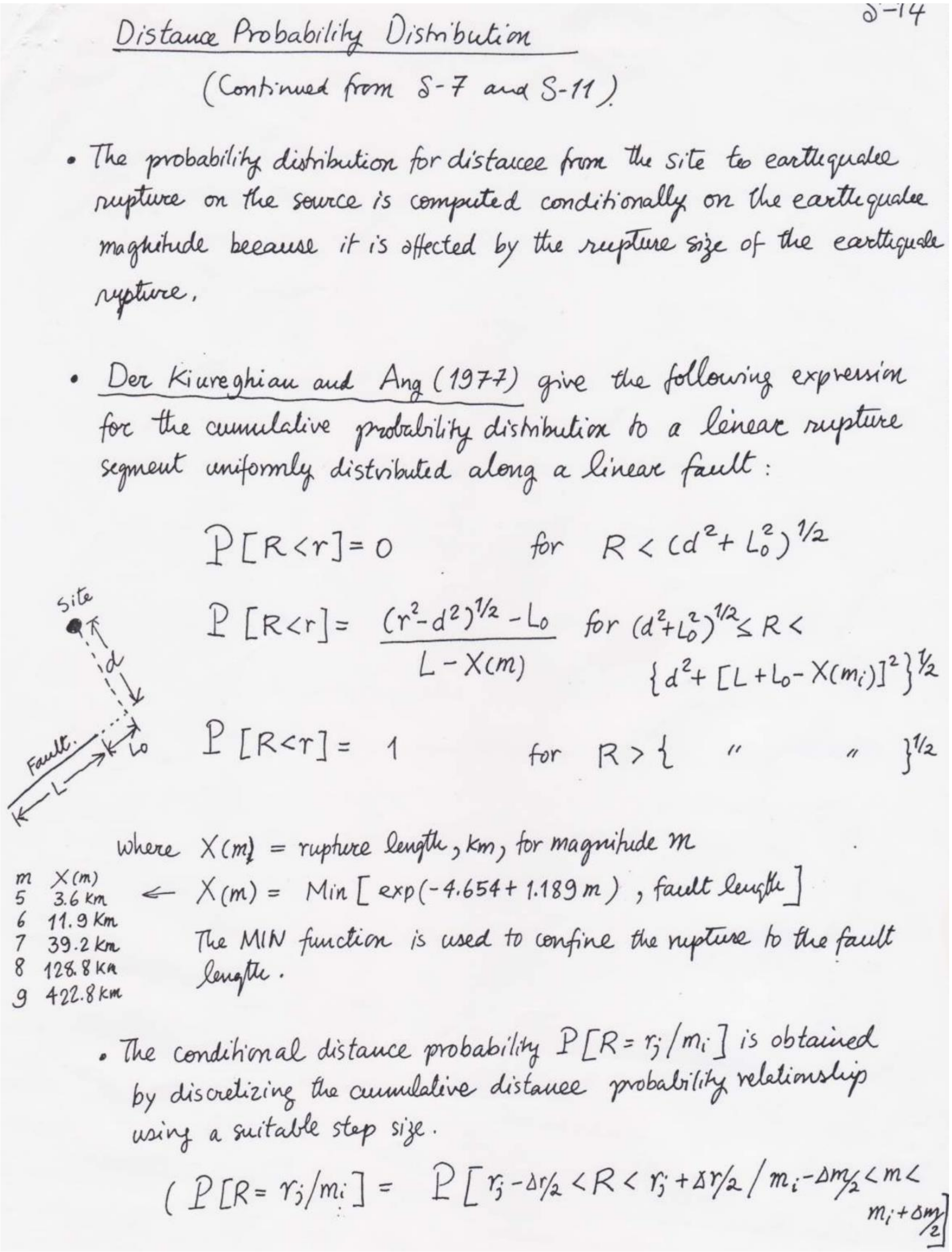
- The probability function should incorporate the magnitude-dependence of earthquake rupture size; larger-magnitude earthquakes have larger rupture areas, and thus have higher probability of releasing energy closer to a site than smaller-magnitude earthquakes on the same source.

- Check - Der Kiureghian and Ang (1977)





- The distance to earthquake rupture must be expressed in terms of the same definition of distance as used in the ground motion attenuation models.



Distance Probability Distribution

(Continued from S-7 and S-11)

- The probability distribution for distance from the site to earthquake rupture on the source is computed conditionally on the earthquake magnitude because it is affected by the rupture size of the earthquake rupture.

- Der Kiureghian and Ang (1977) give the following expression for the cumulative probability distribution to a linear rupture segment uniformly distributed along a linear fault:

$$P[R<r]=0 \qquad \text{for} \quad R<(d^2+L_0^2)^{1/2}$$

$$P[R<r]=\frac{(r^2-d^2)^{1/2}-L_0}{L-X(m)} \qquad \text{for } (d^2+L_0^2)^{1/2} \le R < \{d^2+[L+L_0-X(m_i)]^2\}^{1/2}$$

$$P[R<r]= 1 \qquad \text{for} \quad R>\{\quad '' \qquad '' \quad\}^{1/2}$$

where $X(m)$ = rupture length, km, for magnitude m

$$\leftarrow X(m) = \text{Min}\left[\exp(-4.654+1.189\,m)\ ,\ \text{fault length}\right]$$

m	$X(m)$
5	3.6 km
6	11.9 km
7	39.2 km
8	128.8 km
9	422.8 km

The MIN function is used to confine the rupture to the fault length.

- The conditional distance probability $P[R=r_j/m_i]$ is obtained by discretizing the cumulative distance probability relationship using a suitable step size.

$$\left(P[R=r_j/m_i] = P\left[r_j-\Delta r/2 < R < r_j+\Delta r/2 \;/\; m_i-\Delta m/2 < m < m_i+\Delta m/2\right]\right.$$

2.17. The Seismic Source Characterization for the PSHA

How to develop a seismic Source model for PSHA:

a) Hire an engineering geologist to build your own model

b) Use publicaly available seismic source model (e.g USGS model for US).

- Slightly poor resolution — because built for many applications in any location in US.
- Many faults donot appear as individual sources → instead they are represented using background seismicity → Only active faults get their own seismic source characterization in publically available models.

c) Use the results of previous private studies, if available.

Seismic Source Uncertainty:

PSHA accounts for all uncertainties. But uptill now, we were assuming that we are 100% confident with our seismic sources.

What if we are not sure about our seismic source model or which GMPEs to use to represent them?

Seismic Source Characterization

Up to this point, we have talked about seismic sources as if their characteristics were well-known and easily-obtained parameters.

[Characterizing the seismic sources for PSHA is the most difficult aspect of performing PSHA]

The collection of seismic sources and their corresponding M, R PDFs is called the "seismic source model" of a PSHA. → Most important

[+ Locations of faults, geometry (dip, strike), M-R relationships and slip rates etc. etc.]

a) Geological Evidence: — "Reading" the history recorded in the ground and in the geomorphology

Geologists/
Paleoseismologists

- Surfacial reconnaissance
- Fault trenching
- Aerial photos and Remote sensing
- Geophysical methods

b) Historical Evidence: Pre-instrumental era, historical accounts

c) Instrumental Evidence: Since 1930s. improve with time.

d) Academic Literature Review: beware of quality.

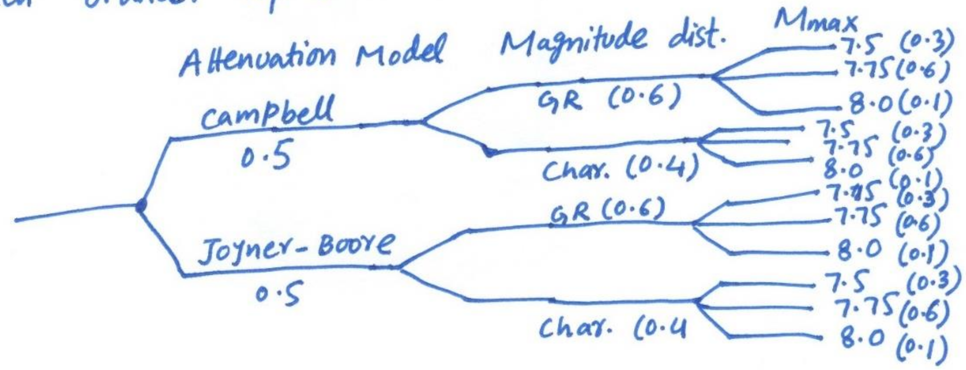
2.18. The Treatment of Epistemic Uncertainty in the PSHA

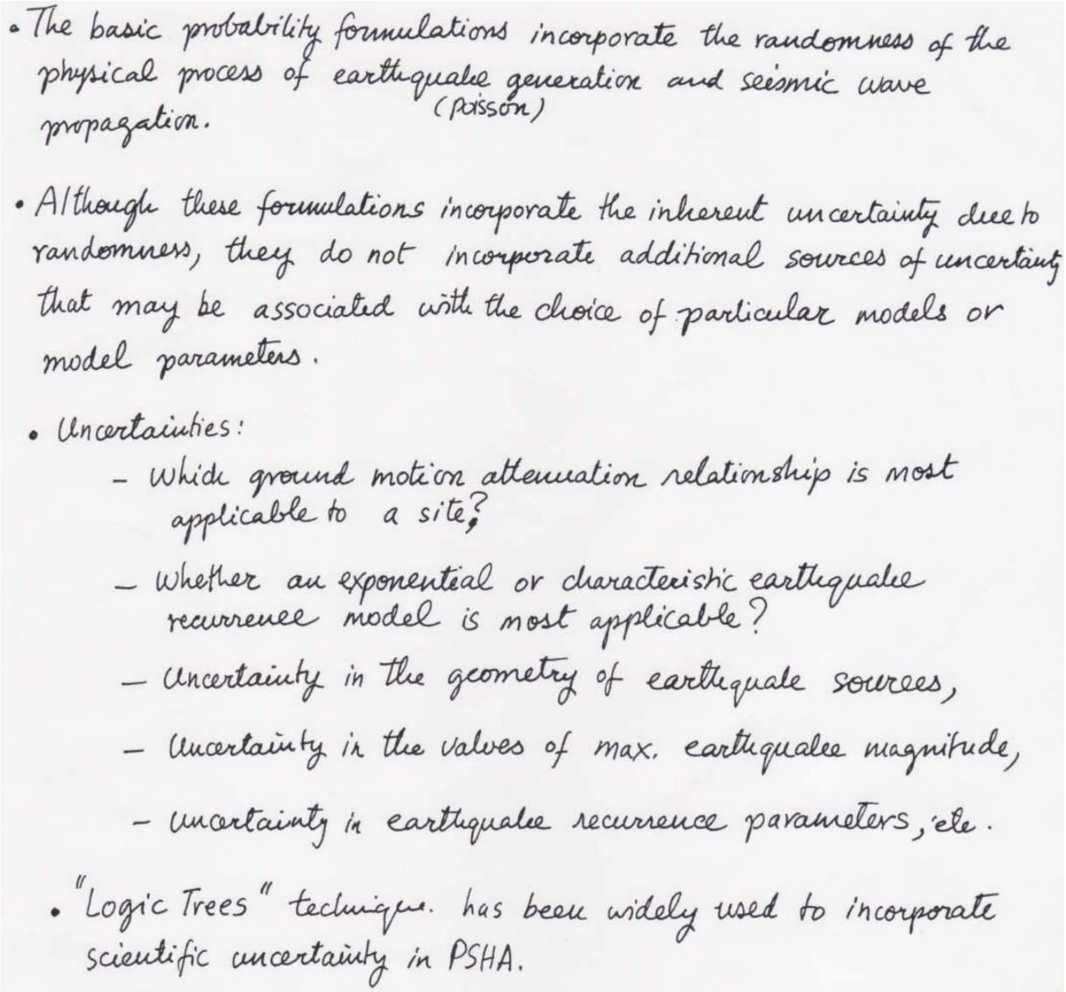
Logic Trees: All plausible scenarios are considered.

Each level deals with a different aspect of epistemic uncertainty. The weighting factors from each level must sum to 1.

Each branch represents a viable alternative within a given level.

Each branch represents its own PSHA.





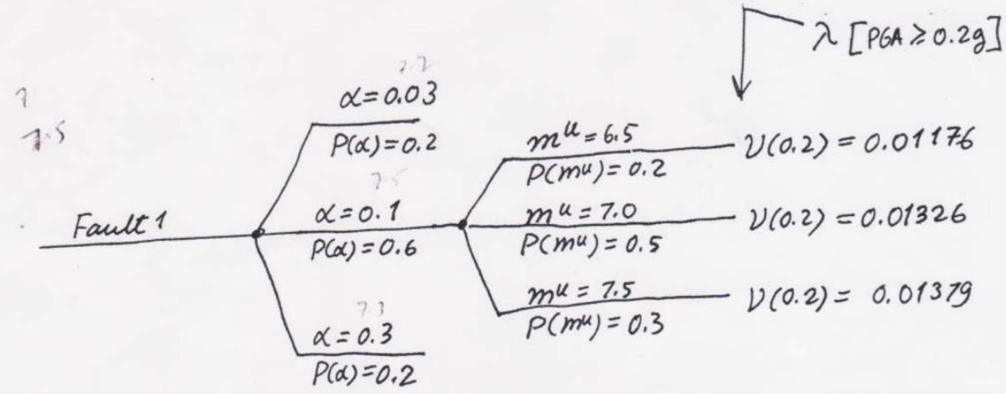
- The basic probability formulations incorporate the randomness of the physical process of earthquake generation (Poisson) and seismic wave propagation.

- Although these formulations incorporate the inherent uncertainty due to randomness, they do not incorporate additional sources of uncertainty that may be associated with the choice of particular models or model parameters.

- Uncertainties:
  - Which ground motion attenuation relationship is most applicable to a site?
  - Whether an exponential or characteristic earthquake recurrence model is most applicable?
  - Uncertainty in the geometry of earthquake sources,
  - Uncertainty in the values of max. earthquake magnitude,
  - uncertainty in earthquake recurrence parameters, etc.

- "Logic Trees" technique has been widely used to incorporate scientific uncertainty in PSHA.

