Lecture 5: Concept of Seismic magnitude and Intensity, earthquake size, different magnitude scales and relations.

Topics

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- Comparison of different intensity scales
- Problems associated with Non instrumental measurement
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- Relationship between moment magnitude and various magnitude scales.
- Seismic energy
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Keywords: *Magnitude, Intensity, Earthquake Size, Magnitude scales*

Topic 1

Introduction

- Earthquake size is expressed in several ways. Qualitative or non-instrumental and quantitative or instrumental measurements exist; the latter can be either based on regional calibrations or applicable worldwide. Non-instrumental measurements are of great importance for pre-instrumental events and are hence essential in the compilation of historical earthquake catalogues for purposes of hazard analysis.

- For earthquakes that have been instrumentally recorded, qualitative scales are complementary to the instrumental data. The assessment and use of historical records is not straightforward and may lead to incorrect results due to inevitable biases.

- Seismograms recorded at different epicentral distances are employed to determine origin time, epicenter, focal depth and type of faulting as well as to estimate the energy released during an earthquake.

- Descriptive methods can also be used to establish earthquake –induced damage and its spatial distribution.

Topic 2

Intensity

- Intensity is a non-instrumental perceptibility measure of damage to structures, ground surface effects and human reactions to earthquake shaking. It is a descriptive method which has been traditionally used to establish earthquake size, especially for pre-instrumental events.

- Discreet scales are used to quantify seismic intensity, the levels are represented by Roman numerals and each degree of intensity provides a qualitative description of earthquake effects. Early attempts at classifying earthquake damage by intensity were carried out in Italy and Switzerland around the late 1700s and early 1900s.

- Earthquake intensities are usually obtained from interviews of observers after the event. Since human observers and structures are scattered more widely than any seismological observatory could reasonably hop to scatter instruments, intensity observations provide information that helps characterize the distribution of ground shaking in a region.

- A plot of reported intensities at different locations on a map allows contours of equal intensity, or isoseisms, to be plotted. Such a map is called isoseismal map. The intensity is generally greatest in the vicinity of the epicenter of the earthquake, and the term epicentral intensity is often used as a crude description of earthquake size. Isoseismal maps show how the intensity decreases, or attenuates, with increasing epicentral distance.

- Some of the most common intensity scales are:
    1. Mercalli-Cancani-Seiberg (MCS): 12-level scale used in southern Europe
    2. Modified Mercalli (MM): 12-level scale proposed in 1931 by wood and Neumann, who adapted the MCS scale to the California data set. It is used in North America and several other countries
    3. Medvedev-Sponheuer-Karnik (MSK): 12-level scale developed in Central and Eastern Europe and used in several other countries
    4. European Macroseismic Scale (EMS): 12-level scale adopted since 1998 in Europe. It is a development of the MM scale
    5. Japanese Meteorological Agency (JMA): 7-level scale used in Japan. It has been revised over the years and has recently been correlated to maximum horizontal acceleration of the ground.

- These intensity scales are listed in the Table 5.1 (a-e)

- Comparison of these intensity scales are given in Table 5.2

Table 5.1 (a): Mercalli-Cancani-Seiberg (MCS)

I.	Instrumental	Not felt by many people unless in favorable conditions.
II.	Weak	Felt only by a few people at best, especially on the upper floors of buildings. Delicately suspended objects may swing.
III.	Slight	Felt quite noticeably by people indoors, especially on the upper floors of buildings. Many do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration similar to the passing of a truck. Duration estimated.
IV.	Moderate	Felt indoors by many people, outdoors by few people during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rock noticeably. Dishes and windows rattle alarmingly.
V.	Rather Strong	Felt outside by most, may not be felt by some outside in non-favorable conditions. Dishes and windows may break and large bells will ring. Vibrations like large train passing close to house.
VI.	Strong	Felt by all; many frightened and run outdoors, walk unsteadily. Windows, dishes, glassware broken; books fall off shelves; some heavy furniture moved or overturned; a few instances of fallen plaster. Damage slight.
VII.	Very Strong	Difficult to stand; furniture broken; damage negligible in building of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken. Noticed by people driving motor cars.
VIII.	Destructive	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture moved.
IX.	Violent	General panic; damage considerable in specially designed structures, well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
X.	Intense	Some well built wooden structures destroyed; most masonry and frame structures destroyed with foundation. Rails bent.
XI	Extreme	Extreme Few, if any masonry structures remain standing. Bridges destroyed. Rails bent greatly.
XII	Cataclysmic	Total damage - Everything is destroyed. Total destruction. Lines of sight and level distorted. Objects thrown into the air. The ground moves in waves or ripples. Large amounts of rock move position. Landscape altered, or leveled by several meters. In some cases, even the route of rivers is changed.

Table 5.1 (b): Modified Mercalli (MM)

I.	Not felt except by a very few under especially favorable conditions
II.	Felt only by a few persons at rest, especially on upper floors of buildings.
III.	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.
IV.	Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
V.	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
VI.	Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
VII.	Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
VIII.	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
IX.	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations
X.	Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
XI.	Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
XII.	Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Table 5.1 (c): Medvedev-Sponheuer-Karnik (MSK)

I.	Not perceptible	Not felt, registered only by seismographs. No effect on objects. No damage to buildings.
II.	Hardly perceptible	Felt only by individuals at rest. No effect on objects. No damage to buildings
III.	Weak	Felt indoors by a few. Hanging objects swing slightly. No damage to buildings.
IV.	Largely observed	Felt indoors by many and felt outdoors only by very few. A few people are awakened. Moderate vibration. Observers feel a slight trembling or swaying of the building, room, bed, chair etc. China, glasses, windows and doors rattle. Hanging objects swing. Light furniture shakes visibly in a few cases. No damage to buildings.
V.	Fairly strong	Felt indoors by most, outdoors by few. A few people are frightened and run outdoors. Many sleeping people awake. Observers feel a strong shaking or rocking of the whole building, room or furniture. Hanging objects swing considerably. China and

