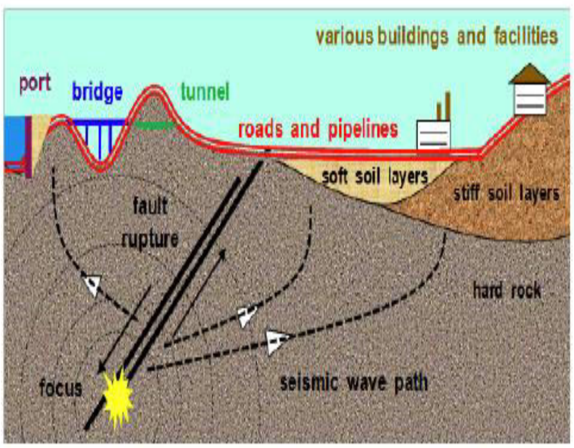
Ministry of Higher Education and Scientific Research

Al-Karkh University of Science

College of Geophysics and Remote Sensing

Department of Geophysics

Engineering Seismology




(a)


(b)

Lectures Prepared and Edited by:

Assistant Professor Dr. Wadhah Mahmood Shakir AL-Khafaji

PhD. In Geophysics

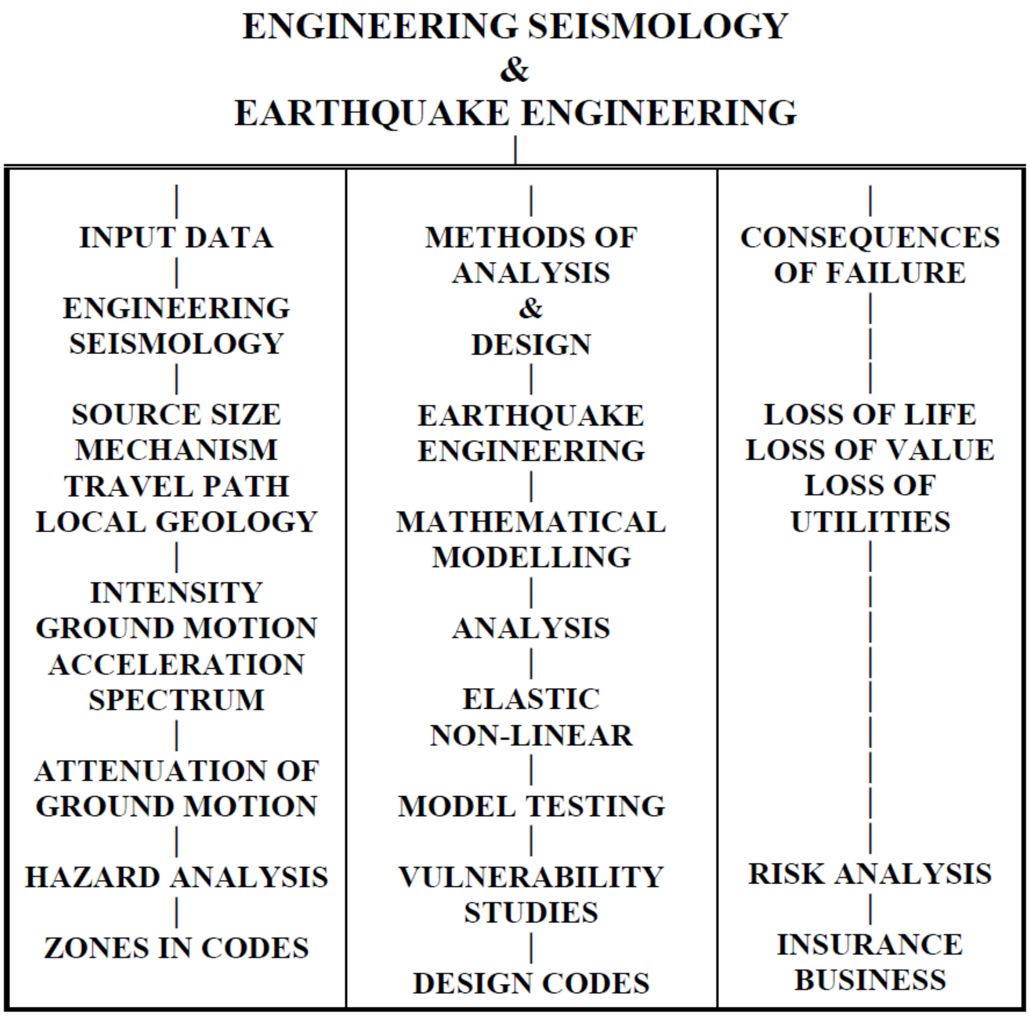
Engineering Seismology

Engineering Seismology: is the study of Seismology as related to Engineering. This involves understanding the source, the size and the mechanisms of earthquakes, how the ground motion propagates from the source to the site of engineering importance, the characteristics of ground motion at the site and how the ground motion is evaluated for engineering design.

This subject is therefore related to the hazard of earthquakes. The seismic hazard at a site cannot be controlled. It can only be assessed. In the same context, **Earthquake Engineering** is the subject of analysis and design of structures to resist stresses caused by the earthquake ground motion. Resisting the stresses imply either resisting without failure or yielding to the stresses gracefully without collapse. This subject is related to the vulnerability of built structures to seismic ground motion. The vulnerability is controlled by design. The decision to control the vulnerability of a structure is based on the economics of the situation and on the judgment about the acceptable risk to the community. See figure 1. Therefore, the assessment of seismic risk is based on the seismic hazard, the vulnerability and the value of the loss. This is expressed by the relation:

Risk = Hazard * Vulnerability * Value

The **value** may be taken in the sense of cost of replacement and is really the problem of insurance business. Ref: Fournier d'Albe (1982). In this context, "**Seismic Hazard**" is defined as the probability of occurrence of a ground motion of a given size within a given period of time at the site of interest. This will depend on the possible sources of earthquakes within a reasonable distance of the site and the seismic activity of these sources in relation to size and time. The "**Vulnerability**" is a measure of the probability of damage (loss) to the structure to a ground motion of a given size. Different structures have different vulnerability curves. Figure 2 expresses the concepts schematically.



RISK = HAZARD * VULNERABILITY * VALUE

Figure (1)

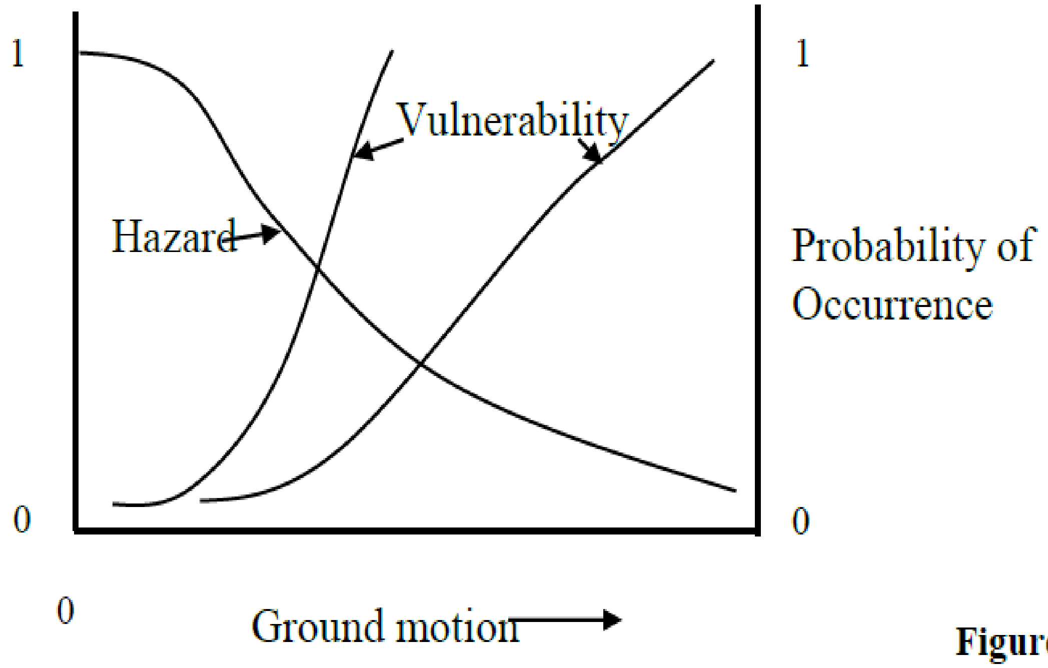


Figure 2

The narrow scope of engineering seismology includes its application to geotechnical site investigations for buildings and engineering infrastructures, such as dams, levees, bridges, and tunnels, and landslide and active-fault investigations. It also includes seismic microzonation to determine soil amplification and liquefaction susceptibility within a municipal area to estimate the earthquake risk. The broad scope of engineering seismology also includes its application to groundwater exploration, coal and mineral exploration, geothermal exploration, and investigations of historic buildings and archaeological sites.

Seismic Engineering: is the discipline which aims to construct an infrastructure and buildings resistant to earthquake and similar phenomena impacts and by this way to protect human lives and health and human property.

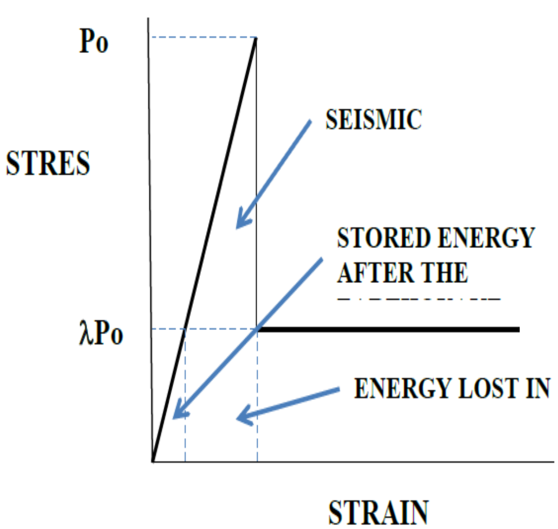
Seismic Modeling of the Soil Column

In engineering seismology, for site investigations required for civil engineering structures, we most commonly use Rayleigh-wave and rarely Love-wave dispersion curves to estimate an S-wave velocity-depth model for the soil column. We use first-arrival times associated with mostly refracted waves to estimate a P-wave velocity-depth model and shallow reflections to derive a seismic image for the near-surface. By using the velocity-depth model and the seismic image, we delineate the geometry of the layers and faults within the soil column, and the geometry of the soil-bedrock interface.

The design and location of civil engineering structures at a project site require, aside from investigation of the site geology and geotechnical field and laboratory tests, knowledge of the soil-column shear-wave velocities and the geometry of the layers within the soil column and that of the soil-bedrock interface. We shall present case studies for seismic, geotechnical, and earthquake engineering site characterization. When the gravity-induced shear stress on a potential slip (failure) surface exceeds the shear resistance, then the soil mass above the slip surface moves downslope. This occurs when the slip surface composed of a clay layer is saturated by water as a result of a heavy rainfall. The land mass may also be set into motion as a result of an earthquake. Factors that control shear stress on the slip surface include the volume of the soil mass above the slip surface, the dip of the slip surface, and the magnitude of the earthquake. Active fault investigations are imperative for major infrastructures – nuclear power plants, refineries, tunnels, and dams. An active fault is defined as a fault that has a history of tectonic activity, at least within the past several tens of thousands of years, and will give rise to an earthquake in the future.

Faults and Energy Release:

Earthquakes are the vibrations of ground caused by the sudden release of strain energy stored in the earth's crust. Figure 3, shows the schematic stress-strain curve of the crustal material and the part of the stored energy which is released as an earthquake. This energy is released by the brittle failure on faults and is carried away by the propagation of seismic waves. Since brittleness of the crustal material is an essential part for the sudden release of energy, earthquakes can happen only in the upper part of the earth's crust. Most earthquakes, particularly the damaging ones, are of shallow origin. The deeper earthquakes happen in the subducted part of the crust before it melts in the heat of the mantle. The earthquakes give rise to two kinds of ground movements- a permanent displacement at the fault and its vicinity and the transient ground motions resulting from the propagation of seismic waves away from the source.



ENERGY BEFORE THE EARTHQUAKE / VOLUME $= \frac{1}{2} P_0^2 / G$

P_0 = FAILURE STRESS

G = SHEAR MODULUS

λ = STRESS DROP FACTOR

$$\frac{\text{SEISMIC ENERGY}}{\text{ENERGY BEFORE EARTHQUAKE}} = (1 - \lambda^2)$$

ENERGY/VOLUME = CONSTANT = (0.10 to 0.15) (kN/m^2)

Bigger Earthquake = Bigger Volume = Larger area of Fault = Longer Length of Fault

Figure (3): Seismic energy is the part of energy that is released in the form of seismic waves.

The elastic strain energy builds up on a fault, which is held static by friction, until the stresses overcome the strength and slip is initiated. Since nature favors’ an existing fault (finds it easier to break) than a new one, the same faults move repeatedly in successive earthquakes. This does not mean that new faults cannot ever be generated and therefore, theoretically, no part on earth is ever safe from earthquakes. There are three basic types of fault movements, figure 4. These are normal, thrust and strike slip movements. These involve extension, shortening and lateral movement of the earth's crust respectively. Within a small geological time scale, the type of motion in a fault is observed to be the same in different earthquakes thus creating geomorphologic features which can be identified.