Logic Tree Analysis



The probabilities assigned to each of the branches on the logic trees represent subjective assessments of the relative credibility of each of the parameters.

$$E[\nu(0.2)]_{Fault\,1} = \sum_k P[\nu(0.2)_k] \cdot \nu_k(0.2) = 0.0165$$

$$E[\nu(0.2)]_{Fault\,2} = \sum_K P[\nu 0.2)_k] . \nu_k(0.2) = 0.0023$$

Considering 2 faults

$$E[\nu(0.2)] = \sum_n E[\nu(0.2)]_n = 0.0165 + 0.0023 = 0.0188$$

The distribution in the computed hazard is found by computing the sum of all possible combinations of the end branches of the logic trees:

$$\nu(0.2)_{ij} = \nu(0.2)_i + \nu(0.2)_j$$

Fault 1 Fault 2

$$P[\nu(0.2)_{ij}] = P[\nu(0.2)_i] \bullet P[\nu(0.2)_j]$$

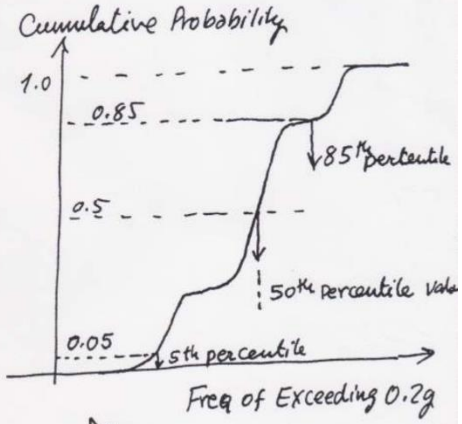
Fault 1 → 3×3 = 9 combinations $i = 1, 2, 3, \dots, 9$

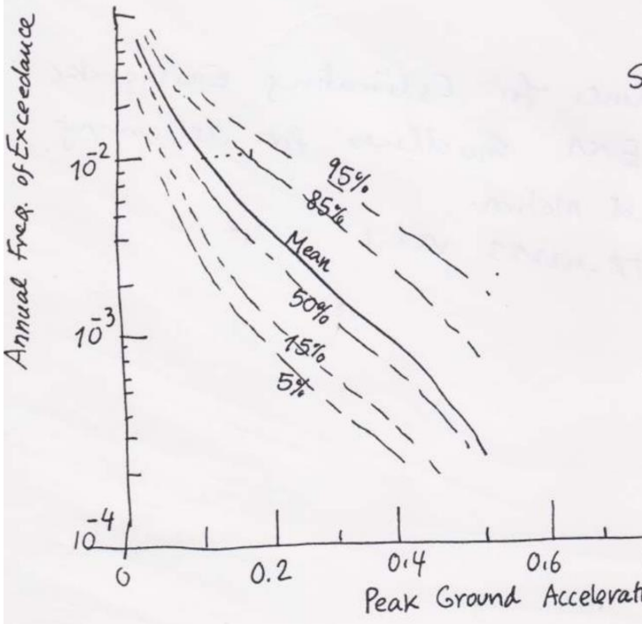
Fault 2 → 3×2 = 6 combinations $j = 1, 2, 3, \dots, 6$

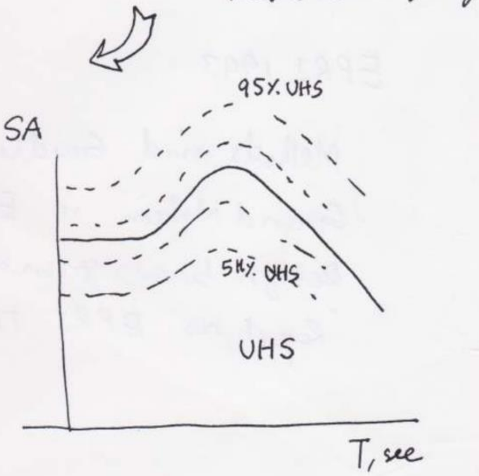
Fault 1 + Fault 2 = 9×6 = 54 combinations

Computing the 54 combinations of possible hazard values ($(\nu(0.2))_{ij}$ where $i = 1,2,\cdots,9$ and $j = 1,2,\cdots,6$) and ordering the result in increasing exceedance frequency (ν) gives the discrete distribution for the exceedance frequency from the two faults:

$\nu(0.2)$	$P[\nu(0.2)]$	$\Sigma P[\nu(0.2)]$
0.00401	0.00320	0.00320
0.00446	0.00800	0.01120
0.00448	0.00960	0.02080
0.00462	0.02400	0.02560
⋮	⋮	⋮
0.04418	0.02160	0.98080
0.04538	0.01200	0.99280
0.04698	0.00720	1.00000







2.19. The Effect of Local Site Conditions

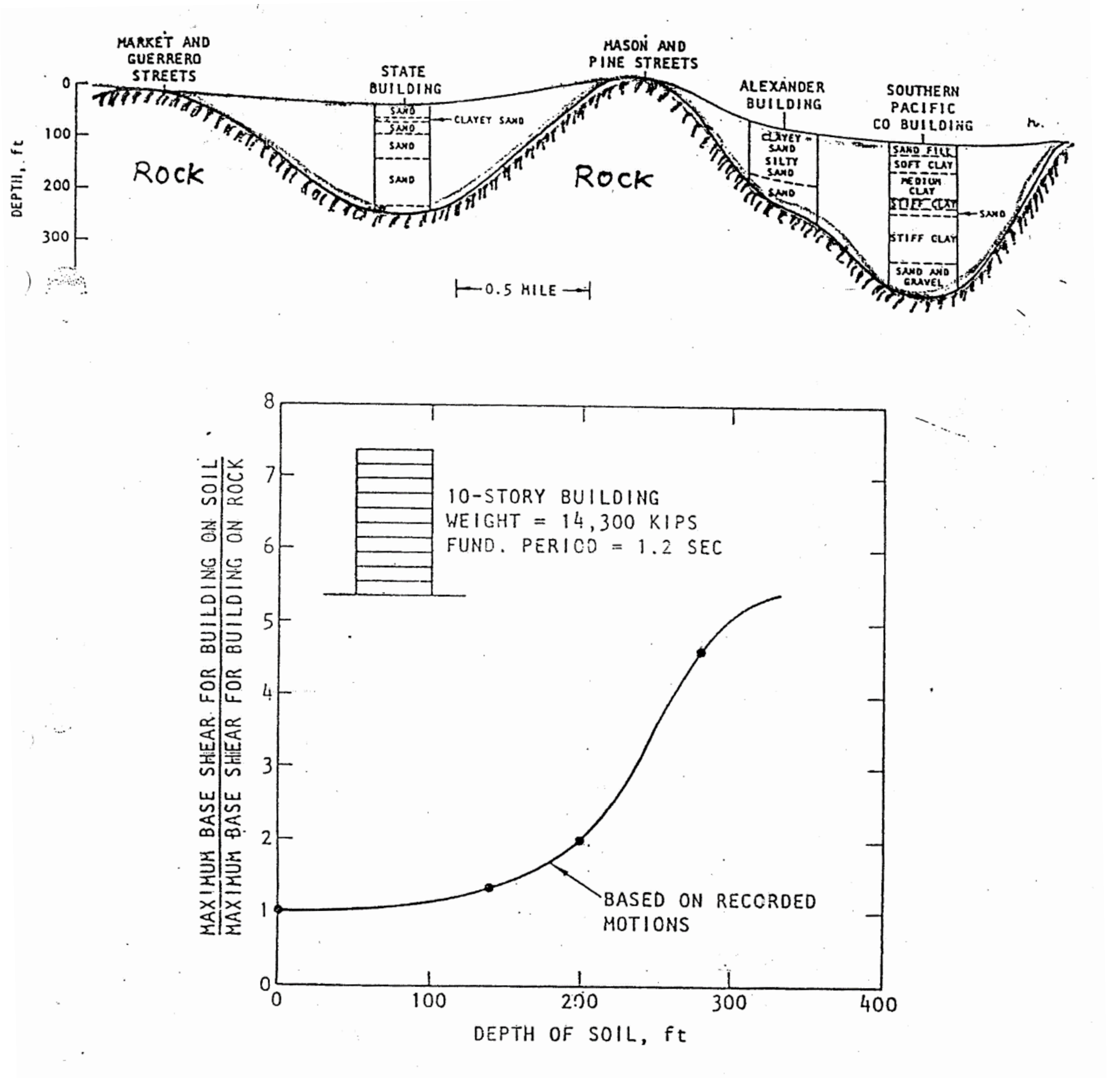


Figure 6. Influence of soil depth on maximum base shear for 10-story building in San Francisco earthquake of 1957.

- Soil type varies widely in a country — so engineer is asked to look at the seismic zone of country and then modify the numbers for soil type. So there is a soil type factor.

In general, seismic hazard map is generated without considering the soil — and then adjusted for soil.

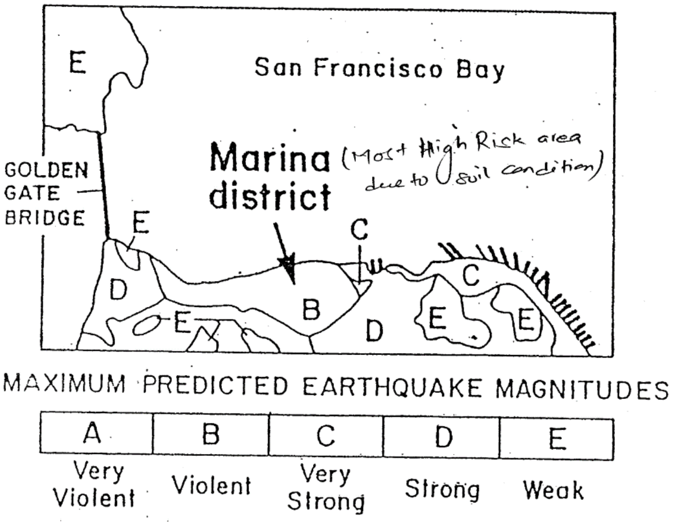


Fig. 11. *1975 U.S. Geological Survey microzonation map fragment for San Francisco showing remarkable correlation with observations after 1989 Loma Prieta earthquake.*

2.20. The Modified Cornell Method for the PSHA

The method was first developed by C.A. Cornell (Stanford University) in 1968.

It was then used by S.T. Algermissen et.al (USGS) for making a probabilistic acceleration map of US in 1976.

The map was later on used as a basis for the development of the US seismic zone map in the “Uniform Building Code” from 1988 onward.

The analysis method is currently used world-wide.

2.20.1. Basic Assumptions

a) Earthquakes occur within the zones of seismic sources.

b) Within a source zone, earthquake epicenters are uniformly distributed spatially, while earthquake focal depths are equal to a constant (this constant is usually set to average value of focal depths of past earthquakes within the source zone).

c) Earthquake occurrences in different seismic source zones are statistically independent.

d) Earthquakes are generated as *“point sources”*. In reality “line sources” or “area sources may be more realistic”, especially for large earthquakes. However for practical reasons, the point source-model is considered to be an acceptable model).

e) Within a source zone, earthquakes randomly occur in time according to Poisson distribution (the mean rate of earthquake occurrence is constant in time)

(From real observations, the occurrence of large earthquakes appear to be "Poissonian" while small earthquakes often are not. However, the ground acceleration associated with small earthquakes are, in most engineering purposes, negligible).

f) Peak ground acceleration at any given site depends on the earthquake magnitude and source-to-site distance. The acceleration can be computed by an attenuation model. (in the following, the ESTEVA model will be used).

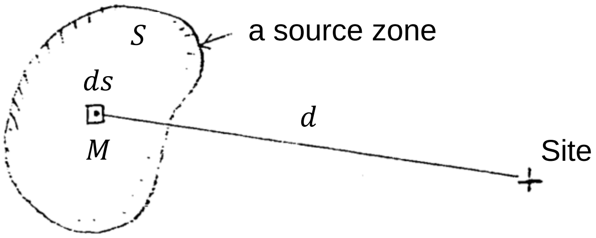
g) The average rate of earthquake occurrences can be derived from the magnitude recurrence relationship $N(m)$, which is given by the Gutenberg-Richter model:

$$Log\, N(m) = a - bm$$

The model is sometimes called "the exponential model".

2.20.2. Theoretical Derivation

Considering a seismic source zone of total area "S" and a small area segment of area "ds" as shown:



On the basis of the assumption (g),

the frequency of earthquake occurrence within this source zone is given by

$$N(M) = N_0\, Exp\, [-\beta\, M]$$

$N(M)$ is the average number per year of earthquakes having magnitude $\geq M$ and epicenter located within the area of this source zone.

N_0 and β are constants; they are conventionally obtained from an appropriate statistical analysis of historical earthquakes.

(The constants for a source zone are different from those for the other zones; the constant depends on the seismicity of the source zones.

On the basis of the assumption (b), the average number per year of earthquakes having magnitude $\geq M$ that occur within the area segment ds, denoted by $\eta(M)$, is then given by

$$\eta(M) = N(M)\frac{ds}{S}$$

Now, suppose that an earthquake of magnitude M occurs within the area segment ds.

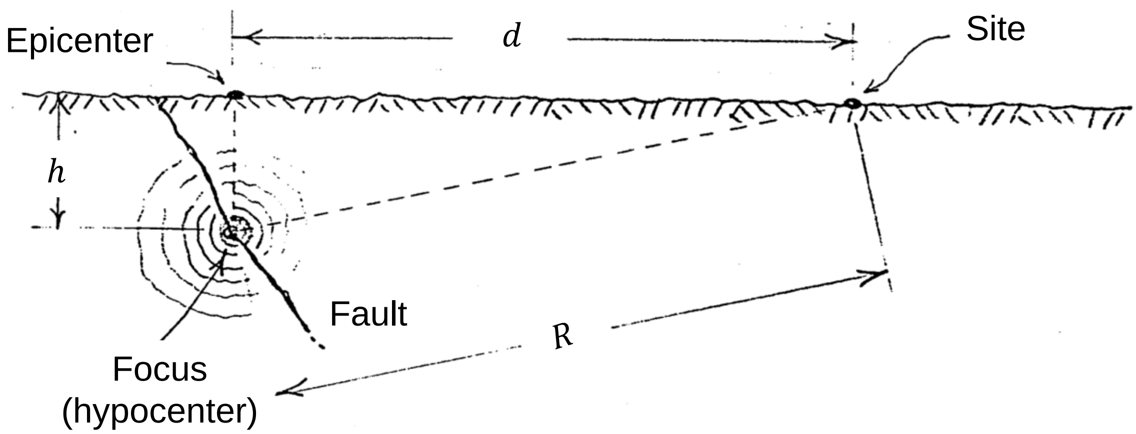
On the basis of the assumption (f), the peak ground acceleration at the site of interest, denoted by a, is then given by

$$a = \frac{5600\, Exp\, [0.8M]}{(R + 40)^2}$$

a is the peak ground acceleration (unit: $cm/sec2$)

M is the magnitude of the earthquake in Richter scale.

R is focal distance (km)



$$R = \sqrt{d^2 + h^2}$$

d is the epicentral distance

h is the focal depth of the earthquake

* In this case, where the earthquake occurs within a small area, the epicenter can be assumed to be located at the center of the small area with losing the accuracy.

Let $\tilde{a}$ can be a level of acceleration of interest.

The condition that the peak ground acceleration at the site, a, exceeds the acceleration level of interest, $\tilde{a}$, is denoted by

$$a > \tilde{a}$$

Substituting Eq. (3) in Eq. (5) yields:

$$\frac{5600\, Exp[0.8M]}{(R + 40)^2} > \tilde{a}$$

$$Exp\, [0.8M] > \frac{\tilde{a}\ (R + 40)^2}{5600}$$

$$0.8M > \frac{log_{10}\left[\tilde{a}\,(R+40)^2\Big/_{5600}\right]}{log_{10}\,e}$$

or

$$M > m$$

where

$$m = \frac{1}{c_2}\{log_{10}\tilde{a} - c_1 + 2\,log_{10}\,(R+40)\}$$

$$c_1 = log_{10}\,(5600) = 3.75$$

$$c_2 = 0.8\,log_{10}\,(e) = 0.347$$

That is to say $(a > \tilde{a})$ is equivalent to $(M > m)$

The equation (9) says that

“If an earthquake occurs within the segment ds and its magnitude is greater than “m”, then the peak ground acceleration at the site of interest is greater than “$\tilde{a}$”.

