Earthquake Engineering

What is an Earthquake ?

- A sudden shaking or vibration of the earth's surface due to geological causes.

Explosions and impacts of falling objects are not considered here.

- Thousands of earthquakes occur every year.

Human sensitivity starts at accelerations of about 0.001g.

Most earthquakes cannot be felt without sensitive instruments. Only a few cause damage to structures.

Effects of Earthquakes

- while earthquakes strong enough to cause damage or collapse have long recurrence periods compared to other loads, they are usually the most severe loading a structure is called on to withstand.
- In this sense, earthquakes serve as a crucible for our structures. By studying their behavior under seismic loads, we can learn valuable lesson about their behavior under other types of lateral loads.
- "Earthquakes will relentlessly seek out any defects made in the design and construction of structures." – Nathan M. Newmark

Specific Effects of Earthquakes

Direct Effects

1) Ground Failure (physical ground dislocation)
- surface rupture: large relative displacement under structure
- soil failure
  bearing failure
  sliding
  large displacements or settlements
  liquefaction (flow, displacement)
- foundation failure : overturning, pile pull-out

2) structural failure (inertial response of structure)
- structural damage : yielding, cracking, buckling

- non-structural damage: plaster, glass, mechanical equipment
- structural collapse

Indirect Effects

1) landslides
2) Seiches : sloshing of liquid in reservoirs or lakes
3) Fires : can be aggravated by infrastructural damage, 80% of San Francisco EQ damage was from fire.
4) Tsunamis : sea waves

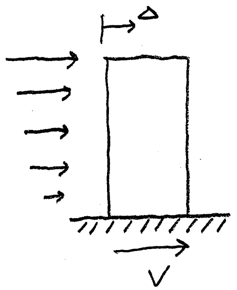
General Earthquake Engineering Problems

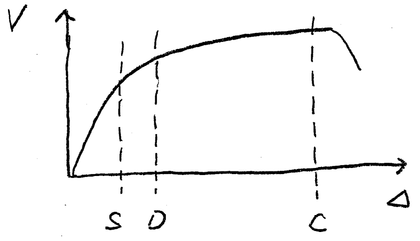
Engineering Seismology

Given a site, predict the characteristics of the earthquake ground motion the site will experience in the future.

Preliminary engineering design

Given a site and predicted ground motions, establish the architectural layout of the structure, and carry out a preliminary design for gravity loads. Select appropriate limit states for the structure (service, damage, collapse). For each limit state, determine the appropriate design earthquakes.

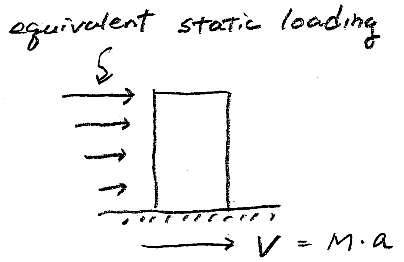


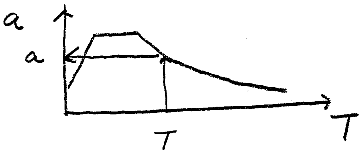


Engineering Analysis

Given a site, ground motion, and structure, determine the response of the preliminary design to those design earthquakes in each limit state, including the effects of soil-structure interaction and inelastic response where appropriate. Compute displacements, forces, stresses, deformations, and damage.

Equivalent static analysis : low rise buildings, symmetric plan

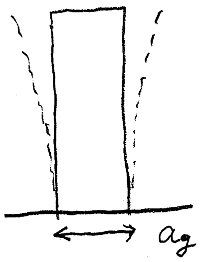


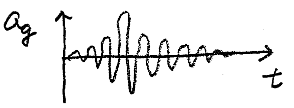


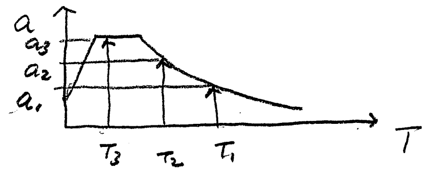
Dynamic analysis : high rise buildings, asymmetric plan

Response spectrum analysis – modal analysis $\underset{\sim}{u} = \underset{\sim}{\phi_1} u_1 + \underset{\sim}{\phi_2} u_2 + \cdots$ (T_1) (T_2)

Time history analysis





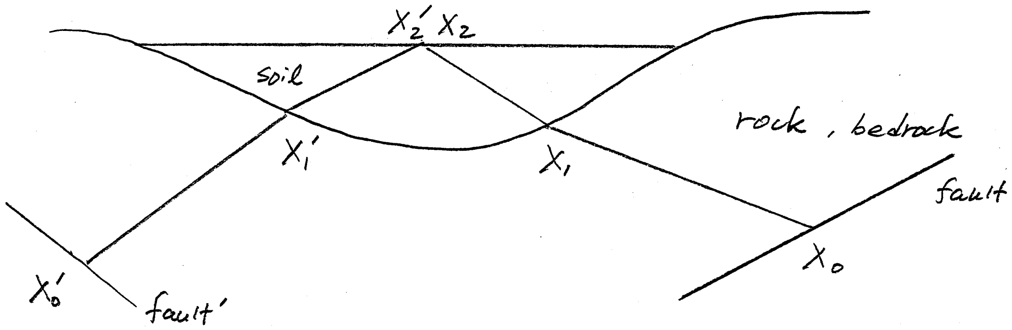


Final engineering design

Revise the preliminary design to resist the forces and deformations associated with response in each limit state. Structural steel, reinforced concrete, timber, masonry.

Parameters affecting the response of structures

The figure below is a schematic representation of the specific steps involved in earthquake engineering response problems.



possible all EQs should be considered (X_0, X_0')

X_0, X_0' : **motion at fault** due to propagation of rupture along fault plane, generally unknown. (magnitude)

$X_1 = f_1(X_0)$, $X_1' = f_1(X_0')$,

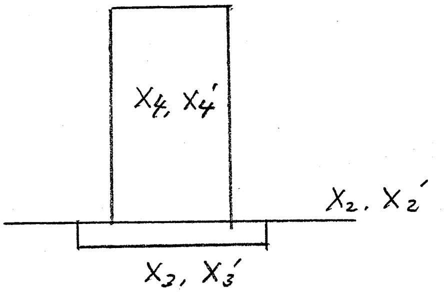
: motion of bedrock close to site. This depends on

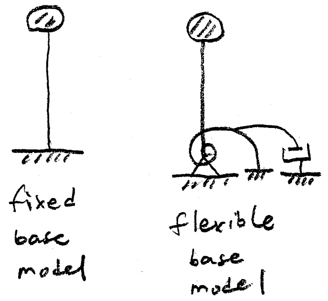
a) type of fault, age, geological structure
b) distance between site and source (**attenuation**)
c) intermediate geological features

$X_2=f_2(X_1)$, $X_2'=f_2(X_1')$,

: **free-field motion** at site due to bedrock motion (**Soil Factor**). This depends on

a) depth of soil
b) type of soil
c) soil layering
d) amplitude of motion
e) local topographic features (river, valley, road, etc)



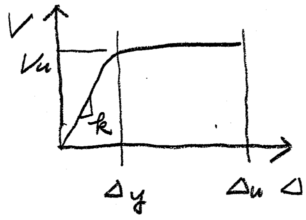


$X_3=f_3(X_2)$, $X_3'=f_3(X_2')$,

: **motion at base of structure** is different from free-field ground motion. This is due to **soil-structure interaction**. If soil-structure interaction is neglected, then $X_3=X_2$, $X_3'=X_2'$

$X_4=f_4(X_3)$, $X_4'=f_4(X_3')$,

: **motion of the structure** depends on base motion. Nonlinear behavior may be important in structural response.



$\mu = \Delta_u/\Delta_y$ ductility
k = stiffness
V_u = strength

In general, the complete problem is
$X_4= f_4\, f_3\, f_2\, f_1\, (X_0)$,
$X_4'=f_4\, f_3\, f_2\, f_1\, (X_0')$

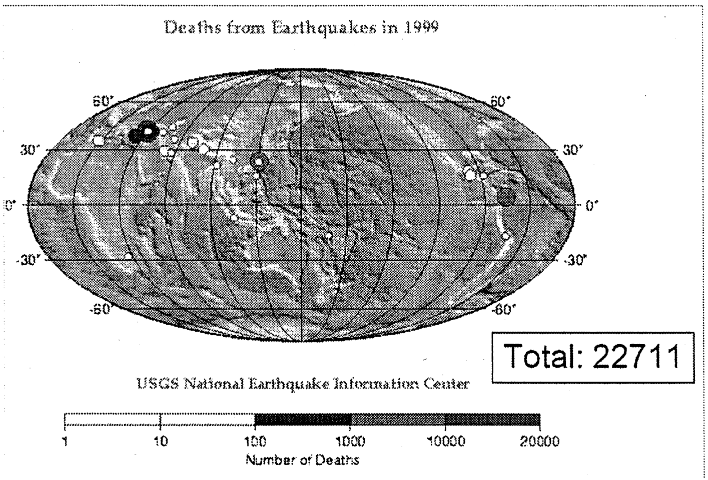
Usually we will have access to record of X_2, X_2' for areas with similar seismicity, geology, and soil conditions.

For highly seismic regions, we may have records of specific local earthquakes. Over time, we must develop the following information for general areas and for specific sites.

a) maximum EQ a given fault can produce. (**Magnitude**) X_0
b) Maximum EQ underlying rocks can transmit (**Attenuation Law**) X_1
c) Maximum EQ overlying soil can transmit. (**Soil factor**) X_2

Final goal is to estimate the **maximum ground acceleration** for the specific site.

Earthquake Fatality



Date	Location	Death	Magnitude	damages
1906.04.18	US, San Francisco	3000+	7.8	Fire
1923.09.01.	Japan, Tokyo	100000	8.3	
1976.07.27.	China, Tangsan	655000	7.9	Biggest damage in china
1985.09.19.	Mexico, Mexicocity	10000	8.1	Soft soil
1988.12.07.	Armenia, 스피탁	25000	7.0	
1990.06.20.	Iran, 카스피해연안	40000	7.3	
1995.01.17.	Japan, kobe	25000	7.2	Epicenter in downtown
1999.08.17	Turkey, 이즈미	12000	7.8	
1999.09.21	Taiwan	2000	7.3	
2000.01.26	India, 구자트라	25000		
2003.12.26	Iran, 동남부	26000	6.5	
2004.12.26	Indonesia, sumatra	234000	9.0	Tsunami
2005.10.08	Pakistan, 동북부	18000	7.6	
2008.05.12.	China, sichuan	80000	7.8	Schools, hospitals. Intraplate EQ
2010.01.12.	아이티, 포르토프랭스	150000	7.2	
2011.03.11	Japan, Tohoku	27000	9.0+	Big EQ. NPP

PARTIAL HISTORY OF DESTRUCTIVE EARTHQUAKES

DATE	PLACE	MAGNITUDE	DEATHS	REMARKS
02/23/1556	Shansi, China		830,000	Possibly most destructive quake ever.
02/09/1693	Sicily, Italy		60,000	
12/31/1693	Odowara, Tokyo, Japan		5,230	Possibly as many as 150,000 deaths
12/30/1730	Hokkaido, Japan		137,000	Many foreshocks
1737	Calcutta, India		300,000	
11/01/1755	Lisbon, Portugal	8.75	60,000	Felt 3500 km away
10/30/1759	Syria		30,000	
02/05/1783	Calabria, Italy		30,000	
02/04/1797	Peru and Ecuador		40,000	
12/06/1811	New Madrid, Mo., USA		few	Felt 1100 miles away (Boston). This series of shocks probably is the largest U.S. earthquake.
01/23/1812	New Madrid, Mo., USA			
02/07/1812	New Madrid, Mo., USA			
03/26/1812	Caracas, Venezuela		20,000	
12/16/1857	Italy	6.5	12,000	Studied by Mallet
08/31/1886	Charleston, S. C., USA			Several thousand buildings damaged
08/13/1868	Peru and Ecuador		40,000	
07/28/1883	Casamicciola, Italy		2,300	Probably of volcanic origin
10/28/1891	Mino-Owari, Japan		7,270	Horizontal displacements of 4 m, vertical displacements of 7 m.
06/15/1896	Riku-Ugo, Japan		27,120	
06/12/1897	Assam,India	8.7		Studied by Oldham. 11m displacements
09/10/1899	Yakutar Bay, Alaska	8.6		Vertical displacements to 11.5 m
12/16/1902	Turkestan	8.6	4,500	
04/04/1905	Kangara, India	8.6	19,000	
09/08/1905	Calabria, Italy	7.9	2,500	
01/31/1906	Colombia	8.9	1,000	
03/16/1906	Kagi, Formosa	7.1	1,300	Studied by Omort.
04/16/1906	San Francisco, Ca., USA	8.3	700	Horizontal displacements of 6.4 m, San Francisco destroyed by fire.
08/17/1906	Santiago, Chile	8.6	20,000	
01/14/1907	Kingston, Jamaica		1,600	
10/21/1907	Central Asia	8.1	12,000	
12/28/1908	Messina, Italy	7.5	29,980	
01/03/1911	Tien-Shan, China	8.7	450	
08/09/1912	Sea of Marmara	7.8	1,950	
01/13/1915	Avezzano, Italy	7.5	29,980	
10/03/1915	Pleasant Valley, Nev.,USA	7.8		
12/16/1920	Shansi, China	8.6	100,000	
11/11/1922	Atacama, Peru	8.4	600	
09/01/1923	Tokyo, Japan	8.3	99,330	Known as Kwanto earthquake.
03/16/1925	Yunnan, China	7.1	5,000	
03/07/1927	Tango, Japan	7.9	3,020	
05/22/1927	Nan-Shan, China	8.3	200,000	Felt in Beijing.
05/01/1929	Kutshan, Iran	7.1	3,300	
06/16/1929	Murchison, New Zealand	7.6	17	Landslides
07/23/1930	Ariano, Italy	6.5	1,430	
02/02/1931	Hawks Bay, New Zealand	7.9	225	
03/02/1933	Japan	8.9	2,990	
03/10/1933	Long Beach, California, USA	6.3	115	Severe damage to school buildings
01/15/1934	Nepal	8.4	10,700	Fissures to 5 m deep, 10 m wide, and 300 m long
04/20/1935	Formosa	7.1	3,280	
05/30/1935	Quetta, Pakistan	7.5	30,000	Quetta totally destroyed
07/25/1939	Chile	8.3	28,000	
12/26/1939	Erzincan, Turkey	7.9	30,000	Displacements of 4 m

05/18/1940	El Centro, Ca., USA	7.1	9	Horizontal displacements of 15 ft, vertical displacements of 4 ft
09/10/1943	Tottori, Japan	7.4	1,190	(좋은 지진기록)
12/07/1944	Tonankai, Japan	8.3	1,000	
01/12/1945	Mikawa, Japan	7.1	1,900	
12/20/1945	Tonkai, Japan	8.4	1,330	
11/10/1946	Ancash, Peru	7.3	1,400	Landslides
07/28/1948	Fukui, Japan	7.3	5,930	Felt much more strongly on soft soil than on rock
10/05/1948	Ashkahabad, Turkestan	7.3		Little previous seismic activity
08/05/1949	Ambato, Ecuador	6.8	6,000	Landslides
08/15/1950	Assam, India	8.7	1,530	Landslides, flooding. Worse damage than in 1897 Assam earthquake.
03/04/1952	Tokachi, Japan	8.3	28	Death toll probably higher
07/21/1952	El Centro, Ca., USA	7.7	12	
09/09/1954	Orleansville, Algeria	6.8	1,250	
03/31/1955	Mindanao	7.9	430	
06/09/1956	Kabul, Afghanistan	7.7	220	Death toll could exceed 200,000.
07/09/1956	Aegean Sea	7.7	57	Volcanic eruption
07/28/1957	Mexico	7.8	55	Long-duration
12/04/1957	Altai Gobi, Mongolia	7.8	30	Landslides, 250-km ruptures
12/13/1957	Farsinaj, Iran	7.1	1,130	
07/10/1958	Southern Alaska, USA	7.8	5	Landslides, liquefaction of soils
02/29/1960	Agadir, Morocco	5.8	10,000	Earthquake occurred directly underneath city.
04/24/1960	Lar, Iran	5.9	450	Great destruction of buildings on soft soils
05/22/1960	Chile	8.3	4,000	Similar to earthquakes in 1835-37
09/01/1962	Qazyin, Iran	7.1	12,230	
07/26/1963	Skopje, Yugoslavia	6.0	1,100	Earthquake occurred just below city.
03/28/1964	Anchorage, Alaska	8.5	115	Landslides. Tsunamis (sea waves) noted in Texas and Lousiana.
08/19/1966	Varto, Turkey	6.9	2,520	
05/16/1968	Hokkaido, Japan	8.6	48	
08/01/1968	Manila	7.7	300	
08/31/1968	Mashad, Iran		20,000	
02/28/1969	Atlantic Ocean near Portugal	7.9	2	Felt in Portugal, Spain and Morocco
07/25/1969	Eastern China	6.1	3,000	
03/28/1970	Gediz, Turkey	7.4	1,100	
04/07/1970	Manila	7.7		
05/31/1970	Huaras, Peru	7.7	50,000	Landslides
02/09/1971	San Fernando, Ca., USA	6.1	5	
07/09/1971	Valparaiso, Chile	7.7	100	Fires
04/10/1972	Southern Iran	6.9	5,054	Qir totally destroyed
09/03/1972	Northwest Kashmir	6.2	100	
12/23/1972	Nicaragua	6.2	4,000	$800 million damages in Managua, profound political effects.
08/28/1973	Veracruz, Mexico	6.2	600	Many thousands left homeless.
10/03/1974	Coast of Peru	7.6	78	Tsunamis noted in Hawaii and California.
12/28/1974	Western Pakistan	6.2	5,300	97,000 left homeless
02/04/1976	Guatemala	7.5	23,000	Hundreds of thousands wounded.
05/06/1976	Austria	6.5	900	Felt in Central Europe.
06/25/1976	Western Iran	7.1	422	Thousands missing, 6 villages destroyed.
07/14/1976	Bali	6.5	563	
07/27/1976	Tanshan, China	7.9	655,237	800,000 wounded (계측이래 가장 큰 피해
08/16/1976	Mindanao	7.9	5,000	90,000 homeless
10/29/1976	Eastern Iran	7.1	133	
11/24/1976	Northeastern Iran	7.3	5,000	
03/04/1977	Bucharest, Rumania	6.4	1,500	Felt throughout Europe
03/21/1977	Southern Iran	6.9	167	