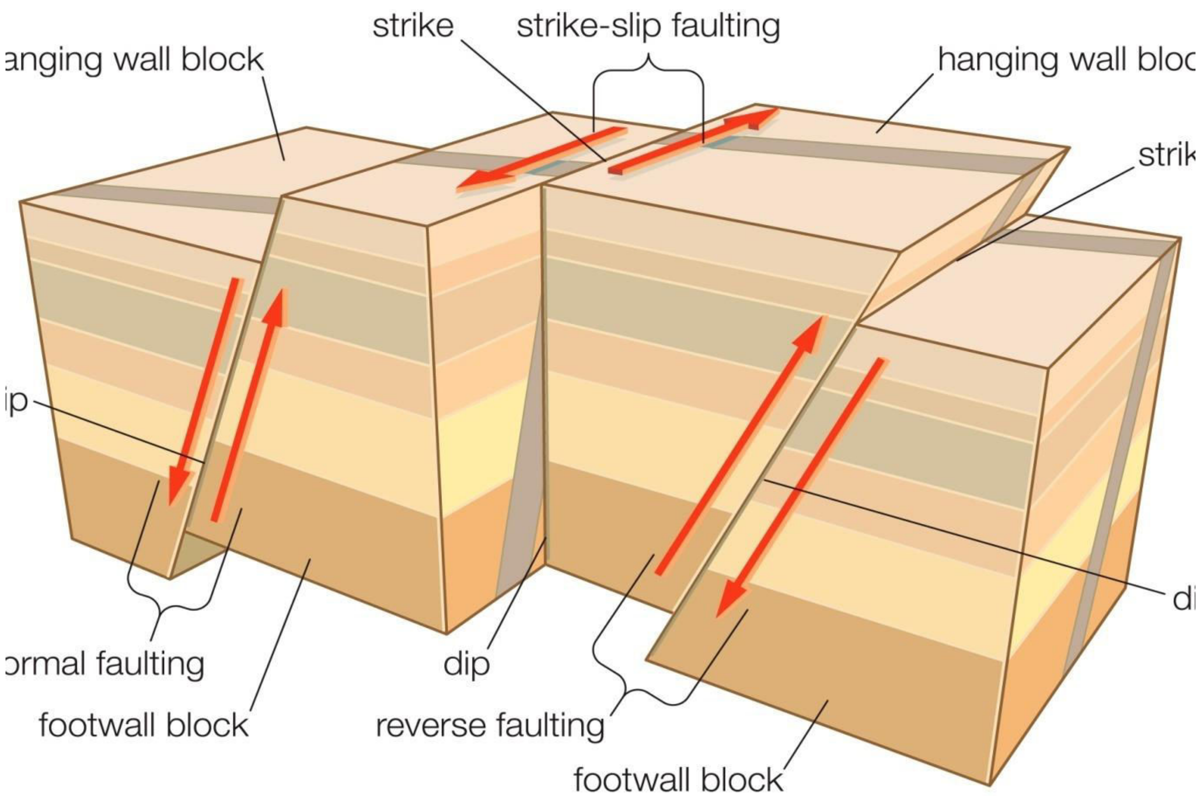


Figure (4): The three main types of faults that produce earthquakes.

Recorded seismic events:

•natural earthquakes, which are mainly produced by motion on active faults which produced by the activity of plate tectonics.

•induced earthquakes – man-made, induced by human activities, like explosions , pumping fluids in deep boreholes , and filling dams lakes.

•artificial explosions, like nuclear explosions.

•vibrations of natural or artificial origin : consequences of technological processes and natural phenomena as fall of meteorites, aircrafts, bombs etc.

Tsunami : waves on sea induced by earthquake the focus of which is under the sea bottom.

Mikroseisms : permanent Earth's surface vibration.

Natural earthquakes are of:

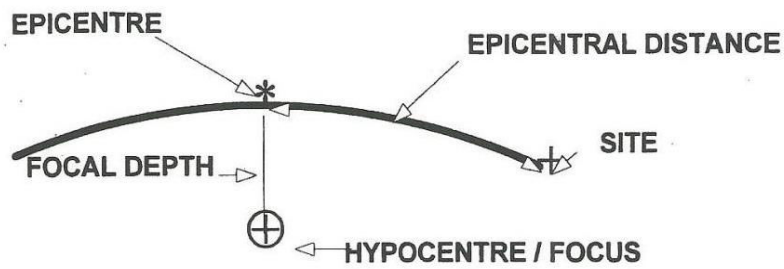
•tectonic origin (90%),

•volcanic origin (7%),

•collapse of underground spaces (3%)

Some definitions:

Here are some definitions, which are supposed to be common knowledge but has some implications. See figure 5.



EPICENTRE

THE POINT ON THE SURFACE OF THE EARTH, BELOW WHICH THE EARTHQUAKE ORIGINATES. IT IS ALSO THE AREA WHERE MAXIMUM DAMAGE OCCURS.

INSTRUMENTAL EPICENTRE ---- POINT (LATITUDE, LONGITUDE)

MACROSEISMIC EPICENTRE ---- AREA OF MAXIMUM DAMAGE

HYPOCENTRE/FOCUS

THE SOURCE OF THE EARTHQUAKE BELOW THE EPICENTRE

INSTRUMENTAL HYPOCENRE -POINT(EPICENTRE, FOCAL DEPTH)

Figure (5): Some seismological definitions.

Hypocentre or Focus:

The point on the fault where slip is first originated. From this point, the slip propagates and spreads over the rupture surface (the fault) until the slip is stopped by either strong material or less stress. The hypocentre is represented by three coordinates: Latitude, Longitude and the depth from the earth's surface. Note that the whole fault does not move at the same instant.

Epicentre:

The point on the earth's surface immediately above the hypocentre. It is represented by the latitude and longitude of the point. The error in the determination of the epicentre is about 10km presently. But in the old days, this error could be very large. There are instances of the determination in the wrong hemisphere. It is therefore essential to correlate the instrumental determination of epicentre with the area of maximum damage.

Focal depth:

This is the depth of focus below the epicentre. There are three grades of depth- Shallow, Intermediate and Deep. Most continental earthquakes are shallow and these are of engineering importance. Focal depth of an earthquake is the most difficult one to determine and should be treated with caution. In the bulletin of earthquakes, most earthquakes are given a focal depth of 33km which simply imply that these are of shallow depth but the depth was not possible to determine any more accurately.

Size of earthquakes:

The magnitude and the moment of an earthquake measure the size of an earthquake.

Magnitude:

The magnitude is derived from instrumental readings of ground displacements. These are empirically related to the energy of the earthquake at source and are in logarithmic scale. Magnitude is derived from the amplitude of ground movements at particular frequencies and then correcting it for distance of the source to the recording site. Measurements are made at about 20 sec period to give surface wave magnitude (Ms) or at about 1 sec period to give the body wave magnitude mb.

Local magnitude ML (commonly known as Richter magnitude) was originally defined by Richter in 1935, Richter (1958). This is the logarithm of the maximum amplitude (recorded on a Wood-Anderson Seismograph in mm) and corrected for distance of the recording site from the epicentre.

$M_s = \log (A/T)_{max} + 1.66 \log (\Delta^o) + 3.3$, known as the Prague Formula,
$m_b = \log (A/T)_{max} + Q (h, \Delta^o)$; Q values are tabulated in literature
$A = A_t/V \bar{M}$
A_t is the measured amplitude in microns, V is the static magnification, $\bar{M}$ is the dynamic magnification.

$M_L = \log A - \log A_0$

A is the maximum amplitude in mm in a standard Wood Anderson Seismograph (T_o=Perod=0.8sec, V=Static magnification=2800, λ=Damping=0.8)
A_0 is the distance correction factor.
[This definition is equivalent to saying that M_L is the logarithm of the measured amplitude in microns at 100 km.]

From the tabulated values given by Richter(1958), log A_0 can be expressed as: (Note: The curve fitting is done by the author and not by Richter)

$\log A_0 = -1.3892 - .0028D - .0007D^2$; $D \le 35$ km
$\log A_0 = -.78747 - .00272D - .96201 \log(D)$; $D > 35$ km
At D=100km, $\log A_0 = -3$.

Other attempts to quantify the size of an earthquake are by the amount of damage to man-made structures at the epicentral region and by the farthest distance at which the earthquake is felt. There are empirical relationships connecting these parameters to the magnitude. Also empirical relationships exist for connecting the magnitude with the length of faulting etc.. However, visible faults may not be there for all earthquakes.

SIZE OF AN EARTHQUAKE

THE SIZE OF AN EARTHQUAKE REFLECTS THE RELEASED ENERGY.
THIS IS MEASURED BY THE FOLLOWING:

1) MAGNITUDE

a) BODY WAVE MAGNITUDE = m_b
b) SURFACE WAVE MAGNITUDE = M_S
c) LOCAL MAGNITUDE = M_L
d) MOMENT MAGNITUDE = M_w

2) MOMENT--- = M_0

MAGNITUDE AND MOMENT ARE DERIVED FROM INSTRUMENTAL READINGS.

SIZE CAN ALSO BE INFERRED FROM THE FOLLOWING:

3) MACROSEISMIC INTENSITY

4) FELT RADIUS

DEFINITIONS:

$m_b = \log (A/T)_{max} + Q(h,\Delta^0)$ => $T \simeq 1$ second

$M_s = \log (A/T)_{max} + 1.66 \log \Delta^0 + 3.3$ => $T \simeq 20$ seconds

$A = A_t / VM$

A_t = measured amplitude in microns
V = Static magnification
M = Dynamic magnification

$M_L = \log (A_t)_{max} - \log (A_0)$ => STANDARD WOOD-ANDERSON SEISMOMETER
$T_0 = 0.8$ second, $V = 2800$, $\lambda = 0.8$

ASSESSMENT OF MAGNITUDE FROM FIELD EVIDENCE

$M_s = 5.86 + 0.4 \log (L^{1.58} \delta^2)$ — L (km) = Length of fault, δ (m) = displacement across fault.

Modified from Ambraseys & Melville (1982) – obtained from 63 observations

$\log (L) = 0.7 M_s – 3.24$, — Ambraseys & Melville (1982) – obtained from 220 observations

Similar relationship can be derived from the definition of Moment (defined later)

$$\log (L) = 0.5 [c + d M_s – \log (eGH)]$$

L = Length of fault, H = Depth of fault, G= Shear Modulus, δ= fault displacement, e=δ/L --- All have consistent dimensions.

$\log (M_0) = c + d.M_s$ --- M_0 has consistent dimensions with the above

for M_0 in dyne.cm , c=16, d=1.5 and $G = 3x10^{11}$ dynes/cm^2, $e \approx 1 – 6 (x10^{-5})$ and converting L from cm to Km and assuming H = 10 km = 10^6cm

$\log (L_{km}) = 0.75 M_s – 3.25$ -- (comparable to observed values)

dyne = gm.cm/sec^2 , 1 N = 10^5 dyne , 1 dyne/cm^2 = 0.1 N/m^2

Ref: Ambraseys N.& Melville C. (1982)- A history of persian earthquakes, Cambridge University Press.

There is another magnitude, called Moment Magnitude, Mw, (Now a days this magnitude is denoted by **M**) which is now being used as the most reliable measure of energy. This is derived from another measure of the size of the earthquake called the Seismic Moment.

The relationship between the magnitude and the energy of the earthquake is empirical. As long as the wavelength at which the earthquake is measured (roughly 80km for Ms) is long compared to the length of fault, the logarithmic nature of seismic energy with magnitude is good. When the length of fault is longer than the wave length, the instrument does not see the wave clearly and the magnitude saturates.

ENERGY OF EARTHQUAKES

$\log E_{ergs} = 11.8 + 1.5\, M_s$ **--------Gutenberg & Richter (1956)**

$\log E_{ergs} = 12.24 + 1.44\, M_s$ **--------Bath (1966)**

M_s	E (ergs)	V (cm^3)	L(km)
0	1.7×10^{12}	1.7×10^{9}	5.7×10^{-4}
3	3.6×10^{16}	3.6×10^{13}	7.2×10^{-2}
5	2.7×10^{19}	2.7×10^{16}	1.8
6	7.6×10^{20}	7.6×10^{17}	9.1
7	2.1×10^{22}	2.1×10^{19}	46
8	5.7×10^{23}	5.7×10^{20}	229

Assumes

$E/V = 1000 (dynes/cm^2)$

$\log (L_{km}) = 0.7 M_s - 3.24$

Gutenberg N. & Richter C.(1956): Magnitude and energy of earthquakes. Annali di Geofisica, 9, 1-15

Bath M.(1966): Earthquake energy and magnitude. Physics and Chemistry of the Earth. 7, 115-165.

From the figure 6, The slope of the magnitude versus energy curve starts to flatten. Very large energy release is then not represented by the Ms. For mb, the flattening happens much earlier.