The average number per year of the events that $(a > \tilde{a})$, denoted by ν , is therefore given by

$$\nu = \eta(m) = N(m)\frac{ds}{S} = N_0\,Exp[-\beta m]\,\frac{ds}{S}$$

$$= N_0\,Exp\left[\frac{-\beta}{C_2}\,\left\{log_{10}\tilde{a} - c_1 + 2\,log_{10}(R+40)\right\}\right]\,\frac{ds}{S}$$

$$= N_0\,\frac{ds}{S}\,Exp\left[\frac{-\beta}{0.8}\,\frac{log_{10}\tilde{a}}{log_{10}e}\right]\,Exp\left[\frac{\beta\,c_1}{0.8}\,log_e 10\right]\,Exp\left[\frac{-\beta\,2}{0.8}\,\frac{log_{10}(R+40)}{log_{10}e}\right]$$

$$= N_0\,\frac{ds}{S}\,Exp\left[\frac{-\beta}{0.8}log_e\,\tilde{a}\right]\,Exp\left[log_e 10^{\frac{\beta\,c_1}{0.8}}\right]\,Exp\left[\frac{-2\beta}{0.8}\,log_e\,(R+40)\right]$$

$$= N_0\,\frac{ds}{S}\,Exp\left[log_e\tilde{a}^{-\beta/_{0.8}}\right]\,.\,10^{\beta c_1/_{0.8}}\,.\,Exp\left[log_e(R+40)^{-2\beta/_{0.8}}\right]$$

$$= N_0\,\frac{ds}{S}\,\tilde{a}^{-\beta/_{0.8}} \times (10^{log_{10}5600})^{\beta/_{0.8}} \times (R+40)^{-2\beta/_{0.8}}$$

$$= N_0\,\frac{ds}{S}\,\tilde{a}^{-\beta/_{0.8}} \times 5600^{\beta/_{0.8}} \times (R+40)^{-2\beta/_{0.8}}$$

$$\nu = N_0\,\frac{ds}{S}\,\left(\frac{5600}{\tilde{a}\,(R+40)^2}\right)^{\beta/_{0.8}}$$

Hence, the occurrence rate of the event $(a > \tilde{a})$, as denoted by ν, is function of

N_0 , β (seismicity of the score)

$^{ds}/_{S}$ (the area ratio)

R (the focal distance)

$\tilde{a}$ (the acceleration level of interest)

Assuming that the probability distribution of earthquakes in time is Poisson distribution (Assumption (e)), it follows that

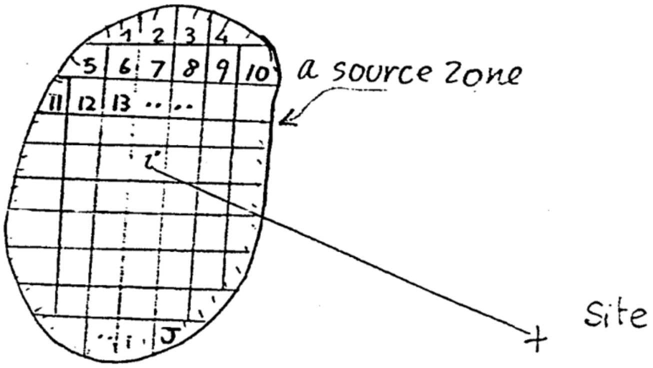
P [no event that $a > \tilde{a}$ occurs within a time period of T years] = $Exp[-\nu T]$

or in the other words,

$$\mathrm{P}\ [a \leq \tilde{a} \quad \text{in a } T\text{-yr period}] \ = Exp[-\nu T]$$

So far, we consider only the effect of earthquakes that occur within a small segment ds, but from now on we will extend our analysis to integrate the effect of earthquakes that occur in the other segments in the source zone.

Suppose that the seismic source zone consist of J (Small) segments as shown. These segments are treated here as independent sources.



Let a_i be the peak ground acceleration, at the site, which is generated by an earthquake within the segment "i"

Let $amax$ be the maximum value of a_i for $i = 1,2,3 \dots, \mathrm{J}$; that is

$$\{a_{max} = max\ [a_1, a_2, a_3, \dots \dots .. a_j\}$$

Hence,

$$\mathrm{P}\ \left[a_{max} \leq \tilde{a}\ in\ a\ T - yr\ period\right] = \mathrm{P}\ [a_1 \leq \tilde{a} \text{ in a T-yr period}$$

And

$$a_2 \leq \tilde{a} \text{ in a T-yr period}$$

And

$$a_J \leq \tilde{a} \text{ in a T-yr period}]$$

By treating each source segment as an independent source, Eq. (13) becomes

$\mathrm{P}\left[a_{max} \leq \tilde{a} \text{ in a T-yr period}\right] = P[a_i \leq \tilde{a} \text{ in T-yr period}]$

$$= \prod_{i=1}^{J} \; Exp\,[-\nu_i T]$$

$$= \; Exp\left[-T\sum_{i=1}^{J} \nu_i\right]$$

where the subscribe "i" denotes that the parameter to which it is attached is directly associated with the source segment "i".

Let P_e be the probability of exceedance, that is, the probability that a_{max} will exceed $\tilde{a}$ in a T-yr period:

$$P_e = 1 - \; P[a_{max} \; \leq \tilde{a} \text{ in T-yr period}]$$

Substituting Eq. (14) into Eq. (15) , we obtain

$$P_e = 1 - \; Exp\left[-T\sum_{i=1}^{J} \nu_i\right]$$

$$-T\sum_{i=1}^{J} \nu_i = log_e(1 - P_e)$$

$$\sum_{i=1}^{J} \nu_i + \; \frac{log_e(1 - P_e)}{T} = 0$$

Introducing Eq. (10) in to Eq. (16) we obtain:

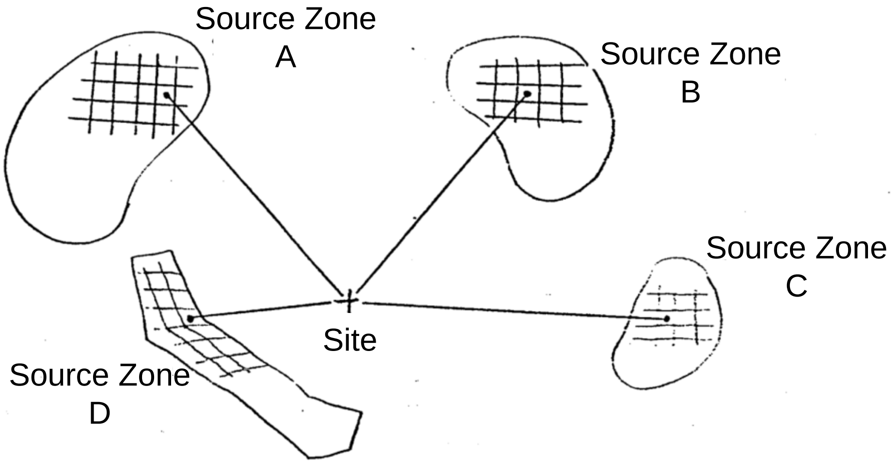
$$\sum_{i=1}^{J} \mathrm{N}_0 \; \left(\frac{5600}{\tilde{a}\,(R_i + 40)^2}\right)^{\beta/_{0.8}} \; \frac{ds_i}{\mathrm{S}} + \; \frac{log_e(1 - P_e)}{T} = 0$$

If the values of P_e and T are specified, then the equation (17) is merely a polynomial equation in terms of $\tilde{a}$ with non-integer coefficients, and $\tilde{a}$ can be easily obtained by numerical iterative procedures.

In practices, the value of $\tilde{a}$ which corresponds to $P_e = 0.1$ and $T = 50$ yr is typically chosen for the design of ordinary structures; that is, an ordinary structure should be able to resist the ground shaking with *peak ground acceleration that has a 10% chance of being exceeded in a 50- years period.*

This peak ground acceleration is, in fact, equivalent to the peak ground acceleration with 475-year mean reoccurrence interval (or a nominal 500 year mean reoccurrence interval).

In the case where there are more than one source zone,



The probabilistic peak ground acceleration can also be evaluated by the same probabilistic technique. The Eq. (17) will have to be changed slightly:

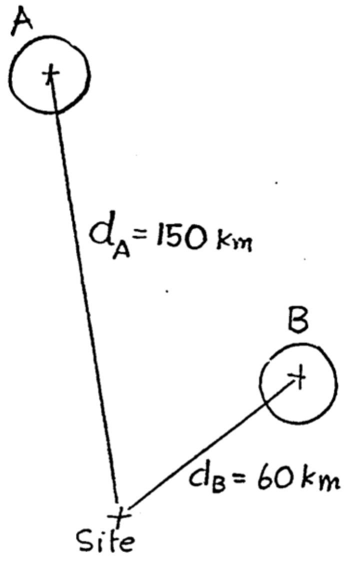
$$\sum_{Zone\ A,B,C,D}\left\{\sum_{i=1}^{J} \mathrm{N}_0\ (\frac{5600}{\tilde{a}\ (R_i+40)^2})^{\beta/_{0.8}}\ \frac{ds_i}{\mathrm{s}}\right\} + \frac{log_e(1-P_e)}{T} = 0$$

2.20.3. Example Problem 1

Given two seismic source zones A and B and a site of interest as shown in the figure below:

Given the sources' characteristics

	Zone A	Zone B
β	1.6	1.4
N_0	3000	300
$N_{(5)}$	1	0.27
$N_{(8)}$	0.008	0.004
d	150	60 km
h	20	30 km



Assuming that the ESTEVA's attenuation model is applicable here.

Determine the expected peak ground acceleration at the site in a 50-year period with 10% chance of being exceeded by considering

a. The effect of earthquakes in zone A only,
b. The effect of earthquakes on zone B only,
c. The effect of earthquakes in both zones.

Solution:

Focal distance:

$$R_A = \sqrt{150^2 + 20^2} = 151.3\ km$$

$$R_B = \sqrt{60^2 + 30^2} = 67.1\ km$$

Occurrence rate:

$$\nu_A = N_{0A}\ \left(\frac{5600}{\tilde{a}\ (R_A + 40)^2}\right)^{\beta_A/0.8} = 3000\ \times\ \left(\frac{5600}{\tilde{a}\ (151.3 + 40)^2}\right)^{1.6/0.8}$$

$$\nu_A = \frac{70.2}{\tilde{a}^2}$$

$$\nu_B = N_{0B}\ \left(\frac{5600}{\tilde{a}\ (R_B + 40)^2}\right)^{\beta_B/0.8} = 3000\ \times\ \left(\frac{5600}{\tilde{a}\ (67.1 + 40)^2}\right)^{1.4/0.8}$$

$$\nu_B = \frac{85.5}{\tilde{a}^{1.75}}$$

$$\frac{log_e(1-P_e)}{T} = \frac{log_e(0.9)}{50} = -2.107 \times 10^{-3}$$

For the case (a):

$$70.2/_{\tilde{a}^2} - 2.107 \times 10^{-3} = 0$$

$$\tilde{a} = 182.5 \text{ cm/sec}^2$$

For the case (b):

$$85.5/_{\tilde{a}^{1.75}} - 2.107 \times 10^{-3} = 0$$

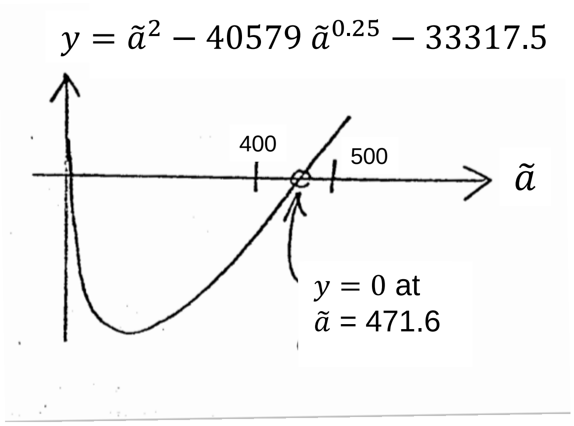
$$\tilde{a} = 429.8 \text{ cm/sec}^2$$

For the case (c):

$$\frac{70.2}{\tilde{a}^2} + \frac{85.5}{\tilde{a}^{1.75}} - 2.107 \times 10^{-3} = 0$$

$$\tilde{a}^2 - 40579\,\tilde{a}^{0.25} - 33317.5 = 0$$

$$\tilde{a} = 471.6 \text{ cm/sec}^2$$



2.20.4. Example Problem 2

Suppose that a site of interest is located near an active fault as shown in the figure below.

Given the fault's characteristics

$$N_0 = 3000 \qquad \begin{pmatrix} N_{(8)} = 0.008 \\ N_{(5)} = 1 \end{pmatrix}$$
$$\beta = 1.6$$

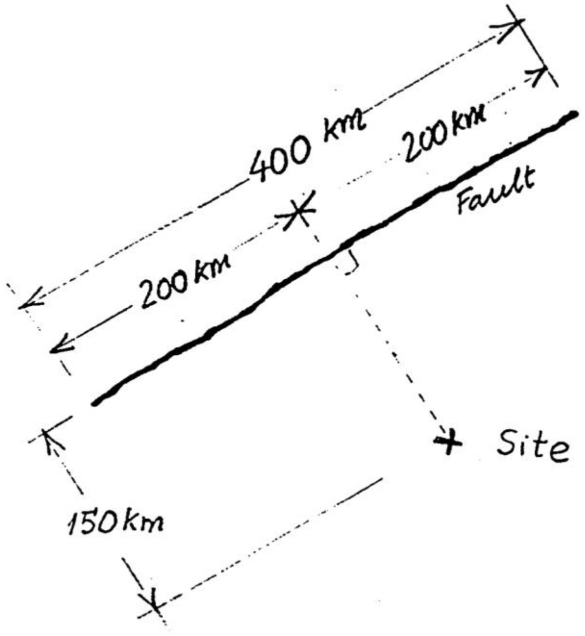
h_{av} = average focal depth=20 km

Assuming that the ESTEVA's attenuation model is applicable here:

Determine the expected peak ground acceleration at the site for

a) A 50 year exposure period with a 10% chance of being exceeded,

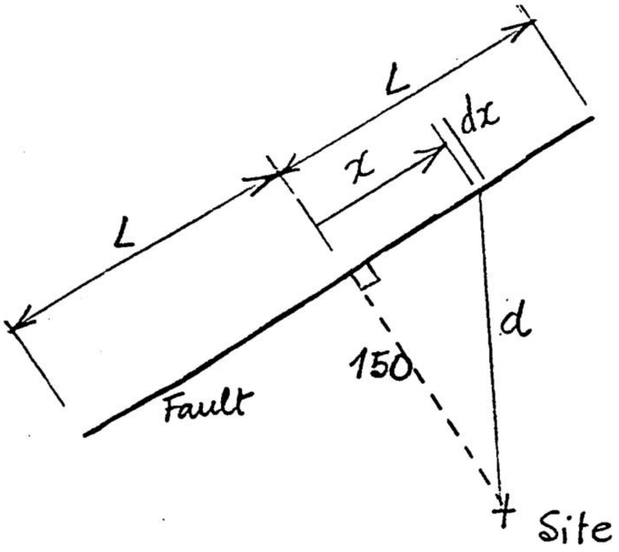
b) 1250 year exposure period with a 10% chance of being exceeded.