9

04/06/1977	Iran	5.9	100	Tsunamis noted in Australia.
1/23/1977	San Juan, Argentina	7.4	70	40,000 homeless, 80% of buildings in San Juan province destroyed, roads over Andes blocked by landslides.
12/19/1977	Iran	5.8	584	
09/16/1978	Iran	7.7	11,000	
03/14/1979	Mexico City, Mexico	6.0	3,000	
04/15/1979	Yugoslavia	7.0	121	
12/12/1979	Coast of Ecuador	7.9	600	20,000 wounded, tsunamis in Hawaii.
10/10/1980	El -Asnam, Algeria	7.2	3,000	Many homeless
03/21/1982	Tokyo, Japan	6.0		
12/14/1982	North Yemen	6.0	350	79 villages damaged
12/23/1983	Dakar, Senegal	6.3	200	
01/01/1984	Pakistan	7.5	5	
03/03/1985	Santiago, Chile	7.8		(연약지반에 대한 피해)
09/19/1985	Mexico City, Mexico	8.1	10,000	Extensive damage to communications
11/25/1988	Sanguenay, Quebec	6.0	0	eastern North America
12/07/1988	Yerevan, Armenia, USSR	6.9	25,000	More than 500,000 homeless
10/17/1989	Loma Prieta, California, USA	7.1	62	$5.6 billion damage
03/25/1990	Cobano, Costa Rica	6.8		
06/21/1990	Manjil, Iran	7.7	50,000	400,000 homeless
07/16/1990	Luzon, Philippines	7.7	2,500	100,000 homeless

Table 1-1. **Magnitudes of Some Recent Damaging Earthquakes**

Date	Region	Deaths	Magnitude (M_S)	
December 7, 1988	Spitak, Armenia	25,000	7.0	
August 1, 1989	West Iran, Kurima District	90	5.8	
October 17, 1989	Santa Cruz Mountains, Loma Prieta	63	7.0	
June 20, 1990	Caspian Sea, Iran	Above 40,000	7.3	
March 13, 1992	Erzinean, Turkey	540	6.8	
July 16, 1990	Luzon, Phillipines	1,700	7.8	
July 12, 1993	Hokkaido, Japan	196	7.8	
September 29, 1993	Killari, India	10,000	6.4	
January 17, 1994	Northridge, California	61	6.8	(기반시설피해. Steel Structure damage)
January 16, 1995	Kobe, Japan	5400	6.9	(대비에도 불구하고 상당한 피해)
August 17, 1999	Izmit, Turkey	16,000	7.4	
September 21, 1999	Chi Chi, Taiwan	2,200	7.6	

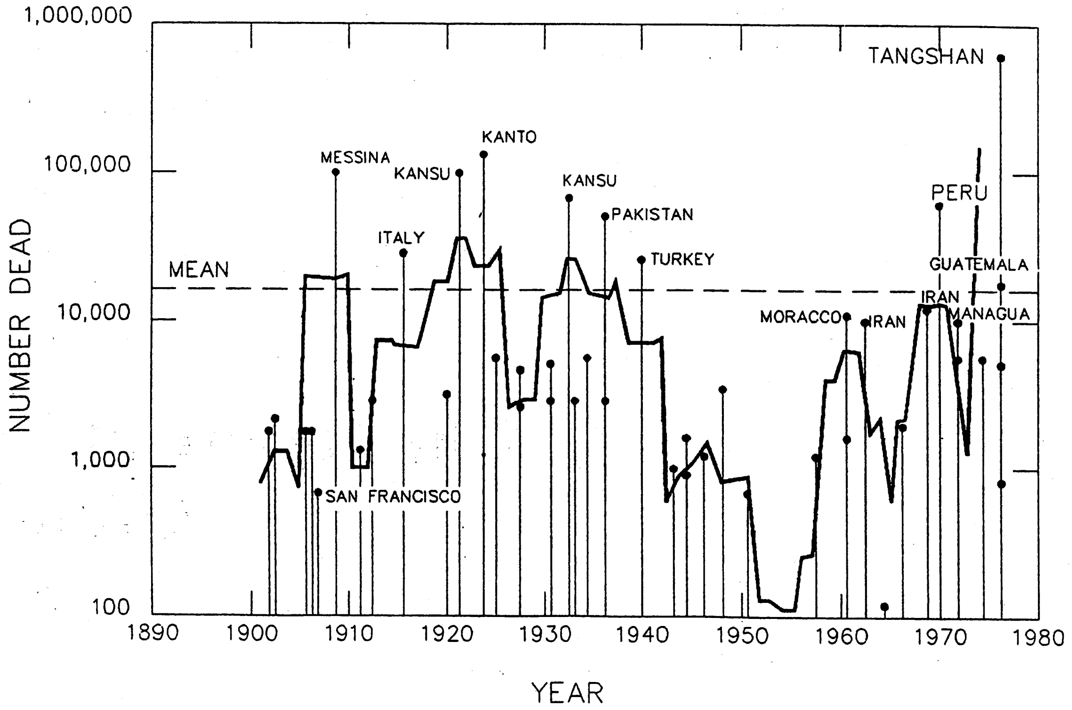


Figure 1-1 Loss of life caused by major earthquakes. (After Hiroo Kanamori (1-5).)

Engineering Seismology

Introduction

To predict behavior of structures during earthquakes and to design earthquake-resistant structures, we need **to study the characteristics of earthquakes and earthquake ground motion**. This topic is called engineering seismology. It is related to strong-motion seismology: characteristics of near-source and very strong earthquakes.

We have a historical problem: While we are interested in events with recurrence intervals of 10,000 to 100,000 years, **engineering seismology is about 110 years old.**

Major questions :

a) causes of EQ
b) size of EQ
c) recurrence intervals of EQ

Causes of EQ

1) **Tectonic movement of crustal plates**
2) **Intra-plate EQ of unknown origin (historically caused major EQs)**
   Dashtee-Bayaz 1968, Iran
   New Madrid 1811-12 Missouri
   Charleston South Carolina
   Northern China, 1976, Dangsan
3) **Volcanic activity (plate related)**
4) Large Reservoir Induced EQs
   Koyna, India M6.5 close to a Dam
5) Underground collapse (caves, sinkholes, oil drilling)
6) Underground explosions (conventional, nuclear)
7) Meterorite

Causes 1) and 2) are most important, and will be emphasized.

Deep-focus EQ
Intermediate-focus EQ
Shallow-focus EQ – most devastating

Plate tectonics (지각 구조)

The earth's surface is composed of 10-14 large plates, 60-90 km thick. These plates, supporting continents and oceans, move relative to each other on the softer mantle. This movement is caused by convection of molten rocks in the interior of the earth.
Most Earthquakes arise from contact between theses plates.

Plate boundaries

1) spreading zones (ridges) : mid-Atlantic ridge
2) subduction zones : Japan, west coast of south America
3) transform boundaries : California

Plates spread towards the subduction zones at rates of 20 – 50 mm per year. Plate thickness is about 80 km.

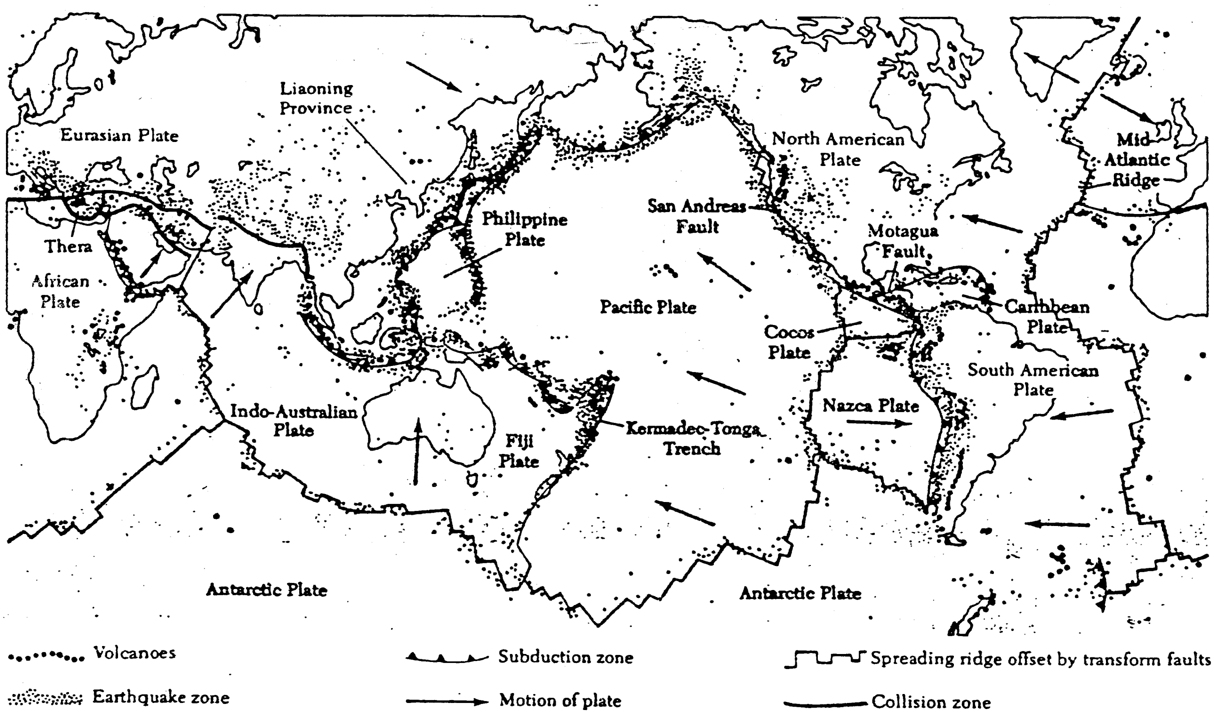
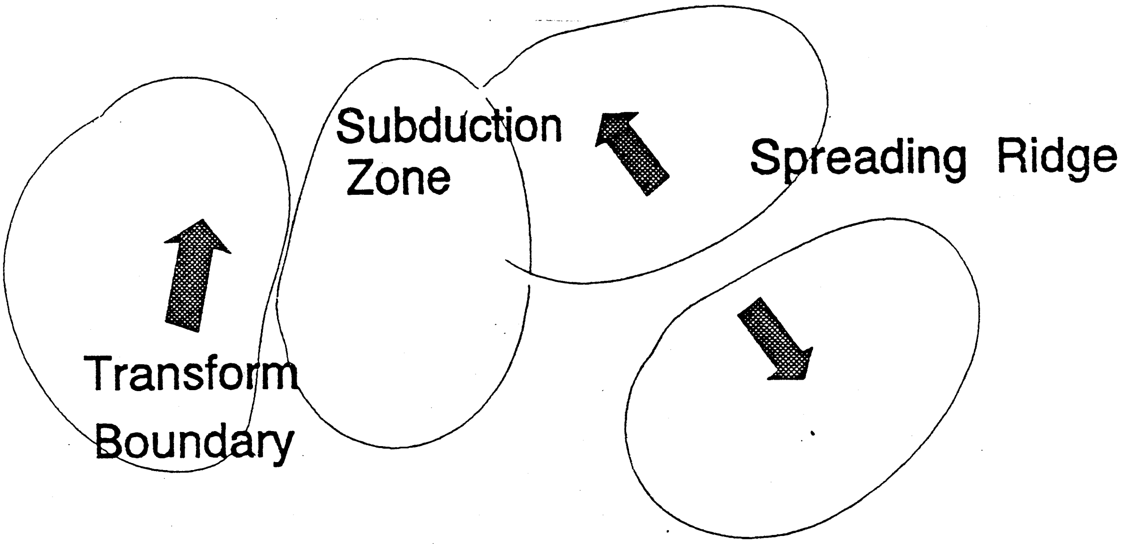
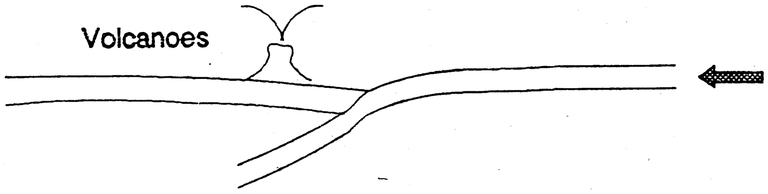


Figure 1-2 Tectonic plates and worldwide distribution of earthquakes. (From *Earthquakes*, by Bruce A. Bolt. Copyright 1978, 1988 W. H. Freeman and Company. Used with permission.)



Section through Subduction Zone



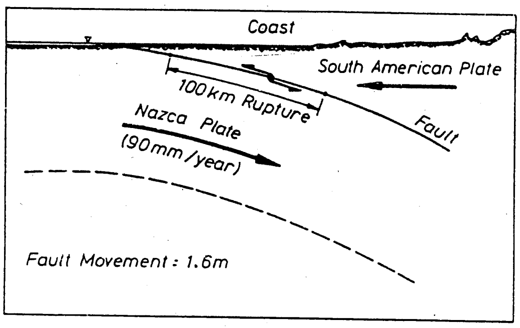


Fig. 2.3 Origin of Chilean earthquake of March 3, 1985.

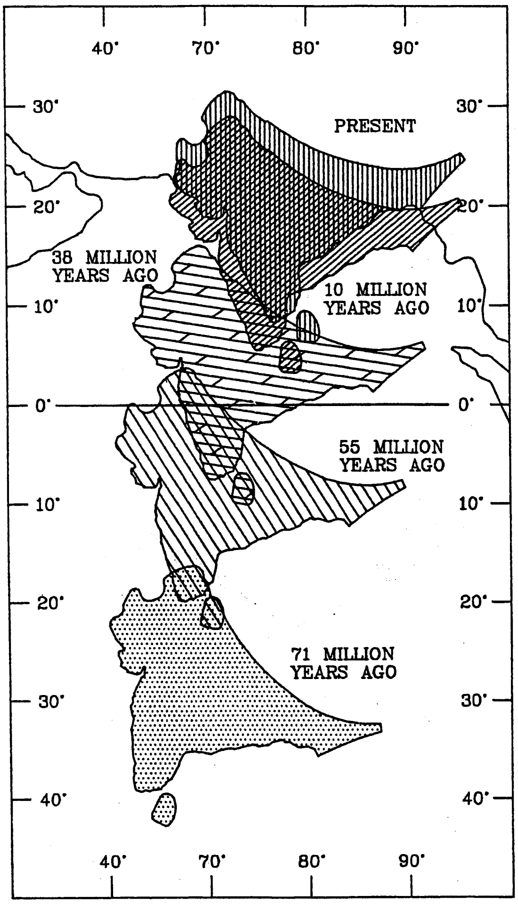


Figure 1-3 Continued drift of the Indian plate towards Asian plate causes major Himalayan earthquakes. (From *The Collision Between India and Eurasia*, by Molnar and Tapponnier. Copyright 1977 by Scientific American, Inc. All rights reserved.)