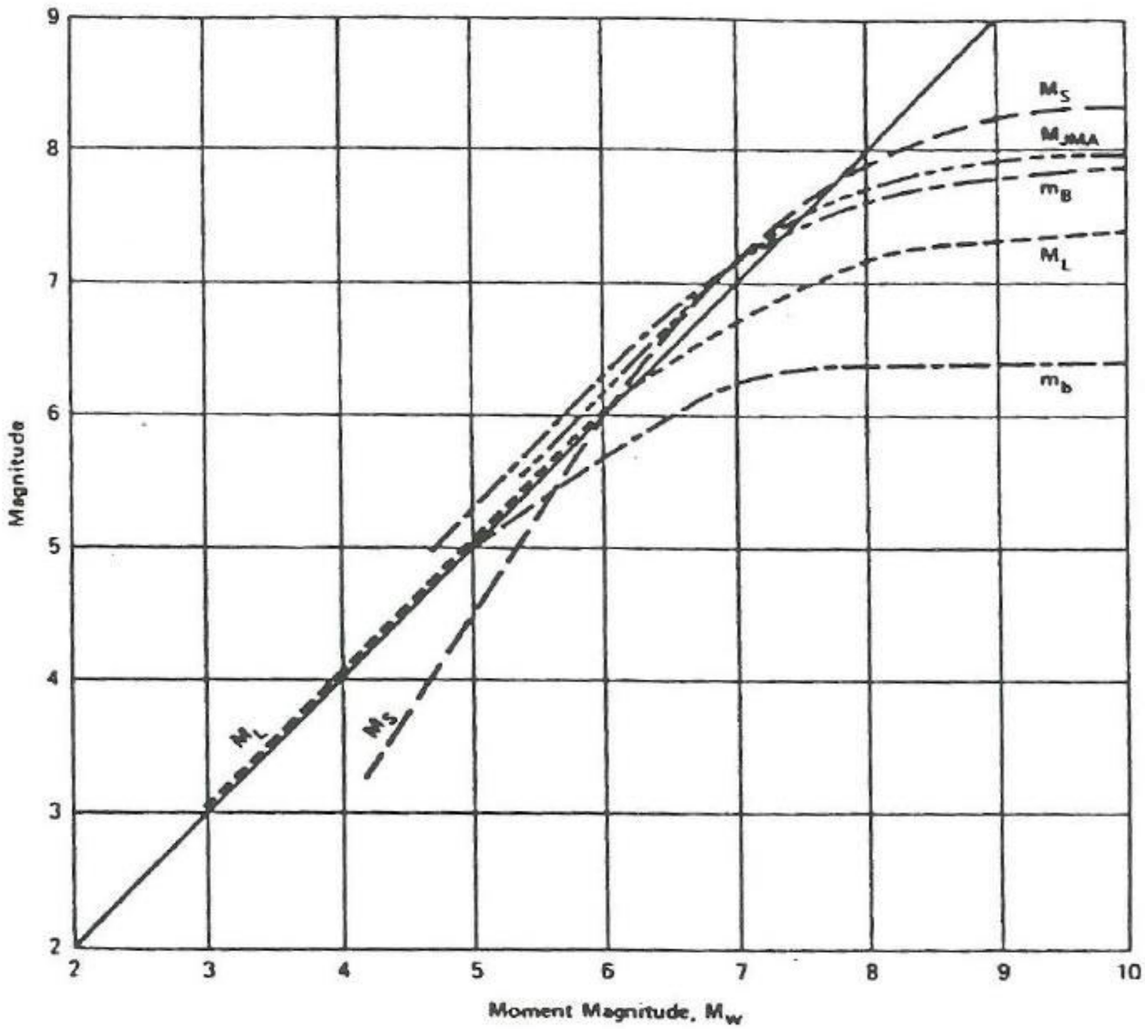


Figure (6): Relation between moment magnitude and various magnitude scales: ML = Local magnitude, Ms = Surface wave, mb = short period body wave, mB = Long period body wave, MJMA= Japan meterological Agency.
(After Heaton et al, 1982, reproduced in Idriss 1985)

Seismic Moment:

Seismic moment is defined as the following: See figure 7.

$$\mathbf{M_0 = \mu\ A\ u}$$

μ is the shear modulus of the medium (μ≈3x1010N/m2), A is the fault area (m2) and **u** is the vector displacement (m) of one side of the fault relative to the other. M_0 has the dimension of (Nm).

M_0 can be calculated from direct measurement in the field if available. This can also be measured from the long period level of the seismic spectrum. Observations from large earthquake show that the fault displacement has a consistent ratio to the fault length (1-6 $x10^{-5}$).

There are relationships linking the moment M_0 to the magnitude Ms. Hanks & Kanamori (1979) gives:

$\log M_0 = 1.5\ M_s + 16.1$; In this formula, M_0 is in dyne.cm . [$1Nm=10^7$ dyne.cm]

[Note that the inversion of this formula defines M_w]

The linear relationship between log M_0 and Ms does not seem to be true for smaller magnitudes. Other non-linear relationships exist, for example, Ekstrom & Dziewonski (1988) and Ambraseys & Free (1997).

We can use these relationships to estimate the maximum possible magnitude in a fault or estimate the permanent fault displacements in a major earthquake in the fault. For example: If a capable fault exists which is say 200 km long and 10 km deep (Anatolian fault for example), the estimated maximum fault displacement can be of the order of $5x10^{-5}L$ which will be about 10m. The moment M_0 for this earthquake will be:

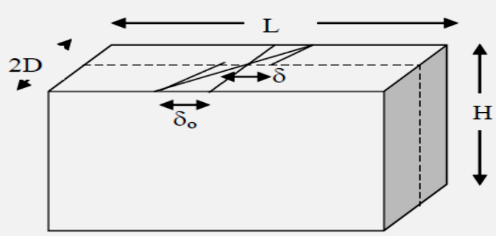
$$M_0 = 3.3x10^{10}(200x10x10^6)x10\ Nm = 6.6x10^{20}\ Nm = 6.6x10^{27} dyne.cm.$$

This will then convert to Ms = 7.8. Thus, on a fault of the size of 200km, 7.8 magnitude earthquakes may be expected.

Similarly, we may estimate the fault displacements for earthquakes of various magnitudes. We can see that displacements across faults for a medium size earthquake, say of magnitude Ms=6 may be of the order of a meter. Using $\{\log(L_{km})=0.7Ms - 3.24\}$, will give **u** = 0.47m. Thus, if we are considering a dam across a fault and the design earthquake is a magnitude 6 one, then the design must consider a possible fault movement of 1/2 meter. Note that rivers may be fault alignments and this is a serious concern in dam engineering. A proper site investigation looking for faults is a must in any dam engineering.

SEISMIC MOMENT

[Strike-slip mechanism is shown]



M_0 = G A δ

G = Shear modulus
A = Area of faulting
δ = Fault Dislocation

Figure (7)

Seismic Energy/ Volume = $\frac{1}{2}\frac{P_0^2}{G}(1-\lambda)^2$

$P_0 = G.\delta_0/D$

$\delta = 2.\delta_0(1-\lambda)$

V = 2LDH

Seismic Energy = ¼ M_0 δ/D

log M_0 = 16.1 + 1.5 M_s ------Interplate Earthquakes

log M_0 = 15.6 + 1.5 M_s ------Intraplate Earthquakes

Kanamori & Anderson(1975)

M_0 is in dyne.cm

M_w = Moment Magnitude = log (M_0) / 1.5 – 10.7

Recognition of active faults:

Faults may be classified as

a) active, b) potentially active, c) uncertain activity and d) inactive

Active fault: These show historical or recent surface faulting with associated strong earthquakes. There may be other indications for fault movements such as geomorphic features characteristic of active fault zones along the fault trace.

Potentially active faults: No reliable report of historic surface faulting but geological settings suggest activity similar to nearby active faults.

Faults of uncertain activity: Not enough data available to establish fault activity.

Inactive faults: No activity based on a thorough study. Geological evidence exist to suggest that the fault has not moved in the recent geological past.

Activity of faults may be assessed geologically and seismically.

The Site Parameters:

The effect of the source of the earthquake is transmitted to the site by seismic waves. There are basically two kinds of waves- the **body waves** and the **surface waves**. In an infinite homogeneous medium, only the body waves can be present. Surface waves are generated in the presence of a free surface or along the boundaries of heterogeneous medium.

There are two kinds of body waves:

P waves - These are the compression waves (same as sound waves), propagated by the compression and rarefaction of the medium. The particle motion in these waves is along the direction (ray) of the wave. The velocity of these waves are the highest.

$$V_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}$$

E= Young's Modulus, ν = Poissons' Ratio of the medium and ρ = mass density.

S waves - These are the shear waves, propagated by the shear action of particles. The particle motion in these waves is perpendicular to the direction (ray) of the waves. The vector of this particle motion can be broken up into two components- one on a vertical plane - called SV component and the other on a horizontal plane - called SH component.

The velocity of these waves is somewhat smaller than the P waves.

$$V_s = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{\rho.2(1+\nu)}} \qquad ; G = \mu = \text{Shear Modulus}$$

This gives

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1-\nu)}{(1-2\nu)}} > 1.0 \text{ always . For } \nu=0.25,\ V_p/V_s = \sqrt{3} = 1.73$$

ν = Poisson's ratio

There are basically two kinds of surface waves:

Rayleigh Waves : The particle motion in these waves is somewhat similar to the ripples in water (but not exactly the same)- The motion behaves like a combination of P and SV (S waves Vertical Component) waves, when the direction of the wave is horizontal.

Love waves: The motion behaves like a combination of P and SH (S waves Horizontal component).

The Rayleigh waves can exist in a homogeneous finite medium. Love waves exist only in heterogeneous medium. The velocities of these waves are smaller than the S waves.

See figure 8.

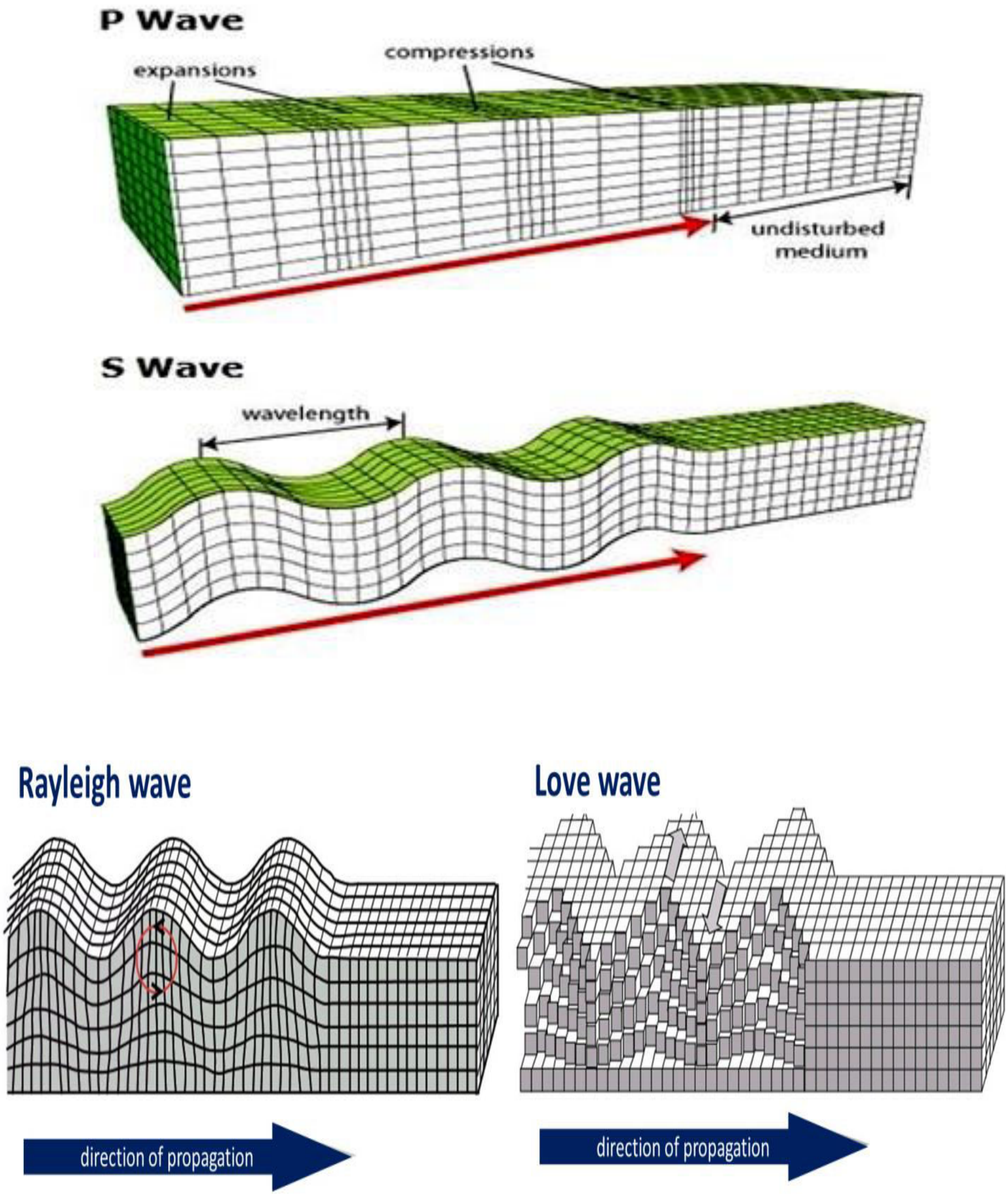


Figure 8: Diagram illustrating the form of ground motion near the ground surface in four types of earthquake waves. [From: Bruce A Bolt, Nuclear explosions and earthquakes, W H Freeman and Company, 1976] modified.

The reflection and refraction in a boundary of two materials of one kind of incident body waves may generate both kinds of body waves. The partitioning of the incident energy into the four components, two in reflection and two in refraction, depends on the incident angle and on the relative properties of the two media. That is why the earthquake ground motion is very complex.