Most equations shown in this lecture can be applied to this case provided that

$\frac{ds}{S}$ is changed to $\frac{dx}{2L}$

And discrete summation is transform into integration



Therefore, the Eq. (17) in the lecture is modified into

$$2\int_0^L N_0 \left(\frac{5600}{\tilde{a}\,(\mathrm{R}+40)^2}\right)^{\beta/0.8} \frac{dx}{2L} + \frac{log_e(1-P_e)}{T} = 0$$

where

$$N_0 = 3000$$

$$\beta = 1.6$$

$$h = 20$$

$$L = 200$$

$$R = \sqrt{d^2+h^2} = \sqrt{150^2+x^2+20^2} = \sqrt{x^2+22900}$$

Introducing Eq. (2) into Eq. (1), we obtain:

$$\frac{N_0}{L}\left(\frac{5600}{\tilde{a}}\right)^{\beta/0.8} \times \int_0^L \frac{1}{(R+40)^{2\beta/0.8}}\,dx + \frac{log_e(1-P_e)}{T} = 0$$

$$\frac{4.70\ \times 10^8}{\tilde{a}^2}\int_0^{200}\frac{1}{\left(\sqrt{x^2+22900}+40\right)^4}\,dx + \frac{\ln(1-P_e)}{T} = 0$$

$$\frac{41}{\tilde{a}^2} + \frac{\ln(1-P_e)}{T} = 0$$

For the case (A),

$$P_e = 0.1,\ T = 50$$

$$\frac{41}{\tilde{a}^2} + \frac{\ln(0.9)}{50} = 0 \Rightarrow \tilde{a} = 139 \text{ cm/sec}^2$$

For the case (B),

$$P_e = 0.1,\ T = 250$$

$$\frac{41}{\tilde{a}^2} + \frac{\ln(0.9)}{250} = 0 \Rightarrow \tilde{a} = 312 \text{ cm/sec}^2$$

2.21. A Quick Comparison of the PSHA Methodologies

<table>
<tr><th></th><th>Simplified analysis in this lecture</th><th>Algermissen’s US seismic zone map (1976) - ATC</th><th>Pennung-Ade’s Thailand seismic zone map (1994)</th></tr>
<tr><td>**a) Seismicity model of source zone:**
Magnitude-reoccurrence relationship
Earthquake records (database)
Number of source zones
Number of segments</td><td>Exponential type
w/o upper bound in earthquake magnitude
-
1
J</td><td>Exponential type
with upper bound in earthquake magnitude (Sharp truncation)
Instrumental earthquake records,
all records are corrected for completeness by the J.C.STEPP’s methods
>70
N.A</td><td>Exponential type
with upper bound in earthquake magnitude (Smooth truncation)
80-yr instrument earthquake record,
all records are corrected for completeness by the J. C. STEPP’s methods
11
149</td></tr>
<tr><td>**b) Attenuation model**</td><td>ESTEVA model</td><td>Schnabel-Seed model (1973)
With some modifications</td><td>ESTEVA model</td></tr>
<tr><td>**c) Probability model**</td><td>Modified CORNELL method</td><td>Modified CORNELL method</td><td>Modified CORNELL method</td></tr>
<tr><td>**d) Results**</td><td>$\tilde{a}$ for $P_e = 0.1$ and
$T = 50$ years</td><td>$\tilde{a}$ and $\tilde{v}$ for
$P_e = 0.1$ and
$T = 50$ years</td><td>$\tilde{a}$ for $P_e = 0.1$ and
$T = 50$ years</td></tr>
<tr><td>**e) Seismic zoning**</td><td>-</td><td>Based on EPA
Effective peak ground acceleration
(see Figures)</td><td>Based on peak ground acceleration $(\tilde{a})$
<table>
<tr><th>Zone</th><th>$\tilde{a}/g$</th><th>Zone Factor (Z)</th></tr>
<tr><td>4</td><td>0.3 up</td><td>0.4</td></tr>
<tr><td>3</td><td>0.2~0.3</td><td>0.3</td></tr>
<tr><td>2B</td><td>0.15~0.2</td><td>0.2</td></tr>
</table></td></tr>
</table>

			2A	0.075~0.15	0.1
			1	0.025~0.075	0.0
			0	Below 0.025	0

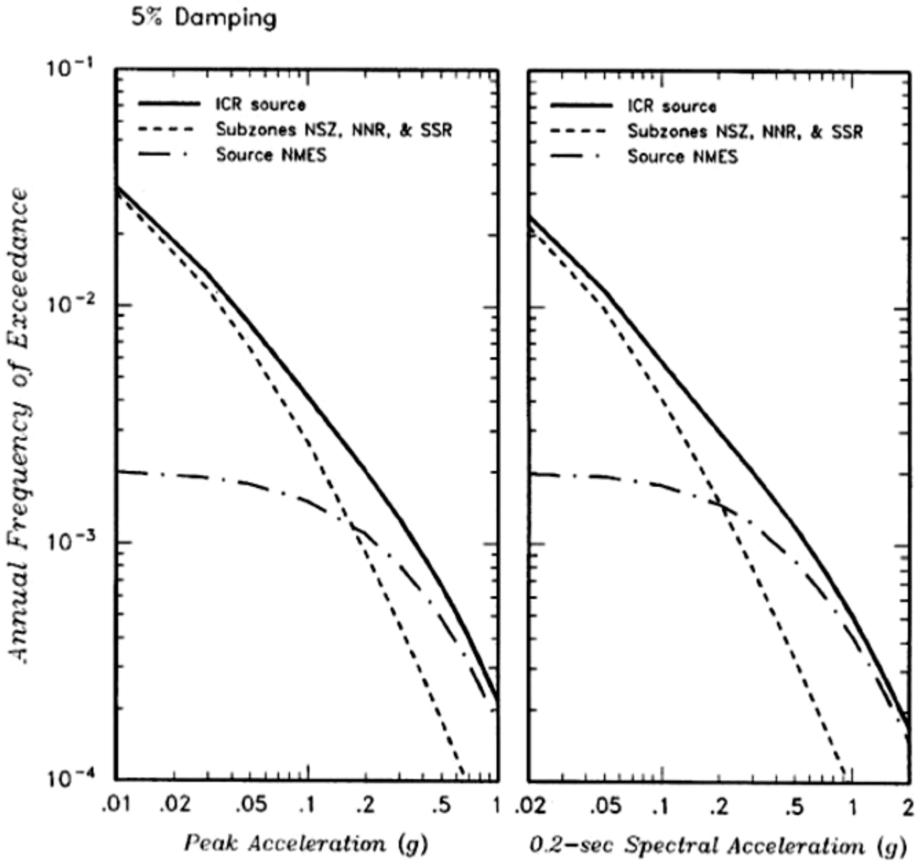
2.22. The Deaggregation of Seismic Hazard

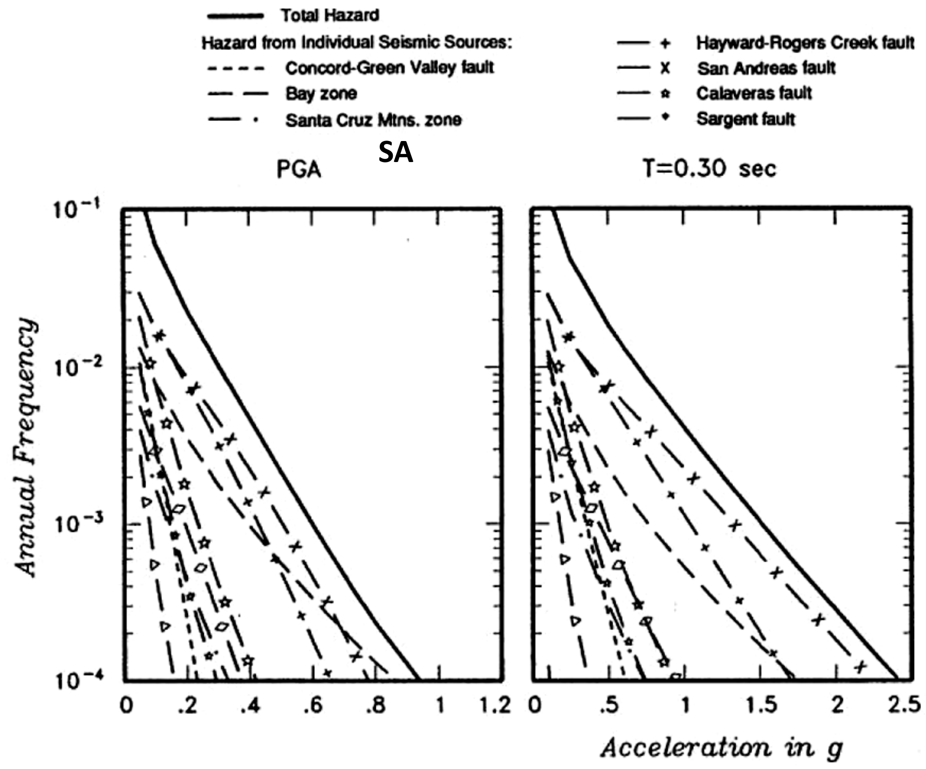
The hazard curve gives the combined effect of all the seismic sources, magnitudes and distances on the probability of exceeding a given ground motion level.

Since all of the sources, magnitudes, and distances are mixed together, it is difficult to get an intuitive understanding of what is controlling the hazard from the hazard curve by itself.

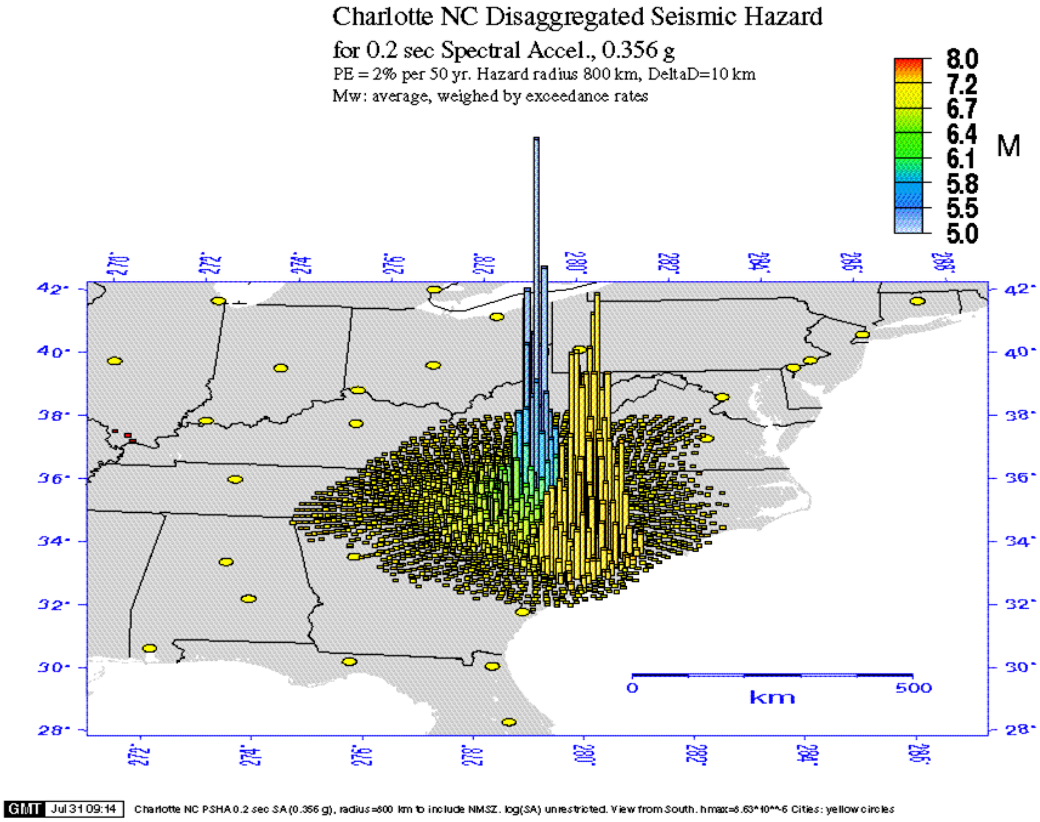
To provide insight into what events are the most important for the hazard at a given ground motion level, the hazard curve is broken down into its contributions from different earthquake scenarios.

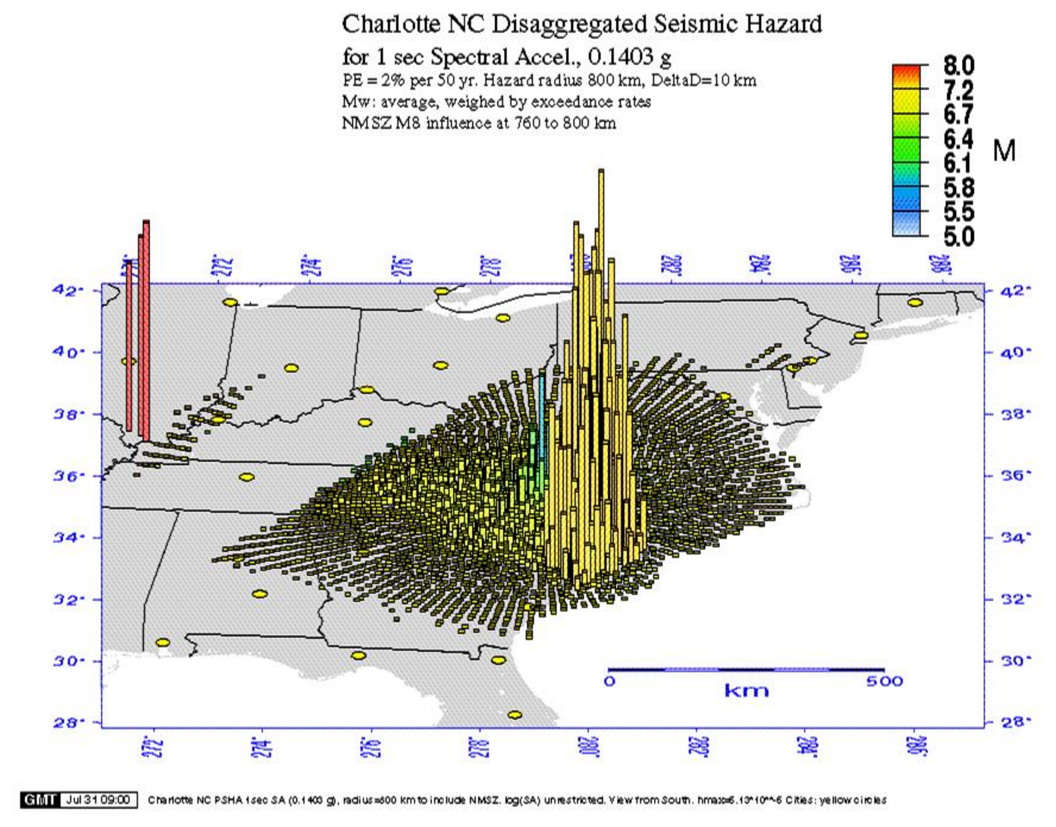
This process is called ‘Deaggregation of Hazard’.





Example of contributions of various seismic sources to the total seismic hazard at the site




Charlotte NC Disaggregated Seismic Hazard
for 1 sec Spectral Accel., 0.1403 g
PE = 2% per 50 yr. Hazard radius 800 km, DeltaD=10 km
Mw: average, weighed by exceedance rates
NMSZ M8 influence at 760 to 800 km
8.0
7.2
6.7
6.4
6.1
5.8
5.5
5.0
M
42°
40°
38°
36°
34°
32°
30°
28°
272°
274°
276°
278°
280°
282°
284°
286°
0
km
500
GMT Jul 31 09:00
Charlotte NC PSHA 1sec SA (0.1403 g), radius=800 km to include NMSZ. log(SA) unrestricted. View from South. hmax=6.13*10**-6 Cities: yellow circles

Deaggregation of Hazard

of different size, at different locations, and at different frequencies of occurrence contributes to to the final hazard

- The hazard curve gives the combined effect of all magnitudes and distances on the probability of exceeding a given ground motion level.

- To provide insight into what events are the most important for the hazard at a given ground motion level, the hazard curve is broken down into its contributions from different earthquake scenarios.

- This process is called "deaggregation".

- Typically, little thought has been given to the grouping of the scenarios. Most hazard studies use equal spacing in magnitude space and distance space. This may not be appropriate for a specific project.

- The most common form of deggregation is a two-dimensional deaggregation in mag. and distance bins:

$$\text{Deagg}\left[X \geq x,\ M_1 < M < M_2,\ R_1 < R < R_2\right] = \frac{\displaystyle\sum_{i=1}^{n\,source} N_i(M_0) \cdot \int_{m=M_1}^{M_2} \int_{r=R_1}^{R_2} P\left[X \geq x / m, r\right] \cdot f_M(m)\, f_R(r)\, dr\, dm}{\lambda\left[X \geq x\right]} \qquad (15)$$

$$\text{Here,}\quad \left.\begin{aligned} N_i(M_0) &= \nu_i \\ P[X \geq x/m, r] &= P[X \geq x/M, R] \\ f_R(r) &= f_{R/M}(r/m) \end{aligned}\right\} \ \text{Eq. (1)}$$

ν_i = ann. freq of occ of equak on seism Source i in a Mag in centered at mi ; mi is $> M_0$ and below the M_{max}.

- The deaggregation is normalized such that it sums to unity for all scenario groups.

Deagg[ ] = the conditional probability of the ground motion being generated by an earthquake with magnitude in the range $M_1 - M_2$ and distance in the range $R_1 - R_2$.

- The results of the deaggregation will be different for different probability levels (e.g. 100 yr vs 1000 yr return periods) and for different spectral periods.

- EX: For the 500 yr return period, the hazard is dominated by large distant earthquakes, but for the 10,000 year return period, the hazard is dominated by nearly moderate magnitude earthquakes.