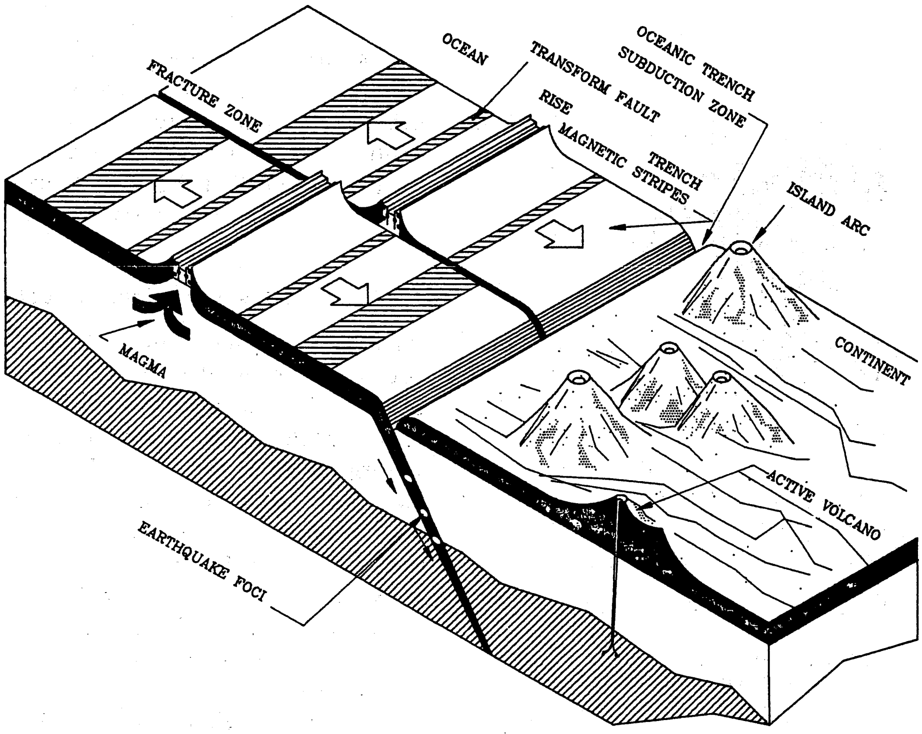


Figure 1-4 A sketch of the Earth's crust showing mid-oceanic ridges and active continental margin along a deep trench.

Faults

Subduction zones and transform boundaries defined fault planes.
Rock formations fracture along fault planes in response to plate motion. Actual geology near plate boundaries is very complicated.

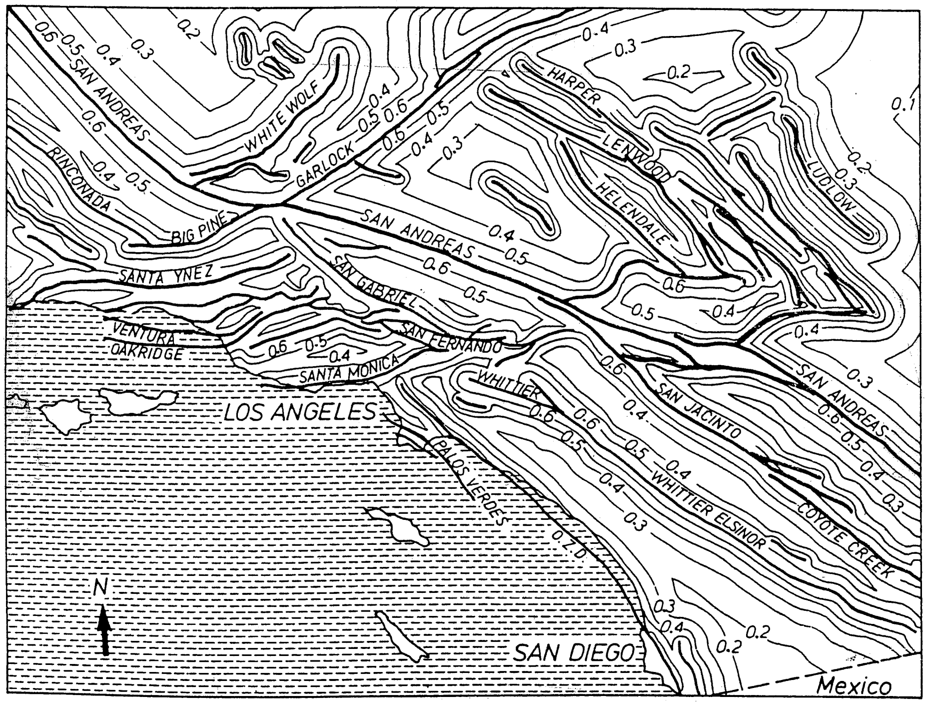
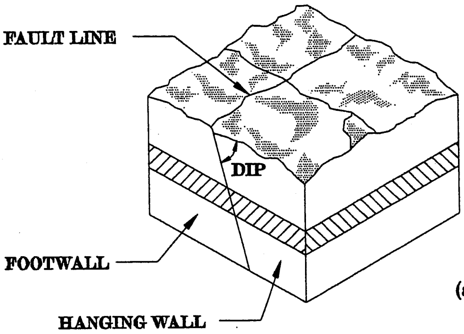


Fig. 2.1 Faults and design ground accelerations for freeway bridges in southern California [Y14]

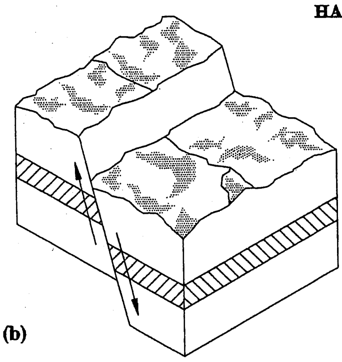
There are 3 main types of faults, described in terms of the relative movement of the earth from one side of the fault to the other.

1) normal fault
2) reverse fault
3) lateral fault

Oblique fault = normal(reverse) slip + lateral slip
No clear type of fault is found in the mid-plate earthquake events

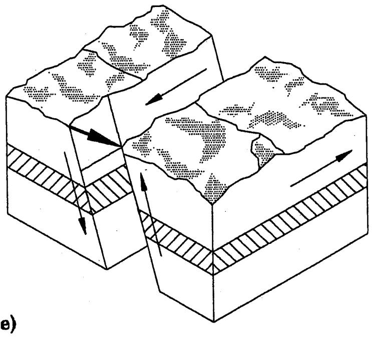


(a)



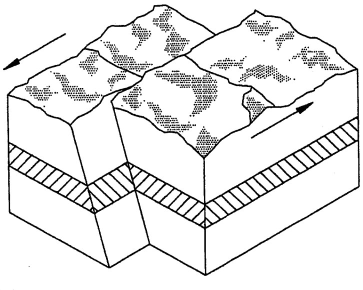
(b)

NORMAL FAULT

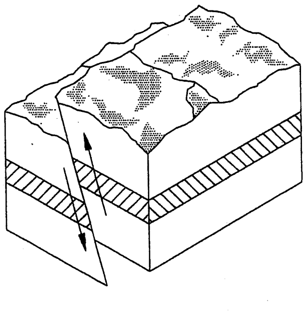


(e)

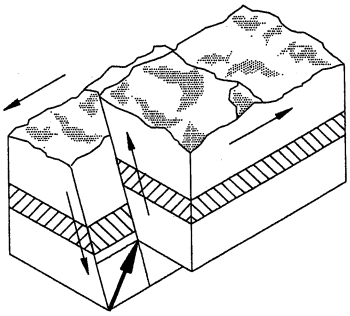
LEFT LATERAL NORMAL FAULT
(LEFT OBLIQUE NORMAL FAULT)



(d) LEFT LATERAL FAULT



(c) REVERSE FAULT



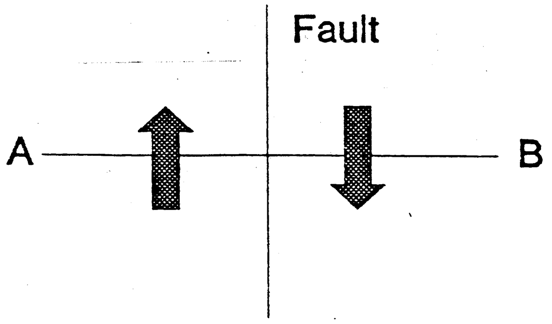
LEFT LATERAL REVERSE FAULT
(f) (LEFT OBLIQUE EVERSE FAULT)

Earthquake Mechanism : Elastic Rebound Theory

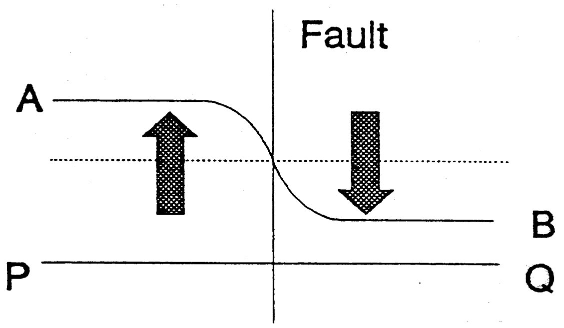
The most accepted theory in use today is the elastic rebound theory, proposed by Reid in 1911 on the basis of his observations of the San Francisco EQ of 1906. The theory postulates the following steps :

1) Tectonic forces attempt to move neighboring plates relative to each other.
2) Friction between the plates results in a buildup of stress in the rock on both sides of the fault
3) When that stress exceeds the strength of the rock, fracture occurs, and relative motion occurs which relieves the stress (elastic rebound).
4) The sudden movement of the rocks initiates vibrations that propagate as seismic waves.

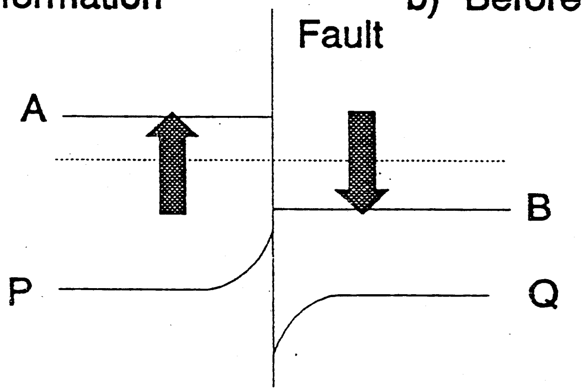
This sequence is shown in the figure below. In that figure, the first diagram (a) shows a right lateral fault, running from north to south.



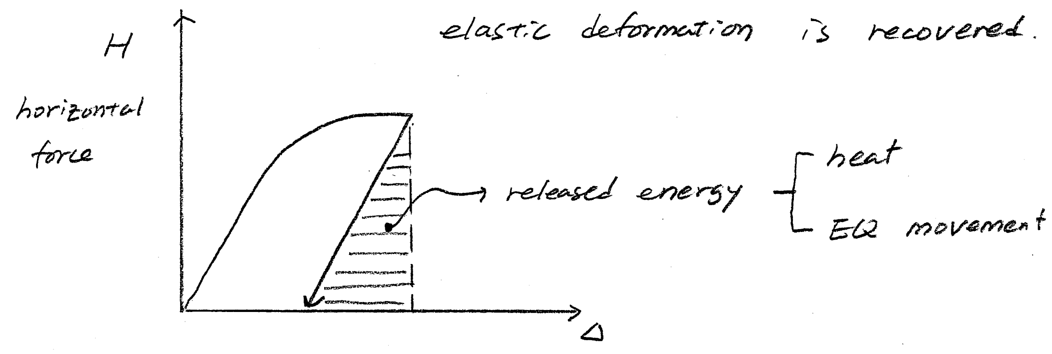
a) Prior to Deformation



b) Before Earthquake



c) After Earthquake



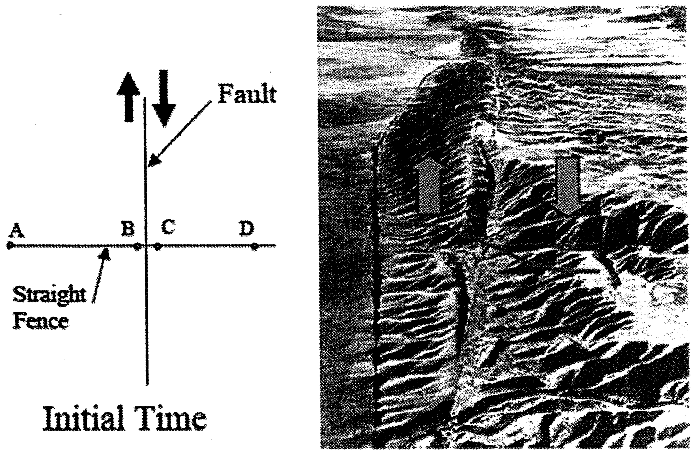
Slow movement of the fault results in deformations as shown in (b).

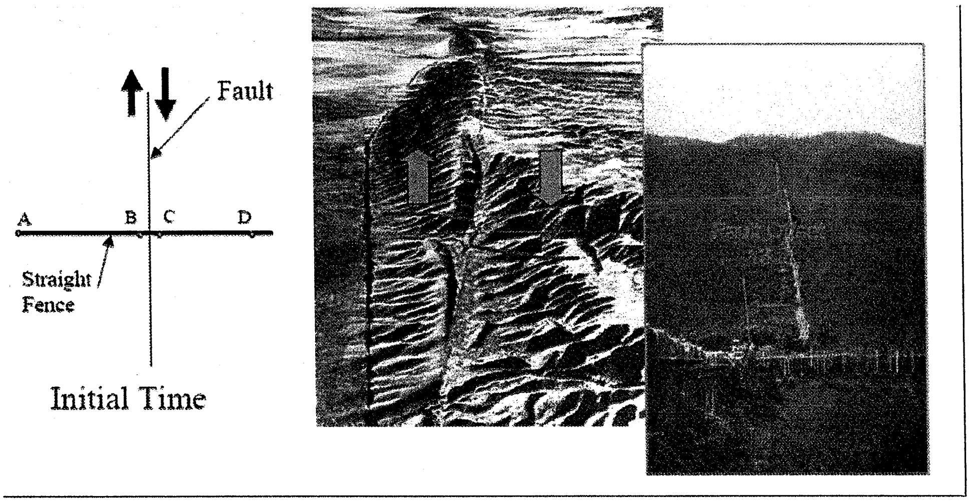
As a result of those movements, the reference line AB, which is straight in (a), becomes curved near the fault in (b).

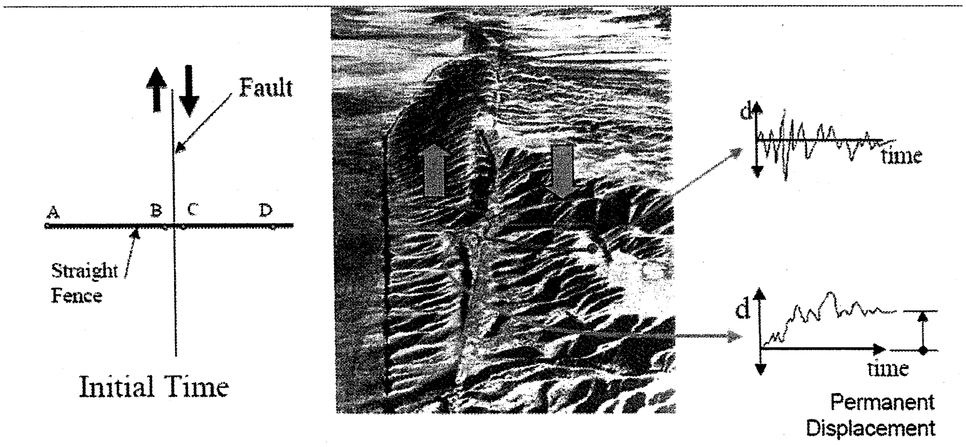
These deformations continue until an earthquake occurs. Just before the earthquake, a new straight-line reference is line PQ. After the earthquake, old reference AB is now straight again but in two parts. The new reference PQ is now curved. The relative displacement between the halves of AB and PQ indicates the relative displacement at the fault. This process repeats.

Further development of the elastic rebound theory has resulted in the following proposed refinements:

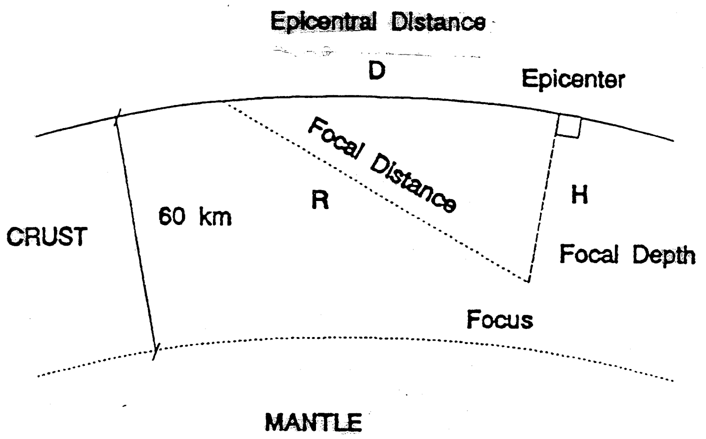
1) Rupture starts at a weak point on the fault, and the dislocation travels irregularly along the fault surface.
2) The velocity of propagation of the rupture is approximately 2.2 km/sec but varies due to roughness and local unbroken zones.
3) Starting and stopping of rupture produces high-frequency components of ground motions.
4) The rupture may reach the surface, causing “break outs”, with large relative displacements.


Fault
A
B
C
D
Straight Fence
Initial Time


Fault
A
B
C
D
Straight Fence
Initial Time


Fault
A
B
C
D
Straight Fence
Initial Time
d
time
d
time
Permanent Displacement

Definition of terms



Focus (hypocenter) : point from which seismic waves first start. This is associated with a focal depth.