		glasses clatter together. Doors and windows swing open or shut. In a few cases window panes break. Liquids oscillate and may spill from fully filled containers. Animals indoors may become uneasy. Slight damage to a few poorly constructed buildings.
VI.	Strong	Felt by most indoors and by many outdoors. A few persons lose their balance. Many people are frightened and run outdoors. Small objects may fall and furniture may be shifted. Dishes and glassware may break. Farm animals may be frightened. Visible damage to masonry, structures cracks in plaster. Isolated cracks on the ground.
VII.	Very strong	Most people are frightened and try to run outdoors. Furniture is shifted and may be overturned. Objects fall from shelves. Water splashes from containers. Serious damage to older buildings, masonry chimneys collapse. Small landslides.
VIII.	Damaging	Many people find it difficult to stand, even outdoors. Furniture may be overturned. Waves may be seen on very soft ground. Older structures partially collapse or sustain considerable damage. Large cracks and fissures opening up, rockfalls.
IX.	Destructive	General panic. People may be forcibly thrown to the ground. Waves are seen on soft ground. Substandard structures collapse. Substantial damage to well-constructed structures. Underground pipelines ruptured. Ground fracturing, widespread landslides.
X.	Devastating	Masonry buildings destroyed, infrastructure crippled. Massive landslides. Water bodies may be overtopped, causing flooding of the surrounding areas and formation of new water bodies.
XI.	Catastrophic	Most buildings and structures collapse. Widespread ground disturbances, tsunamis.
XII.	Very catastrophic	All surface and underground structures completely destroyed. Landscape generally changed, rivers change paths, tsunamis.

Table 5.1 (d): European Macro-seismic Scale (EMS)

I.	Not felt	Not felt, even under the most favorable circumstances.
II.	Scarcely felt	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.
III.	Weak	The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.
IV.	Largely observed	The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.
V.	Strong	The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Top heavy objects topple over. Doors and windows swing open or shut.

VI.	Slightly damaging	Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings; for example, fine cracks in plaster and small pieces of plaster fall.
VII.	Damaging	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.
VIII.	Heavily damaging	Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.
IX.	Destructive	Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.
X.	Very destructive	Many ordinary buildings collapse.
XI.	Devastating	Most ordinary buildings collapse.
XII.	Completely devastating	Practically all structures above and below ground are heavily damaged or destroyed.

Table 5.1 (e): Japanese Meteorological Agency (JMA)

0	Imperceptible to people. Less than 0.008 $\mathrm{m/s^2}$
1	Felt by only some people in the building. 0.008–0.025 $\mathrm{m/s^2}$
2	Felt by many people in the building. Some sleeping people awake. 0.025–0.08 $\mathrm{m/s^2}$
3	Felt by most people in the building. Some people are frightened. 0.08–0.25 $\mathrm{m/s^2}$
4	Many people are frightened. Some people try to escape from danger. Most sleeping people awake. 0.25–0.80 $\mathrm{m/s^2}$
5−	Most people try to escape from danger, some finding it difficult to move. 0.80–1.40 $\mathrm{m/s^2}$
5+	In many cases, unreinforced concrete-block walls collapse and tombstones overturn. Many automobiles stop due to difficulty in driving. Occasionally, poorly installed vending machines fall. 1.40–2.50 $\mathrm{m/s^2}$
6−	In some buildings, wall tiles and windowpanes are damaged and fall. 2.50–3.15 $\mathrm{m/s^2}$
6+	In many buildings, wall tiles and windowpanes are damaged and fall. Most unreinforced concrete-block walls collapse. 3.15–4.00 $\mathrm{m/s^2}$
7	In most buildings, wall tiles and windowpanes are damaged and fall. In some cases, reinforced concrete-block walls collapse. Peak ground acceleration greater than 4 $\mathrm{m/s^2}$

Topic 3

Comparison of different intensity scales

Table 5.2: Comparison of different intensity scales

Damage %	Rossi-Forel	Modified Mercalli	JMA	MSK
	I	I	0	I
		II		
			I	
				II
	II			III
	III	III		
				IV
	IV	IV	II	
	V			
			III	
				V
		V		VI
	VI			
0-		VI	IV	
				VII
	VII			
			V	
				VIII
10- 20-	VIII	VII		
30-	IX			
			VI	
				IX
		VIII		
				X
		IX		
40-	X	X	VII	
50- 60-				XI
70-				XII
90-		XI		
		XII		

Table 5.3: Intensity of Earthquake expressed by Radius of the felt area

Radius (km)	Earthquake intensity
R < 100	Local
100 < R < 200	Small Region
200 < R < 300	Rather conspicuous
R > 300	Conspicuous

- Intensity scales include description of construction quality for structures in the exposed region. Intensity scales do not account for local soil conditions, which may significantly affect the earthquake-induced damage and its distribution.

- Intensity value I_o at the epicenter, or 'epicentral intensity', is equal to the maximum intensity I_{max} felt during ground motion. However, for offshore earthquakes I_{max} is recorded on the coast and hence does not correspond to I_o.

- In JMA scales the intensity of earthquakes can also be expressed by the radius R of the felt area as shown in Table 5.3. Epicentral regions in perceptible earthquakes experience ground motions ranked not less than intensity V in the JMA scale.

- The intensity is generally greatest in the vicinity of the epicenter of the earthquake, and the term epicentral intensity is often used as a crude description of earthquake size.

- The basis for establishing the EMS was the MSK scale, which preceded it one of a family of intensity scales which originated with the widely used simple ten degree scale by Rossi and Forel this was revised by Mercalli, subsequently expanded by Cancani to twelve degrees, and then defined in a very full way be Sieberg as the Mercalli-Cancani-Sieberg (MCS) scale.

- The major difference between the EMS-98 and other intensity scales is in the detail with which different terms used are defined at the outset, in particular, building types, damage grades etc.

