Engineering Seismology and Seismic Hazard - 2019

Lecture 14

Measuring Earthquake Size

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Size Measure Types

There are basically two methods to quantify the earthquake size:

1) Maximum Intensity

- Outdated method based on damage description and human ground shaking perception
- Very subjective, not based on actual seismic recordings
- Still very used to quantify the size of historical (preinstrumental) earthquakes

2) Magnitude

- Modern method based on measurable earthquake parameters
- Objective and reproducible
- Drawback: many variants, subject to various limitations and of not easy comparison

Macroseismic Intensity

Macroseismic intensity concept was introduced by **Robert Mallet** by studying the great earthquake occurred in Southern Italy in 1857.

He related the intensity of the earthquake to the human perceptions of the felt ground motion and the observed distribution of damage on buildings and territory.

In this way, the <u>maximum (observed)</u> <u>intensity</u> I_0 , often called **epicentral intensity**, gives an rough estimate of the size of the earthquake.



Macroseismic Scales

- 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.

Mercalli Scale

TABLE 1:9-1	Modified Merca	lli Intensity Scale
		in muchally ocale

Intensity Level	Description
1	Not felt.
1	Felt only by a few people at rest. Suspended objects may swing.
Ш	Felt noticeably indoors. Many people do not recognize it as an earthquake. Parked cars may rock slightly.
IV	Felt indoors by many, outdoors by few. Dishes, windows, doors rattle. Parked cars rock noticeably.
V	Felt by most; many awakened. Some dishes, windows broken. Unstable objects overturned.
VI	Felt by all. Some heavy furniture moves. Damage slight.
VII	Slight to moderate damage in well-built structures; considerable damage in poorly built structures; some chimneys broken.
VIII	Considerable damage in well-built structures. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls.
IX	Damage great in well-built structures, with partial collapse. Buildings shifted off foundations.
х	Some well-built wooden structures destroyed; most masonry and frame structures destroyed. 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.

Subjective damage evaluation because of its qualitative nature, related to population density, familiarity with earthquake and type of constructions.







Improvements of the EMS98

Scaling to buildi category and vulnerability type

DS1

Grade 1: Negligible to

slight damage

(no structural damage,

slight non-structural

damage)

Fine cracks in plaster over

frame members or in walls

at the base. Fine cracks in partitions and

infills

 $\min\left(\Delta_{cr}^{inf}; \Delta_{cr}^{RC}\right)$

 $\Delta^{\rm RC}_{\rm buckling}$

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anna hern anna Al-	THE DAME NET BE THE	And the second descent	1000	(III)	ULNERABILITY CLASS			
Grade 2: Moderate	Grade 3: Substantial to	Grade 4: Very heavy	Grade 5: Destructio		3E			
damage	heavy damage	damage	(very he	avy structural	PROBABLE, EXCEPTIONAL CASES			
(slight structural damage,	(moderate structural	(moderate structural (heavy structural damage,						
damage)	structural damage)	damage)						
Cracks in columns and	Cracks in columns and	Large cracks in structural	Collapse of	ground floor or				
beams of frames and in structural walls	beam column joints of frames at the base and at	elements with compression	parts (e.	g. wings) of				
Cracks in partition and infill	joints of coupled walls.	frames at the base and at joints of coupled walls. fracture of rebars; bond Spalling of concrete cover, failure of beam reinforced						
walls; fall of brittle cladding	Spalling of concrete cover,							
and plaster. Falling mortar	buckling of reinforced rods.	bars; tilting of columns.						
from the joints of wall	Large cracks in partition	Collapse of a few columns						
panels	individual infill panels	or of a single upper floor						
	$\left(\Delta_{\text{ult}}^{\inf}; \Delta_{\text{stating}}^{\text{RC}};\right)$	20			1			
$\min\left(\Delta_{\max}^{m};\Delta_{v}^{RC}\right)$	min	Δ_{ult}^{RC}		Δ_{coll}^{RC}				