Epicenter : point on the earth's surface directly above the focus

Neglecting the curvature of the earth's surface, the focal distance, epicentral distance, and focal depth are related by

$$R = \sqrt{D^2 + H^2}$$

If the focus is located within the crust (on land, at depths of about 60 km or less), the earthquake is usually referred to as **shallow**. **Deep-focus earthquakes** are located in the mantle.

Local Effects of Earthquakes

Shallow-focus EQs often produce local effects: if the fault zone extends to the surface of the earth, this can produce visible evidence of the relative movement on the two sides of the fault. The fault trace is visible on the ground surface: roads and railway lines are distorted. Because these local effects are restricted to the fault zone itself, they are relatively unimportant, and primarily affect roads and pipelines. Of far more importance are the long-distance effects.

Long-distance Effects of EQs : seismic waves

The initial rupture, and the propagation of the rupture, induce vibrations near the fault. These propagate in all directions in the form of seismic waves. This can be viewed as an energy conversion process: **the stored strain energy of deformation in the rupture zone is released** by the EQ. and is converted into **heat (friction)** and into **kinetic energy (seismic waves).**
A very complex mixture of seismic waves is produced.
Elastic wave theory predicts the following types of waves:

Primary wave (body wave)

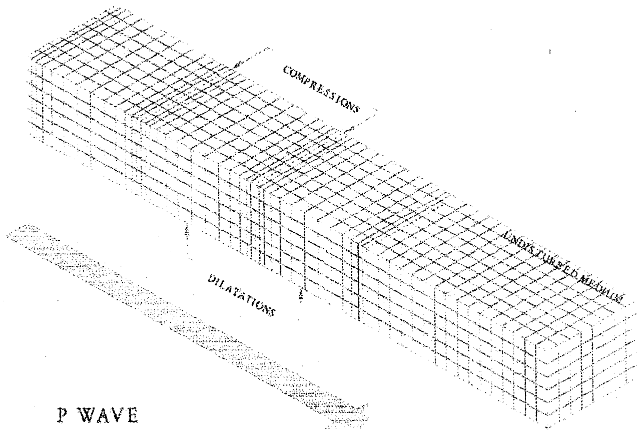


Figure 1-11. Ground Motion near the ground surface due to P waves. (From *Nuclear Explosions and Earthquakes*, by Bruce A. Bolt. Copyright 1976 W. H. Freeman and Company. Used with Permission.)

Secondary wave (body wave)

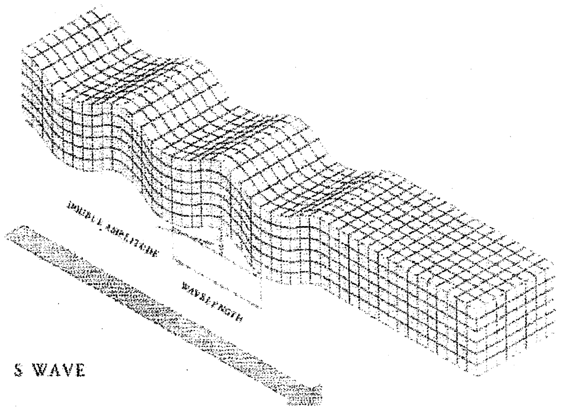


Figure 1-12. Ground motion near the ground surface due to S waves. (From *Nuclear Explosions and Earthquakes*, by Bruce A. Bolt. Copyright 1976 W. H. Freeman and Company. Used with Permission.)

Surface waves

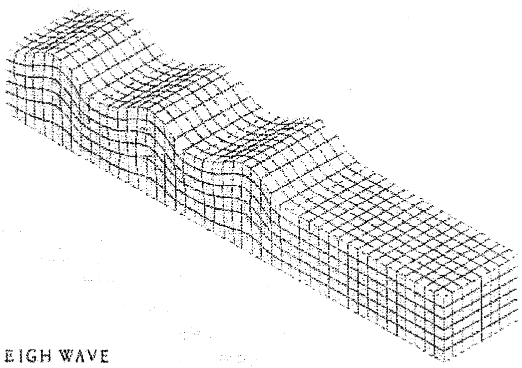


Figure 1-14. Ground motion near the ground surface due to Rayleigh waves. (From *Nuclear Explosions and Earthquakes*, by Bruce A. Bolt. Copyright 1976 W. H. Freeman and Company. Used with Permission.)

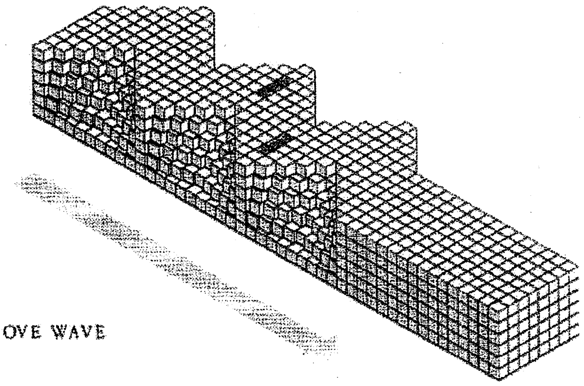
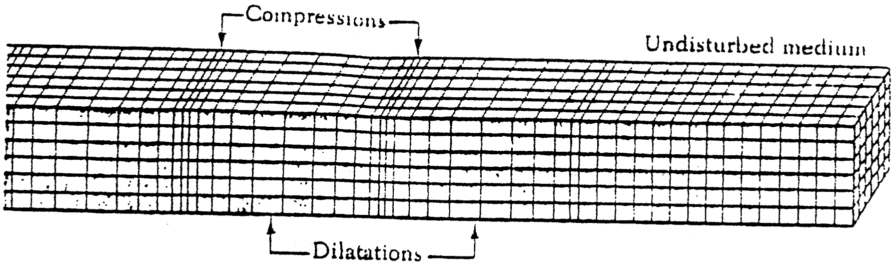
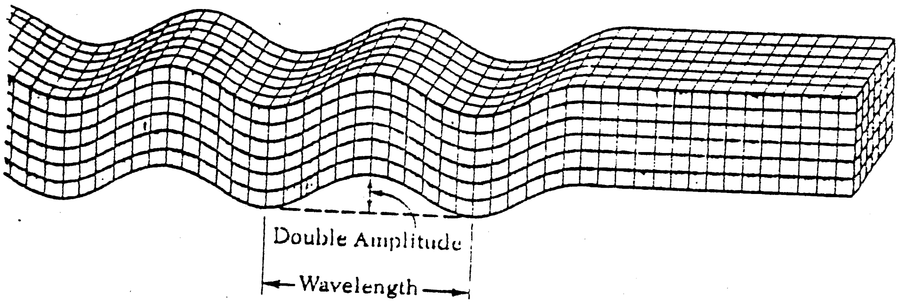


Figure 1-13. Ground motion near the ground surface due to Love waves. (From *Nuclear Explosions and Earthquakes*, by Bruce A. Bolt. Copyright 1976 W. H. Freeman and Company. Used with Permission.)

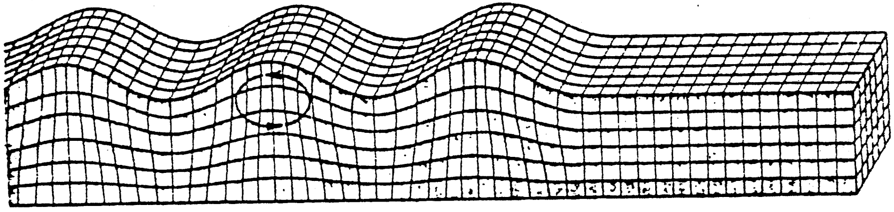
P wave



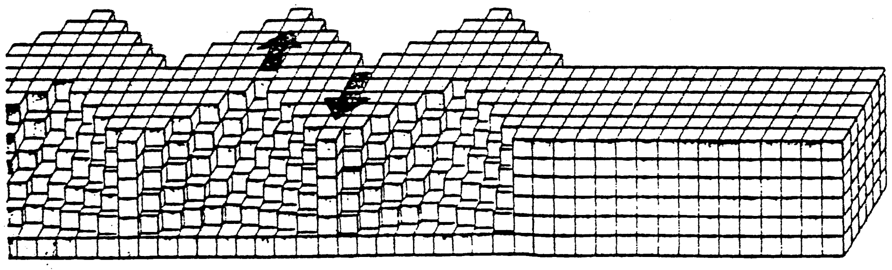
S wave



Rayleigh wave



Love wave



Body waves which travel through the body of a material :

Longitudinal waves (irrotational)

These are stress waves caused by alternating compression and dilation of material in the direction of wave propagation. Seismologists refer to these as **P waves** (primary waves) because they have the fastest velocity of wave propagation, and arrive at distant stations first. The velocity of propagation of P waves, Cp, is given by

$$C_p \propto \sqrt{\frac{\lambda+2G}{\rho}} = \sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)\rho}}$$

λ : Lame's constant $= \dfrac{\nu E}{(1+\nu)(1-2\nu)}$

ρ : mass density of medium

$$u = A \sin wt$$

$$\dot{u} = Aw \cos wt$$

$$\dot{u} \propto w = \sqrt{\frac{k}{M}}$$

$$\sigma_{11} = (\lambda+2G)\,\varepsilon_{11} + \lambda \overset{0}{\cancel{\varepsilon_{22}}} + \lambda \overset{0}{\cancel{\varepsilon_{33}}}$$

$$= (\lambda+2G)\,\varepsilon_{11} \quad \text{in plane strain}$$

a typical value for crustal rock is $C_p = 5.7 km/\sec$. C_p increases with depth.

Shear Waves (rotational)

These are stress waves caused by particle oscillation normal to the direction of propagation without volume change. They are often referred to as **S waves** (secondary waves) because they arrive second, after P waves. S waves generally transmit more energy than P waves. The velocity of propagation of S waves, Cs is given by

$$C_s \propto \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+\nu)\rho}}$$

Therefore $\dfrac{C_p}{C_s} = \sqrt{\dfrac{2(1-\nu)}{(1-2\nu)}}$

for $\nu = 1/4$, $\dfrac{C_p}{C_s} = 1.7$.

A typical value for crustal rock is $C_s = 3.3 km/\sec$. For firm soil, C_s is about 1000 m/sec; for soft soil, it can be as low as 300 m/sec.

Estimation of Epicentral distance

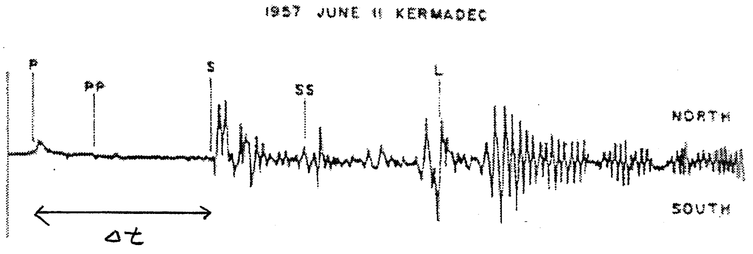
For short epicentral distances (< 100 km), C_p and C_s can be assumed constant (invariant with depth), and epicentral distance can be estimated from the delay in arrival times of S and P waves.

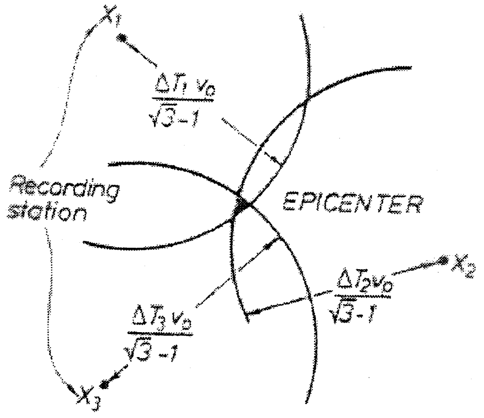
$$t_p = R/C_p, \quad t_s = R/C_s$$

$$\Delta t = t_s - t_p = R/C_s - R/C_p = R(C_p - C_s)/C_pC_s$$

and $R = \dfrac{C_pC_s}{(C_p - C_s)}\Delta t = 7.84 km/\sec \Delta t$

Using this information, calculated epicentral distances from three close stations can be used to locate the epicenter by triangulation.





Surface waves

Waves that exist between boundaries of two media. Most important seismic surface waves occur at the earth's surface. Wave amplitude decreases exponentially with depth. Surface waves are dispersive.

Rayleigh Waves

These exist **at a free surface**, particles move in a retrograde elliptical motion in a vertical plane parallel to the direction of propagation. $C_R = 0.92C_s$ (slower than S waves). Periods range from a few seconds to hours.

Love Waves

These exist **at the interface between two dissimilar materials**. Particles move horizontally, perpendicular to the direction of propagation. If layer 1 overlies layer 2, and if $C_{s1} < C_{s2}$, then Love waves can exist in the upper surface, and $C_{s1} < C_Q < C_{s2}$.

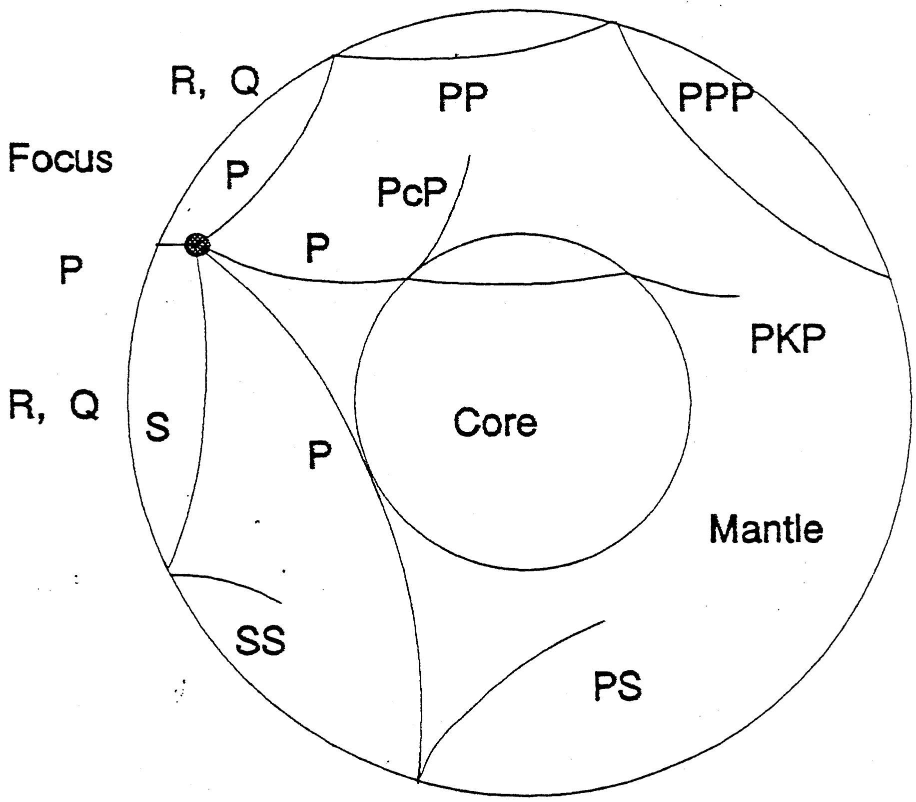
Body waves have many possible trajectories, each of which has its own distance from the focus to the point where the wave is recorded. Nevertheless, it has been observed that after en earthquake, **all P waves arrive at the recording point at about the same time**. This implies that **wave velocity increases with depth**. Knowing the arrival time of P waves as a function of the distance from the focus to the recording point, it is possible to back-calculate the variation of velocity with depth. The **Mohorovicic discontinuity** that indicates the boundary between the earth's crust and the mantle, occurs at s depth of as little as 30 km in the oceans, and as much as 60 km in the continents. It is characterized by an abrupt change in velocity.

locations	Depth (km)	$C_p(km/\sec)$	$C_s(km/\sec)$
Surface of earth	0	5	3
Continental crust		6	3.5
Mohorovicic discontinuity	30	7	4
mantle	2900	13.5	8
core	5000	8-10	-
Inner core center	6370	11.5	-

Wave trajectories

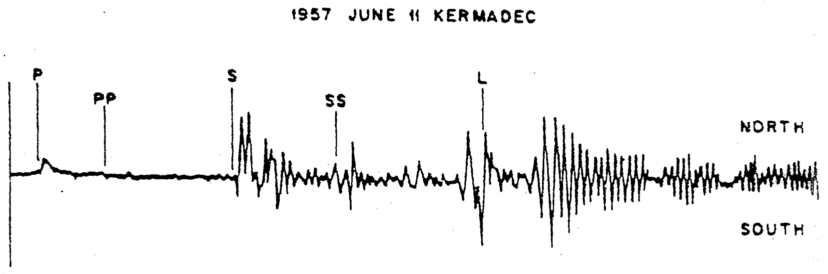
The figure shows various possible trajectories for different paths of seismic waves various points are of interest:

1) Owing to the increase of velocity with depth, the trajectories of the body waves are curved, just as a ray of light is curved when it is refracted through a material of non-uniform density.
2) S waves cannot be transmitted through the liquid core of the earth .
3) Waves are reflected on the earth's surface. A P wave, after one reflection, is called a PP wave. Waves can also change form upon reflection. For example, we can have PS or SP waves.
4) Body waves can reflect against the boundary between the mantle and the core. This type of reflection is indicated by a small letter "c": for example, PcP, PcS and so forth.
5) Body waves can be refracted when they pass through the mantle to the core, and back into the mantle. This type of refraction is indicated by a capital letter "K" : for example, PKP, PKS, and so forth.