- The equations relating the ground acceleration to the seismic intensity level are presented in Table: 5.4

Table 5.4: Proposed Equations relating Peak Acceleration and Seismic Intensity

Study	Proposed Equations*
Gutenberg and Ritcher (1942 and 1956)	Log $a_h = 0.333\ I_{mm} - 0.500$
Kawasumi (1951)	Log $a_h = 0.500\ I_{jma} - 0.347$
Neumann (1954)	Average distance of 25 kilometers Log $a_{max} = 0.308\ I_{mm} - 0.041$ Average distance of 160 kilometers Log $a_{max} = 0.308\ I_{mm} - 0.429$
Hershberger (1956)	Log $a_h = 0.429\ I_{mm} - 0.900$
Medvedev and Sponheuer (1969)	Log $a_{max} = 0.301\ I_{mm} - 0.408$
Coulter, WSaldron and Devine (1973)	Correlation assumes a strong dependence between acceleration and site geology and site amplification factors and is not placed in equation from conveniently.
Ambraseys (1974)	Log $a_{h\ max} = 0.36\ I_{mm} - 0.16$ Log $a_v = 0.38\ I_{mm} - 0.55$
Trifunac and Brady (1975)	Log $a_h = 0.30\ I_{mm} + 0.014$ Log $a_v = 0.30\ I_{mm} - 0.180$

*I_{mm} - intensity measured on Modified Mercalli scale
I_{jma} – intensity measured on Japanese Meteorological Agency scale
a_h – average horizontal component peak acceleration in cm/sec^2
a_{max} – maximum peak acceleration in cm/sec^2
a_v – vertical component peak acceleration in cm/sec^2
a_{hmax} – maximum horizontal peak acceleration in cm/sec^2

Topic 4

Problems associated with Non instrumental measurement

- The assessment of earthquake intensity on a descriptive scale depends on actual observations of effects in the meizoseismal zone, not on measuring the ground motion with instruments.

- At a particular town or village, the effect reflecting the greatest intensity is often chosen, thus increasing the local rating of the earthquake.

- A particular difficulty is the use of landslides caused by earthquakes. The modified Mercalli scale gives landslides a rating of intensity X, but the fact is that landslides are common in many regions even non-seismic area and quiet small seismic shaking is known to be an effective landslide trigger.

- During the study of intensity of an earthquake, questionnaires are often circulated to inhabitants of the affected region. Based on the responses to these questionnaires, isoseismal maps are drawn. Isoseismal maps show how the intensity decreases, or attenuates, with increasing epicentral distance.

- Isoseismal maps indicate the effect of the underlying irregular rock layers and surficial soil on the intensity of shaking. Figure 5.1 clearly shows the harder rock in the hills coincides with an area of rather low damage to structures whereas high intensities occurred on the filled lands around the Bay Shore.

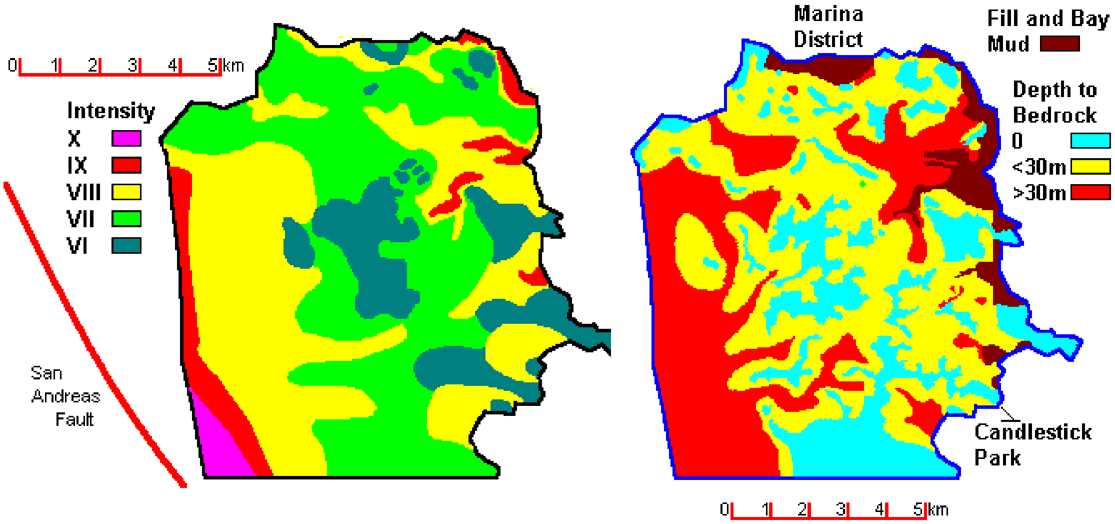

Fig 5.1 Intensity and Bedrock Depth in San Francisco, 1906

- The intensity of earthquake shaking varies from place to place even in local area due to changes in rock structure and properties, the soil properties often play a dominant role.

- Soft soils particularly when water saturated, often slide, slip, or lose their cohesive strength when shaken, resulting in building foundations moving, cracking or subsiding. But, in addition, the incoming seismic waves that are shaking the underlying rock are modified by the different elastic properties of any soil layers above it.

- Because no instrumental measurements are made, historical accounts are used to estimate intensity values for pre-instrumental earthquakes which are not straightforward and may lead to incorrect results due to inevitable biases.

Topic 5

Magnitude

- A quantitative measure is needed to compare the size of earthquakes worldwide, which is independent of the density of population and type of construction. Magnitude is the quantitative measurement of the amount of energy released by an earthquake.

- Richter (1935) magnitude of a local earthquake is a logarithm base 10 of the maximum seismic wave amplitude recorded on a standard seismograph at a distance of 100 km from the epicenter. As earthquake sources are located at all distances from seismographic stations, Richter further developed a method of making allowance for the attenuation.

- Richter scale magnitude is calibrated in such a way that ML = 3 corresponds to an earthquake about a distance of 100 km with maximum amplitude of A = 1mm. The most common modern magnitude scales are surface wave magnitude and body wave magnitude. Richter's local magnitude does not distinguish between different types of waves.

Topic 6

Richter Magnitude (or Local Magnitude) ML

- Richter (1935) defined the local magnitude ML of an earthquake observed at a station to be

$$ML = \log A - \log A_o(\Delta) \qquad (5.1)$$

- Where A is the maximum amplitude in millimeters recorded on the Wood-Anderson seismograph for an earthquake at epicentral distance of Δ km, and Ao (Δ) is the maximum amplitude at Δ km for a standard earthquake.