Head to Head Scales

Μ	lodified Mercalli Scale	Richter Magnitude Scale	JMA	MERCALLI CANCANI SIEBERG	MEDVEDEV SPONHEUER KARNIK	EMS-98 Intensity	Felt	Impact	Magnitude (Approxi- mat Value)	Building Damage (Masonry)
Т	Detected only by sensitive instruments	1.5		п	I	1	Not felt	Not feit	2	
Ш	Felt by few persons at rest, especially on upper floors; delicately suspended objects may swing	2	I	ш	П.,	11-111	Weak	Felt indoors by a few people. People at rest feel a swaying or light trembling.	3	
III	Felt noticeably indoors, but not always recognized as earthquake; standing autos rock slightly, vibration like passing truck	2.5		IV	ш	IV	Light	Felt indoors by many people, outdoors by very few. A few people		
IV	Felt indoors by many, outdoors by few, at night some may awaken; dishes, windows, doors disturbed: autos rock noticeably	3	п	v	īV			are awakened. Windows, doors and dishes rattle.		
v	Felt by most people; some breakage of dishes, windows, and plaster; disturbance of tall objects	3.5	ш	VI	v	v	Moderate	Felt indoors by most, outdoors by few. Many sleeping people wake up. A few are frightened. Buildings tremble throughout. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.	44	
VI	Felt by all, many frightened and run outdoors; falling plaster and chimneys, damage small	4.5	IV	vп	VI	vi	Strong	Many people are frightened and run outdoors. Some objects fall. Many houses suffer slight non-structural damage like hair-line		
VII	Everybody runs outdoors; damage to be finge varies depending on quality of construction; noticed by drivers of autos		v	IX	VII			cracks and falling of small pieces of plaster.		
VIII	Panel walls thrown out of frames; fall of walls, monuments, chimneys; sand and mud ejected; drivers of autos disturbed	5.5		x	vin	VII	Very strong	and objects fall from shelves in large numbers. Many well-built ordinary buildings suffer moderate damage: small cracks in walls, fall of plaster, parts of chinneys fall down; older buildings may show large cracks in walls and failure of in-fill walls.	5	T T T T T
IX	Buildings shifted off foundations, cracked, thrown out of plumb; ground cracked; underground pipes broken	6	vi	XI	IX	VIII	Severe	Many people find it difficult to stand. Many houses have large cracks in walls. A few well built ordinary buildings show serious		
x	Most masonry and frame structures destroyed; ground cracked, rails	6.5		ХШ	x			naiture oi waiis, while weak older structures may collapse.	6	
хі	Few structures remain standing; bridges destroyed, fissures in ground, pipes broken landslides rails bent	7.5	VII		XI	IX	Violent	General panic. Many weak constructions collapse, Even well built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.		Sample Colorador
XII	Damage total; waves seen on ground surface, lines of sight and level distorted, objects thrown up in air	8			XII	X+	Extreme	Most ordinary well built buildings collapse, even some with good earthquake resistant design are destroyed.	7	© Swiss Seismological Service

Isoseismals & Contour Maps

By tracing lines on maps joining the points in which the intensity was similar (isolines, isoseismals, isointensity line), it is possible to determine the centre on the shaking (called macroseismic centre), which is characterized by the highest damage and corresponds to a small area.



Uncertainty and Subjectivity

Tracing of isoseismals is highly subjective. Given the same damage description, intensity maps from different analysts can be very different.



Historical Earthquakes

Links past with the future: Intensity – ground motion relationships are essential for the use of historical earthquakes for which no instrumental records exist.

These relations must be calibrated on present day recordings.



Examples in Italy





Probabilistic hazard map in MCS intensity (10% in 50 years)

Intensity in ShakeMaps

ShakeMap®, developed by the U.S. Geological Survey (USGS), portrays the distribution and severity of shaking.

Using macroseismic intensity facilitates communication of earthquake information beyond just magnitude and location for <u>emergency management and</u> <u>response.</u>

NOTE: Not a representation of actual damage distribution!



PAGER content is automatically generated, and only considers losses due to structural damage Limitations of input data, shaking estimates, and loss models may add uncertainty. http://aerthquake.usgs.gov/bager

Limitations

The maximum intensity measure is biased by many factors not always directly dependent to the earthquake:

- Depth of the event
- Distribution of the population and personal perception
- Construction practice
- Effect of local geology (seismic site effects)
- Regional geology (path attenuation)



This makes earthquakes from different regions hardly comparable.

Local Magnitude

The concept of magnitude was introduced by Richter (1935) to provide an <u>objective instrumental measure</u> of the size of the earthquake.

Contrary to seismic intensity, the magnitude (M) uses instrumental measurements of the earth ground motion adjusted to **epicentral distance** and **source depth**.

Such magnitude estimate is called **local** (M∟) or simply Richter, from its inventor.



Local Magnitude

The original Richter scale was based on the observation that the (log) amplitude of seismic waves decreases with epicentral distance.