By observing the different arrival times of each type of wave, and knowing the variation of velocity with depth for each type of wave, it is possible to estimate the focal distance. Using such information, recorded at three or more sites, an earthquake focus can be estimated by triangulation, and the earthquake mechanism and fault surface orientation also can be established.

The same wave conversion process that occurs on a gross scale at boundaries between the mantle and the core, can also occur at boundaries between minor layers. As a result, a mix of earthquake waves at a particular site can be very complex, and quite different from the waves arriving at a nearby site from the same event.



Earthquake Recording Instruments

We need a way to measure the vibration of the ground during an earthquake. At any point there are 6 components of motion: three translations and three rotations. The translational components can be measured readily; the rotational components are difficult to measure.
Instruments are readily available to measure translational ground acceleration, which is often expressed in g units: 1g = 981 cm/sec2 = 1000 gals = 3.2 ft/sec2 = 386.4 in/sec2
Two principal types of instruments are available for measuring ground acceleration:

Seismograph

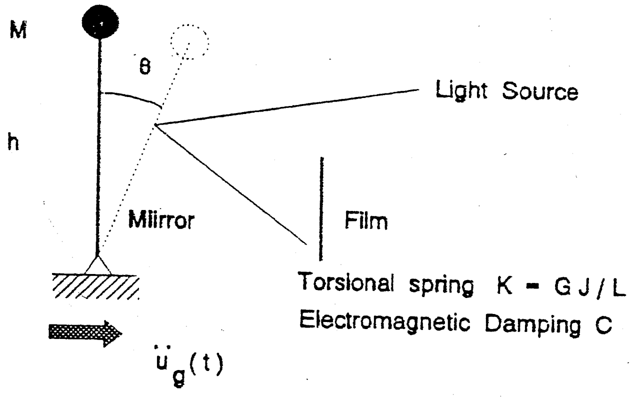
These are primarily used by seismologists for measuring distant earthquakes. Because they are adjusted for very high magnification, they are driven off scale by strong ground motions. They usually operate continuously.

Strong motion accelerograph

These are used to record ground motions and building response from nearby earthquakes. Their sensitivity is adjusted for strong ground motion. Rather than operating continuously, they are triggered by strong ground motion.

Accelerograph operation

An accelerograph is basically a SDOF oscillator with an associated motion recorder and a trigger mechanism. Its major components are:



a) a transducer: usually a pendulum connected to a torsional spring.

b) A light source and recording film, which records a light trace proportional to the transducer response

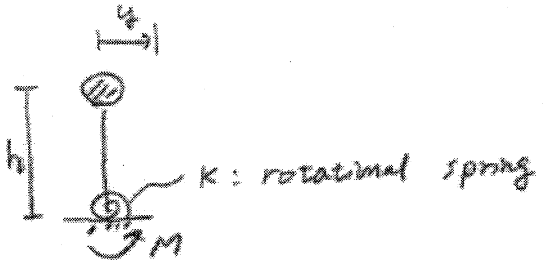
c) A starter mechanism which detects some threshold level of motion and starts the recorder.

For pendulum structure,

$y = \theta h$

$M = h(K'y) = K\theta$

$K = K' yh / \theta = K' h^2$



The natural frequency of the transducer is given by

$$\omega = \sqrt{\frac{K}{Mh^2}} = \sqrt{\frac{K'}{M}}$$

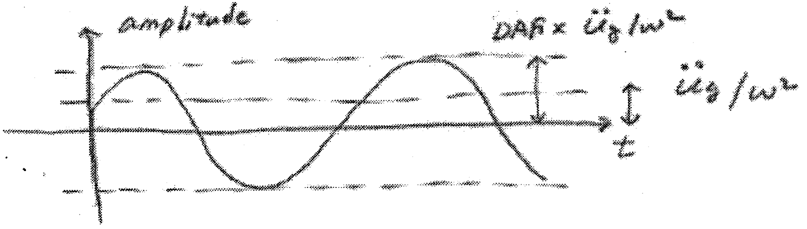
The equation of motion of this system is given by

$$M\ddot{y} + C\dot{y} + K'y = -M\ddot{u}_g$$

$$\ddot{\theta} + 2\xi\omega\dot{\theta} + \omega^2\theta = -\ddot{u}_g / h \quad (= \ -u_g / h \cdot \sin pt \ )$$

under sinusoidal ground acceleration, the system's response is

$$\theta = \frac{-\ddot{u}_g}{\omega^2} \frac{\sin(pt - \phi)}{\sqrt{(1-\beta^2)^2 + (2\xi\beta)^2}}$$



where $\beta = p/\omega$ and ξ = critical damping ratio = $c/2M\omega$

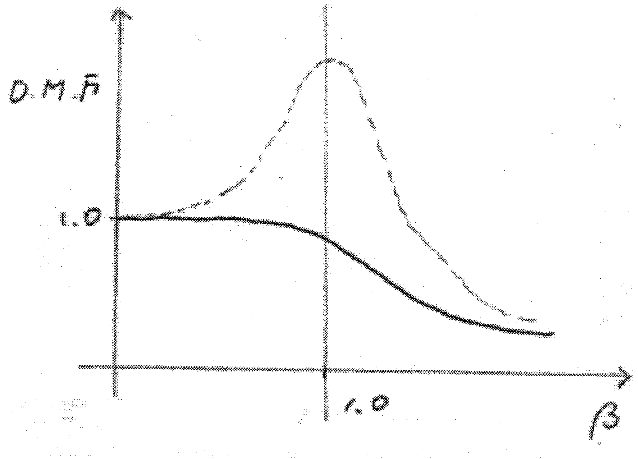
The natural frequency ω of the system is fixed. Knowing the frequency range of interest, β

is then known. Finally, by choosing the proper values of ξ, the dynamic amplification factor can be made almost constant over the range of interest of β .

Specifically, suppose we choose $f = \omega / 2\pi =$ 20 to 50 Hz. Now examine the dynamic amplification factor for values of $\beta <1$: that is, excitation frequencies less than 20 to 50 Hz. For ξ between 0.6 and 0.7, the dynamic amplification factor will be almost constant and equal to one: In other words, the displacement response of the strong motion accelerograph will be proportional to the input acceleration. The trace recorded on the film will be an input acceleration record.

Value of dynamic amplification factor

β	ξ=0.6	ξ=0.7
0	1.00	1.00
0.2	1.01	1.00
0.4	1.03	0.99
0.6	1.04	0.95
0.8	0.98	0.85
1.0	0.83	0.71



$$\text{Dynamic amplification factor} = \frac{1}{\sqrt{\left(1-\beta^2\right)^2 + \left(2\xi\beta\right)^2}}$$

Typical strong motion accelorograph (kinemetrices SMA-1)

1) measures two horizontal and vertical translational components of ground motion.
2) Has a natural frequency f = 20 – 50 Hz
3) Has electromagnetic damping equal to 60% of the critical ξ=0.6
4) Has a starter that triggers on vertical motion of 0.005 to 0.05 g. start-up time is 0.1 sec.
5) Weighs 20 lbs(9 kg)
6) Requires careful installation, calibration, and periodic maintenance.

Strong motion records and processing

A typical strong motion record shows ground acceleration as a function of time. Timing comes from two sources.

Local time : 2 ticks marks per second are recorded on the film.

Absolute time : the accelerograph has a receiver tuned to WWVB (international time signal). This information is used to compare arrival times at various stations.

The instrument is typically triggered by the P wave arrival.

The instrument then records the end of the P wave arrival, and S and surface wave arrivals.

Recording processing involves the following principal steps:

1) digitization : the film trace is converted to numerical time value and corresponding acceleration ordinates.
2) Transducer correction : the recorded values are corrected for the dynamic amplification curve of the transducer.
3) Baseline correction : baseline errors in the recorded acceleration are evaluated and reduced. For example, suppose that due to a recording or digitizing error, a recorded acceleration has a constant error of 0.01g. The corresponding velocity obtained by integrations will have a linearly increasing error, and the corresponding displacement will have a parabolically increasing error. This is clearly unrealistic. At the end of the record, the final velocity should be zero. Records are often corrected by assuming either constant or linearly varying errors in acceleration over the record, solving for that value of error which will give zero residual velocity and displacement, and then correcting the acceleration accordingly.
4) Filtering: high and low-pass filtering is performed to remove noise from the record.
5) Integration : single and double integration are performed on the record. These steps are carried out together with the baseline correction.

Instrumental Data

미국버클리웹사이트

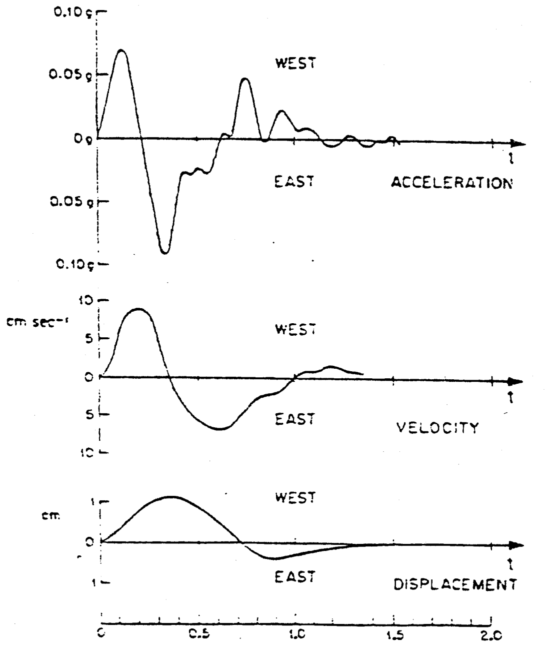
http://peer.berkeley.edu/peer_ground_motion_database/

기상청 웹주소

http://www.kma.go.kr/mini/earthquake/main.jsp

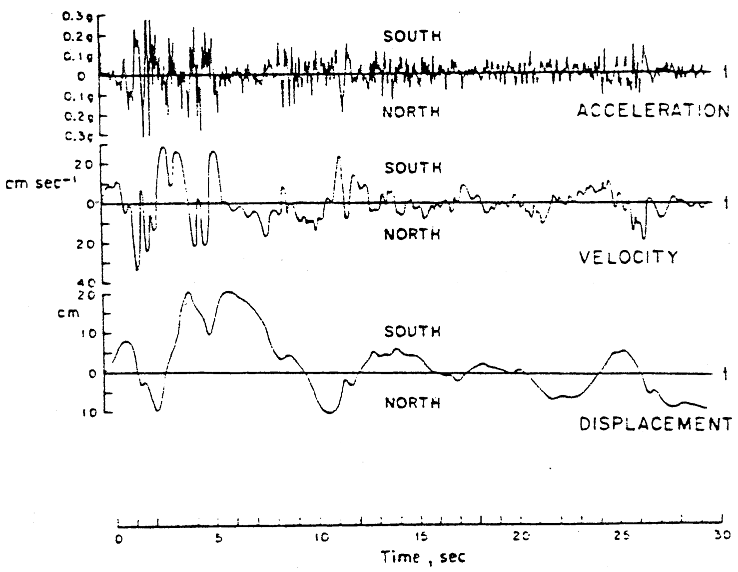
Typical strong-motion records

1) **Near-field records** : as shown below, these can be very simple in nature. **A large single pulse type wave.** They can be explained in terms of a single elastic rebound that takes place in a small region, and is reforded on rock or firm soil. Examples are the port Heyneme (1957) and Parkfield (1966) records.



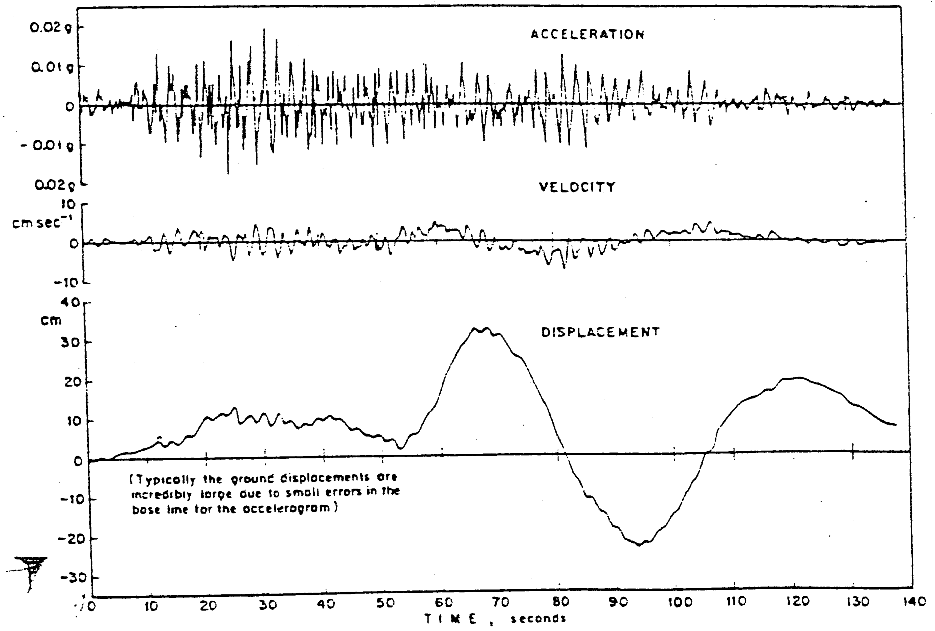
Port Hueneme earthquake of 18 March 1957, EW component. *After Housner and Hudson (1958).*

2) **Medium-field records** : these are extremely complex in nature. In spite of their apparently stochastic nature, they can have velocity pulses. For example, the El Centro 1940 NS record shown below has such pulses. Between 2 and 4 seconds. Records of this type are recorded at epicentral distances of 5 to 100 km on firm soil.



El Centro, Cal. earthquake of 18 May 1940, NS component. *After Blume, Newmark, and Corning (1961).*

3) **far-field records** : at large epicentral distances, surface waves dominate. Because surface waves are dispersive, the resulting wave train can be quite long. As a result, these records are usually of long duration. Since the seismic waves are filtered through thick, soft soil layers, the resulting record can be almost sinusoidal in nature. A very famous example of this is Mexico city, located on an old lake bed now filled with soft clay and volcanic ash having a fundamental period of about 2.5 seconds. The vibrating response of the old lake bed can be compared to a gigantic bowl of gelatin.



Mexico City earthquake of 6 July 1964, NS component. *After Rosenblueth (1966).*

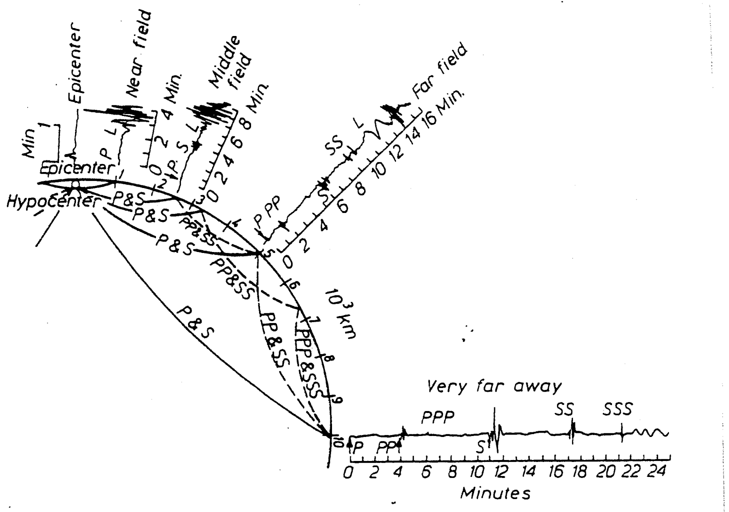


Fig. 2.5 Seismic waves at large distances from the hypocenter [M16].