- The local magnitude is thus a number characteristic of the earthquake, and independent of the location of the recording station. Three arbitrary choices are made in the above definition:
  - (i) the use of standard Wood-Anderson seismograph,
  - (ii) the use of common logarithms to the base 10, and
  - (iii) Selection of the standard earthquake whose amplitudes as a function of distance are represented by Ao (Δ).

- The zero level of Ao (Δ) can be fixed by choosing its value at a particular distance. Richter chose the zero level of Ao (Δ) to be 1 μm (or 0.001 mm) at a distance of 100 km from the earthquake epicentre. Thus, an earthquake with trace amplitude A = 1mm recorded on a standard Wood-Anderson seismograph at a distance of 100 km is assigned magnitude 3.

- Richter arbitrarily chose –log Ao = 3 at Δ = 100 km so that the earthquakes do not have negative magnitudes. In other words, to compute ML a table of –log Ao as a function of epicentral distance in kilometers is needed. Based on observed amplitudes of a series of well located earthquakes the table of –log Ao as a function of epicentral distance is given by Richter (1958).

- In practice, we need to know the approximate epicentral distance of an earthquake, which can be estimated from S-P time. The maximum trace amplitude on a standard Wood-Anderson seismogram is then measured in millimeters, and its logarithm to base 10 is taken.

- This number is then added to the quantity tabulated as –log Ao for the corresponding station-distance from the epicentre. The sum is a value of local magnitude for that seismogram. Since there are two components (EW and NS) of Wood Anderson seismograph, average of the two magnitude values may be taken as the station magnitude. Then average of all the station magnitudes is an estimate of the local magnitude ML for the earthquake.

- The S-P time and the maximum trace amplitude on the seismogram are used to obtain ML = 5.0 in this example. In Richter's procedure, the largest amplitude recorded on the seismogram is taken.

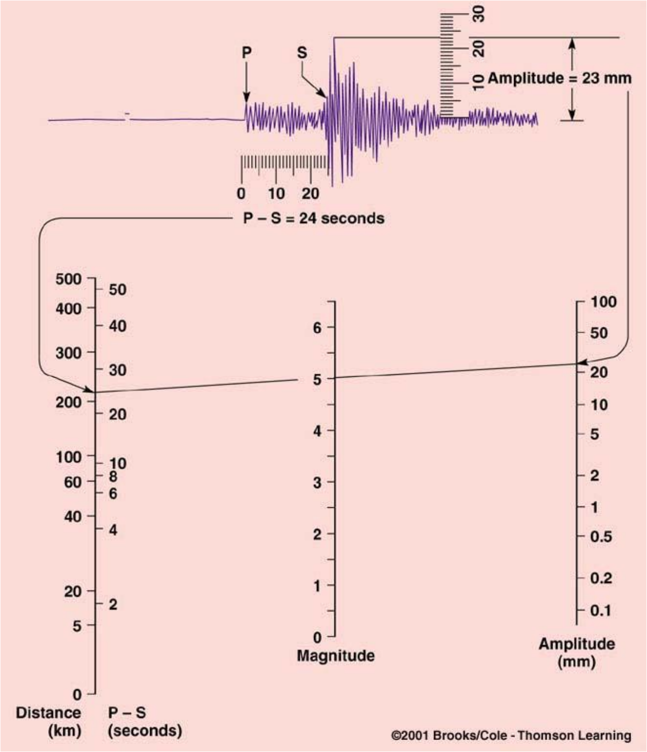

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Fig 5.2: Example of estimating Richter magnitude (ML) of a local earthquake

- Procedure: measure the S-P interval (=24 seconds), maximum amplitude (= 23 mm), and draw a straight line between the appropriate points on the distance (left) and amplitude (right) scales to obtain ML = 5.0 (See Fig 5.2).

- It follows from its definition that there is no upper or lower limit in the magnitude scale. The size of an earthquake is, however, limited by the strength of rocks in the Earth's crust. The maximum size of an earthquake that has been recorded in south Asia is 8.9 in the Richter magnitude scale December 26, 2004 Sumatra earthquake, IMD report, 2005).

- The Richter magnitude, however, gets saturated at this level. In such cases moment magnitude may be more stable, and the moment magnitude of the Sumatra earthquake was estimated to 9.3.

Topic 7

Other types of magnitudes

Duration Magnitude (Md)

- Analog paper or film recordings have limited dynamic range. These records are often clipped for strong or even medium magnitude local seismic events. This makes magnitude determination from Amax impossible. Therefore, alternative magnitude scale such as Md was developed.

- This scale is based on signal duration. It is almost routinely used in micro earthquake surveys.

Macroseismic Magnitude (Mms)

- Macroseismic magnitudes (Mms) are particularly important for analysis and statistical treatment of historical earthquakes. There are three main ways to compute Mms:
  (i) Mms is derived from maximum reported intensity as:

$$Mms = aI_o + b \tag{5.2}$$

or when focal depth (h) is known

$$Mms = cI_o + \log h + d \tag{5.3}$$

(ii) Mms is derived from the total area (A) of perceptibility as:

$$Mms = e \log AI_i + f \tag{5.4}$$

where AIi in km^2 shaken by intensities Ii with i > III, and a, b, c and d are constants. Examples of regionally best fitting relationships are published for California Italy Australia.

For Europe we get best results using

$$Mms = 0.5I_o + \log h + 0.35 \tag{5.5}$$

(iii) Another Mms is related to the product P = Io × A (km^2), which is independent of the focal depth:

$$Mms = \log P + 0.2(\log P - 6) \tag{5.6}$$

Topic 8

Teleseismic Magnitude scales

Body Wave Magnitude (m_b)

- It is now a routine practice in seismology to measure the amplitude of the P-wave which is not affected by the focal depth, and thereby determine P-wave or body-wave magnitude (mb). Gutenberg (1945a) defined body wave magnitude mb for teleseismic body waves P and PP in the period range 0.5 to 12 s,

$$m_b = \log(A/T) - f(\Delta, h) \tag{5.7}$$

- where A/T is amplitude-to-period ratio in micrometres per second, and f (Δ,h) is a calibration function of epicentral distance in degree and focal depth h in kilometre.