Because of the difference in velocity of these various waves, different waves arrive at different times at the site. See figure 9. Therefore, knowing the velocity profile of the earth, it is possible to estimate the distance of the source to the site. Seismologists use this information from many sites to locate the epicenter and the focal depth of the earthquake. Since there are four unknowns in the location of epicenters i.e. the latitude, the longitude,

The focal depth and the origin time of the earthquake, a minimum of 4 stations is required to locate the source of the earthquake. International Seismological Centre (ISC) in Newbury, Berkshire is equipped to collect the station information from all over the world and determine the hypocenter with as much accuracy as possible by using least-square fitting technique. NEIC (National Earthquake Information Centre- USGS) in the USA is another similar centre. There are centers in every country which collects data from stations in that country and determine epicentres. NEIC also determines magnitudes and moments of earthquakes. ISC usually does not determine magnitudes and moments but reports those given by NEIC and other stations.

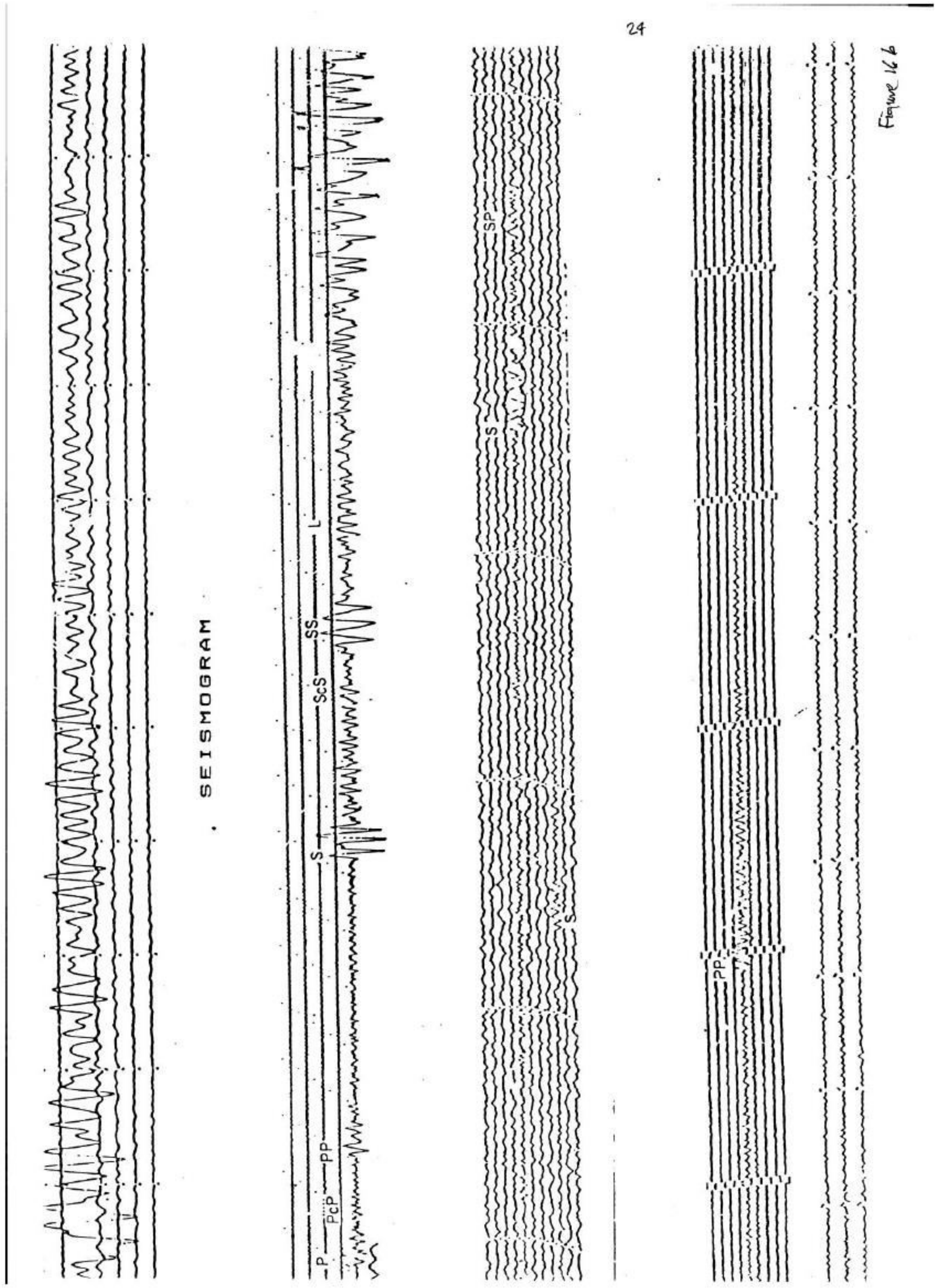


Figure 9: the seismogram or station seismic record.

Seismic Energy at a site

The propagation and attenuation of seismic energy:

The energy released at the source is propagated by the seismic waves in the form of particle motion. In an infinite medium, the propagation will take place in all direction equally from the source. This is known as the spherical propagation. In this case, the energy of the source is spread around the expanding wave front. In this case, the wave front is the surface area of the sphere that expands with the distance. Therefore, the energy per unit area of the wave front becomes smaller. The site which exists in the wave front will feel this energy. This reduction of energy from source to the site is known as geometric attenuation. The spreading of energy can be in a cylindrical front (for example, if the fault breaks instantly as a line, the spreading will be cylindrical). It can be on a plane front as well in which case there is no geometric attenuation. In reality, geometrical attenuation is a mixture of all kinds.

Besides the geometric attenuation, there is also the energy loss due to the inelastic work done during the particle motion. This is caused by the inter-particle friction but this loss is represented by the viscous damping characteristics (strain rate effect). Due to the viscous damping, the particle motion decreases with distance. The factor by which the ground motion decreases with distance is given by $e^{-\lambda\Omega s/S}$. In this expression, λ is the viscous damping coefficient as a fraction of the critical, Ω is the circular frequency of the wave in radians, s is the distance travelled and S is the wave velocity. In seismology, the value λ is represented by the Q factor (Q=Quality) where $Q = 1/ 2\lambda$

ATTENUATION RELATIONSHIP (IN TERMS OF ENERGY)

$$E_s = E_o\, e^{-kR}/CR^n$$

$$\log Eo = a + b\,M$$

$$\log Es = c + d\,I$$

THUS, $I = B_1 + B_2M + B_3R + B_4 \log R$

WHERE B_2 SHOULD BE A POSITIVE NUMBER AND B_3 AND B_4 SHOULD BE NEGATIVE

ALSO, ENERGY IS PROPORTIONAL TO SQUARE OF GROUND MOTION

THEREFORE, GROUND MOTION y IS OF THE FORM

$$y = b_1\, e^{b2M}\, e^{b3R}\, R^{b4}$$

OR $\log y = C_1 + C_2M + C_3R + C_4 \log R$

WHERE C_2 SHOULD BE POSITIVE AND C_3 AND C_4 SHOULD BE NEGATIVE.

GROUND MOTION CAN BE MEASURED IN TERMS OF ACCELERATIONS, VELOCITIES OR DISPALCEMENTS. THE VALUE OF THE CONSTANTS WILL CHANGE WITH THE GROUND MOTION PARAMETER

DEFINITION OF R

THERE ARE MANY ATTENUATION RELATIONSHIPS IN WHICH R IS DEFINED IN MANY DIFFERENT WAYS

EPICENTRAL DISTANCE $R = D_e$

FAULT DISTANCE $R = D_f$

HYPOCENTRAL DISTANCE $R = \sqrt{(D_e^2 + h^2)}$

SLANT DISTANCE TO THE FAULT $R = \sqrt{(D_f^2 + h^2)}$

A BEST FIT h TERM SAME FOR ALL EARTHQUAKES $R = \sqrt{(D_e^2 + ho^2)}$
$R = \sqrt{(D_f^2 + ho^2)}$

A BEST FIT CONSTANT ADDITIVE TERM $R = \bar{R} + C$

WHERE $\bar{R}$ COULD BE ANY OF THE R TERMS ABOVE AND C IS A BEST FIT CONSTANT

A BEST FIT ADDITIVE TERM DEPENDENT ON MAGNITUDE $R = \bar{R} + C_5 e^{C6M}$

The effect of the seismic energy at the site is measured indirectly in two ways:

a) Intensity of earthquakes and b) Ground motion parameters.

Intensity of Earthquakes:

Intensity of earthquakes is a measure of the damage to structures, grounds, slopes etc. and the way human beings and animals react to the earthquake. This is a subjective measure and therefore can be in error, particularly when comparing notes of different observers. When comparing effects on a particular class of structure, the measure could be very effective. But by mixing different class of structures or ground effects, the measures could be confusing. It is even more confusing when slope failures are taken into account. Slopes do fail even without earthquakes. The failure depends on the available factor of safety at the time of the earthquake which depends on many seasonal factors. Therefore, to use the failure of slopes to measure the size of the earthquake is not correct. Intensity serves an important purpose, particularly when assessing pre-instrumental historical earthquakes.

There are several intensity scales that are presently in use. The most common is perhaps the Modified Mercalli Scale, developed originally by Mercalli in 1902 and later modified by Wood (1932). The most common scale used in Europe is MSK scale (Medvedev, Sponheur, Karnik). The scales are more or less similar.

After an earthquake, Intensity data is collected and plotted in a map, figure 10. In this map, contours of equal Intensity is drawn which are known as Isoseismals. Generally, isoseismals are not circular, quite often showing signs of high intensity in low intensity regions, mainly due to soil effects. From these isoseismals, an average radius can be computed. From the size of the average radii for different levels of isoseismals, the magnitude of the earthquake can be assessed. See attenuation relationship in terms of Intensity, Figure 11.

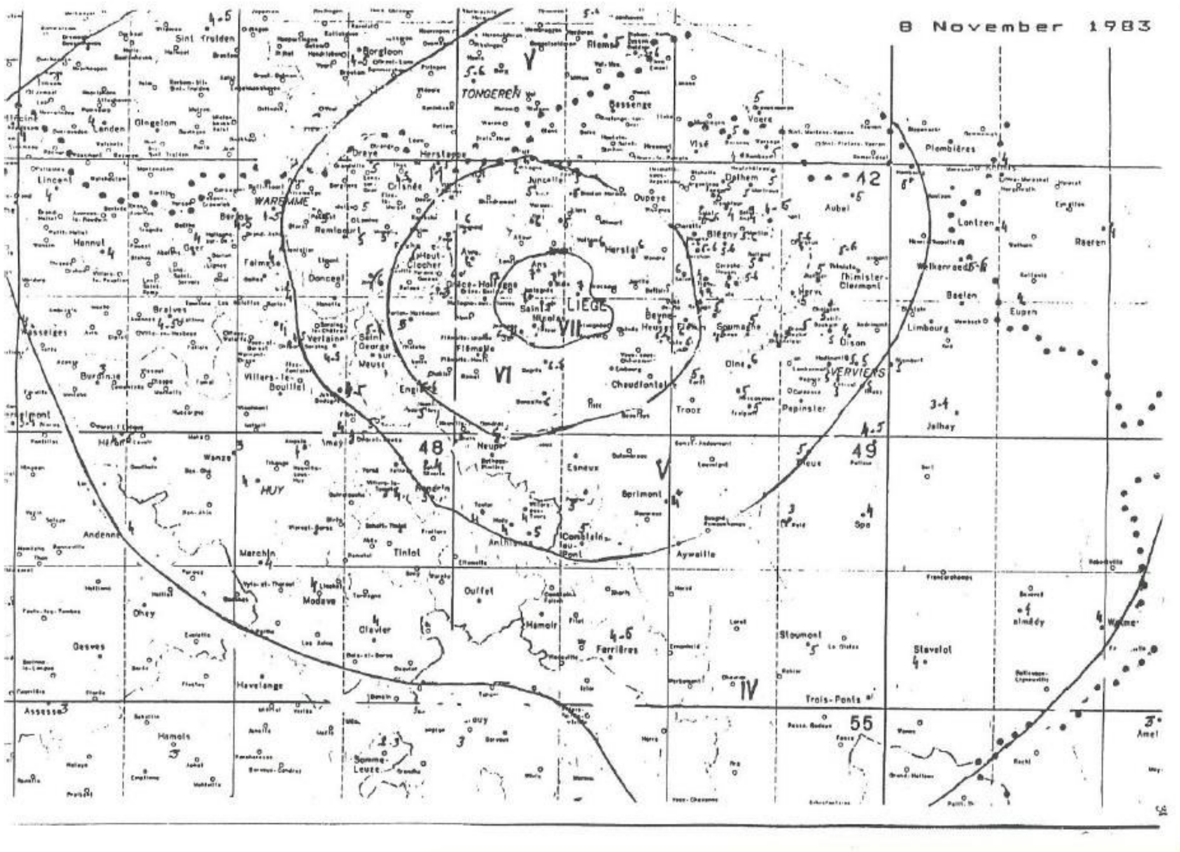


Figure 10: equi-intensity contour map or isoseismals which show seismic intensity variation on a region in the terms of (seismic intensity zones).