4) Influence of soil stiffness

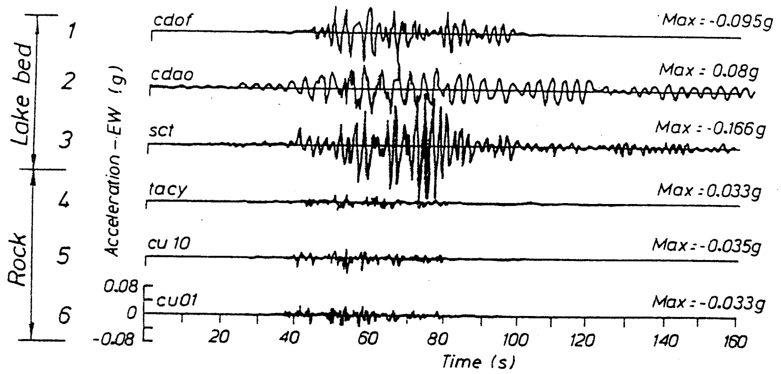
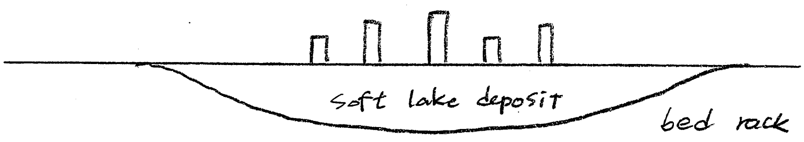
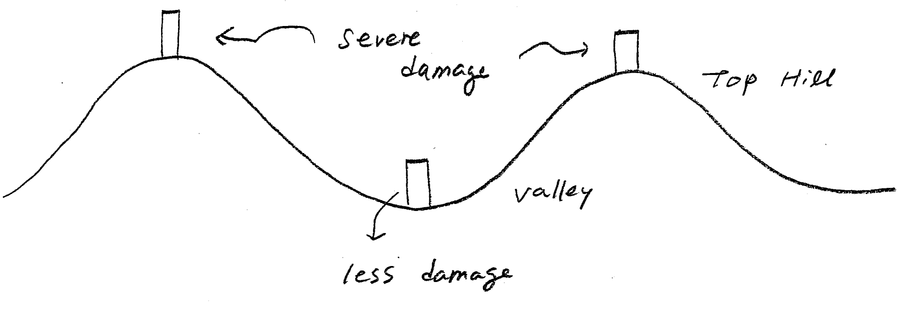


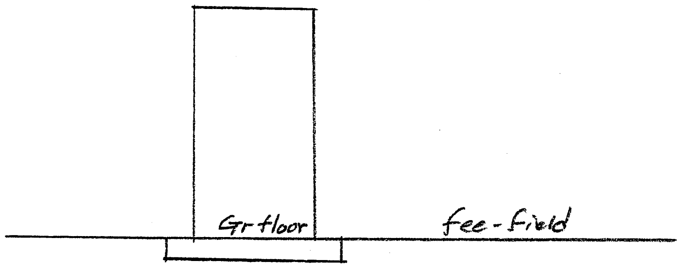
Fig. 2.8 Comparison of lake bed (1–3) and rock (4–6) accelerographs, Mexico City, 1985.

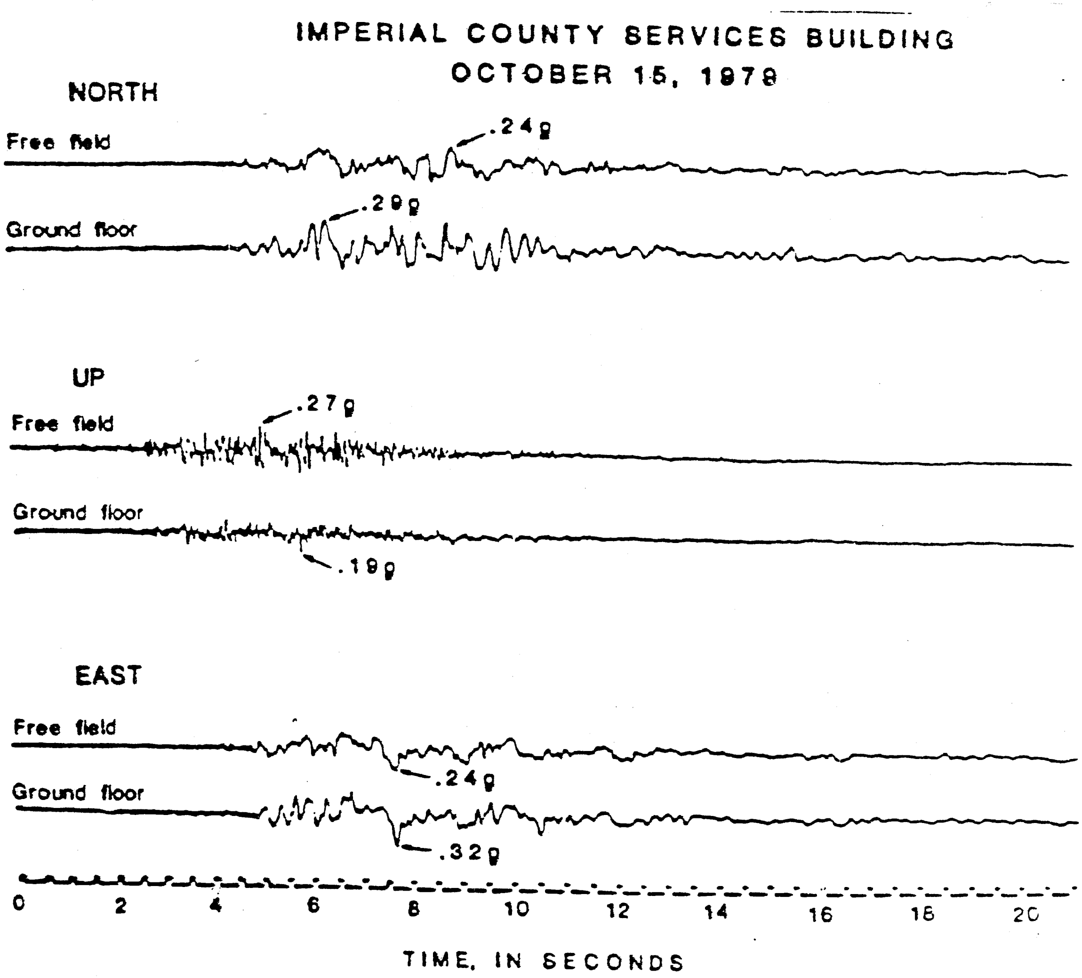


5) geological influence

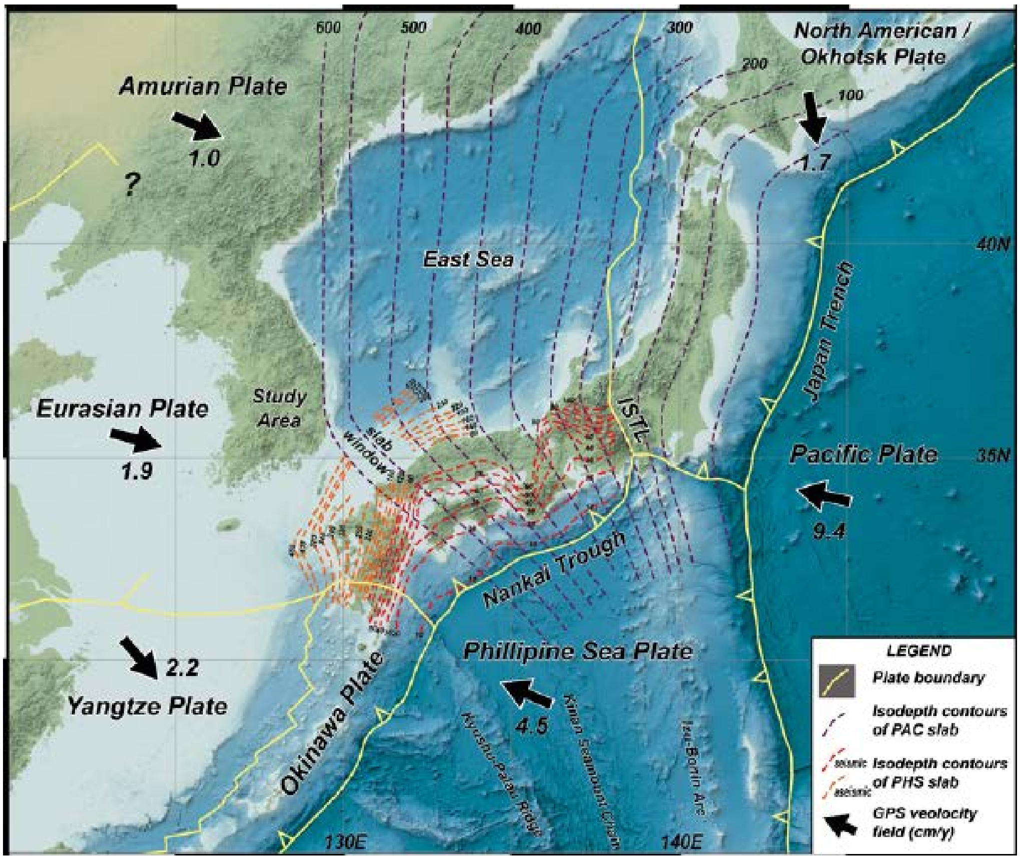


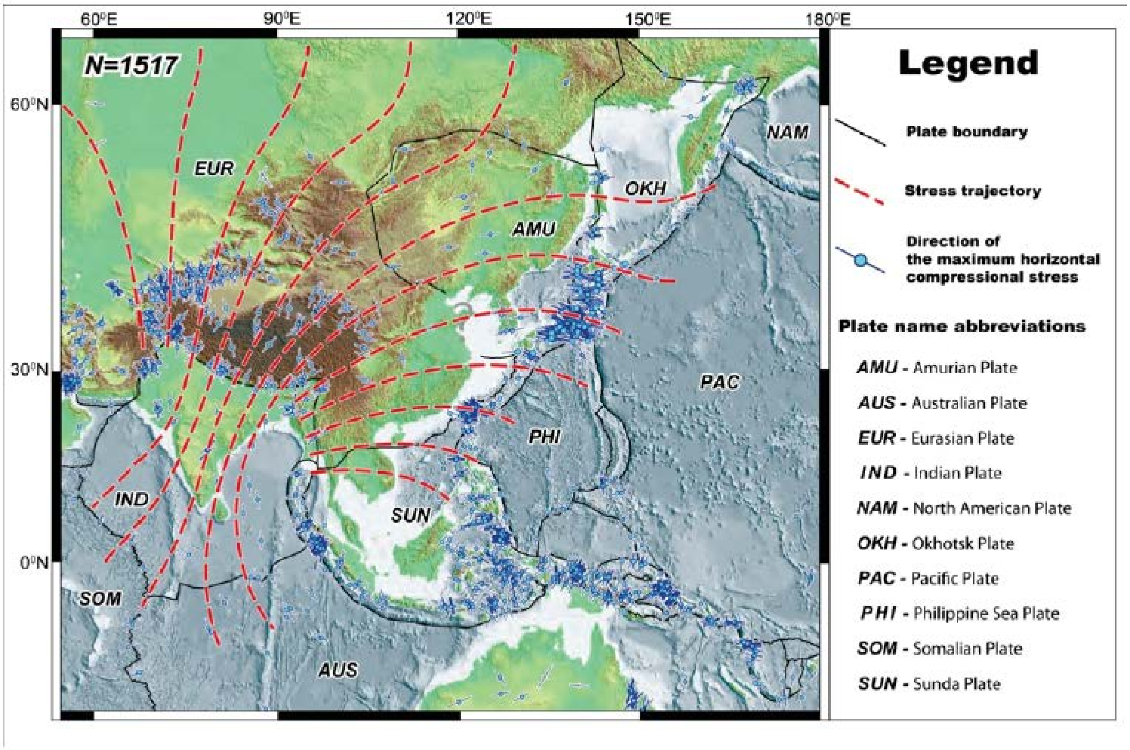
6) soil – structure interaction



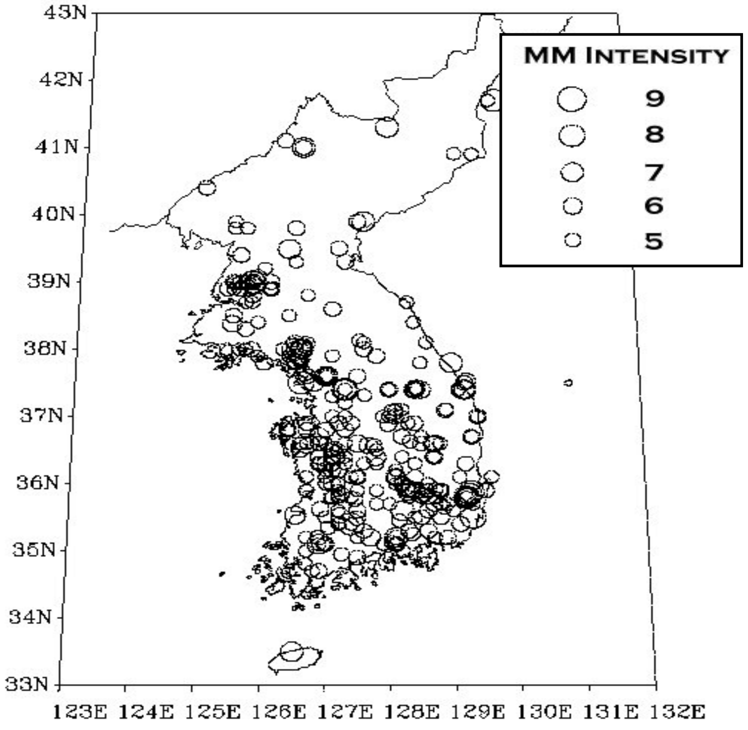

IMPERIAL COUNTY SERVICES BUILDING
OCTOBER 15, 1979

Earthquakes in Korea : tectonic setting of east asia



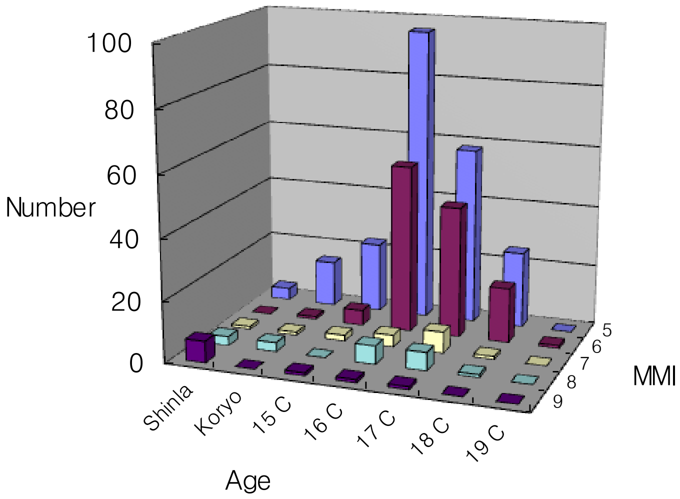


EQs in Korea (AD2 ~ 1904) : intensity



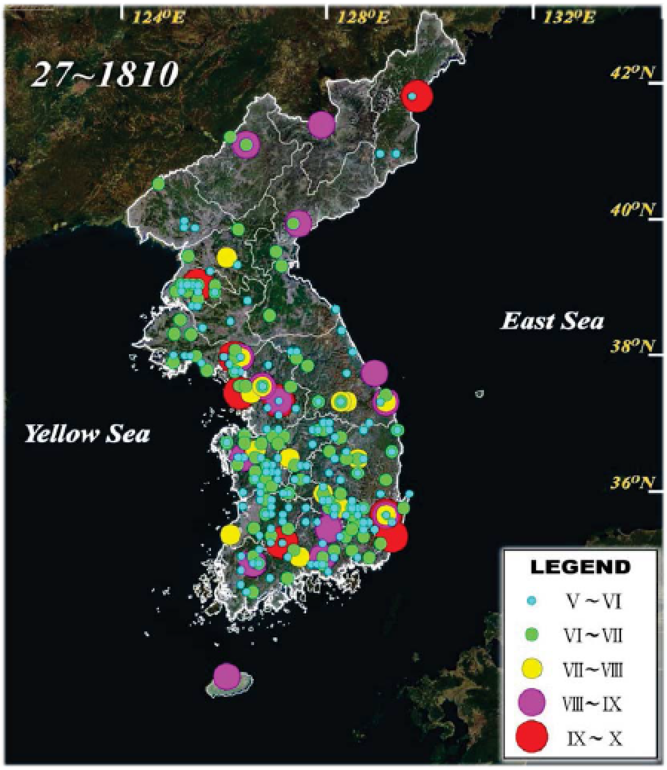
Number of felt earthquakes in historical literature : about 1800

Number of earthquakes with MMI ≥ VII (*M*L ≥ 5.5) : about 40 with damages casualties



Historical Earthquakes

: At least 1,800 felt earthquakes since AD 27



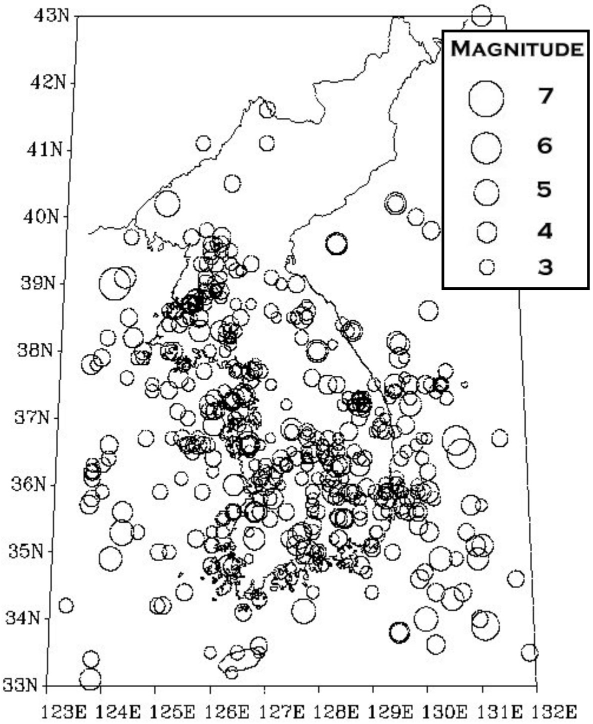
Major Events

1) **AD 779, Gyeongju**
(the Silla Dynasty)
- IX (MM Scale), M6.7~7.0
- Killed ca. 100 people
- The worst casualties in history