- It is recommended that the largest amplitude be taken within the first few cycles instead of considering the whole P-wave train (Willmore, 1979). Both the ISC and NEIC, however, determine body wave magnitude only from vertical component short period P-wave readings of T<3 s.

Surface Wave Magnitude (Ms)

- For shallow and distant earthquakes, a surface wave train is present that is used for estimation of surface wave magnitude Ms. Gutenberg (1945b) defined the surface wave magnitude Ms as:

$$Ms = \log A_{H\max} - \log A_o(\Delta°) \tag{5.8}$$

- where A_{Hmax} is the maximum combined horizontal ground amplitude in micrometres for surface waves with a period (T) of 20 + 2 second, and (–log Ao) is a calibration function that is tabulated as a function of epicentral distance Δ in degrees in a similar manner to that for local magnitude.

- In a collaborative research Karnik et al. (1962) proposed a new Ms scale as below:

(5.9)

$$Ms = \log(A/T) + 1.66 \log \Delta + 3.3$$

- For epicentral distances 2° < Δ < 160° and source depth h < 50 km. The IASPEI committee on magnitudes recommended at its Zurich meeting in 1967 the use of this formula as standard for Ms Determination for shallow seismic events (h < 50 km). Today, both ISC and NEIC use the above equation for determination of Ms. The ISC accepts surface waves with period 10-60 s from stations at a distance range 20°-160°.

- A difficulty in using the surface-wave magnitude-scale is that it can be applied only for the shallow earthquakes that generate observable surface waves. For shallow focus earthquakes, an approximate relation between mb for P-waves and Ms is given by:

$$mb = 2.5 + 0.63Ms \tag{5.10}$$

Topic 9

Magnitude discrepancies

- Discrepancies arise among magnitudes as derived from local earthquake data (ML), body waves (MB) and surface waves (MS). The relation of ML to the others is as yet not definitive; but MS – mB = a (MS – b).

- The latest revision gives a = 0.37, b = 6.76. Pending further research it is recommended that ML continue to be used as heretofore, but MS (and ultimately ML) should be referred to mB as a general standard, called the unified magnitude and denoted by m. Tentatively log E = 5.8 + 2.4 m.

- A necessary correction for relating local network magnitude scales to Richter's local magnitude (ML) involves accounting for the shape of the far-field body-wave spectrum of the phases used for determining magnitude. When not corrected for, this effect causes errors of about one magnitude unit at ML ~3 for some southern California earthquakes.

- The discrepancy should be comparable for ML > 3, but at smaller magnitudes will decrease with decreasing ML. It may be corrected for either by direct comparison of network scales with magnitudes determined from Wood-Anderson seismograms, or by spectrum measurements over a range of magnitudes.

- The nature of the discrepancy and the corrections required to account for it are demonstrated by an example, the aftershocks of the 1968 Borrego Mountain, California earthquake.

- Among the various source parameters shown in Table 5.5, we use the surface-wave magnitude Ms, the seismic moment Mo (or the corresponding moment magnitude Mw = (log Mo – 16.1)/1.5), the fault length L, and the fault width W.

- The surface-wave magnitude, Ms, is the most widely used parameter and is available for very old events as well as recent events. Although the seismic moment, Mo, is not available for some of the old events, it directly represents the overall size of the source (Mo= μDS, where μ = rigidity, D= fault offset, S= fault area), and allows more quantitative interpretations of the data than does the magnitude.

Table 5.5: Earthquake Source Parameters

Event	M_S	M_W	M_O (10^{27} dyne – cm)	L (km)	W (km)	S (km^2)	t (years)
Alaska(1958)	7.9	7.8	7.0	300	16	4800	60-110
Borah peak(1983)	7.3	7.0	0.34	30	18	540	5600
Borrego Mt. 1968	6.7	6.6	0.1	40	13	520	100
Coyote lake,1979	5.7	5.6	0.0035	25	8	200	75
Daofu,1981	6.8	6.7	0.13	46	10	460	100
Guatemala	7.5	7.5	2.6	250	15	3750	180-755
Haiyuan, 1920	806			220			700-1000
Hebegeb Lake, 1959	7.5	7.3	1.0	30	15	450	2800±1100
Imperial valley, 1979	6.5	6.5	0.006	42	10	420	40
Izu, 1930	7.2	6.9	0.25	22	12	264	700-1000
Izu- Oki,1974	6.5	6.4	0.059	20	11	220	1000
Kern County, 1952	7.7	7.3	1.0	70	20	1400	170-450
Luhuo, 1973	7.4	7.4	1.8	110	15	1650	100
Mikawa, 1945	6.8	6.6	0.087	12	11	132	2000-4x10^4
Morgan Hill, 1984	6.1	6.1	0.02	30	10	300	75
N. Anatolian, 1939	7.8			350	15	5250	150-200
N. Anatolian, 1943	7.6			265	15	3975	150-200
N. Anatolian, 1944	7.4			190	15	2850	150-200
Niigata,1964	7.5	7.6	3.0	60	25	1500	560
Parkfield, 1966	6.0	6.0	0.014	30	13	390	22
Pleasant valley, 1915	7.7			62			5000
San Fernando,1971	6.6	6.7	0.12	17	17	289	100-300
Tabas, 1978	7.4	7.4	1.5	65	20	1300	>1300
Tango, 1927	7.6	7.0	0.46	35	13	455	2000-6x10^4
Tangshan, 1976	7.8	7.4	1.8	80	15	1200	>2000
Tottoro, 1943	7.4	7.0	0.36	33	13	429	6000

Topic 10

Why don't magnitude scales agree?

- Many of these scales are frequency-dependent because they measure amplitudes of seismic waves with different properties. Scales related directly to source parameters have also been proposed. These do not depend on specific waves and hence are frequency-independent.

- Richter magnitude M_L exhibits several limitations. It is applicable only to small and shallow earthquakes in California and for epicentral distances less than 600 km. it is, therefore, a regional scale, while m_b, M_S, and M_W are world wide scales.