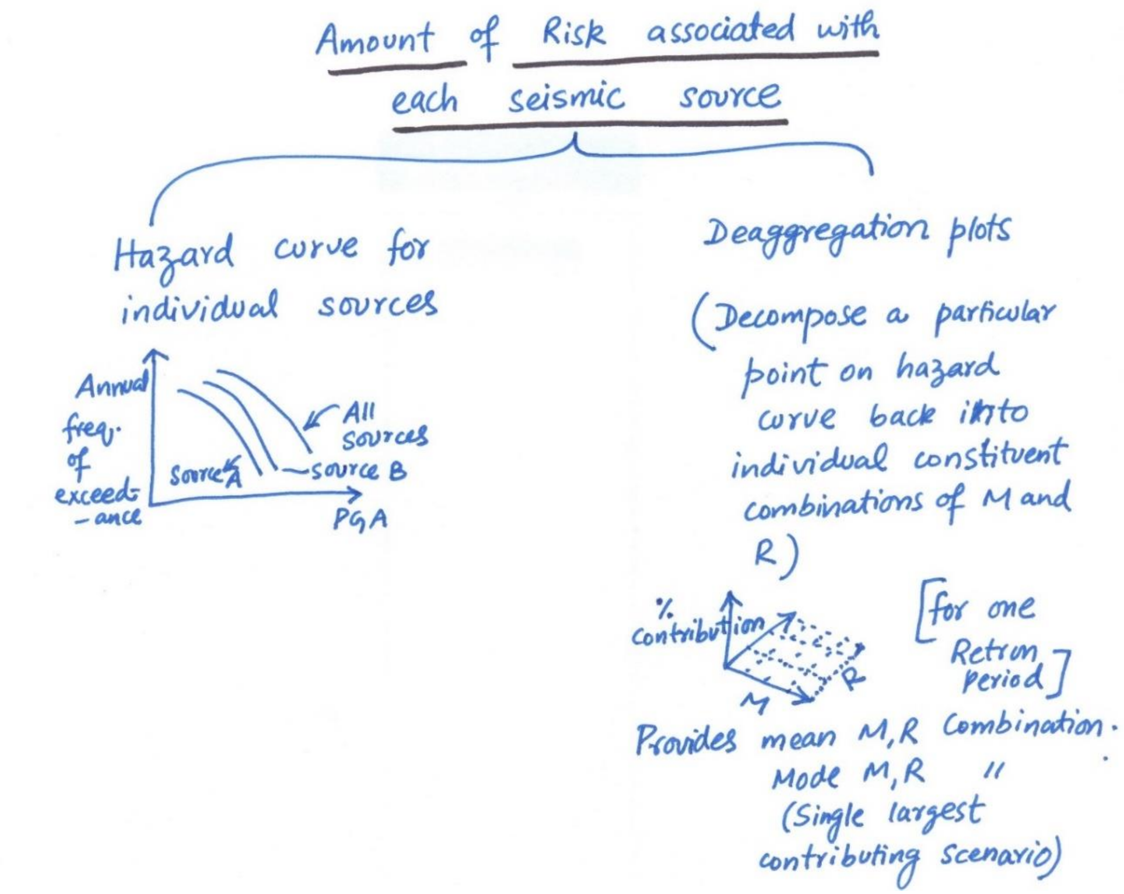
- The mean magnitude and distance:

$$\overline{M} = \frac{\sum_{i=1}^{n\,Source} N_i(M_0) \int_{m=M_0}^{M_{max}} \int_{r=0}^{\infty} m . f_M(m) . f_R(r) . P[X \geq x / m, r] \, dm \, dr}{\lambda[X \geq x]} \qquad (16)$$

$$\overline{R} = \frac{\sum_{i=1}^{n\,Source} N_i(M_0) \int_{m=M_0}^{M_{max}} \int_{r=0}^{\infty} r . f_M(m) . f_R(r) . P[X \geq x / m, r] \, dm \, dr}{\lambda[X \geq x]} \qquad (17)$$

- Rates of Scenarios:

$$\lambda[X \geq x, M_1 < M < M_2, R_1 < R < R_2] = \text{Degg}[X \geq x, M_1 < M < M_2, R_1 < R < R_2] \times \lambda[X \geq x] \qquad (18)$$



2.23. Probabilistic Ground Motions in Earthquake-resistant Design

For ordinary structures, it is not practical to establish design criteria at such a high level that no damage will be sustained even in the event of the strongest possible earthquake.

It is known that large earthquakes occur much less frequently than small earthquakes and the probability of experiencing the strongest possible shaking is very small compared to probability of experiencing moderate ground shaking at a site.

It is cost-effective to accept extensive damage once per 500 years, “acceptable risk”

The expected performance of buildings in modern earthquake-resistant design codes are:

Resist a minor level of earthquake ground shaking (SE) without damage

SE = Serviceability earthquake—50% probability of exceedance in 30 years (43-year return period)

Resist the design level of earthquake ground shaking (DBE) with damage (which may or may not be economically repaired) but without causing extensive loss of life.

DBE = Design basis earthquake—10% probability of exceedance in 50 years (472-year return period)

Resist the strongest earthquake shaking expected at the site (MCE) without collapse, but potentially with extreme damage.

MCE = Maximum considered earthquake—2% probability of exceedance in 50 years (2475-year return period)

Seismic Design Criteria of Major Dam Projects

- According to ICOLD (International Commission of Large Dams) Bulletin 72 (1989), large dams have to be able to withstand the effects of the Maximum Credible Earthquake Shaking Level (MCE).
- This MCE is the strongest earthquake shaking level that could occur in the region of a dam, and is considered to have a return period of several thousand years (typically 10,000 years in regions of low to moderate seismicity).

MCE = Maximum considered earthquake—0.5% probability of exceedance in 50 years (about 10,000-year return period)

Probabilistic Ground Motion Parameters: PGA, PGV, SA

- Traditionally Peak Ground Acceleration (PGA) has been used to quantify ground motion in PSHA. PGA is a good index to hazard for low-rise buildings, up to about 7 stories.
- PGV, peak ground velocity, is a good index to hazard to taller buildings. However, it is not clear how to relate velocity to force in order to design a taller building.
- Today the preferred parameter is Response Spectral Acceleration (SA).
- While PGA (peak acceleration) is what is experienced by a particle on the ground, SA is approximately what is experienced by a building, as modeled by a particle mass on a massless vertical rod having the same natural period of vibration as the building.
- SA = The maximum acceleration experienced by a damped, single-degree-of-freedom oscillator (a crude representation of building response).
- Max. Earthquake Force in the Building = Building Mass x SA

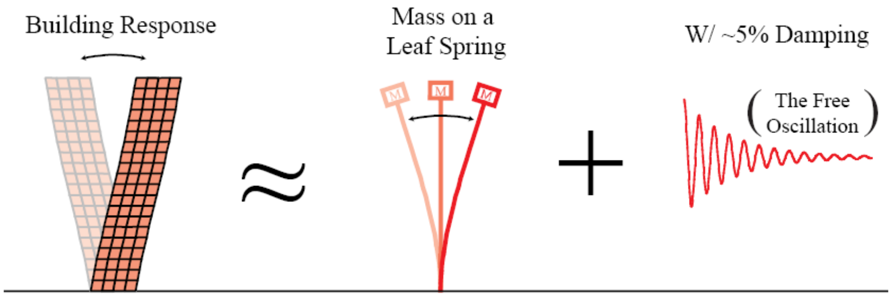


Figure 1. The response-spectrum value is the peak motion (displacement, velocity, or acceleration) of a damped single-degree of freedom harmonic oscillator (with a particular damping and resonant period) subjected to a prescribed ground motion.

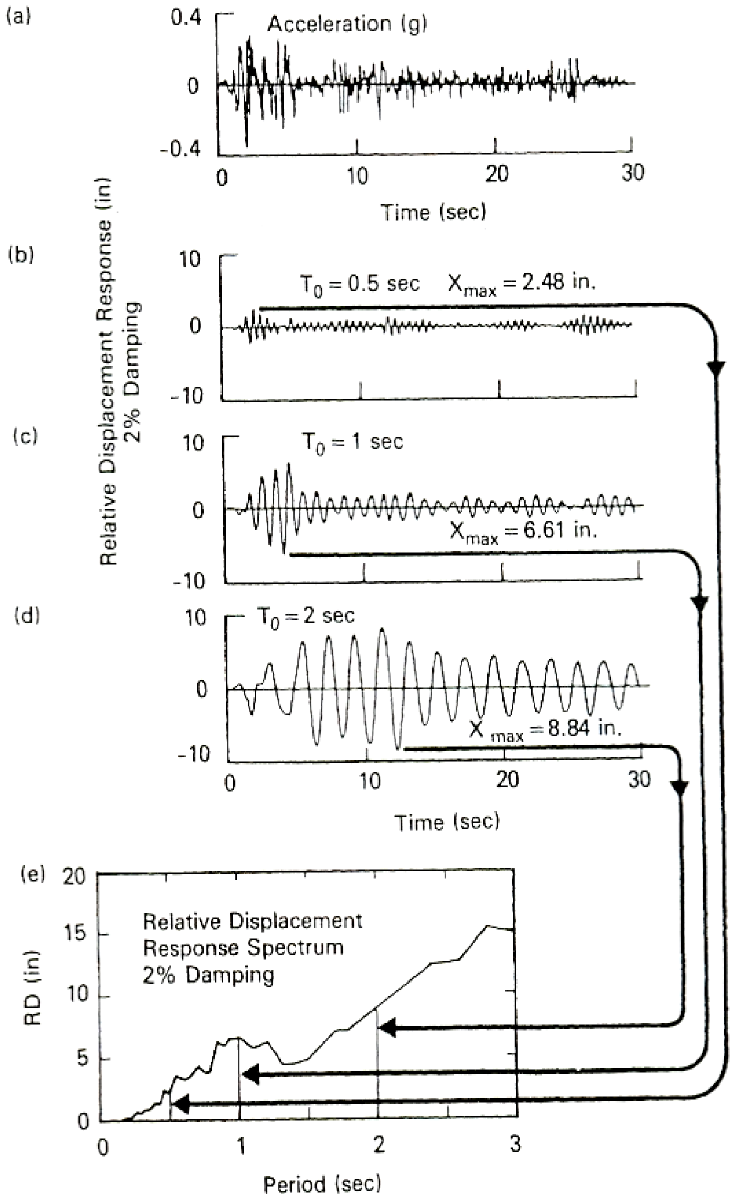
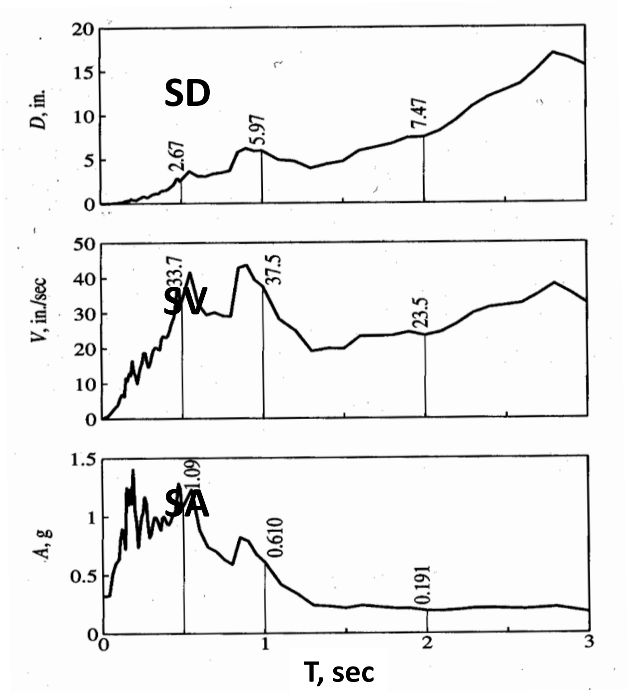
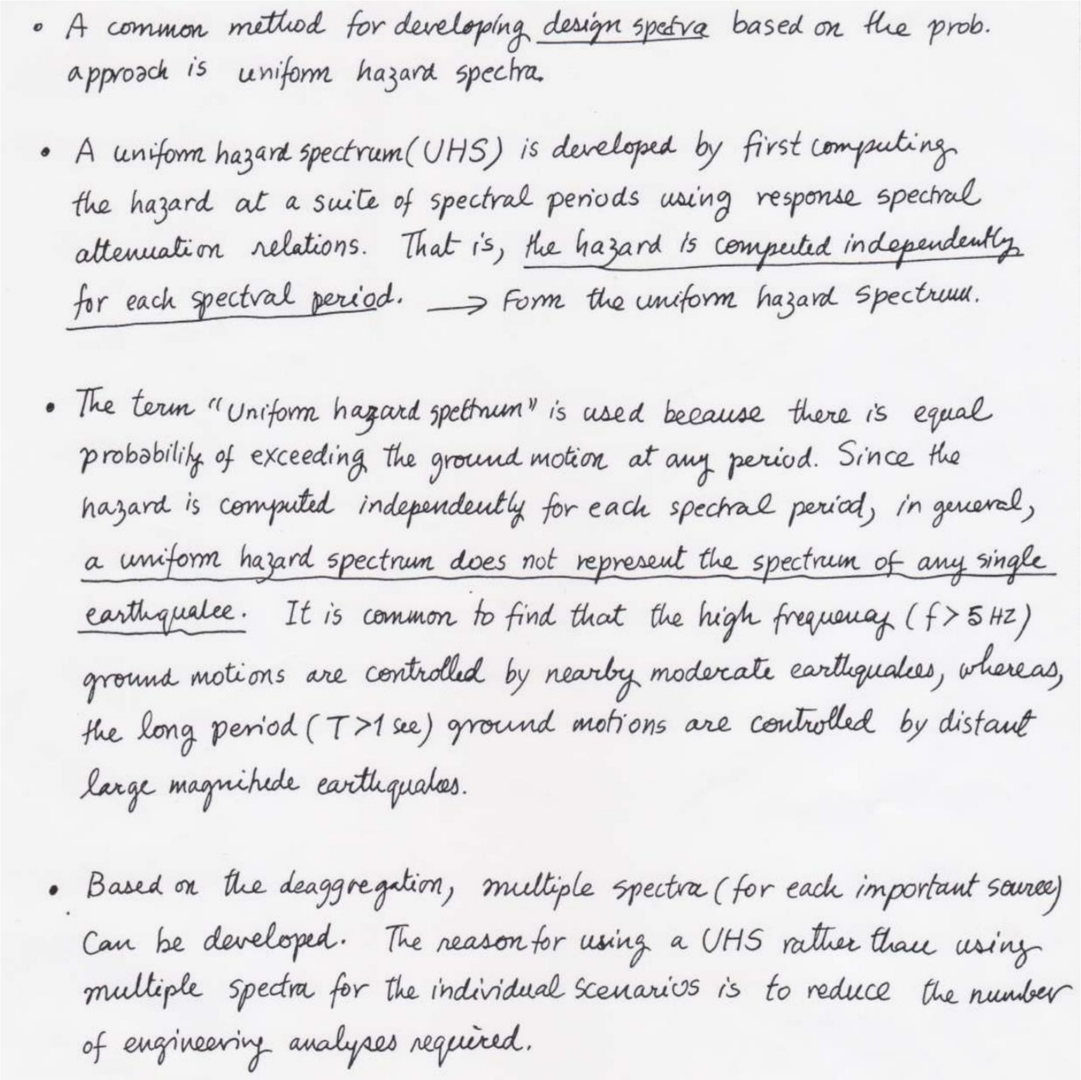


FIGURE 6.3 Construction of a response spectrum. (a) earthquake acceleration time history (El Centro, California 1940) used as input, (b) relative displacement response of a 2% damped oscillator with a natural period of 0.5 seconds, (c) relative displacement response of a 2% damped oscillator with a natural period of 1.0 seconds, (d) relative displacement response of a 2% damped oscillator with a natural period of 2.0 seconds and (e) maxima of b, c and d become points on the 2% damped relative displacement response spectrum (after Chopra 1981).