2) **AD 1643, Korean Peninsula**
(the Joseon Dynasty)
- Occurred pervasively in whole country
- Ground cracks & Water gush (Ulsan)
- Rampart breaks (e.g.Daegu)

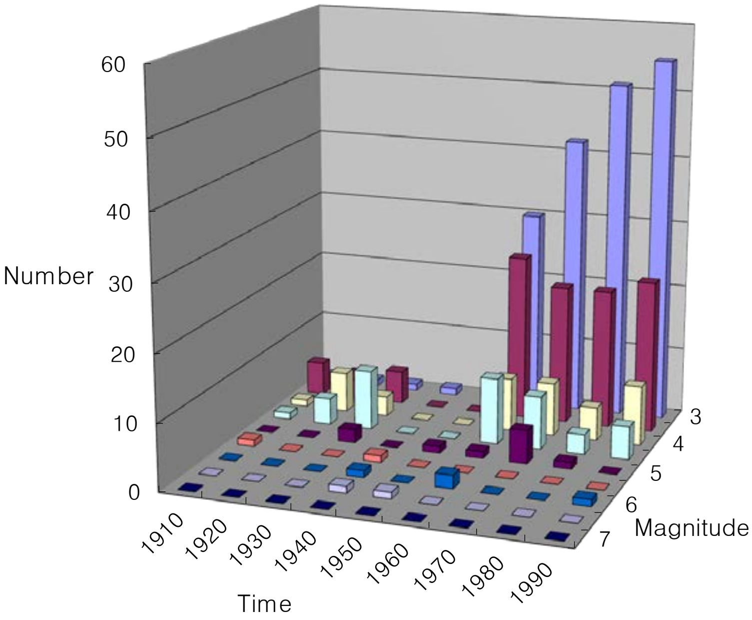
3) Other M6.0 over events
- AD 1518, Seoul
- AD 1597, Samsu
- AD 1810, Cheongjin

EQs in Korea (1905 ~ 1999) : magnitude



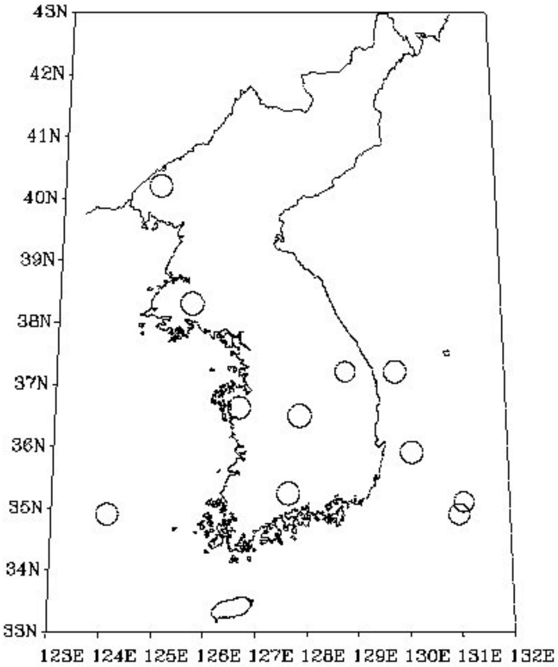
Number of earthquakes with $M_L \geq 4.0$ occurring on land : about 50

Number of earthquakes with $M_L \geq 5.0$ occurring on land : about 7

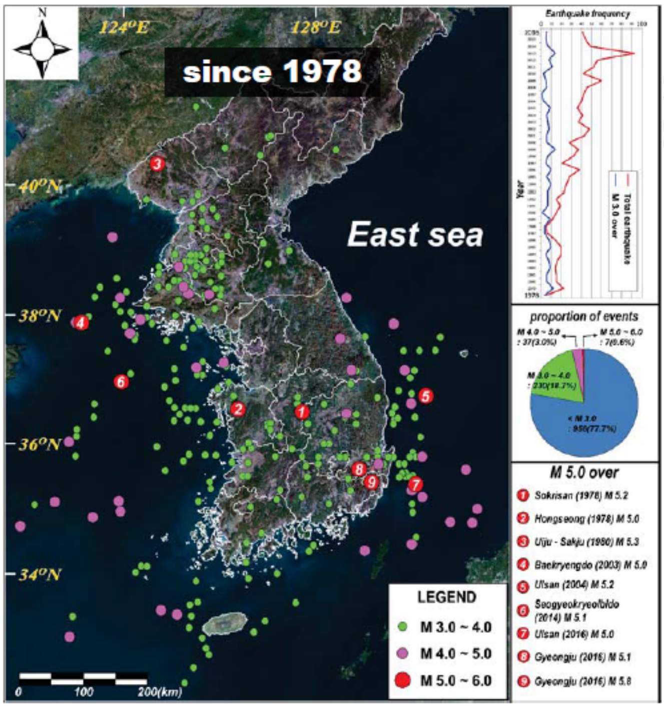


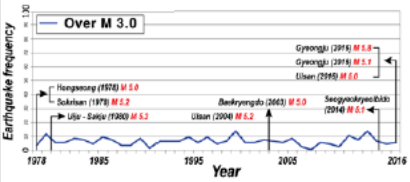
Inland earthquakes greater than M=4.5 in Korea

- 쌍계사 지진 (1936) M=5.1
- 평양 지진 (1952) M=6.2
- 속리산 지진 (1978) M=5.2
- 홍성 지진 (1978) M=5.0
- 삭주 지진 (1980) M=5.0
- 포항 지진 (1981) M=5.0
- 사리원 지진 (1982) M=5.1
- 울진 지진 (1982) M=5.0
- 울산 지진 (1994) M=4.6
- 울산 지진 (1994) M=4.5
- 홍도 지진 (1994) M=4.9
- 영월 지진 (1996) M=4.5
- 백령도지진 (2003) M=5.0
- 울진지진 (2004) M=5.2
- 경주지진 (2016) M = 5.8

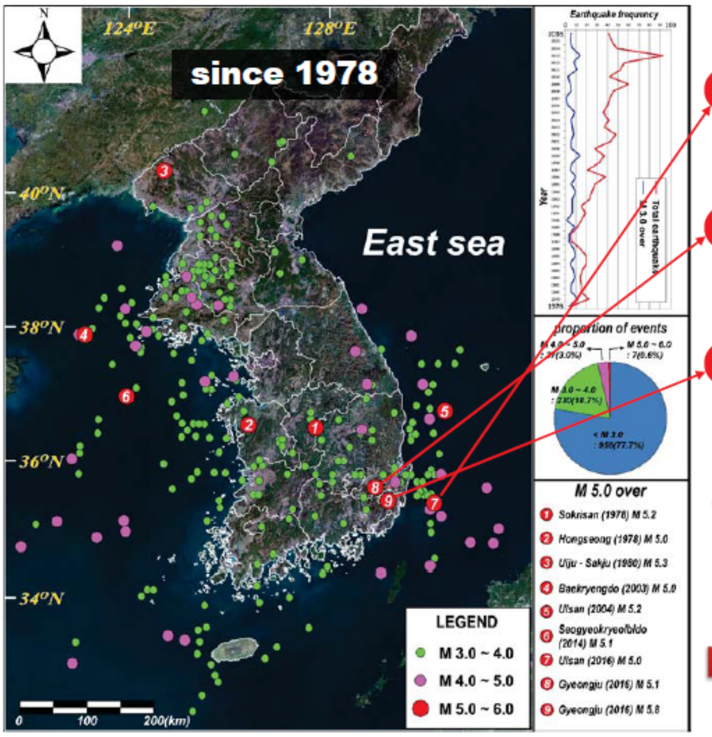


Instrumental Earthquakes
: Gyeongju Earthquakes (2016. 07. 05 ~ present)





		KMA	JMA		China
		M	Md	Mv	Ms
1936	Ssanggyesa	-	5.1	-	
1952	Pyongannam-do	-	6.3	-	6.3
1978	Mt. Sokli	5.2	5.0	-	4.7
1978	Hongsung	5.0	5.0	-	4.2
1980	Uiju	5.3	5.5	-	5.3
1982	Anak	4.5	5.8	-	5.3
1996	Yeongweol	4.5	-	5.6	4.7
2004	Offshore Uljin	5.2	-	5.1	4.9
2007	Mt Odae	4.8	-	5.0	4.6



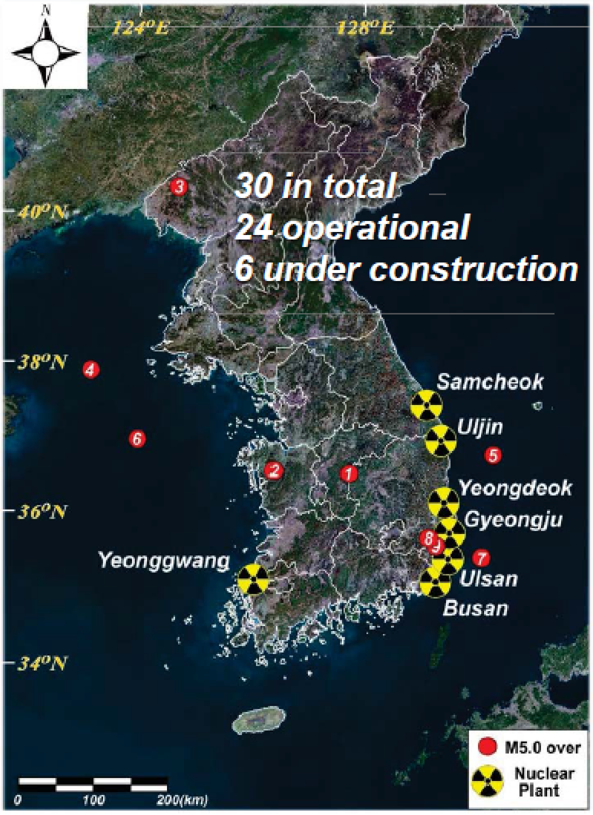
⑦ **Ulsan Earthquake M5.0 (2016. 07.05)**

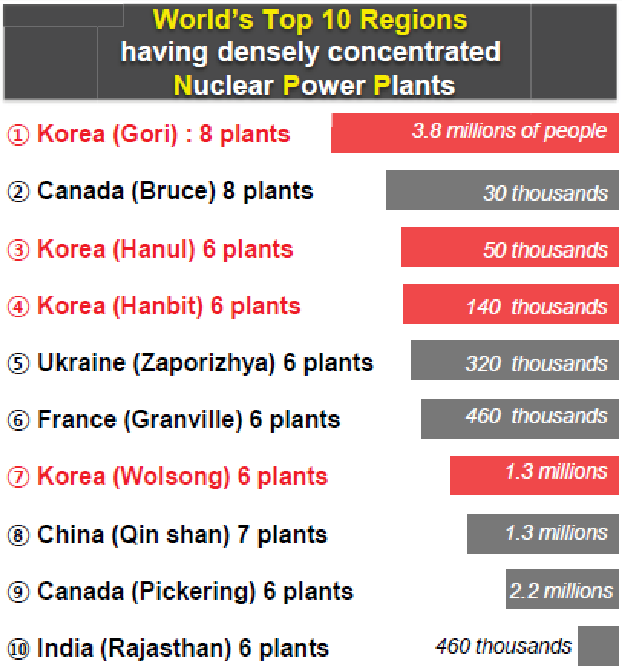
⑧ **Gyeongju Earthquake M5.1 (2016. 09.12)**

⑨ **Gyeongju Earthquake M5.8 (2016. 09.12)**

● **Gyeongju Earthquake M4.5 (2016. 09.21)**

➡ **Recent earthquakes are the warning to our safety frigidity !**





World's Top 10 Regions having densely concentrated Nuclear Power Plants

① Korea (Gori) : 8 plants	3.8 millions of people
② Canada (Bruce) 8 plants	30 thousands
③ Korea (Hanul) 6 plants	50 thousands
④ Korea (Hanbit) 6 plants	140 thousands
⑤ Ukraine (Zaporizhya) 6 plants	320 thousands
⑥ France (Granville) 6 plants	460 thousands
⑦ Korea (Wolsong) 6 plants	1.3 millions
⑧ China (Qin shan) 7 plants	1.3 millions
⑨ Canada (Pickering) 6 plants	2.2 millions
⑩ India (Rajasthan) 6 plants	460 thousands

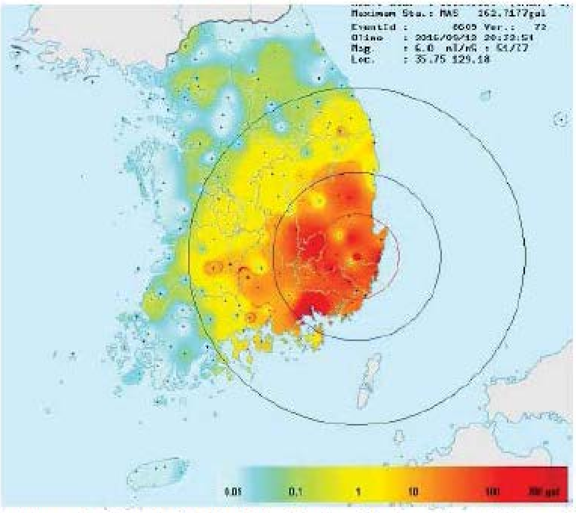
The most densely concentrated area in the world !

김토일 기자 / 20140315
@yonhap_graphics(트위터)

Kyungju EQ (2016, 9.12)

• Gyeong-Ju Quake M= 5.2/5.8, 09/12/2016

The first (pre-) shock: ML 5.2, 19:44
The main shock: ML 5.8, 20:32
Focal depth: 13km (relatively deep)



Steel Structures & Seismic Design Lab, Dept. of Arch and Arch Engrg, SNU

Magnitude reported

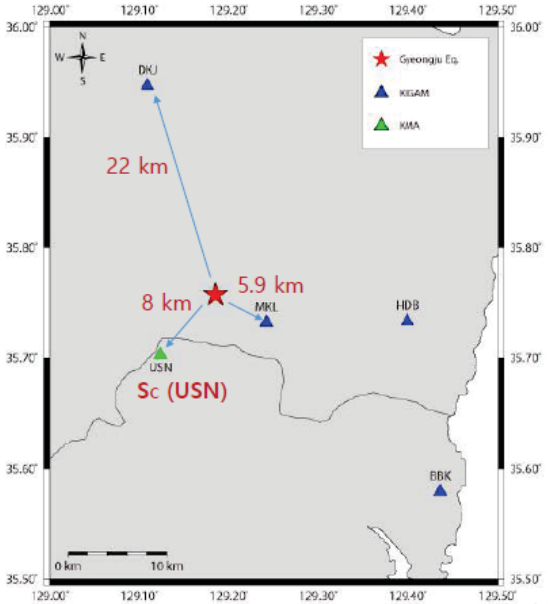
$$\log(E) = 11.8 + 1.5M_L;\ E = 10^{11.8+1.5M_L}\ (ergs) \qquad (1)$$

$$M_W = (2/3)\log(M_0) - 10.7;\ M_0(seismic\,moment) = 10^{16.05+1.5M_W}\ (dyne) \qquad (2)$$

The main shock: ML 5.8
Focal depth: 13km

⇨

The main shock: Mw 5.36
Focal depth: 15km
(per Prof. YH Kim, SNU)



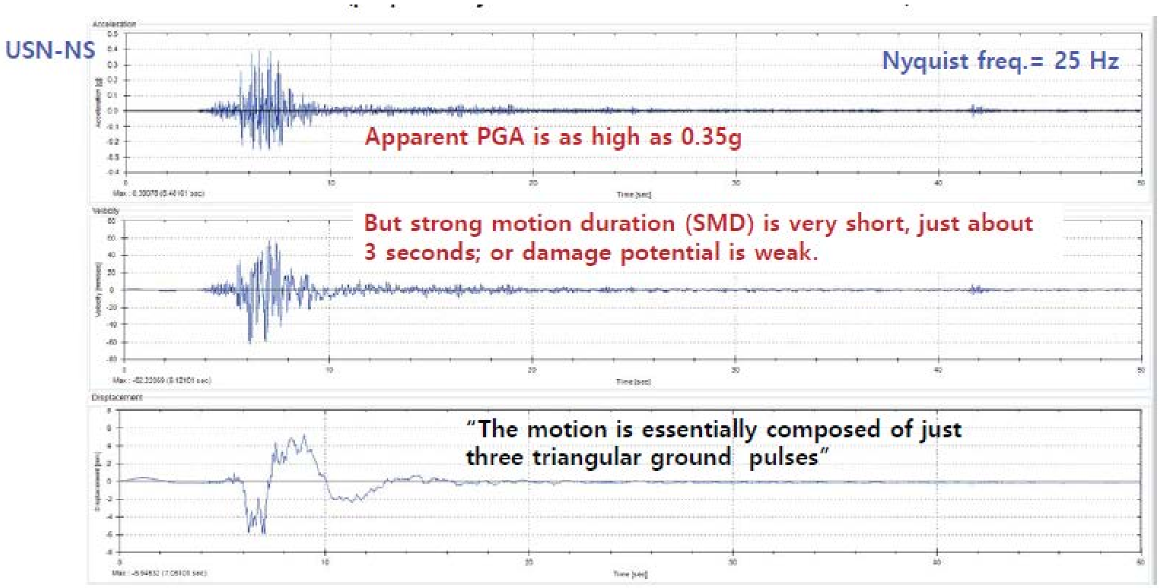
Three stations near the epicenter available

관측소명	위도	경도	가속도센서	기록계
MKL	35.7322	129.2420	ES-T	Q330
USN	35.7024	129.1232	ES-T	Q730
DKJ	35.9468	129.1089	CMG-5T	Q330HRS

"SB (MKL, DKJ) or Sc (USN) soil condition speculated"

Steel Structures & Seismic Design Lab, Dept. of Arch and Arch Engrg, SNU

Quite high PGA, but the duration is short.