Table 5.6: Applicability of Different Magnitude Scales

Scale Type	Author	Earth quake Size	Earth quake Depth	Epicentral distance (km)	Reference parameter	Applicability	Saturation
M_L	Richter (1935	Small	Shallow	<600	Wave amplitude	Regional (California)	Saturation occurs
m_b	Gutenberg and Richter (1956)	Small-to-medium	Deep	>1,000	Wave amplitude (P-waves)	Worldwide	Saturation occurs
M_S	Richter and Gutenberg (1936)	Large	Shallow	>2,000	Wave amplitude (LR-waves)	Worldwide	Saturation occurs
M_W	Kanamori (1977)	All	All	All	Seismic moment	Worldwide	N.A.

- The mathematical definition of magnitude implies that all the scales shown in Table 5.6 have virtually no upper and lower bounds. Notwithstanding, the upper bound is provided by strength of materials in the Earth's crust and the characteristics of the waves measured, while minimum values of magnitude that may be recorded by sensitive seismographs are around -2.

- As a general guideline earthquakes with magnitude between 4.5 and 5.5 can be defined as local, while large seismic events generally have a magnitude 6.0 to 7.0. Great earthquakes are those with magnitude larger than 7.0.

- The ranges for the various magnitude scales represent not only the observational errors but also the intrinsic variations. A magnitude scale represents a gross property of earthquakes and because of the intrinsic variations in the source properties such as the stress drop, complexity, fault geometry and size, and depth, considerable variations in the inter-magnitude relations are expected.

Topic 11

Saturation and causes of Saturation

- Earthquakes of different size and energy release may have the same magnitude. Typical examples are the 1906 San Francisco (California) and the 1960 Chile earthquake. Both events showed Ms = 8.3. However the fault rupture area in Chile was about 35 times greater than that observed in California. Different fault rupture lengths correspond to different amounts of energy released; moment magnitude accounts for the extent of fault rupture.

- The moment magnitude Mw is about 8 for the San Francisco fault while the Chile earthquake has a moment magnitude Mw of 9.5. Magnitude scales do not increase monotonically with earthquake size. This observation is known as 'saturation' and affects all scales that are related to seismic waves of particular period and wavelength, i.e. frequency-dependent scales.

Causes of Saturation

- Up to magnitude 7 the frequency of occurrence of earthquakes decreases exponentially with their size as described by

$$\log N = a - bM \tag{5.11}$$

- Where N is the number of earthquakes per year of magnitude, M, and a and b are constants. Above magnitude 7 there is a saturation effect which causes the frequency of occurrence to be less than the above equation predicts. No earthquake of Richter magnitude 9 or larger has ever been observed.

- Since the distance corrections depend on geology each region must have a slightly different definition of local magnitude. Also, since at different distances we rely on different waves to measure the magnitude, the estimates of earthquake size don't always precisely agree. Also, deep earthquakes do not generate surface waves as well as shallow earthquakes and magnitude estimates based on surface waves are biased low for deep earthquakes.

- Also, measures of earthquake size based on the maximum ground shaking do not account for another important characteristic of large earthquakes - they shake the ground longer.

- Consider the example shown in the Fig 5.3. The two seismograms are the P-waves generated by magnitude 6.1 and 7.7 earthquakes from Kamchatka. The body-wave magnitude for these two earthquakes is much closer because the rule for estimating body-wave magnitude is to use the maximum amplitude in the first five seconds of shaking.

- As you can see, the difference in early shaking between the two earthquakes is much less than the shaking a little bit later which indicates the larger difference in size.

- Even after 5 seconds the amplitude ratio of these P waves does not accurately represent the difference in size of these two earthquakes. The magnitude 6.1 event probably ruptured for only a few seconds, the magnitude 7.7 ruptured for closer to a minute.

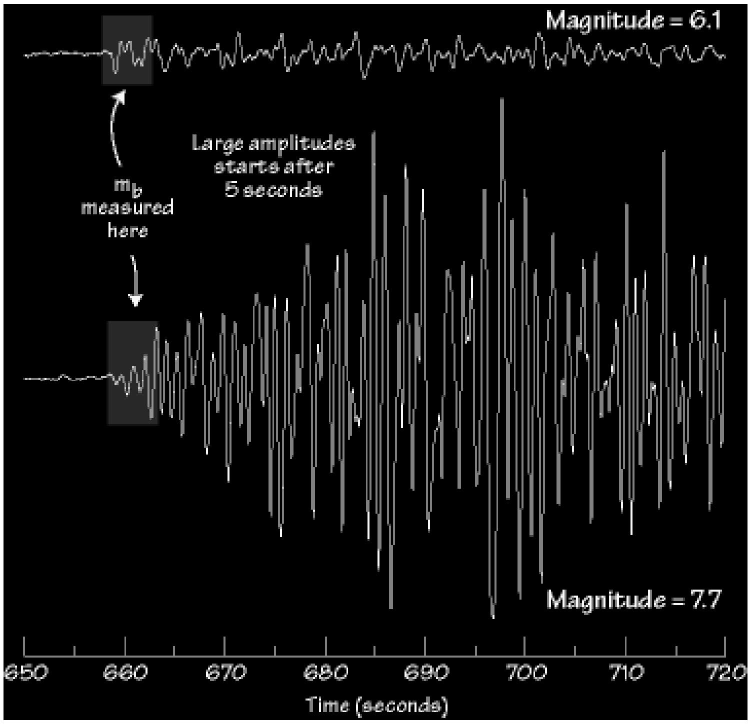

Fig 5.3: P-waves generated by magnitude 6.1 and 7.7 earthquakes from Kamchatka

Topic 12

Are m_b and M_s Still useful?

- For values of magnitude of about 5.5, scales m_b and Ms coincide; for smaller earthquakes, e.g. Mw<5.5, m_b >Ms, while for large magnitude Ms> m_b. Thus, surface wave magnitudes underestimate the size of small earthquakes while they overestimate the size of large events.

- Magnitudes m_b and Ms saturate at about 6.5 and 8.5 respectively. The Richter scale stops increasing at Mw=7.0. Mw does not suffer from saturation problems in the practical range of magnitude of 2<Mw<<10. Therefore, it can be employed for all magnitudes.

- For shallow earthquakes use of M_D referred to as ‘coda-length magnitude’, for magnitudes less than 3, either ML or m_b for magnitudes between 3 and 7, and MS for magnitudes between 5 and 7.5.