If we look at the displacement response, we can identify the maximum displacement. If we take the derivative (rate of change) of the displacement response with respect to time, we can get the velocity response. The maximum velocity can likewise be determined. Similarly for response acceleration (rate of change of velocity) also called response spectral acceleration (SA).



2.24. Uniform Hazard Spectra

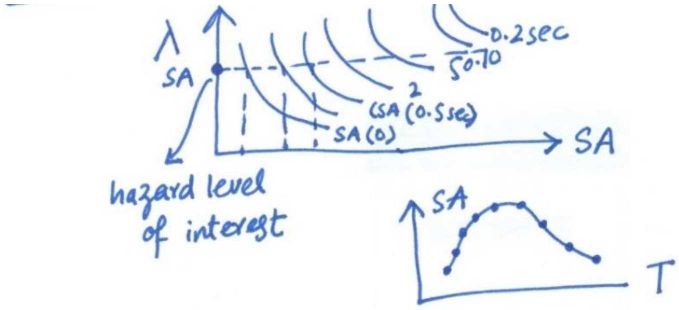


- A common method for developing design spectra based on the prob. approach is uniform hazard spectra.

- A uniform hazard spectrum (UHS) is developed by first computing the hazard at a suite of spectral periods using response spectral attenuation relations. That is, the hazard is computed independently for each spectral period. ⟶ Form the uniform hazard spectrum.

- The term "Uniform hazard spectrum" is used because there is equal probability of exceeding the ground motion at any period. Since the hazard is computed independently for each spectral period, in general, a uniform hazard spectrum does not represent the spectrum of any single earthquake. It is common to find that the high frequency ($f > 5$ Hz) ground motions are controlled by nearby moderate earthquakes, whereas, the long period ($T > 1$ sec) ground motions are controlled by distant large magnitude earthquakes.

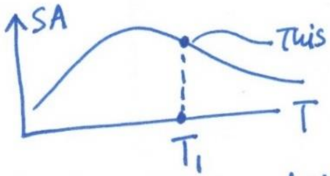
- Based on the deaggregation, multiple spectra (for each important source) can be developed. The reason for using a UHS rather than using multiple spectra for the individual scenarios is to reduce the number of engineering analyses required.



UHS

Building Codes (ASCE 7-05):

S_s S_1 → (Assuming $V_{s30} = 760$ m/s)
↳ From UHS



This is the SA we are mostly interested in.

Each point on UHS is design hazard level individually.

[What is the likelihood that an actual earthquake will produce spectral response values that exceed the design hazard level across "all periods simultaneously"?]

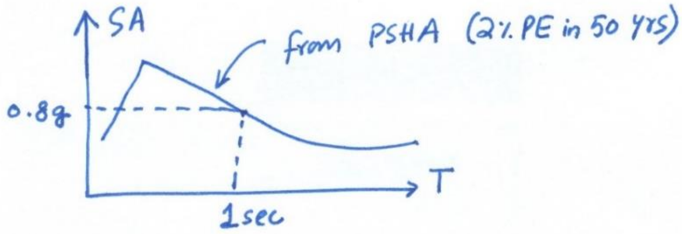
A: Ridiculously small

It is physically very unlikely for nature to produce a RS as extreme as a UHS.

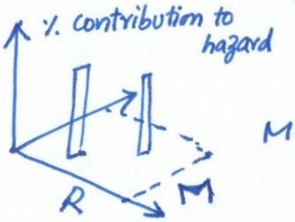
[Does it make sense for engineers to design for something that likely is not possible to occur???]

Designing for UHS is equivalent to designing for an EQ which will never occur.

2.25. Conditional Mean Spectra



⇓ Deaggregation (at 2% PE in 50 years)
(at 1 sec SA
at same site)



Mean M, R, ϵ_0

$$= 12.2\text{ km},\ 7.03\,M,\ \underbrace{2.02}$$

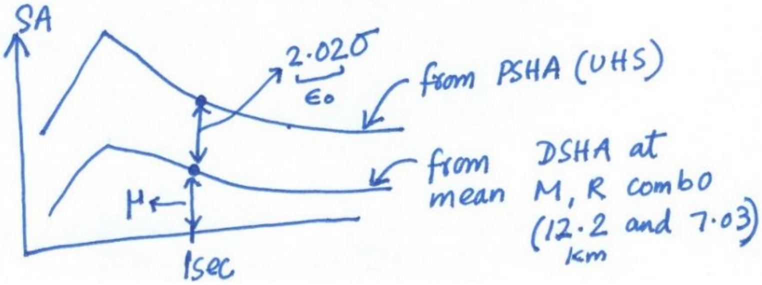
The no. of SDs by which 0.8g is greater than the SA(1 sec) caused by R~~M~~=12.2km and ~~R=~~M=7.03.

$$\epsilon = \frac{\ln SA(T) - \mu_{\ln SA}(M,R,T)}{\sigma_{\ln SA}(T)}$$

e.g $\epsilon = 2$ means that e.g $SA(1\text{ sec}) = 0.8g$ is 2σ larger than mean SA(1 sec) caused by 12.2Km, 7.03 combination.

so UHS is identical to
at T=1sec

$$\left[\begin{array}{l}\text{Mean RS at 1sec} \\ \text{caused by} \\ 12.2\text{Km}, 7.03 \\ \text{combo}\end{array} + 2\sigma\right]$$



What if we still utilize UHS value at the T_1 of the structure but allow the rest of UHS to merge into an RS which more closely matches with real EQ spectra. (Baker and Cornell 2006).

Conditional Mean Spectrum

↓ conditioned at T_1 and a specified $SA(T_1)$ ↓ from PSHA spectrum

→ The remainder of the spectrum consists of the mean spectra values

Step 1: $T^* \longrightarrow SA(T^*)$ at a particular λ or T_R

↓

Mean M, R, ϵ_0 ⟵ Deaggregation

Step 2: Perform DSHA at Mean M, R.
Use GMPEs to determine deterministic RS that matches $SA(T^*)$ value of UHS.
Use ϵ_0 number of SDs in developing deterministic RS.
(Set $R_{rup} = R_x = R(\text{mean})$ from deaggregation and adjust R_{jb} until $SA(T^*)$ is achieved by $\underbrace{\text{resulting deterministic RS}}$.

[Compute spectrum as well as σ for all periods]

$\mu + \epsilon_0 \sigma \xrightarrow{\text{approaches}} SA(T^*)$ ↓ UHS
(at T^*)

Step 3: Compute the ϵ for all other periods.

We know ϵ at our period of interest T^*. we can correlate the ϵ at other periods.

$$\underset{(\text{given } \epsilon(T^*))}{\epsilon(T_i)} = \rho(T_i, T^*) \, . \, \epsilon(T^*)$$

$$\rho(T_i, T^*) = 1 - \cos\left[\frac{\pi}{2} - \left(0.359 + 0.163 . I . \ln\frac{T_{min}}{0.189}\right) . \left(\ln\frac{T_{max}}{T_{min}}\right)\right]$$

T_i for which we are computing ϵ

T^* Period of interest

T_{min} = Smaller of T_i and T^*

T_{max} = larger of " " ".

$I = 1$ if $T_{min} < 0.189$

$= 0$ if " $\geq$ "

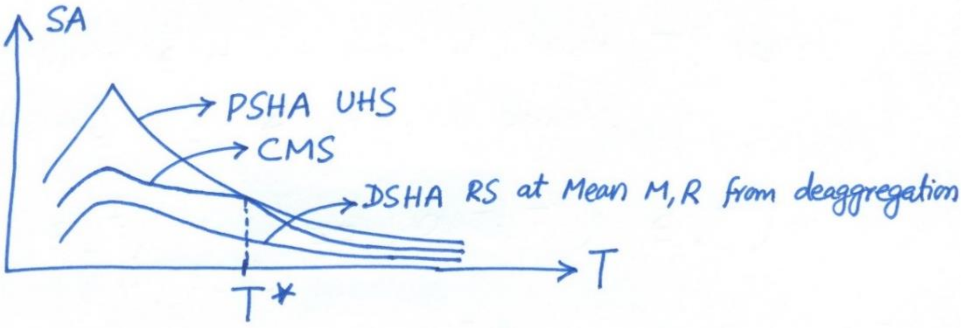
Step 4:

$$\ln SA_{CMS}(T_i) = \ln SA_{T_i} + \underbrace{\overbrace{\epsilon(T_i)}^{\text{Baker's relation}} . \overbrace{\sigma_{\ln SA_{T_i}}}^{\text{SD for GMPES}}}_{\text{Changes for each period } T_i = 0.01 \text{ to } 5 \text{ sec}}$$

- at $T_i = T_* - \epsilon(T_i) = \epsilon(T^*)$

  $=$ Same as deaggregation mean M, R, ϵ_0

  i.e $SA_{CMS} = SA_{UHS}$
- for all other periods $\longrightarrow SA_{CMS} < SA_{UHS}$

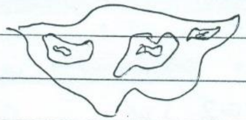


Note:

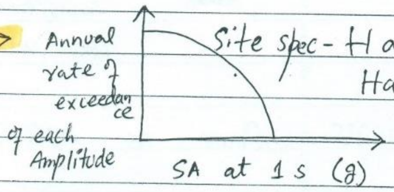
What if you have more than one T^* (most engineers just envelop multiple CMS)

How do you account for scatter in the residual plots in calculations?

→ Hazard Maps



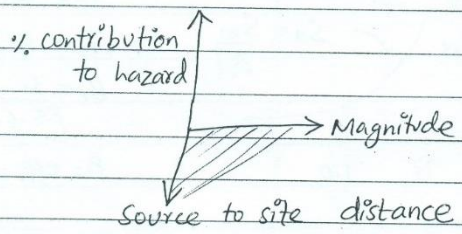
PGA with 2% probability of exceedance in 50 years

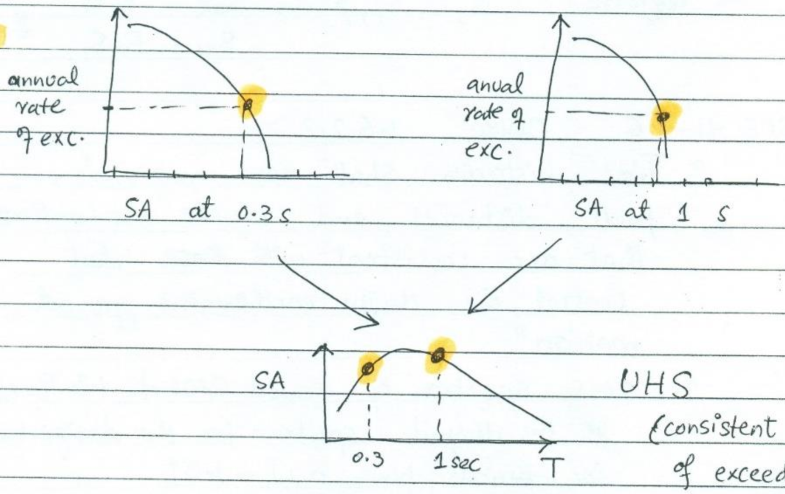
→ 

Site spec- Hazard curve → for all rates of exceedance

Hazard Map → for one " " "

→ Hazard Deaggregation



→ 

UHS
(consistent rate of exceedance)
Just a collection

doesn't say anything about simultaneous occurrance of SAs in a single GM.

→ UHS — unsuitable as it consevatively implies that large-amplitude spectral values will occur at all periods within a single ground motion.

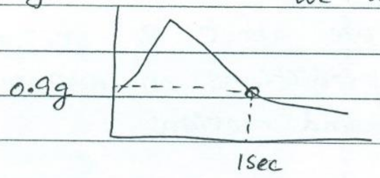
→ CMS provides the expected (i-e mean) response spectrom "conditioned" on occurrance of a target SA value at the period of interest.

→ we need a "Typical" RS associated with the specified large amplitude SA value at a single T.

→ CMS maintains the probabilistic rigor of PSHA

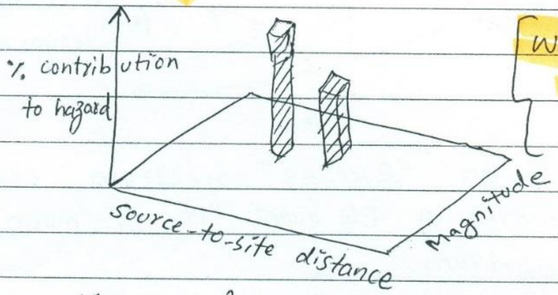
→ lets say we are interested in $T = 1sec$

$SA(1sec) = 0.9g$



↓

do deaggregation to know relationship b/w R, M and ε for $SA(1sec) = 0.9g$

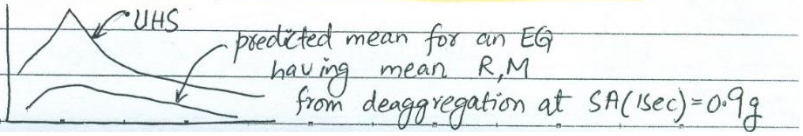


What M, R EQs are providing max or min contribution

Deggregation also provides Mean (R, M, ε_0)

eg (12.2 Km, 7.03, 2.02)

Now a median predicted spectrum with this R, M can be very low than this UHS.



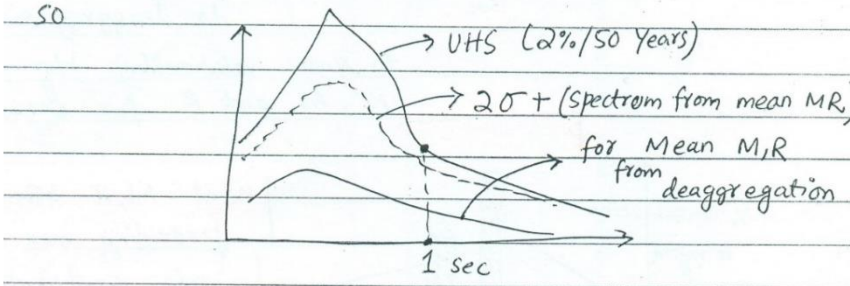
This difference is quantified by ε.

ε = no of Standard Deviations by which a given lnSA value differs from the mean predicted value for a given R, M.

$$\varepsilon = \frac{\ln SA(T) - \mu_{\ln Sa}(M,R,T)}{\sigma_{\ln Sa}(T)}$$

ε tells us, of the ground motions with the 0.9g SA, how many standard deviations is larger than the median prediction are these GM SA values.

$\varepsilon = 2$ means we are about 2 st. Dev larger than median predictions on average with these high amp. ground motions.



UHS is not an "Average" Spectrum corresponding to a Scenario of EQ event. It is much larger than medium spectrum.

lets say
$\varepsilon = 2$ indicates that the SA(1s) = 0.9 is caused by GMs that are on average 2σ larger than mean GMs predicted from casual event.

UHS is identical to $(2\sigma + \text{mean})$ RS.

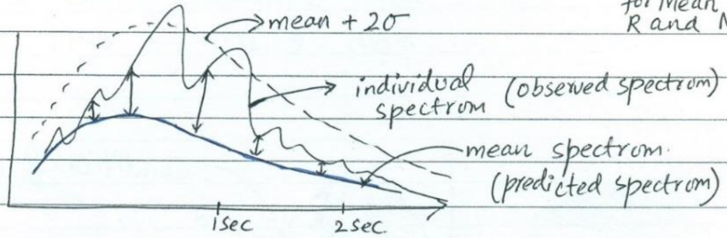
If we plot individual spectra of 20 GMs all with same "mean" R and M, we will see a lot of scatter.

We can select that "one Spectra" which exactly have SA (1sec) = 0.9 g means it has $\varepsilon = 2$.

But it is not "Equally" large at all other periods (as UHS). so UHS not representative of individual ground motion spectra.