Nyquist freq.= 25 Hz

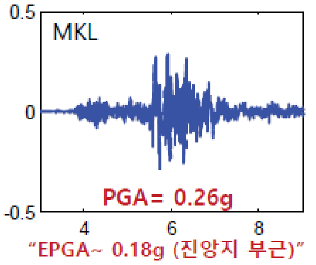
Apparent PGA is as high as 0.35g

But strong motion duration (SMD) is very short, just about 3 seconds; or damage potential is weak.

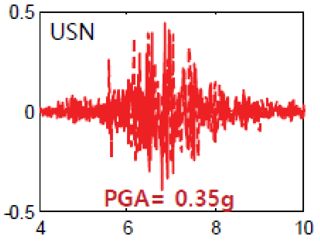
"The motion is essentially composed of just three triangular ground pulses"

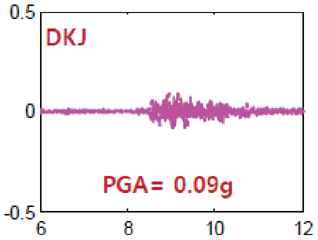
Steel Structures & Seismic Design Lab, Dept. of Arch and Arch Engrg, SNU

Nyquist freq.= 25 Hz



"EPGA~ 0.18g (진앙지 부근)"





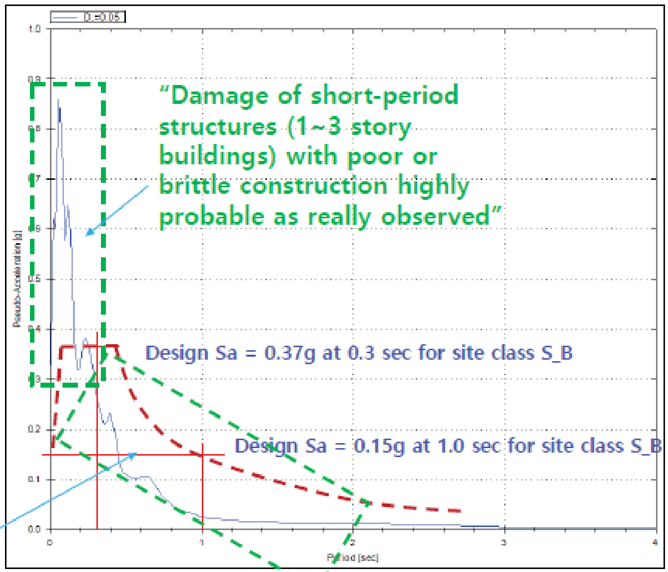
	Arias Intensity (m/s)	PGA (g)
MKL	0.18	0.257
USN	0.70	0.351
DKJ	0.05	0.092

"Apparent magnitude of PGA is a weak damage indicator"

"Amplitude, strong motion duration and frequency contents should considered all together"

MKL-EW

Comparison of elastic spectral acceleration caused by 912 Geong-Ju EQ with KBC (SB) spectrum



"Damage of short-period structures (1~3 story buildings) with poor or brittle construction highly probable as really observed"

Design Sa = 0.37g at 0.3 sec for site class S_B

Design Sa = 0.15g at 1.0 sec for site class S_B

"Damage of building structures of average construction with periods longer than 0.3~0.4 sec. difficult to occur"

Pseudo-acceleration Response Spectrum

Show window shattered

Unreinforced block wall fallen down

Typical corner cracking at opening

Failure in an already poor (non-engineered) construction

Damage observed in a 3-story RC Building (Ulju, Ulsan)_ ceiling and brick wall failure

The most impressive failure mode_ “short-column” shear failure

1952 M 6.2 EQ near Pyung-Yang "during Korea War"

- Known during the technical meeting between south and north Korean seismologists for the KEDO program (supporting program for north Korea's NPP) once promoted but now halted
- Seismic design is one of the top priority issues in any nuclear power plant construction
- The information following is based on the presentation made by Drs. TS Kang and MS Jeon (former KIGAM researchers) at the EESK symposium last year: "Seismological evaluation of major earthquakes in Korean peninsular and seismic safety of building and civil structures", Feb. 23, 2016
- The occurrence of this major EQ was not well recognized probably due to the turmoil during the war, but…

Epicenter location reported by USGS

- Date and Time
  - 1952-03-19 09:04:18 (UTC)
  - 1952-03-19 18:04:18 (Local Time)
- Epicenter (USGS)
  - 38.872°N, 125.834°E
  - Nearby cities
    - Chung-HWA: 3 km
    - Pyung-Yang: 19 km
    - Sariwon: 41 km
  - Focal depth : 35.0 km (estimate; appear to be rather deep, less damaging)
- Magnitude reported by various researchers based on measured records: M= 6.2~6.5

RUSSIA_ Rustanovich et al.(1963): M=6.3

CHINA_中国国家地震局科技情報中心(1987) Ms=6.5

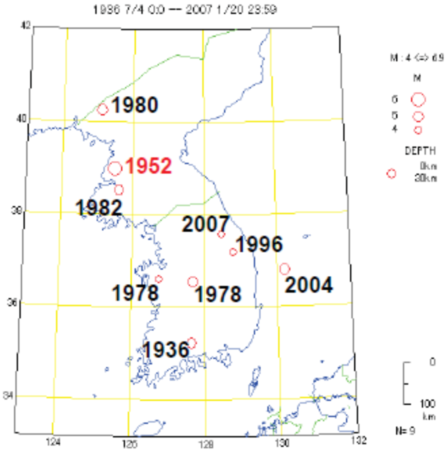
Yuche Li (2001): M=6.5

JAPAN_Ishikawa et al.(2008): Md=6.5

USA_ USGS Mw 6.3

KOREA_ Kang (2011) Mw 6.2

"100 or 1000 times more meaningful than historical EQs since this is instrumental"

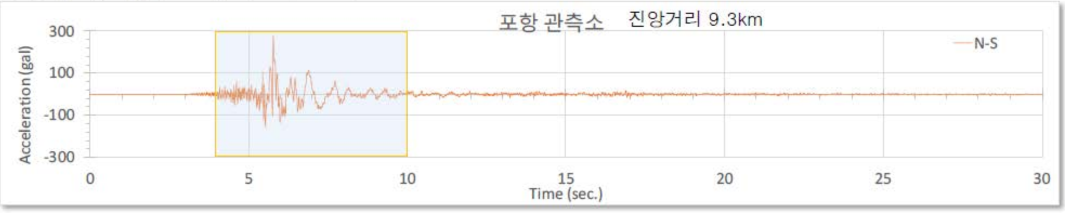


(Ishikawa et al., 2008)

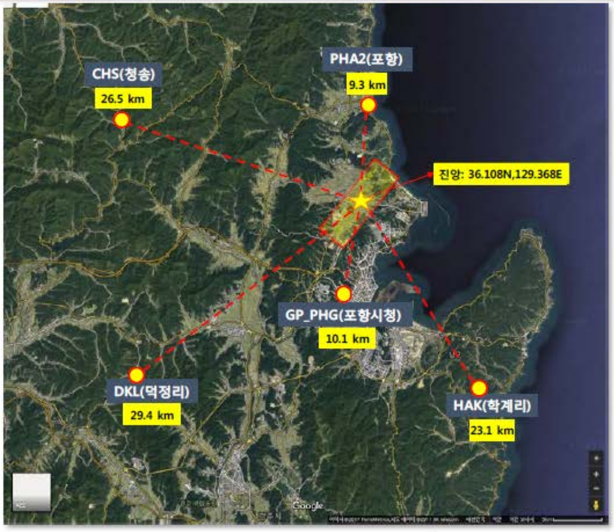
SOURCE: the presentation made by Drs. TS Kang and MS Jeon at the EESK symposium last year: "Seismological evaluation of major earthquakes in Korean peninsular and seismic safety of building and civil structures", Feb. 23, 2016

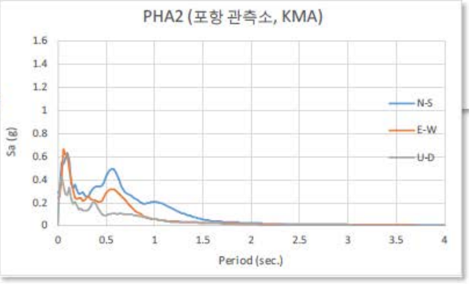
2017 포항 지진의 개요

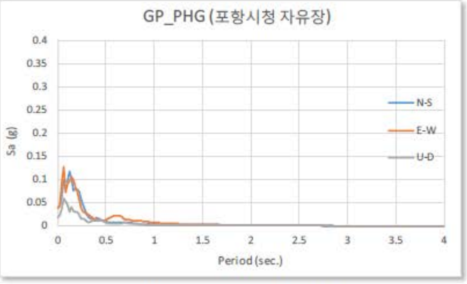
- 2017년 11월 15일, 수요일
  14시 29분 31초 (KST)
- 진앙: 36.10°N, 129.37°E
  경북 포항시 북구 북쪽 6km 지역,
  진원 깊이 3.5 km.
- M_L 5.4: 계측된 국내 지진 중에서
  2번째로 큰 지진 (2016 경주
  지진이 최대 지진 M_L 5.8)
- 강진지속시간: 약 4~6 초.

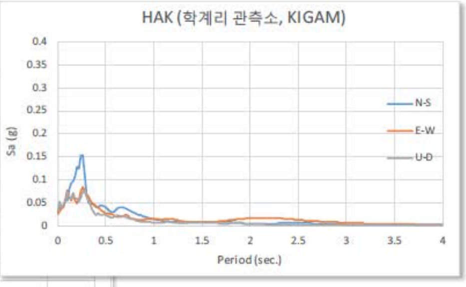


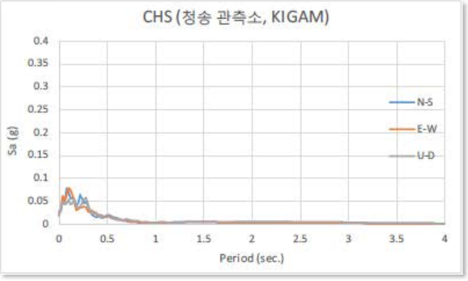
응답 스펙트럼

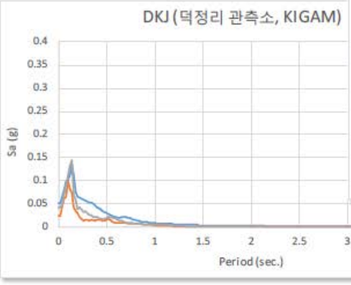




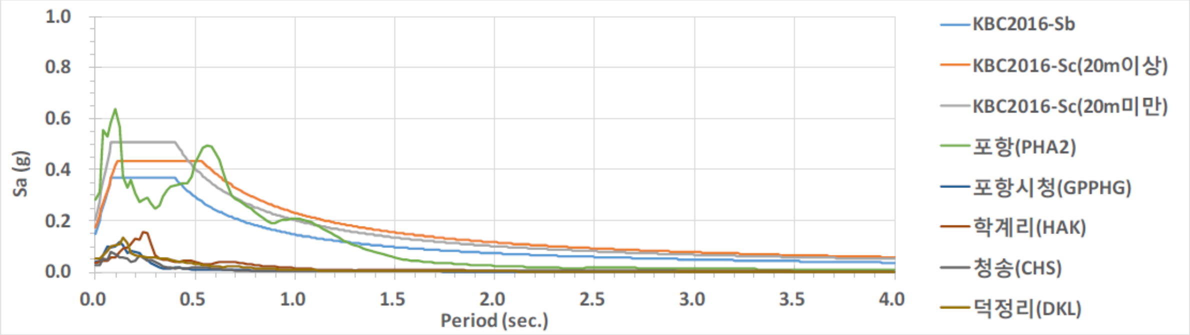








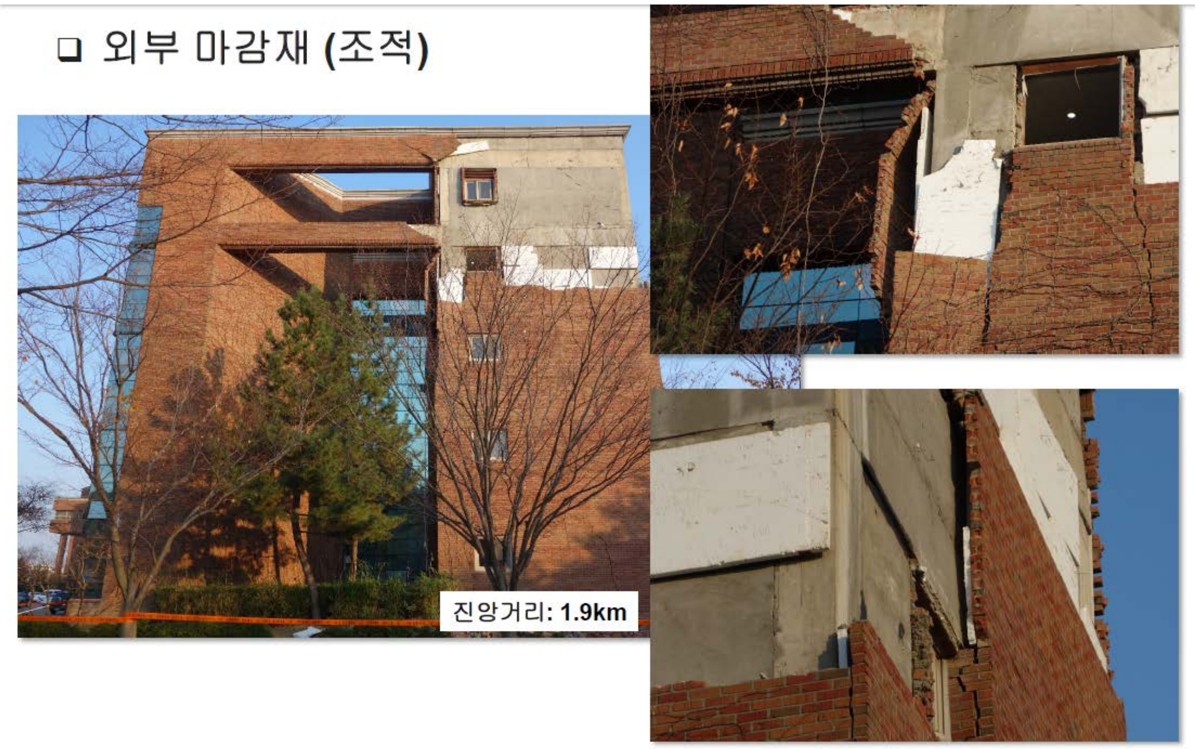
□ KBC 2016 설계스펙트럼 비교



□ 포항(PHA2) 관측소 기록은 설계 지진력을 초과했는가?

- 포항(PHA2) 관측소 기록은 지반운동예측식의 모든 범위를 벗어남. 관측값을 재점검 할 필요가 있음.
- 0초~0.14초, 0.5초~0.7초 주기에서 설계스펙트럼(Sc-20m미만)을 초과했음.
- 설계스펙트럼은 불확실성이 큰 지진파의 통계적 예측 임. 따라서, 하나의 계측값이 짧은 구간에서 평균+1σ 를 벗어났다고 통계적 예측이 틀렸다고 할 수 없음.

□ 외부 마감재 (조적)



5층 이하 필로티 건물

□ 내진설계 오류: 기둥의 취성파괴, 연약층

□ 구조설계 기준 미준수: 구조안전에 대한 책임감 결여

❑ 내진보강 미적용 교사동