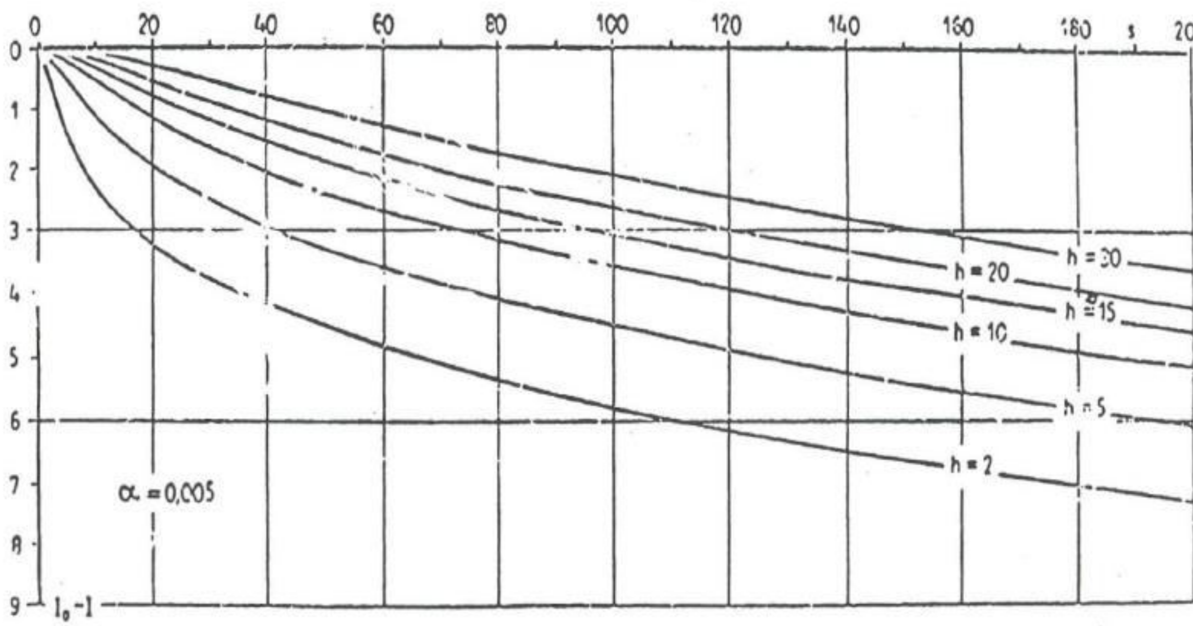


Figure 11: attenuation relationship in terms of Intensity.

The Modified Mercalli Scale:

I Not felt except by a very few under especially favourable circumstances.

II Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III Felt quite noticeably indoors, especially on upper floors of buildings but many people do not recognise it as an earthquake. Standing motor cars may rock slightly. Vibration like passing trucks. Duration estimated.

IV During the day, felt indoors by many and outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make creaking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V Felt by nearly everyone; many awakened. Some dishes, windows etc. broken; a few instances of cracked plaster; unstable objects overturned. Disturbances of trees, poles and other tall objects sometimes noticed. Pendulum clocks may stop

VI Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plasters or damaged chimneys. Damage slight.

VII Everybody run outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motor cars.

VIII Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Disturbs persons driving motor cars.

IX Damage considerable in especially designed structures; well designed frame structures thrown out of plumb; great in substantial buildings with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed over banks.

XI Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips on soft ground. Rails bent greatly.

XII Damage total. Waves seen on ground surfaces. Lines of sight and level distorted. Objects thrown upward into the air.

Ground Motion:

The effect of the energy at the site can also be measured by the ground motion parameters. The ground motion is measured in terms of accelerations in the near field of earthquakes by using the "Strong motion" instruments. The engineers use these. Seismologists use ground displacements to determine epicenters and other source parameters. These are measured by "Seismographs". Both strong motion instruments and seismographs produce time-history records.

Theoretically, acceleration records can be integrated to obtain ground velocity and displacements. However, there are problems associated with the integration process coming from the "noise" in the records. Therefore, often the displacements obtained from integration process is not reliable. (We do however use them after filtering out the noise, but filtering process is not perfect.) Similarly, the displacement record obtained from seismographs can be differentiated numerically to obtain velocity and accelerations. However, the numerical differentiation process is always inaccurate when spikes are involved in the records. See figure 12.

Now-a-days, banks of strong motion records exist (For example, ISESD, the strong motion Data Bank originally stored at Imperial College) where, records from all over the world are collected and processed. Because of their engineering importance, some owners of records tend not to give the records away.

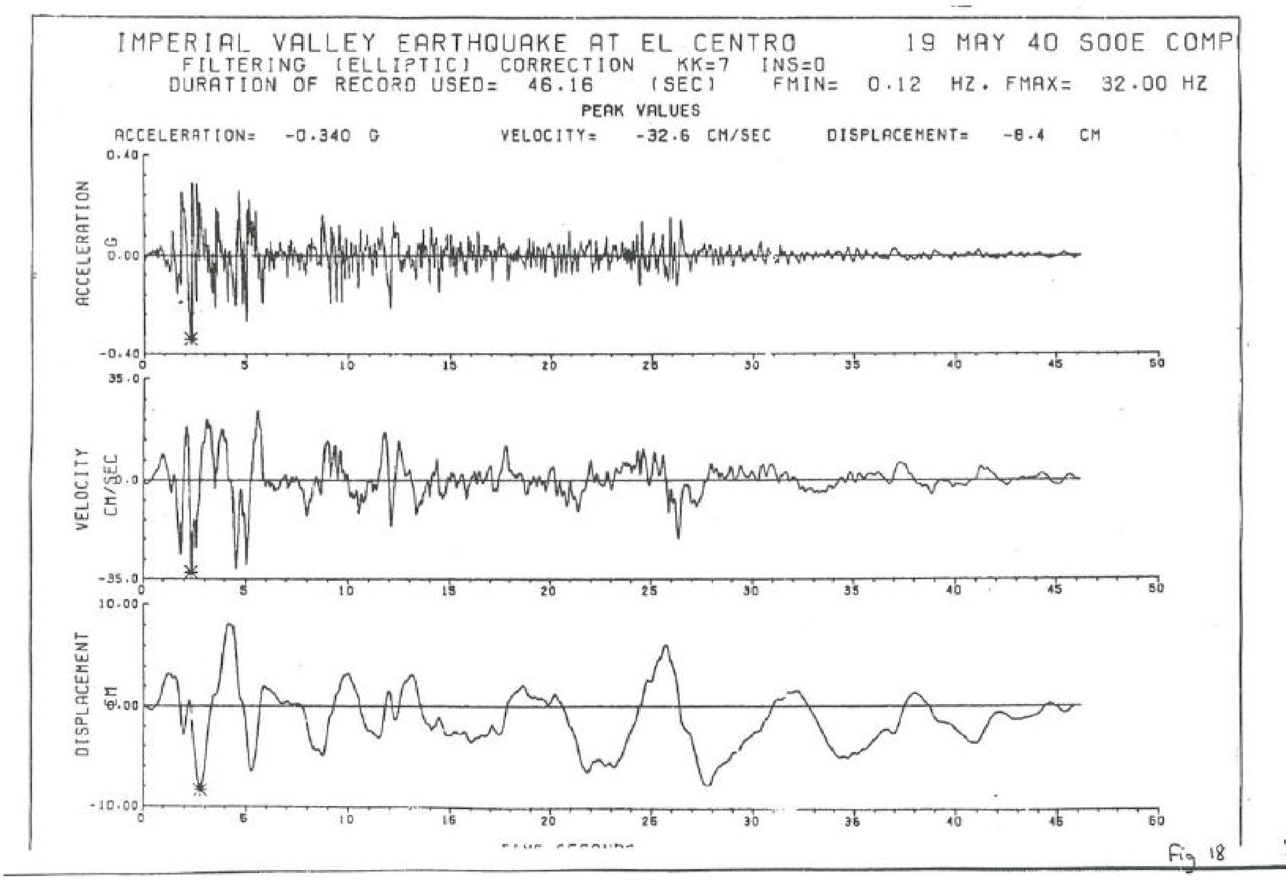


Figure 12: the integrated acceleration records to obtain ground velocity and displacements.

Attenuation of Strong motion Data:

Using the bank of data, attenuation relationships are derived for different ground motion parameters by various authors. These relationships differ because of the choice of data from the bank and the choice of the type of relationship. There are global relationships and there are relationships derived from data from single countries. There are also relationships derived from data of similar tectonic environments or of similar site geology. There can be many such classifications. Because of the complex nature of the strong motion records, the relationships appear to be crude with large standard deviations. Many attempts are going on to obtain better relationships but not with much success. See figure 13.

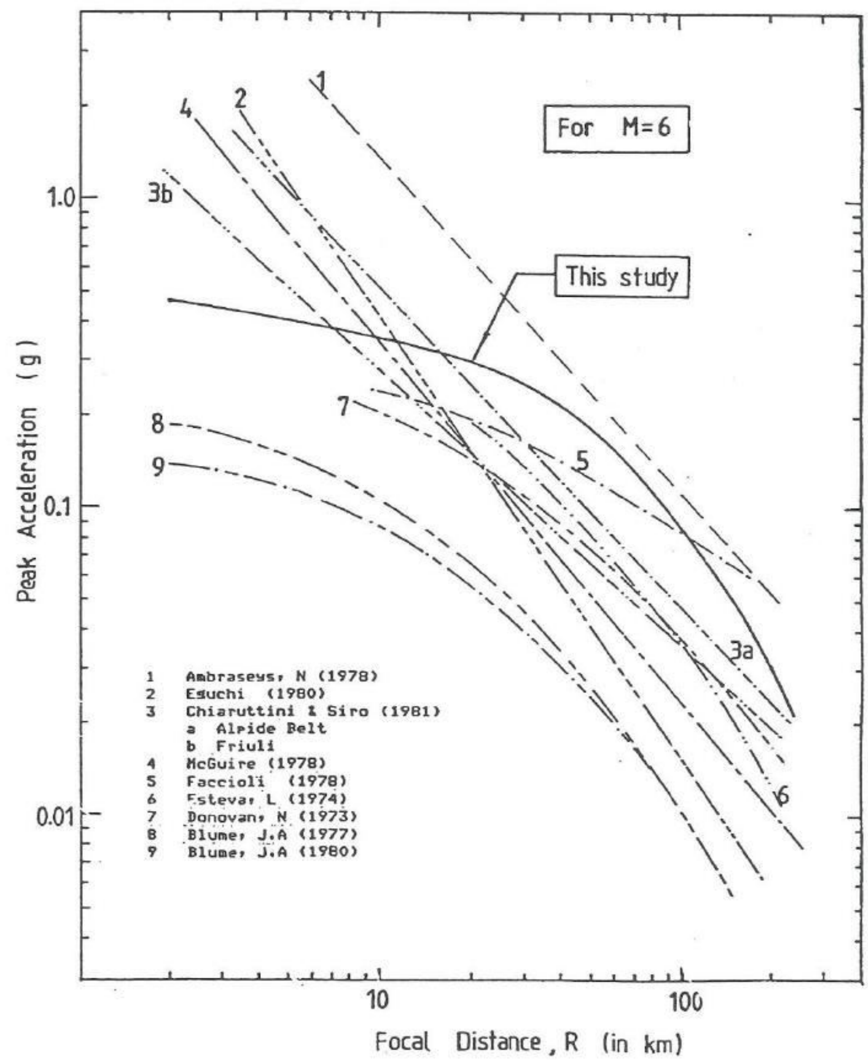


Figure 13: attenuation relationships derived for different ground motion parameters by various authors.

The two most common relationships that are in use are

1. Ambraseys N. and Bommer J.(1991):

$\log a(g) = -1.09 + 0.238\, M_s - \log r - .0005r + 0.28p$; where $r=\sqrt{(D_e^2 + 6^2)}$
p=0 for mean value
p=1 for mean + 1sd
D_e = Shortest distance to the fault rupture.

2. Joyner W.& Boore D. (1981):

$\log a(g) = -1.02 + 0.249\, M - \log r - .00255r + 0.26p$; where $r=\sqrt{(D_e^2 + 7.3^2)}$
Other definitions are same.

Sarma & Srbulov (1998) defined attenuation relationships for other ground motion parameters.

Figure 14, shows that the Intensity of earthquakes and the peak ground acceleration do not really have any correlation even though there is a trend. Any correlation found in the literature between these parameters should be treated with extreme caution.

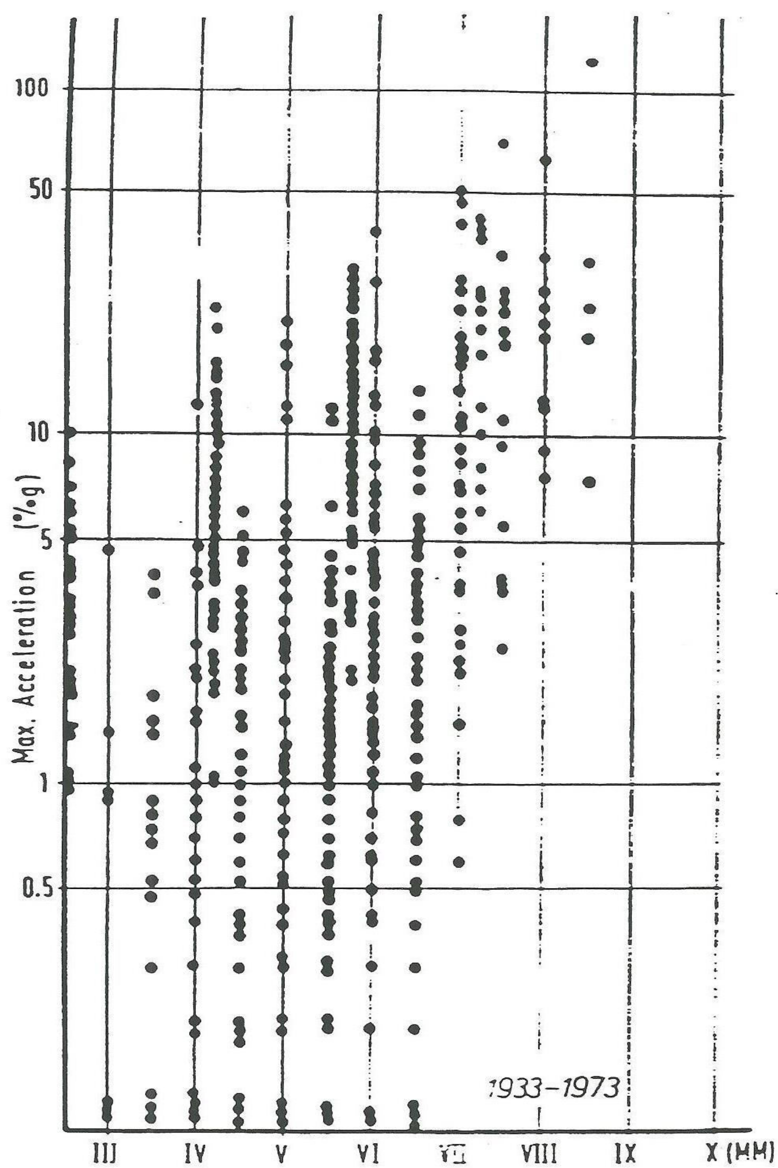


Figure 14: shows that the Intensity of earthquakes and the peak ground acceleration do not really have any correlation even though there is a trend.