If M = mean (7.03) and R = 12.2 km was the only EQ occurring on site,

UHS = identical = $2.02\,\sigma$ + Spectrum for Mean R and M.

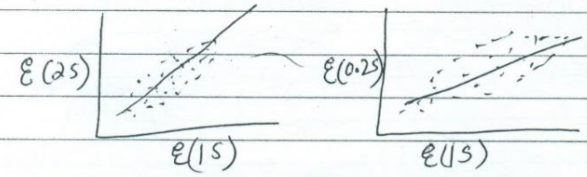


↕ = epsilon = ε, value varrying. → by GMPE

$$\epsilon = \frac{(\text{log of observed SA} - \text{mean of log of predicted SA})}{\text{St. Dev of log SA (provided by GMPM)}}$$

Now we are given that $\varepsilon\,(1\text{ sec}) = 2.02 \simeq 2$

we can run 100s of GM and pl0t their Spectra together and pick their εs at different Ts.



mean ε (any T) =
= correlation coefficient
× ε (1 sec)

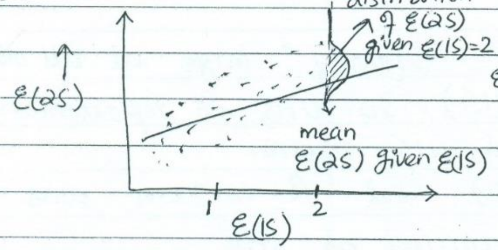
determine St. Dev for each T also.

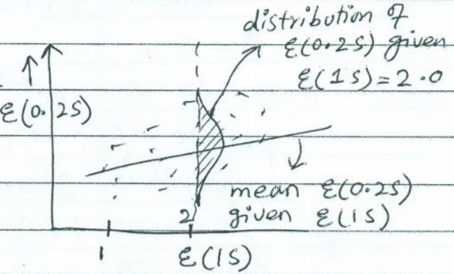
Using this we can find the mean ε and St.Dev of ε at all periods "Conditioned on a target ε at T^*"

↓

The period of primary interest.

so





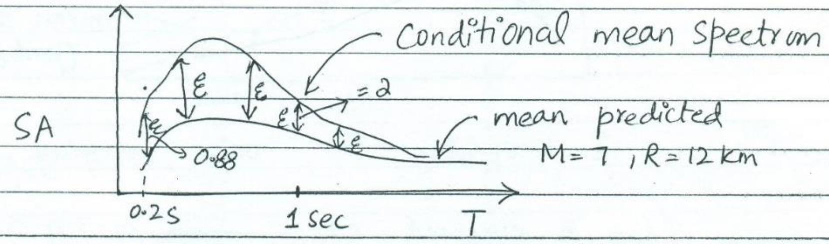
lets say we get both means and St.Devs of εs at all Ts.

mean $\varepsilon(2S) = 0.75\,\varepsilon(1S)$, St.D of $\varepsilon(2S) = 0.5$

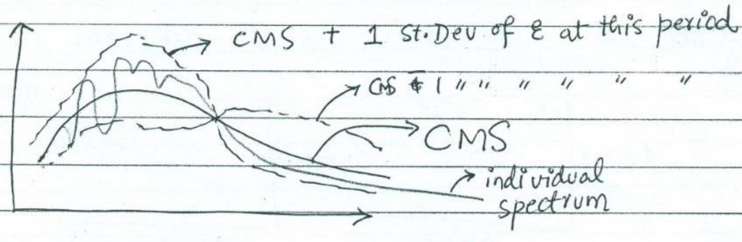
mean $\varepsilon(0.2S) = 0.44\,\varepsilon(1S) = 0.44 \times 2 = 0.88$

⋮

Now



[ε(1sec) = 2 is our "conditional" ε
we determine what value of ε is expected at other Ts if at 1 sec its value is 2.]



Now

we can select and scale GMs to match this CMS.

Two ways to scale GMs (Two options)

(a) Match both mean and standard deviation
At any given T both mean and σ or ground motion spectra should be matched with mean and σ of Conditional mean spectrum.

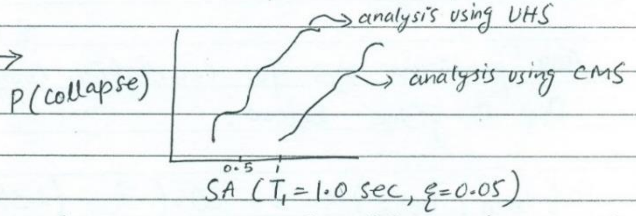
(b) Match only mean
Scale all gms ~~which~~ so that they have SA (1sec) = 0.9 g (Target, conditioned). Dont much woried about variability.

(a) → Conditional Spectrum
(b) → " Mean Spectrum.

Shape of CMS change w-r-t probability of exceedance.

If cause of M and R change with return period (prob of exceedance) the shape of CMS change. If its not changing the shape will still change because of change in ε values w-r-t change in probability of exceedance.

Implications →



So for a given SA level the P(collapse) for CMS < UHS

CMS Pros → Realistic than UHS, less conservative, utilizes deaggregation Info (M, R, ε) to predict spectral shape. If M ↑, spectrum change shape.

CMS Cons → less widely available, less conservative, structure and site specific, Spectrum changes with ↑M requiring multiple GM sets.

6

Procedure for computing CMS :-

(a) Determine Target SA at a period of interest

(b) Determine the associated M, R and ε

if target $SA(T^*)$ is obtained from PSHA
then $M, R, \varepsilon(T^*)$ can be taken from/as
mean $M, R, \varepsilon(T^*)$ from deaggregation.

(c) Compute

mean of $\ln(SA)$ function of M, R, T
St. Dev of $\ln(SA)$ function of T

using GM models also called attenuation
models. Online tools.

(d) Compute ε at other periods given $\varepsilon(T^*)$

$$\text{mean } \varepsilon(T_i) \text{ given } \varepsilon(T^*) = \begin{bmatrix}\text{Correlation coefficient} \\ \text{b/w } \varepsilon \text{ at } T_i \text{ and } T^*\end{bmatrix} \times \varepsilon(T^*)$$

Any predictive eq/s for correlation coeff can be used
One is given below.

$$\rho(T_{min}, T_{max}) = 1 - \cos\left(\frac{\pi}{2} - \left(0.359 + 0.163 I_{(T_{min} < 0.189)} \ln\frac{T_{min}}{0.189}\right) \ln\frac{T_{max}}{T_{min}}\right)$$

where

$$I_{T_{min} < 0.189} = 1 \text{ if } T_{min} < 0.189 \text{ s}$$
$$= 0 \text{ if not.}$$

T_{min}, T_{max} are smallest and largest of the Two periods of interest.

(e) Compute CMS

mean of $\ln SA(T_i)$ given $\ln SA(T^*)$ =

$$= \text{mean of } \ln SA(M, R, T_i) + \rho(T_i, T^*)\,\varepsilon(T^*)\left(\sigma_{\ln SA(T_i)}\right)$$

σ = Standard deviation
ρ = Correlation Coefficient

The exponential of LHS of equation = CMS

SO CMS requires – Existing GM models
– PSHA results

Choice of T^* for conditioning:

The conditioning creates SA values at other periods that are always less "extreme" than $SA(T^*)$.

If the structural response parameter of interest is driven primarily by excitation at a period other than T^*, ground motions selected to match a CMS conditioned at T^* may produce inappropriately low responses.

Traditionally, for first mode dominant structures → T_1 but FA and upper story shear forces may be more sensitive to higher-mode excitation.

Multiple periods also.

Using multiple CMS is similar to using individual load cases (wind, snow, dead) etc in structural analysis. Using UHS is similar to simultaneously applying peak wind loads, peak snow loads, peak live loads etc.

Using multiple CMS is analogous to considering each peak load individually while applying relatively smaller values of other load types.

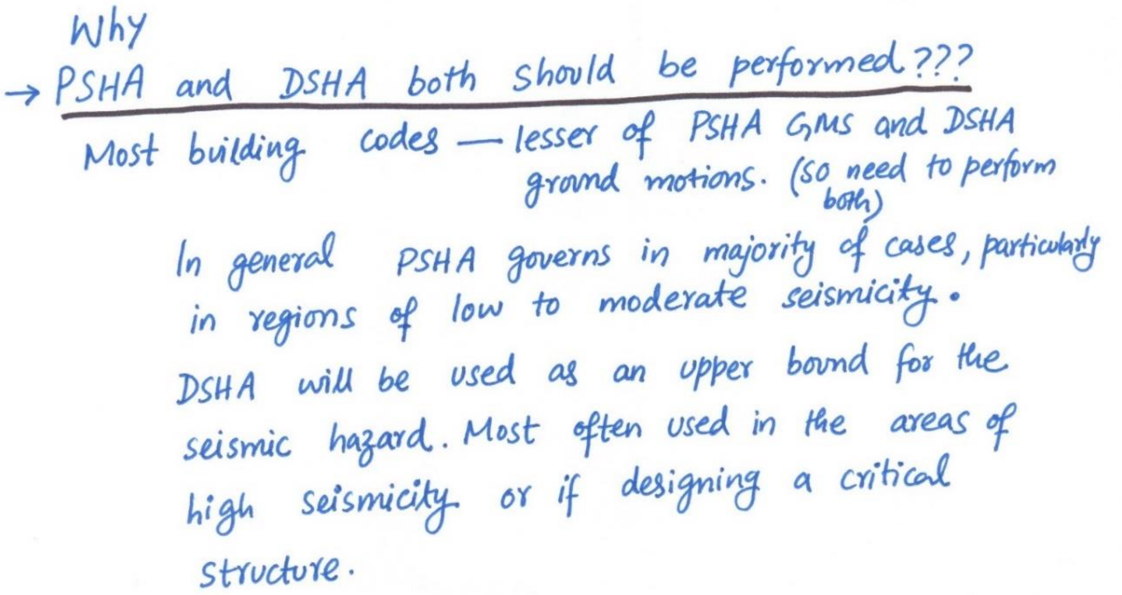
The peak responses of an Elastic SDOF with Period T* = for UHS - matched and CMS - matched ground motions. if SA(T*) are same. Non Linear SDOF may be sensitive to excitation at a wide range of periods and will be sensitive to target RS.

Unlike results obtained using a UHS, ground motions selected and scaled to match the CMS procedure structural responses comparable to unscaled ground motions that naturally have the target SA(T*)

SUMMARY

CMS answers the question, what is the expected RS associated with a target SA(T*)? Using knowledge of the M, R and ϵ value caused occurrence of that SA(T*).

2.26. Why PSHA and DSHA both should be performed?



Why

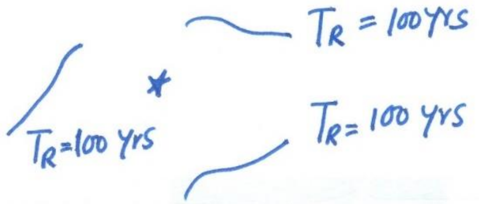
→ PSHA and DSHA both should be performed???

Most building codes — lesser of PSHA GMs and DSHA ground motions. (so need to perform both)

In general PSHA governs in majority of cases, particularly in regions of low to moderate seismicity.

DSHA will be used as an upper bound for the seismic hazard. Most often used in the areas of high seismicity or if designing a critical structure.

e.g if



In PSHA there is a possibility that multiple EQs start contributing at the same time (simultaneously)

→ This is not practical design scenario.

So in such high seismicity areas → lets evaluate an design EQ scenario at each fault individually and compare the max with PSHA results.

If PSHA GM > max (Individual sources), then it means that PSHA is adding the possibility of multiple EQs simultaneously. So then design on DSHA.

If T_R = say 1800 yrs then PSHA will give real (liklihood) hazard. DSHA will be too conservative because it will just consider the M_{max} scenario directly.

* * *

Why is PSHA still used?

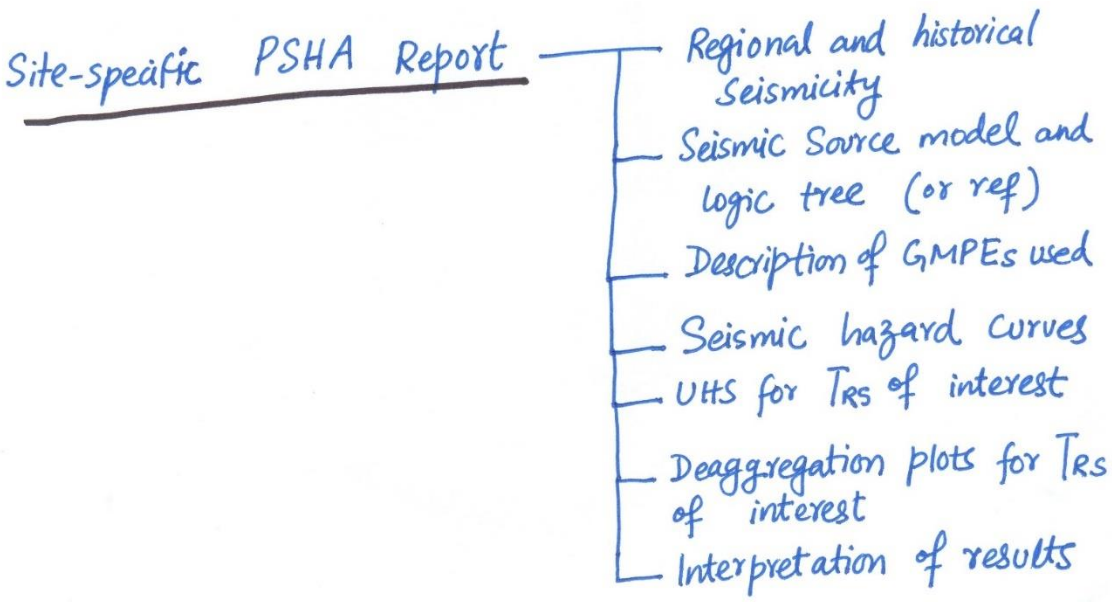
→ EQ prediction — unsuccessful research

Therefore, Hazard maps — not agree well with actual seismic events.

→ Known Unknowns → Statistical uncertainties within model

Unknown Unknowns → Uncertainties due to limitation of model.

2.27. Site-specific PSHA Report



2.28. Ground Motion Selection Guidelines

ASCE 7-10 site classification :-

$\bar{V}_{s30}$ = Average shear wave velocity in first 30 m of soil.

$$= \sum_{i=1}^{n} d_i \Big/ \sum_{i=1}^{n} \frac{d_i}{V_{si}}$$

$$= \frac{\Sigma \text{ thickness of any layer b/w 0–100 ft (30m)}}{\Sigma \text{ (" " " " " ") / the Shear wave velocity in ft/s, m/s}}$$

$$\sum_{i=1}^{n} d_i = 100 \text{ ft} \quad (30 \text{ m})$$

$\bar{V}_s$	Site class
> 5000 ft/s	A. Hard Rock
2500 – 5000 ft/s	B. Rock
1200 – 2500 ft/s	C. Very dense soil /soft rock
600 – 1200 ft/s	D. Stiff soil
< 600 ft/s	E. Soft clay soil

ASCE 7-10 Design spectra :-

- get S_s , S_1 and T_L values from map for specific site

S_s = Spectral response acceleration parameter at Short periods

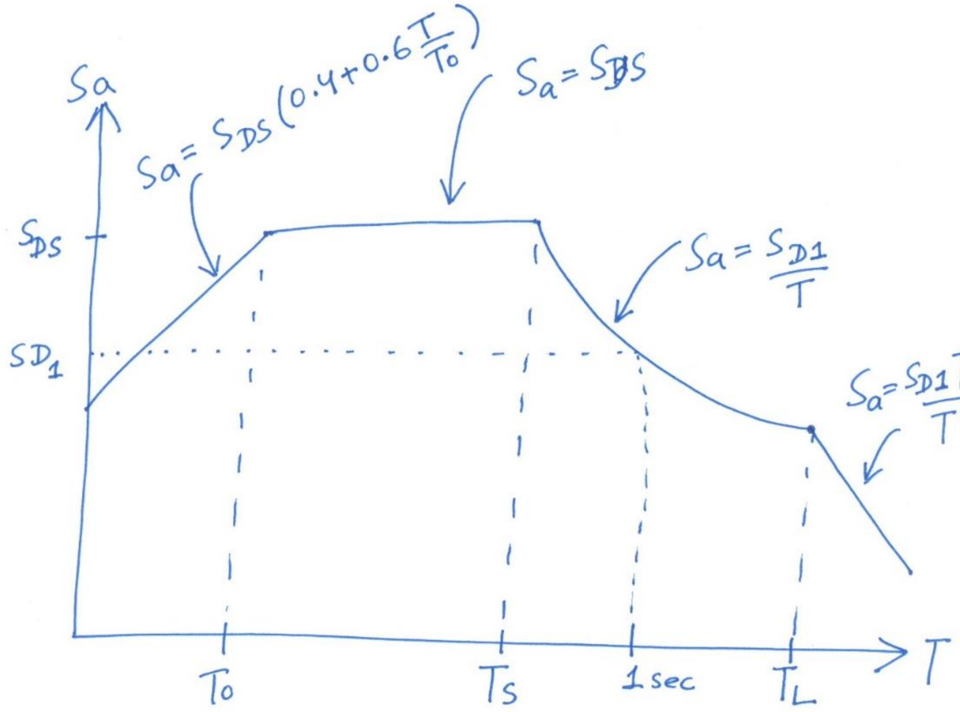
≤ 0.15

$S_1 =$ " " " " "
" " " 1 sec.