Topic 13

Seismic Moment Mo and Moment Magnitude

- For a gross description of earthquake size and character, seismologists use two terms seismic moment and stress drop. A full understanding of the concept of seismic moments is required: a driving force has a particular direction in three-dimensional space and will drive motion on a two dimensional fault that has its own orientation.

- An earthquake involves the interaction of the blocks of crust on opposite sides of a fault, a mechanical process that can be characterized by a torque, or seismic moment. Scalar moment can be shown to be equal to the multiplicative product of three terms: the area of the rupture, the slip produced by the earthquake, and a measure of material strength known as shear resistance

- If the smallest felt earthquake were normalized to have a moment of 1, the largest earthquakes that occur would have a moment of 1,000,000,000. Although seismic moment best characterizes the size of an earthquake, the quantity is unwieldy, especially for use outside the scientific community.

- Seismic moment is a quantity used by earthquake seismologists to measure the size of an earthquake. The scalar seismic moment M0 is defined by the equation

$$M_0 = \mu AD \tag{5.12}$$

- μ is the shear modulus of the rocks involved in the earthquake (in dyne / cm2), A is the area of the rupture along the geologic fault where the earthquake occurred (in cm2), and D is the average displacement on A (in cm).

- The seismic moment of an earthquake is typically estimated using whatever information is available to constrain its factors. For modern earthquakes, moment is usually estimated from ground motion recordings of earthquakes known as seismograms. For earthquakes that occurred in times before modern instruments were available, moment may be estimated from geologic estimates of the size of the fault rupture and the displacement.

- Seismic moment is the basis of the moment magnitude scale introduced by Hiroo Kanamori, which is often used to compare the size of different earthquakes and is especially useful for comparing the sizes of especially large (great) earthquakes.

Moment Magnitude

- For large earthquakes the Richter as well as body wave magnitude scales saturate. No matter how large the earthquake is, the magnitude computed from body waves tend not to get much above 6.0 to 6.5.

- The surface-wave scale is less affected by this problem, but for very large earthquakes M>8 the surface-wave scale also gets saturated. It turns out that the limitation is in the instrument recording the earthquake.

- The moment magnitude scale (abbreviated as MMS; denoted as MW) is used by seismologists to measure the size of earthquakes in terms of the energy released. The magnitude is based on the moment of the earthquake, which is equal to the rigidity of the Earth multiplied by the average amount of slip on the fault and the size of the area that slipped.

- The scale was developed in the 1970s to succeed the 1930s-era Richter magnitude scale (ML). Even though the formulae are different, the new scale retains the familiar continuum of magnitude values defined by the older one. The MMS is now the scale used to estimate magnitudes for all modern large earthquakes by the United States Geological Survey.

- The symbol for the moment magnitude scale is Mw, with the subscript w meaning mechanical work accomplished. The moment magnitude Mw is a dimensionless number defined by

  $$M_w = \frac{2}{3}\log 10 M_0 - 10.7 \qquad (5.13)$$

  where M_0 is the magnitude of the seismic moment in dyne centimeters (10−7 Nm). The constant values in the equation are chosen to achieve consistency with the magnitude values produced by earlier scales, most importantly the Local Moment (or "Richter") scale.

- As with the Richter scale, an increase of 1 step on this logarithmic scale corresponds to a 101.5 ≈ 32 times increase in the amount of energy released, and an increase of 2 steps corresponds to a 103 = 1000 times increase in energy.

- The moment magnitude scale is consistent with ML: 3-6, Ms: 5-8. The moment magnitude Mw has the advantages that it does not saturate at the top of the scale, and it has a sound theoretical basis than ML or Ms. However, for moderate magnitude shallow focus damaging earthquakes, it is sufficient for engineering purposes to take ML, Ms and Mw to be roughly the same.

Topic 14

Magnitude Summary

- Symbols used to represent the different magnitudes are given in Table 5.7
- Earthquake effects and number of events per year is presented in Table 5.8

Table 5.7: symbols used to represent the different magnitudes

Magnitude	Symbol	Wave	Period
Local (Richter)	M_L	S or Surface Wave*	0.8 s
Body-Wave	m_b	P	1 s
Surface-Wave	M_s	Rayleigh	20 s
Moment	M_w	Rupture Area, Slip	> 100 s

*at the distances appropriate for local magnitude, either the S-wave or the surface waves generally produce the largest vibrations.

Table 5.8: Earthquake Magnitude Scale

Magnitude	Earthquake Effects	Estimated Number Each Year
2.5 or less	Usually not felt, but can be recorded by seismograph.	900,000
2.5 to 5.4	Often felt, but only causes minor damage.	30,000
5.5 to 6.0	Slight damage to buildings and other structures.	500
6.1 to 6.9	May cause a lot of damage in very populated areas.	100
7.0 to 7.9	Major earthquake. Serious damage.	20
8.0 or greater	Great earthquake. Can totally destroy communities near the epicenter.	One every 5 to 10 years

- Earthquake Magnitude Classes - Earthquakes are also classified in categories ranging from minor to great, depending on their magnitude shown in Table 5.9.

Table 5.9: Earthquake Magnitude Classes

Class	Magnitude
Great	8 or more

Major	7 - 7.9
Strong	6 - 6.9
Moderate	5 - 5.9
Light	4 - 4.9
Minor	3 -3.9

Topic 15

Relationship between moment magnitude and various magnitude scales.

- Figure 5.4 shows a comparison between different magnitude scales. Saturation is evident as Mw increases (Mw>6.5).

- Another magnitude scale, i.e. m_B is included in the plot; m_B is a body wave scale measuring different types of body waves with periods between 1.0 and 10 seconds and is distinct from m_b.