Seismicity & Hazard Evaluation Of A Site

In order to evaluate the seismic hazard of an engineering site we need the following information.

a) Historical seismicity of the region;

b) Geology and tectonics of the region;

c) A mathematical (statistical) model for analysis;

d) Local soil conditions at the site.

In general, the hazard analysis concerns with the first three factors while the local soil conditions are considered as a special case if necessary.

The study begins with the establishment of the region of interest around the site, which in general could be large, say 5ox5o or even bigger. The idea is to establish regions within this area which can be called homogeneous in the seismic sense, i.e. that the region belongs to the same tectonic province, the earthquakes within the area has the same sort of mechanisms.

Historical seismicity of the region:

For the area in question, we then collect all the data about the earthquakes, i.e. the size (magnitude, moment), location (epicenter, focal depth) that has happened in the past. The data can be divided into two groups, instrumental data and pre-instrumental historical data.

The instrumental data can be obtained from the International Seismological Centre (ISC in UK), the National earthquake Information Centre (NEIC in USA) and the National Geophysical Data Centre (NGDC in USA). These agencies can supply data covering the period from 1906 to the present. The accuracy associated with the instrumental data varies with time. At the early stage, the errors associated could be large, particularly with epicenter determination (±25km). There are instances of gross errors in locations. The reason being very few instruments, unevenly located around the world and with low sensitivity. The location errors in the present time could be ±5km. In the early period, smaller events were not located and therefore incomplete.

The locations of pre-instrumental period earthquakes are obtained from historical studies, extending the period as far back as possible. Obviously, the historical earthquakes will concentrate on the large events. The magnitudes are determined from macro-seismic information, such as felt radius or epicentral Intensity.

The magnitude determination for the instrumental period is non-homogeneous in the sense that different formulae were used in different periods. It is often necessary to recalculate magnitudes in a homogeneous way from the original data or look for published data. The error associated with magnitudes could be of the order of ±0.25.

The focal depth determination is not accurate at all. In the early period, the focal depth was generally given as 'Normal' or 33 km depth. In the catalogues, 33 km depth usually implies unknown shallow focus earthquake. Even in the present day, errors associated with focal depth determination could be large.

Following the collection of this data, map the epicenter locations, distinguishing between the instrumental and the historical ones and distinguishing the size.

Geological and tectonic data:

We map the known fault location within the area, particularly the active faults, which moved in the quaternary period.

The combination of the two maps will give us an idea of the source region of earthquakes within the area. The sources therefore could appear to be points, lines(faults) and areas. The area source appears due to the uncertainty of the location of faults and the association of faults with epicentres. The source region determination is subjective and not conclusive.

Activity of the source regions:

It has been found that the activity of a source region follows a relationship, Guttenberg & Richter(1954)

$\text{Log}(N.) = a - bM$

where M is the earthquake magnitude and N. is the number of earthquakes of magnitudes greater than or equal to M. In general, the numbers are normalised to a year and to unit area for area source and unit length for linear source. 'a' is therefore a measure of the activity of the region, when normalised. 'b' is a measure of the 'brittleness' of the region. If the crust is highly faulted so that there exists many small faults and few large faults, then 'b' will be large. There will be a tendency for many small earthquakes compared to large earthquakes. The value of b lies between 0.5 to 1.5. Considering the activity of the whole earth, b value is approximately equal to 1.

Due to the incompleteness of the data, deviation from the linear trend exists. We generally do not consider magnitudes less than about 4 in the trend analysis. Also for the highest magnitude, since the period of the catalogue is very limited, this may have to be discarded in the trend analysis.

Maximum magnitude:

For any region, we expect a maximum magnitude. It is essential to assess this maximum magnitude. From the study of the past earthquakes and the tectonic activity of the region, this can be estimated. In the absence of such a study, the largest historical earthquake + a small increment (0.5) is generally considered.

Statistical model:

The statistical model generally applied in hazard analysis is the Poisson process. The Poisson process is memory less, which implies that earthquakes in one period of time does not depend on the past. This is therefore an assumption. However, it is acceptable for normal hazard analysis. When the hazard is controlled by the very large earthquakes, this assumption maylead to errors.

Return periods:

The return period of an event is simply the average time between events in the past and is given by the inverse of the annual frequency. If n is the number of favorable events per year, then the return period of the same is

$T = 1/n$

Probability of exceedence:

This is the probability of at least one favorable event in the life time of the structure. This is given by the expression

$p = 1 - \exp(-L/T)$

where

p is the probability of exceedence

L is the life time of the structure

T is the return period of the favorable event.

Exp(-L/T) represents the probability of non-exceedence.

Attenuation model:

To convert the seismicity information to the ground motion, we need an attenuation model. This model should reflect the geology and the tectonics of the area. For example, the attenuation for Intraplate earthquakes are different from that of Interplate earthquakes. It is preferable to have attenuation relationship for the particular area of concern. This relationship is the most important in the final result and should be chosen with care. Attenuation relationship for ground motion is of the general form:

$$y = b_1 e^{b_2 M} r^{-b_3} e^{-b_4 r}$$

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

There are other forms of r as well such as

$r = (d + c)$

b_i are constants dependent on regions.

Hazard Evaluation:

Point Source Model: This model is the basic "building block" for more elaborate source model such as a fault line source or an area source. In this model, a point source with an expected recurrence relationship (a,b parameters) is situated at a given distance (R) from the site and an attenuation relationship exist for the region. For the point source model, there are two approaches that can be adopted for the analysis.

A) Direct approach: Given the expected life (L) of a structure and the acceptable probability of exceedance (p), we can determine the return period (T) of the event. Thus

$p = 1- \exp(-L/T)$

The return period (T) is the inverse of the average number (n) of earthquakes per year.

$T = 1/n$

(n) is related to the magnitude of the earthquake through the recurrence relationship

$\log(n)= a-bM$

(Note: If the computed magnitude is bigger than the maximum magnitude, then M is the maximum magnitude)

From the magnitude of the event and the distance, we find the design ground motion.

$$y = b_1 e^{b_2 M} R^{-b_3} e^{-b_4 R}$$

(Note: In this relationship, R is a distance parameter and not the distance directly). Because of the presence of the maximum magnitude, this approach is applicable for a point source only.

B) Indirect approach: This approach can be extended to more elaborate source models. This is a reverse procedure from the direct approach.

We start with an assumed value of the ground motion y and determine its return period T which is then related to p.

$$y \Rightarrow M \Rightarrow n \Rightarrow T$$

Plot y versus T and determine the design ground motion from the plot.

Many point sources model:

In this model, for any given value of the ground motion (y), the (n) values from all point sources are added together. The return period is then given by:

$$\mathbf{T = 1/\Sigma n}$$

The seismic risk of new and existing dams

The main issues of the design and construction of any dam are undoubtedly the safety and serviceability. It is evident that both of them depend mainly on the capability of the design group (a) to assess realistically all the local site conditions (hydrological, hydraulic, topographical, geological, geotechnical, etc.), (b) to decide the optimum dam shape and type (i.e. embankment dam, concrete gravity dam or arch dam), and (c) to design the dam accordingly in order to withstand all the potential hazards and/or loadings (e.g. gravity, hydrostatic pressure, differential settlements, etc.). Nevertheless, in areas characterized by moderate or high seismicity the design of a dam may be a more challenging and demanding task since both safety and serviceability are directly related to the earthquake-related geohazards and the seismic vulnerability of the dam under consideration. The term "earthquake-related geohazards" is used to describe various geological/geotechnical phenomena, such as strong ground motion, surface rupture of an active seismic fault, earthquake-triggered slope instabilities, and soil-liquefaction phenomena. Therefore, the main emphasis of the current study is on the seismic risk of new or existing dams. The seismic risk may be estimated by the assessment of the earthquake-related geohazards and the realistic estimation of the seismic distress of a dam. The first part of the study is devoted on the qualitative and quantitative assessment of the main earthquake-related geohazards, while in the second part the main issues related to the seismic response and vulnerability of dams are presented.

The dams and all the related facilities are usually critical structures that must be designed and constructed to withstand all the potential loadings and hazards during their lifetime. One of the main types of hazards is the geohazards. The term "geohazard" is used to describe any hazard associated with geological features or processes in the vicinity of a dam that potentially pose a threat to the integrity or serviceability of the components of the dam. Apart from very compressive soils, karst phenomena and soil erosion, the main geohazards under static conditions are the potential ground movements from creep, slope intabilities and landslides. As shown in Figure 1, many dams have been damaged by geohazards in the past. In some case histories the damage has been related to the fact that the geohazard had not been identified by the geoscientists during the design phase. On the other hand, in some other cases the geoscientists had identified the problematic area, but their qualitative assessment was not followed by a quantitative assessment (with geotechnical surveys and realistic geotechnical analyses), being thus incapable to estimate the criticality of the area.

Nevertheless, it should be emphasized that many failures especially of earth-fill dams have been related to poor design and/or construction.

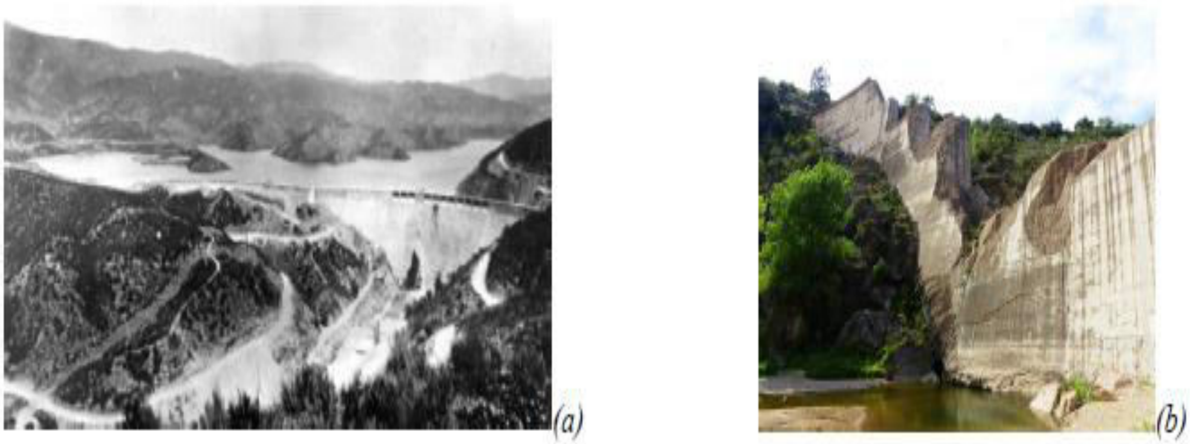


Figure 1. Geohazards and dam failures: (a) St. Francis Dam before the 1928 failure in Los Angeles County, California,in USA, (b) the 1959 failure of the Malpasset Dam in France. In both cases the failure have been attributed to poor geological and geotechnical conditions that had not been identified by the related surveys and studies.

In areas characterized by moderate or high seismicity the design against geohazards is a more demanding and challenging task since, apart from the typical geohazards, various earthquake-related geohazards should be taken into consideration. The term "earthquake-related geohazards" is used to describe various geological/geotechnical phenomena that are related to the seismic activity. One of the main earthquake-related geohazard is the propagation of seismic waves and the consequent strong ground motion at the ground surface. Under these circumstances, during an earthquake the shaking at the ground surface will cause the vibration of a concrete or an earth-filled dam causing the development of horizontal and vertical inertial forces acting on its mass.

As shown in Figures 2 and 3, in the past dams have been damaged in areas that are characterized by moderate or high seismicity all over the world. Judging from figures 2 and 3, it becomes evident that a serious failure or a collapse of a large dam may cause a disaster with exceptional risk to life and extreme economic and social consequences of failure.