- get Fa and Fv from table

$S_{MS} = F_a S_s$, $S_{DS} = \frac{2}{3} S_{MS}$

$S_{M1} = F_v S_1$, $S_{D1} = \frac{2}{3} S_{M1}$



where

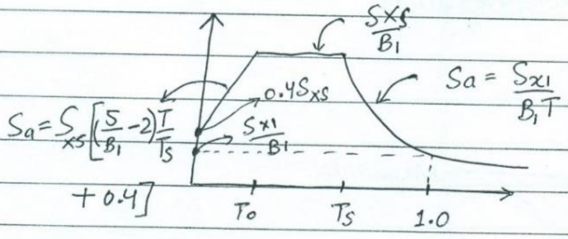
S_{DS} = Design spectral response acceleration parameter at short periods

S_{D1} = " " " "
" " 1-sec "

$T_0 = 0.2\,\frac{S_{D1}}{S_{DS}}$, $T_S = \frac{S_{D1}}{S_{DS}}$, T_L = Long period Transition period. (from Maps)

→ ASCE 41-06 Site classes = Same as ASCE 7-10

→ ASCE 41-06 General Response Spectrum



$T_S = S_{X1}/S_{XS}$

$T_0 = 0.2\,T_S$

$B_1 = \frac{4}{[5.6 - \ln(100\beta)]}$

β = eff. viscous Damping

we require S_S, S_1, β → $S_{XS} = F_a S_S$

$S_{X1} = F_v S_1$

→ ASCE 41-06 Clause 1.6.2.2

"Time histories shall have magnitude, fault distances, and source mechanisms that are consistent with those that control the design earthquake ground motion"

SRSS spectra of scaled GMs ≮ 1.3 Times the 5% damped spectrum for the design EQ for periods b/w $0.2T_1 - 1.5T_1$.

Design GMs from Building Codes

Building seismic Safety Committee $\xrightarrow{1yr}$ NEHRP $\xrightarrow{1yr}$ ASCE 7 $\xrightarrow{2yr}$ IBC

ASCE 7-05
IBC 2009] – UHS Approach
UNIFORM HAZARD Approach

, MCE — 2% PE, 50yr
DBE = $\frac{2}{3}$ MCE

ASCE 7-10
IBC 2012] – Risk targeted Approach or Performace-based approach , NO PE but P[Collapse of building]

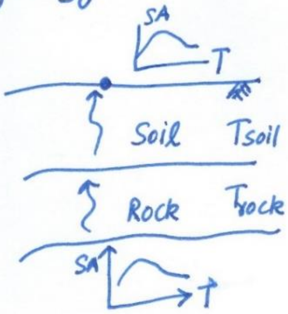
$MCE_R \rightarrow$ 1% P[collapse] within 50 year

General Code procedure:

Step 1 : S_s and S_1 → maps (different from MCE level PSHA maps in ASCE 7-10 onwards → modified for risk-targeted P(collapse))
(for bed rock)

Step 2 : Site Classification
You need V_s^{30} or blow counts of SPT (N), or undrained shear strength $\bar{S_u}$

Step 3: Determine F_a and F_v
(site correction) factors



$$F_a = \frac{(S_s)_{Top}}{(S_s)_{rock}}$$

$$F_v = \frac{(S_1)_{top}}{(S_1)_{rock}}$$

Step 4: $S_{MS} = F_a S_s$
$S_{M1} = F_v S_1$

Step 5: $S_{DS} = \frac{2}{3} S_{MS}$
$S_{D1} = \frac{2}{3} S_{M1}$
[$\frac{2}{3}$ comes from Engr. of California. They decide to design on 2/3 of MCE]

Step 6: T_0, T_L, T_S $f(S_{DS}$ and $S_{D1})$

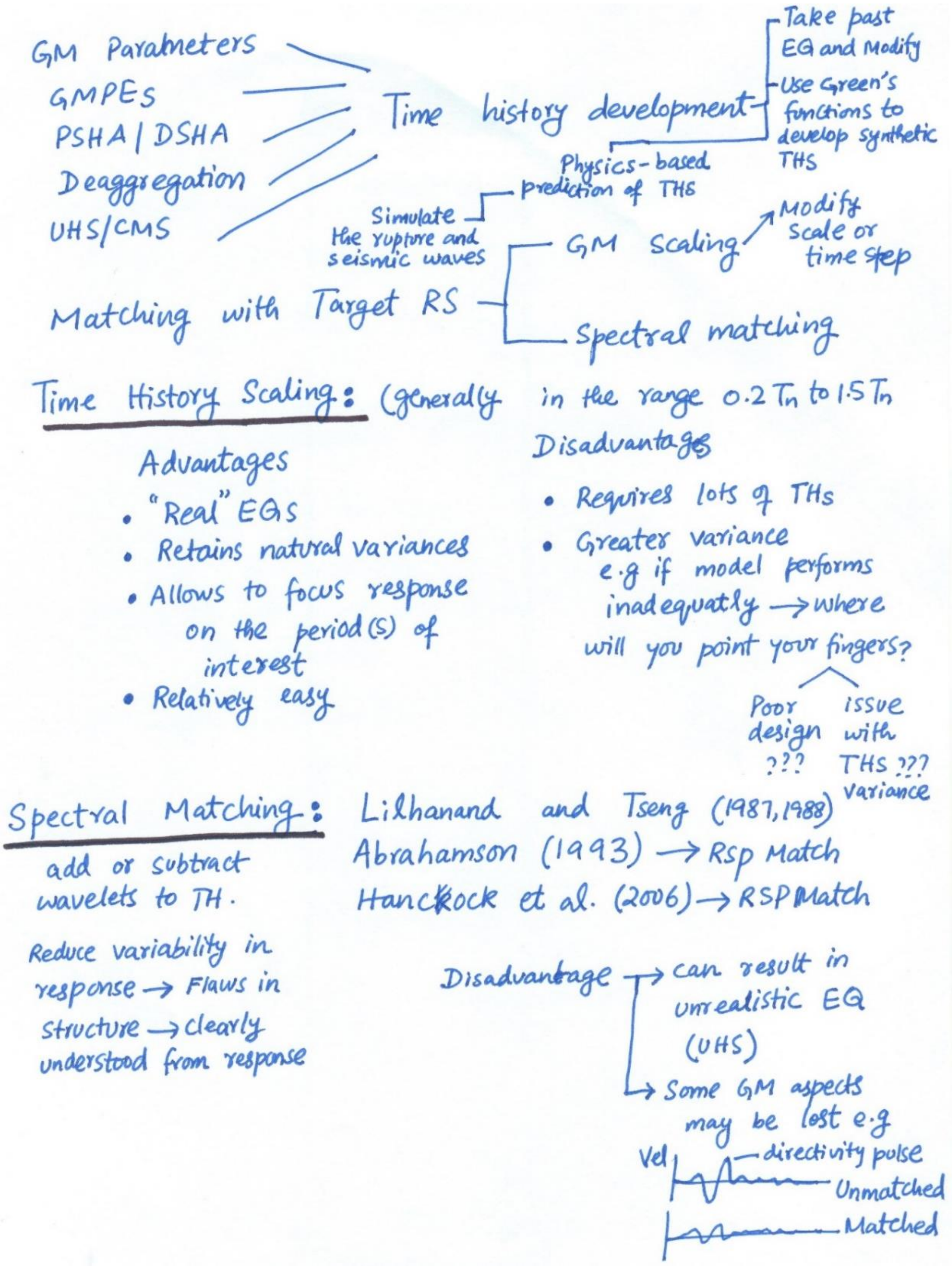
Step 7: Construct spectrum using code equation

Step 8: Assign Occupancy Category or Risk Category
to your structure (I, II, III, IV)

Step 9: Identify the Seismic Design category
used to design → details of structural design.
(A, B, C, D)

SDC A → min seismic detailing required.
⋮
SDC D → Substaintial seismic detailing required.

2.29. Time History Development



GM Parameters
GMPEs
PSHA | DSHA
Deaggregation
UHS/CMS

Time history development
- Take past EQ and Modify
- Use Green's functions to develop synthetic THS
- Physics-based prediction of THS — Simulate the rupture and seismic waves

Matching with Target RS
- GM Scaling → Modify scale or time step
- Spectral matching

Time History Scaling: (generally in the range 0.2 T_n to 1.5 T_n

Advantages
- "Real" EQs
- Retains natural variances
- Allows to focus response on the period(s) of interest
- Relatively easy

Disadvantages
- Requires lots of THs
- Greater variance e.g if model performs inadequatly → where will you point your fingers?
  - Poor design ???
  - issue with THS ??? variance

Spectral Matching: Lilhanand and Tseng (1987, 1988)
Abrahamson (1993) → Rsp Match
Hancock et al. (2006) → RSPMatch

add or subtract wavelets to TH.

Reduce variability in response → Flaws in structure → clearly understood from response

Disadvantage
→ can result in unrealistic EQ (UHS)
→ Some GM aspects may be lost e.g

Vel
directivity pulse
Unmatched
Matched

Factors considered while Selecting THs:

- ✓ M (±1 Mag)
- ✓ R (±10 km)
- ✓ Fault Mechanism (more important for reverse/thrust faults, subduction zones)
- ✓ SA (T_1) (±20, 30% of Target value)
- ✓ Soil Class
- ✓ Directivity Effects (Yes/No) (pulse-like records)

Evaluating the Results:

a) Plot $\ddot{U}_g$, $\dot{U}_g$ and U for both matched and unmatched and check that the peaks should not be much altered.

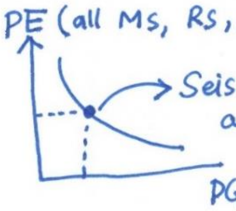
b) All desired aspects of GMs (e.g directivity) are still there.

c) Areas Intensity pot — for both matched and unmatched (energy run-up shouldn't be significantly altered).

2.30. The PSHA of Pakistan

DSHA → Seismic hazard for any site A is a PGA of 0.33g resulting from an earthquake of M_w 6.0 on a fault B at a distance of 20 Km.

PSHA →



→ Seismic hazard for any site A is a PGA of 0.27 with a 10% PE in 50-yr exposure period.

Seismic hazard Assessment of Pakistan :-

a) 1974 → GSP → Seismic hazard zonation map
7 Zones (<0.01g to 0.31g PGA)

b) Ghalib (1985) → Contour maps of PGA and PGV
for RP of 100 yrs and 200 yrs
(0.04g to 0.2g)

c) 1986 → Pakistan Building Code (based on 1982 UBC)
(1905 – 1979 recorded data) → Four zones 0,1,2,3

d) UBC 97 → Isb, Khi, Lahore, Peshawar

e) 1999 → Geophysical Center of Pakistan Meteorological Dept (PMD) → Seismic zoning map → 4 zones
($M_w > 6$ available data + available record of intensities of past events (Ahmed et al., 2006)

f) 1992 – 1999 → GSHAP (Zhang et al., 1999)

- PSHA using Cornell – McGuire approach
- FRISK88M

- 20 sources, uniform seismicity, G-R
- No crustal fault modeling, No subduction zone (modeled as area source).
- 1900 – 1997 records, $M_w > 5.0$ + historical.
- No classification of depth
- One GMPE → Huo et al., (1992)
- PGA with 10% PE in 50 years.

g) 2007 → PSHA by PMD and NORSAR

- Cornell - McGuire approach using CRISIS
- 19 source zones, uniform seismicity, G-R
- No crustal fault modeling, subduction zone modeled as area source.
- 1905 – 2007 data, $M_w > 4.8$
- Depth classification only for Hindukush region (0-30km, 30 - 120 km, 120 – 300km)
- One GMPE → Ambraseys et al., 2005
- detailed PGA and SA (at diff periods) at different RPs (100, 475, 1000 yrs) ↳ (0.2, 0.5, 1, 2 sec)
- Hazard curves and UHS for some cities.
- Deaggregation → PGA (475 yr RP)

h) 2007 → PSHA by Nespak

- Cornell - McGuire approach using EZ-FRISK
- 17 source zones, uniform seismicity, GR
- 28 active faults, characteristic fault sources
  No slip rate are used in estimating EQ recurrence rate.
- Subduction zone modeled as area source
- 1904 – 2006 data, $M_w > 4.5$
- Depth classification only for Hindukush and punjab seismic zone

- One GMPE used → Boore et al., 1997
- PGA with 10% PE in 50 years
  Part of BCP (2007)

2016 → PSHA by Zaman and Warnitchai (2016)

- "National Seismic Hazard Maps (NSHM) USGS Software with Frankel (1995) spatially smoothed-grided seismicity"
- Background source zone (spatially smoothed-gridded seismicity), GR
- 13 Active crustal faults. Length, width, dip and slip rates are determined from past available paleoseismic investigations as well as GPS studies. GR truncated and Charecteristics EQ models.
- For subduction zone, sloping plane is considered. Subduction EQs are assumed to be created by rupture along an inclined plane at the interface between two tectonic plates. [depth classification
  Shallow, interm. deep]
- Different GMPEs
  - Shallow crustal → 3 NGA GMPES
  - Intermediate and deep in-slab → 2 GMPEs
  - Subduction zone → 3 GMPEs

  Logic tree approach
- PGA, SA (0.2, 1, 2 sec) for 475 and 2475 years
- UHS and Hazard curves for major cities
- Deaggregation <
  - M-R-ε₀ deaggregation.
  - Geographic " .

Objective: ✓ Determination of Ground motion Parameters (PGA, SA (0.2 sec), SA (1 sec), PGV, PGD etc.) for your study area (SLE Level, DBE level and MCE level)

✓ Determine Hazard curves for each seismic sources

✓ Determine/Draw Hazard maps for your study area.

✓ Determine complete spectra for important sites in your study area. (SLE, DBE, MCE)

✓ Develop an online tool for convenient access to your results by anyone (public, design engineers etc.)

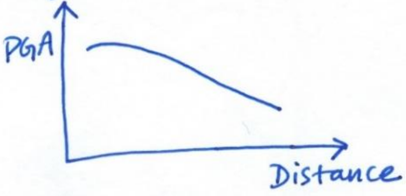
Methodology: ① Study Area, ② seismic sources

faults — Area sources (source zones)

Modeling of sources

③ Define seismicity of each source.

④ GMPE:



⑤ Compute PGA, PGV, PGD SA, etc. etc.

Cornell's PSHA Methodolog

Modified Cornell's Methodology