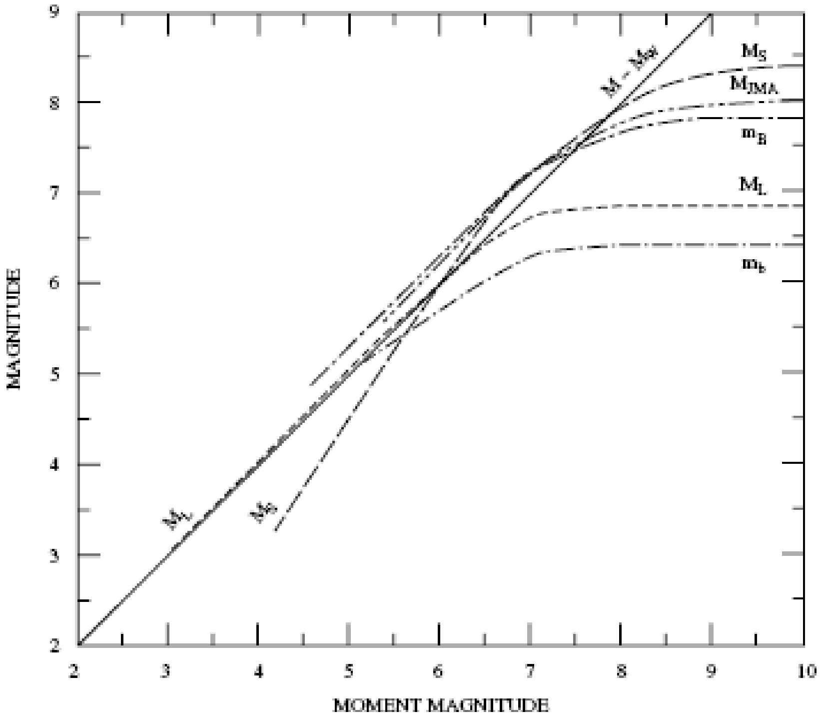

Fig 5.4: Comparison between different magnitude scales

- Both scales are still used, but the Moment Magnitude scale is gradually replacing the Richter scale and is preferred now by most seismologists. The numbers generated by the two scales are usually very similar. For example, the earthquake in Northridge California in 1994 measured 6.4 on the Richter and 6.7 on the Moment Magnitude scale.

Topic 16

Seismic energy

- In order to discuss energy quantitatively, we must recognize that energy is the measure of the work that can be done by some machine; in the metric system, common units of energy are ergs. The present total consumption of energy in the United States per annum is about 10^{26} ergs.

- From a global perspective, such an amount of energy is really quite small. The amount of heat that flows out of the earth as a whole, to be lost through the atmosphere into space each year, is about 10^{28} ergs. Earthquakes too, emit a great deal of energy.

- They are the result of the sudden release of strain energy stored previously in the rocks in the earth. From measurements of the seismic-wave energy produced by the sudden fracture, it is estimated that each year the total energy released by earthquakes throughout the world is between 10^{25} and 10^{26} ergs.

- An earthquake of Richter magnitude 5.5 turns out to have energy of about 10^{20} ergs. A magnitude 5 M_L earthquake is equivalent to the explosion of 1000 tons of TNT, whereas a magnitude 6 M_L earthquake is the energy equivalent of 30,000 tons of TNT or a 30-kiloton nuclear explosion.

- Earthquake waves, of course, carry energy, and when they encounter buildings some of it is transferred to vibrate the structure.

Topic 17

Magnitude versus Energy

- Energy propagating by seismic waves is proportional to the square root of amplitude-period ratios. Magnitude is proportional to the logarithm of seismic energy E (Fig 5.5). a semi-empirical relationship between surface wave magnitude Ms and E is formulated:

$$\log E = 1.5 M_s + 11.8$$

Where E is in ergs. As the magnitude increases by one unit, the energy increases by a factor of 31.6 and the difference between two units of magnitude is a factor of 1,000 on energy release. Similarly, m_b and M_s are related to seismic energy E

(Where E is expressed in joules (1joule = 107 ergs)) by the following empirical relations:

$$\log(E) = 2.4m_b - 1.3 \qquad (5.15)$$

$$\log(E) = 1.5M_s + 4.2 \qquad (5.16)$$

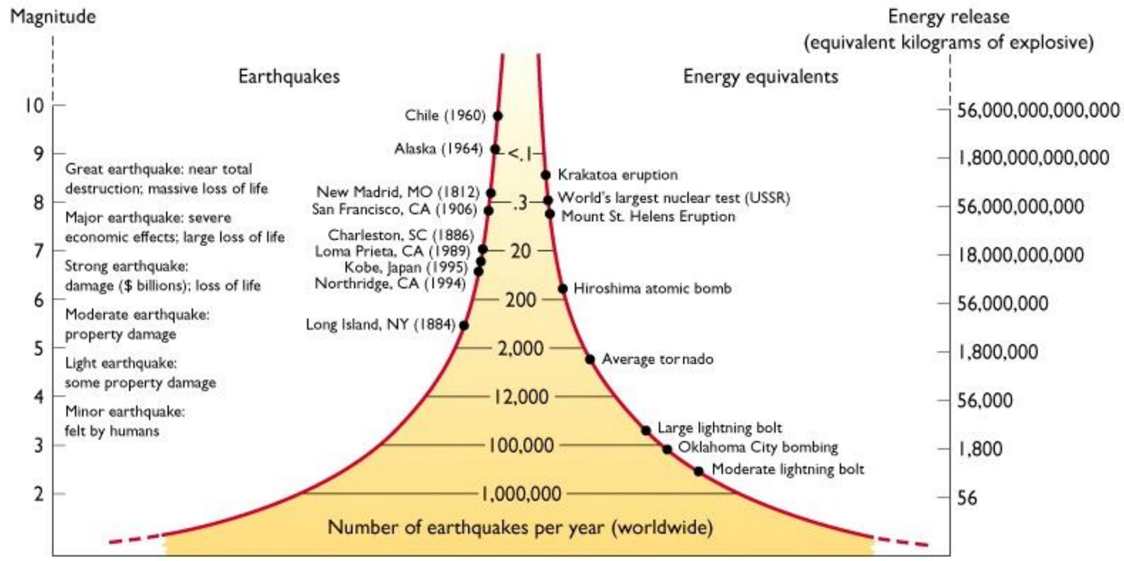

Fig 5.5: Correlation between surface wave magnitudes M_s and energy released during earthquakes

End of Lecture 5 in Concept of Seismic magnitude and Intensity, earthquake size, different magnitude scales and relations.