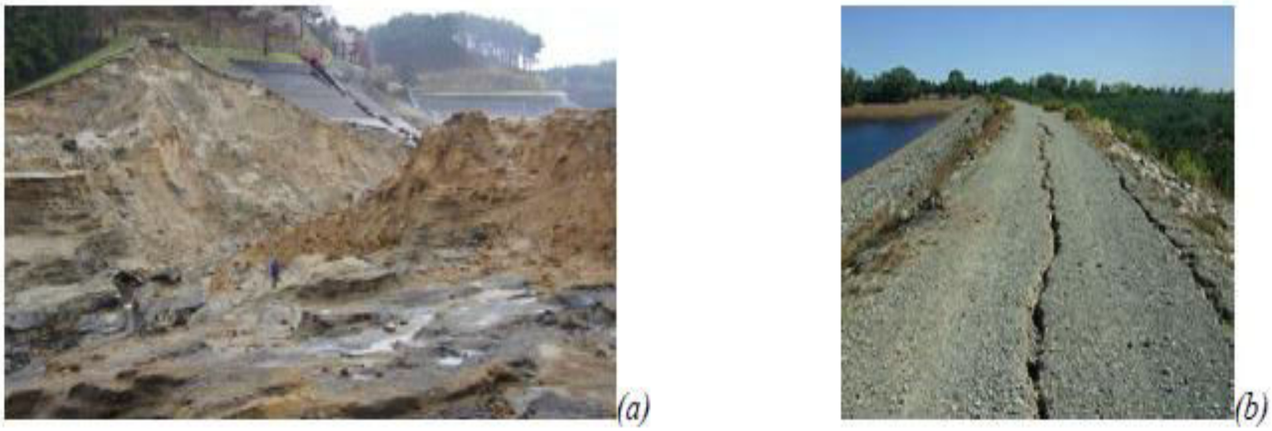


Figure 2. Earthquake-related geohazards and failure of dams: (a) collapse of the earth-filled Fujinuma Dam during the 2011 Tohoku earthquake in Japan, (b) damage to the Coihueco Dam during the 2010 Chile earthquake.

Figure 3. Earthquake-related geohazards and failure of dams: (a) collapse of the concrete Shih-Kan Dam during the 1999 Chi-Chi earthquake in Taiwan due to active fault rupture, (b) severe damage to the Lower Van Norman Dam during the 1971 San Fernando earthquake in USA.

Apart from the earthquake-related geohazard of strong ground motion (and the consequent inertial loading to the dam), there exist various earthquake-related geohazards that may induce permanent ground deformations (PGDs) to the dam and to any other related structure during (or just after) a moderate or strong earthquake. As shown in Figure 4, the main earthquake-related geohazards of this type are the active-fault ruptures, the soil-liquefaction phenomena (i.e. buoyancy, settlements or lateral spreading) and the earthquake-triggered slope instabilities and rockfalls. Note that in the case of a dam with a full reservoir the developed hydrodynamic pressures may be regarded as an additional earthquake-related geohazard. More details on the dynamic interaction of dams with the reservoir can be found in Papazafeiropoulos et al. (2010).

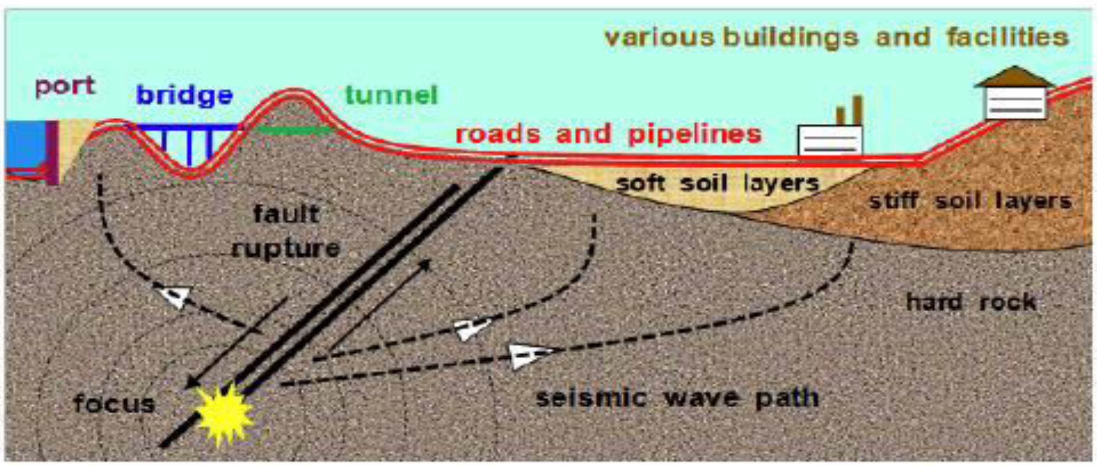


Figure 4. Sketch showing the main earthquake-related geohazards for various structures and infrastructures :(a) strong ground motion, (b) active fault rupture, (c) soil liquefaction phenomena (i.e. settlements and/or lateral spreading), (d) earthquake-triggered slope instabilities (i.e. landslides)

Note that strong ground motion and active fault rupture(s) at the ground surface are regarded as direct geohazards to any structure, while earthquake-triggered slope instabilities, soil liquefaction phenomena and the hydrodynamic pressures are indirect geohazards that depend primarily on the characteristics of the strong ground motion. In addition, strong ground motion and hydrodynamic forces are dynamic loadings to a dam, while the rest are actually quasi-static loading to the

Examined structure as they cause induced PGDs.

In contrast to long structures (such as highways, railways, pipelines), the dams are not very long structures, and therefore their installation is usually being performed in an area that is supposed to be characterized by no geohazards. Nevertheless, the decision for the location of a dam is taken at a very preliminary phase of the project when the geological and mainly the geotechnical data are rather limited, and therefore the assessment is mainly qualitative (and not quantitative). On the other hand, apart from the observable geohazards (such as very compressive soils, karst phenomena, rockfalls, etc.), there exist some earthquake-related geohazards the intensity of which depends on the seismicity of the area under examination and the local site conditions (i.e. topographical, geomorphological, geological, geotechnical, etc.). For these geohazards there is a need for quantitative assessment in order to quantify both strong ground motion and potential induced PGDs.

The current paper is involved with (a) the quantitative assessment of the main earthquake-related geohazards and (b) the optimum seismic design of dams. Emphasis is given to the strong ground motion as usually the geohazards of landslide and fault rupture can be avoided during a preliminary phase of the design with the appropriate selection of the location of the dam. An exception may be the geohazard of soil liquefaction in liquefiable areas (i.e. areas with cohesionless soil materials and high groundwater table), since liquefaction potential is directly related to the strong ground motion (i.e. the acceleration levels at the ground surface).

It becomes evident that in many cases, the simplistic provisions of seismic norms cannot cover sufficiently all the issues of the seismic design. In these cases the geotechnical earthquake engineers and the structural engineers, with the help of seismologists and geologists, should perform special surveys and studies in order to assess quantitatively the earthquake-related geohazards and to verify that the dams (including their foundation) are capable to withstand the seismic distress (developed by the inertial forces and/or the induced PGDs). It is evident that in case that the seismic distress is excessive, the engineers should apply mitigation measures in order to reduce the geohazard(s) and/or increase the structural capacity depending on the circumstances. The final solution is directly related to various criteria such as risk, cost, environment issues, etc.

Strong Ground Motion At The Ground Surface

As it was mentioned, a dam comprises of various structures and facilities made of concrete or soil materials. The impact of strong ground motion on the structures and facilities of a dam is mainly the development of horizontal and vertical inertial forces. These forces depend on the mass of each structure and the accelerations that will be developed at the center of this mass. These accelerations depend, not only on the geometrical and mechanical characteristics of the structure itself, but on the characteristics of the strong ground motion at the ground surface which is a function of (a) the strong ground motion at the seismic bedrock that have been defined by the seismological study and (b) the local site conditions (soil, geomorphology and topography) in two or three dimensions. Figure 5 depicts the main categories of local site conditions that usually coexist in nature.

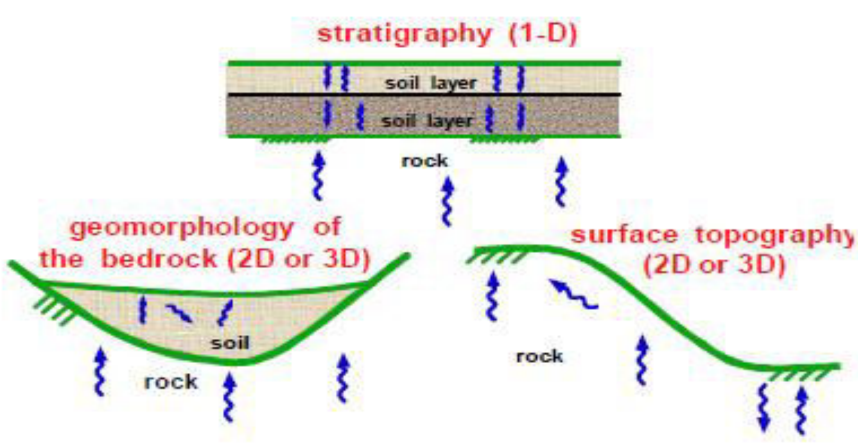


Figure 5. Sketch showing the three main categories of local site conditions: (a) soil stratigraphy, (b) geomorphology of the bedrock, and (c) surface topography

In general, the local site conditions tend to amplify the strong ground motion at the ground surface and modify its frequency content in comparison with the strong ground motion at the ground base. This phenomenon is taken into account in most of the modern seismic norms, such as EN1998 (i.e. Eurocode8) which introduces (a) a topographic amplification factor ST, and (b) a soil amplification factor S. The topographic amplification factor ST ranges between 1 and 1.4, while the soil amplification factor S with values ranges from 1 to 1.4 for high and moderate seismicity regions depending on the ground type (see Table 1). Note that ground type A corresponds to rock or rock-like geological formations, while on the other hand, ground types D and E correspond to soft and/or deep sediments.

Table 1. Soil amplification factor S for various ground types (according to EN1998) in the case of high and moderate seismicity regions (i.e. magnitude MS > 5.5)

Ground type	S
A	1.00
B	1.20
C	1.15
D	1.35
E	1.40

However, it should be emphasized that most of the seismic norms worldwide ignore the potential impact of the geomorphology of the bedrock, and therefore, in the case of a valley or a basin, norms may underestimate substantially the amplitude and the spatial variability of the seismic motion at the ground surface. In addition, large dams are beyond the scope of many norms (such as EN1998), and therefore special geotechnical earthquake engineering studies are required.

It becomes evident that in these cases the design of a demanding project such as a dam with the simplistic and rather conservative norms may have a substantial impact on the cost of the project.

For this reason, in the case of a dam (provided that a cost-effective solution is desired) there is need for reliable geophysical and geotechnical data and the consequent performance of one-dimensional or even two-dimensional ground response analyses (i.e. a soil amplification study) in order to assess realistically the acceleration levels at the ground surface. Note that these acceleration levels will dominate (a) the structural design (i.e. the developed inertial forces) and (b) the geotechnical design (e.g. induced PGDs from soil liquefaction phenomena and/or slope instabilities and selection of the optimum foundation system).

Finally, when the foundation of the dam is on soil layers (and not on rock) the common assumption of "fixed-based structures" cannot be regarded as realistic. Therefore, in the case of an earthquake there exists a dynamic interaction between the soil and the structure. The dynamic soil structure interaction is a very important and complex phenomenon, since the presence of a structure makes the soil to deform under dynamic loading, while the underlying soil (a) reduces the structural stiffness, leading to higher natural periods, and (b) increases the overall damping, since the material damping and the radiation damping of the soil layers are being developed as well.

Therefore, in many cases the analysis of the dynamic response of a structure requires the realistic simulation of the foundation and of the underlying soil as well. As a result of the presence of soil and local site conditions, the foundation compliance and other aspects should be carefully examined. Note that in current engineering practice, the dynamic soil-structure interaction is mainly considered via "soil springs", which in some cases may be an inadequate design simplification.

Rupture Of Active Seismic Faults

The rupture of an active fault may cause, apart from strong ground motion, substantial PGDs at the ground surface. Nevertheless, these deformations may be low in the case of areas characterized by soft and deep sediments. It is evident that the rupture of an outcropped fault is a direct threat to a crossing structure, such as a dam. However, in the case of a fault covered by soft and deep sediments the local ground conditions may alter the fault rupture propagation and the pattern of the PGDs at the ground surface. In other words, a possible fault rupture at the bedrock would propagate through the overlying soil(s) and alter the shape (i.e. the topography) of the surface.

The aforementioned alteration of the surface profile inevitably would cause differential settlements to the dam, which should be designed to sustain this fault-induced distress. Unfortunately, the assessment of the faulting hazard (dislocation and angle of emergence) is possible only within rock formations. Whereas the fault rupture at the bedrock is unambiguously defined by the dip angle and the magnitude of the expected dislocation (i.e. offset), as the rupture propagates through the softer soil layers, it usually deviates, bends and causes a rather smooth deformation of the surface, at least when compared with the abrupt dislocation at the rock (Figure6).

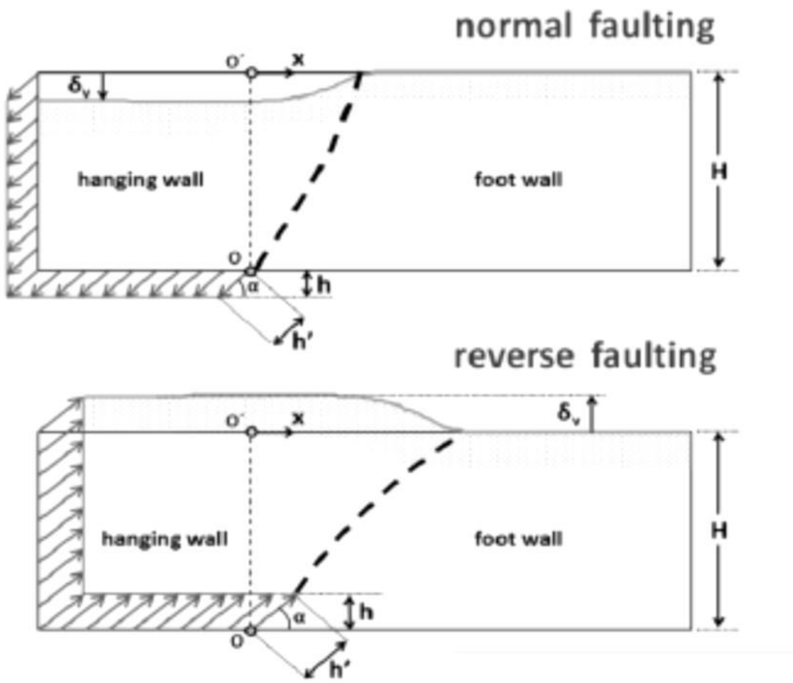


Figure 6. Schematic of the fault rupture propagation through soil, indicating the main parameters of the problem.

The PGD pattern is a function of fault displacement and angle, soil deposit thickness and mechanical properties. To predict the deformation of the soil surface induced by the rupture propagation, a special analysis is required. Figure 7 shows some representative results of fault rupture propagation analysis with the finite-element code ABAQUS, where it becomes evident that the existence of a soft soil layer of 6m covering the hard bedrock leads to the following phenomenon: the applied fault offset of 0.2 m within a very narrow zone at the bedrock is transformed to a PGD of around 0.2 m which is extended along a zone of around 5 m at the ground surface. Despite the aforementioned capability of engineers to estimate realistically the pattern of PGDs at the ground surface in the case of a covered fault, and taking into account the limited capability of the dam to withstand differential settlements, it is recommended to avoid the construction of a dam in the vicinity of any active seismic fault (outcropped or covered).

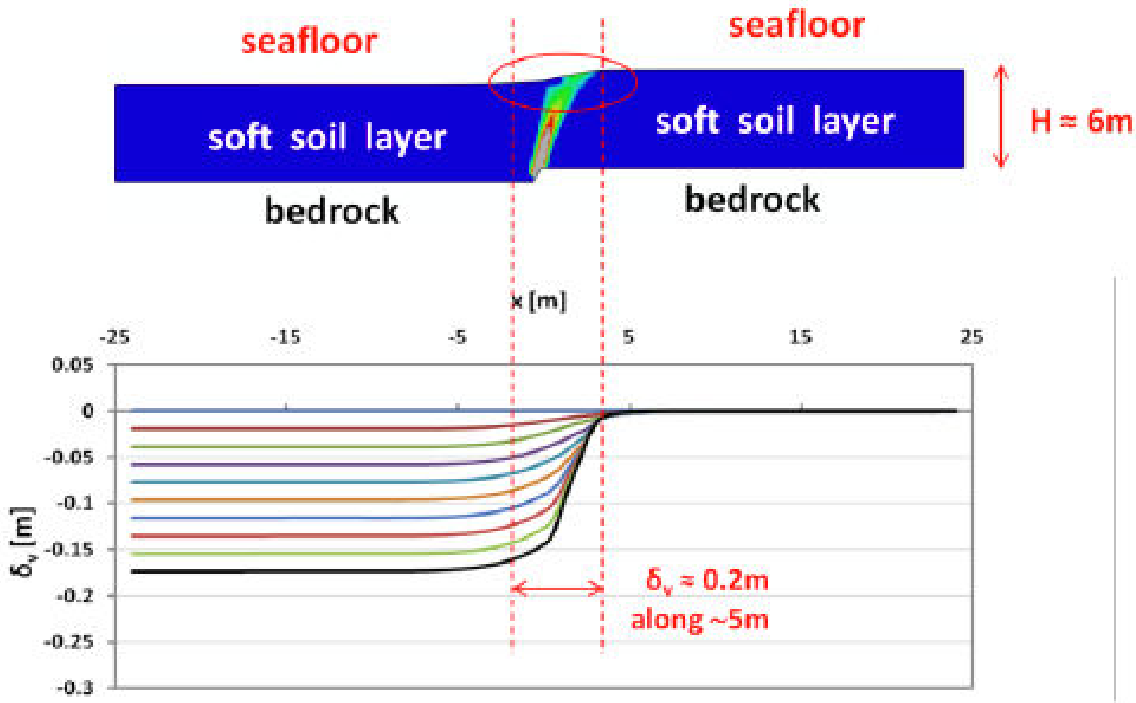


Figure 7. (a) Numerical simulation of the rupture propagation path of a covered normal fault with offset of 0.2 m. (b) Pattern of the PGD at the ground surface. Note that the vertical scale of the graph is exaggerated.

SOIL LIQUEFACTION

Soil liquefaction is an extreme consequence of strong ground motion which leads to practically total loss of shear strength in relatively loose cohesionless soil formations below the ground water table. Soil liquefaction may cause either liquefaction-induced (differential) settlements (i.e. almost vertical PGDs) and/or lateral spreading (i.e. almost horizontal PGDs). In the presence of structures, foundation failure (i.e. excessive settlement or tilting) is possible. Soil liquefaction assessment is achieved through the estimation of soil liquefaction potential through simple design charts based on semi-analytical methods or advanced numerical modeling (Seed and Idriss, 1971). Finally, for silty and clayey sands, Andrews and Martin (2000) define a criterion based on liquid limit (LL) and clay content (%) for liquefaction susceptibility (Table 2).

Table 2. Liquefaction susceptibility of silty and clayey sands (Andrews and Martin, 2000)

	Liquid limit < 32	Liquid limit > 32
Clay content < 10%	susceptible	further studies required
Clay content ≥ 10%	further studies required	not susceptible

The following equation evaluates the liquefaction potential. Therefore, two primary seismic variables are required: (a) the level of cyclic stress induced by the earthquake on a sediment layer, expressed in terms of cyclic stress ratio (CSR), and (b) the capacity of a sediment layer to resist liquefaction, expressed in terms of cyclic resistance ratio (CRR). Seed and Idriss (1971) formulated the following equation for calculating CSR:

$$CSR = \frac{\tau_{av}}{\sigma'_{vo}} \approx 0.65 \left(\frac{a_{max}}{g}\right) \left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) r_d$$

where

α_{max} : peak horizontal acceleration at the surface of the sediment deposit,

g : gravitational acceleration,

σ_{v0} and σ'_{v0} : total and effective overburden stress, respectively, and

r_d : stress reduction factor.

Evaluation of the cyclic resistance ratio (CRR) has developed either using methods based on the results of laboratory tests, or methods based on in situ tests and field observations of liquefaction behavior in past earthquakes. In laboratory testing, the number of shear stress cycles to achieve liquefaction is the basis for expressing the resistance of sediment to the initiation of liquefaction.

Liu et al. (2001) developed empirical regression equations that can be used to evaluate the number of uniform shear stress cycles of shaking as a function of magnitude, site-source distance, site condition, and near-fault rupture directivity effects, thus the cyclic resistance ratio of the sediment, CRR can be estimated. The potential for liquefaction can then be evaluated by comparing the earthquake loading (CSR) with the liquefaction resistance (CRR) in terms of factor of safety (FS) against liquefaction. Values of FS (= CRR/CSR) greater than one indicate that the liquefaction resistance exceeds the earthquake loading, and therefore, that liquefaction would not be expected.

If the potential for liquefaction is proven to be high, there exist various analytical and empirical methods in the literature for the realistic estimation of vertical (and horizontal) PGDs. If the latter are excessive for the integrity and serviceability of the dam, mitigation measures should be adopted. One option is to apply measures that aim to the reduction of the liquefaction-induced PGDs. This may be achieved by (a) dynamic compaction, (b) preloading, (c) increasing the dissipation of porewater pressure (usually by gravel-columns), (d) grouting and deep soil mixing, and/or (e) lowering the groundwater level (if possible). An expensive alternative is to reduce the liquefaction risk by replacing liquefiable soils in the area of the dam with non-liquefiable materials. Note that in the case of extensive lateral spreading (i.e. horizontal PGDs), the relocation of the dam may be the wiser option since the cost of mitigation measures against lateral spreading is usually prohibitive.

Earthquake-Triggered Slope Instabilities and Rockfalls

As it was mentioned before, the selection of the location of a dam is performed at a preliminary phase of the design with various criteria. Usually, this location is at an area where the risk of landsliding under static conditions is regarded low. Nevertheless, in some cases the area under examination may have a high inclination, while on the other hand a rather stable slope under static conditions may become unstable under certain seismic conditions (i.e. subjected to strong ground motion). Additionally, the existence of rock slopes around the dam may be characterized by rockfalls where great boulders of rock may be dispatched from their initial position (for various reasons) and travel for long distances (e.g. tens or even hundreds of meters), depending on the circumstances and the local site conditions (shape of the boulders, topography, geology, etc.).

Therefore, although slope stability assessment is regarded as a secondary issue for the design of a dam (provided that the dam will not be constructed in areas with steep inclination), a quantitative assessment may be required in cases of inclined areas with high acceleration levels.

Seismic Response of A Dam

The seismic distress of a dam depends mainly on its geometry (i.e. height, inclinations) and its type (i.e. concrete or earth-filled), but many other parameters (such as local soil conditions, water level, etc.) may determine its dynamic/seismic response. In the case of concrete dam (i.e. arch dam or gravity dam), the structural engineers should perform numerical dynamic simulations of the dam in order to estimate the horizontal and vertical inertial (and the hydrodynamic) forces that will develop on the dam mass in the case of the design earthquake. These forces (in addition to gravitational and hydrostatic forces) will lead to the total design stresses and strains that have to be assessed with the highest realism. It is evident that these forces will determine the reinforcement of the concrete. On the other hand, in the case of earth dams soil material nonlinearity and topographic aggravation are key parameters that will dominate the seismic slope stability of the dam body.

According to the modern philosophy of seismic design and the concept of "strain-based design", repairable damages to an earth dam are allowed, provided that the non-collapse requirement has been fulfilled. Therefore, apart from (the static and) the pseudostatic factors of safety, the permanent deformations of the dam should be estimated. The design should try to keep these deformations in low levels in order to achieve the integrity and the serviceability of the dam after the design earthquake. In any case, after a strong earthquake damages have to be identified and repaired as fast as possible since an aftershock may have a detrimental impact. This fact makes realtime monitoring and early-warning systems extremely challenging issues of the dam safety.

The dams usually comprise critical structures, and therefore they must be designed to withstand all the potential loadings and hazards. In areas characterized by moderate or high seismicity this design is more demanding and chalenging since, apart from the typical geohazards, various earthquake-related geohazards should be taken into consideration. The current paper is involved with (a) the quantitative assessment of the main earthquake-related geohazards (such as strong ground motion, earthquake-triggered landslides, soil liquefaction phenomena, and fault rupture) and (b) the optimum seismic design of dams. It becomes evident that in many cases, the simplistic provisions of seismic norms cannot cover sufficiently all the issues of the seismic design. In these cases the geotechnical engineers and the structural engineers, with the help of seismologists and geologists, should perform special surveys and studies to assess quantitatively the earthquake related geohazards and to verify that all the structures and facilities of a dam (including its foundation) are capable to withstand the seismic distress (developed by the inertial forces and/or the induced PGDs). It is evident that in case that the seismic distress is excessive, the engineers should apply mitigation measures in order to reduce the geohazard(s) and/or increase the structural capacity.

References

1-Psarropoulos P.N., 2017, "The seismic risk of new and existing dams" ,E.W. Publications, *European Water* 60: 81-88, 2017.

2-Andrews, D.C.A., Martin, G.R. (2000) Criteria for liquefaction of silty soils. 12th World Conference on Earthquake Engineering,Proceedings, Auckland, New Zealand.

3-Eurocode 8 (2004) Design of structures for earthquake resistance, CEN, European Committee for Standardization, Brussels.

4-IASPEI Handbook. Chapter 42. A List of Deadly Earthquakes in the World: 1500-2000. Tokuji Utsu, The University of Tokyo, Japan

5-Kramer S. (1995). Geotechnical Earthquake Engineering.

6-Liu, A.H., Stewart, J.P., Abrahamson, N.A., Moriwaki, Y. (2001) Equivalent number of uniform stress cycles for soil liquefaction analysis. Journal of Geotechical and Geoenvironmental Engineering, 127(12), 1017– 1026.

7- Papazafeiropoulos G., Tsompanakis Y., Psarropoulos P. N. (2010) Dynamic interaction of concrete dams-reservoir-foundation:Analytical and numerical solutions. In: Computational Methods in Earthquake Engineering, M. Papadrakakis, N.D. Lagaros andM. Fragiadakis (eds.), ECCOMAS Series, Springer.

8- Psarropoulos, P. N., Tazoh, T., Gazetas, G. Apostolou, M. (2007) Linear and non-linear valley amplification effects on seismic ground motion. Soils & Foundations, 47(5), 857-872.

9- Seed, H.B., Idriss, I.M. (1971) Simplified procedure for evaluating soil liquefaction potential. Journal of the Soil Mechanics and Foundations Division, ASCE 97(SM9), 1249–1273.

10 -Engineering Seismology With Applications To Geotechnical Engineering Authors: Öz Yilmaz,Copyright year: 2015,Pages: 964,Publisher: Society of Exploration Geophysicists

11- Principles of the Seismology and Seismic Engineering , Assoc. Prof. RNDr. Dana Prochazkova, PhD., DrSc. ,Czech Technical University in Praha

12 - Sarma S.K.,2013, Engineering Seismology,Civil Engineering Department , Imperial College of Science,Technology & Medicine London SW7 2BU, ISSN 2346-4119