A magnitude 0 earthquake is defined as the size event that generates a maximum ground motion of 1 micrometer at epicentral distance f 100 km with a Wood-Anderson instrument.

Wood-Anderson Seismograph

The ML magnitude scale is based on the use of the Wood-Anderson seismograph, which is a torsion horizontal seismometer with period of about 0.8 seconds.



Magnitude Calculation

A for the original formulation, ML can be computed with respect to a reference amplitude, which depends on distance to the event:

$$M_{L} = \log_{10}(A) - \log_{10}(A_{ref})$$

Several empirical formulations exist as function of epicentral or hypocentral distance, e.g. the Lillie formulation:



$$M_L = \log_{10}(A) - 2.48 + 2.76 \log_{10}(\Delta)$$

ML vs Mercalli Intensity

Approximate relations between epicentral Mercalli intensity and Richter magnitude scale exist (e.g. Gutenberg and Richter, 1956):

$$M_L = \frac{2}{3}I + 1$$

This is useful to homogeneously quantify the size of historical earthquakes, but with large uncertainty.

Merc scale	e alli e	Richter scale
1	not perceived	A
н.	growing perception,	- 2.0
- 111	reactions of fear, fall of	- 0.0
IV	objects, no damage to	- 3.0
V	buildings or structures	- 4.0
VI.		
VII	light damage	- 5.0
VIII		
IX	collapses and destruction	- 6 0
х	of a growing percentage of	- 6.0
XI	buildings and structures	- 7.0
XII	catastrophic	₩

Problems with ML

Richter Magnitude suffers from many limitations, such as:

- It is strictly valid only for Souther California (in original form) and adjustments are needed for other regions
- Depends on a specific type of seismometer, whose dominant periods limits the capability of the scale to resolve large magnitudes (the saturation problem)

Magnitude	Description	How it feels	Frequency
Less than 2.0	Micro	Not felt by people.	Millions per year.
2.0 to 2.9	Minor	No building damages.	More than 1 million per year.
3.0 to 3.9	Minor	Often felt, may shake objects inside buildings.	More than 100,000 per year.
4.0 to 4.9	Light	Indoor objects shake or fell to the floor. Not significant damage.	10,000 to 15,000 per year.
5.0 to 5.9	Moderate	Extensive damage to buildings not designed correctly.	1,000 to 1,500 per year.
6.0 to 6.9	Strong	Can cause damage up to	100 to 1500 per



Other Magnitude Scales

After local magnitude, the concept has been developed and extended so as to be applicable to a variety of wave types and distances.

In general form, all magnitude scales based on amplitude measurements are like:

$$M = \log(A/T) + f(\Delta, h) + C_s + C_r$$

M = Magnitude A = Amplitude T = Period f = Correction for distance and depth Cs = Correction for site Cr = Correction for source region

Surface Wave Magnitude

For distances 20°< Δ <160° with hypocentres in the uppermost 50 km

Measured by the amplitude of the Rayleigh waves Dominant period of around 20 seconds.

$$M_{s} = \log_{10} (A/T)_{max} + 1.66 \log_{10} \Delta + 3.3$$



Body Wave Magnitude

Used for deep earthquakes and earthquakes measured at distances > 600 km (teleseismic events) Measured by the amplitudes of the first arrivals of P-waves Dominant period of around 1 second

$$mb = \log_{10}(A/T)_{max} + g(\Delta, h)$$



Magnitude Saturation

The frequency (or period) at which the earthquake spectrum is "sampled" strongly controls the resolving power of a specific magnitude type.



For instance, mb saturates above 6, while Ms never gets above 8.2-8.3

Conversion Relations

As earthquake is a complex phenomenon, different magnitude scale might provide inconsistent estimates for the same event.

Example:

- Turkey 8/17/1999: Ms = 7.8, mb = 6.3
- Taiwan 9/20/1999: Ms = 7.7, mb = 6.6

Magnitude conversion relations are often necessary (e.g. in hazard analysis). Although global relations exists (e.g. Di Giacomo, Weatherill), relations calibrated ad-hoc for specific region are to be preferred.



Are ML, mb and Ms useful?

These scales are still routinely used nowadays, first of all for their simplicity, but also because, being sensitive to different characteristics of the earthquake (different waves, different periods), they bring useful information in specific analysis (e.g. nuclear test verification)

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Energy Magnitude Relation

MS and mb magnitudes represents different parts of the frequency spectrum of seismic waves, therefore different phisical parameters of an earthquake. Gutenberg and Richter's studies suggests that, being related, they can be used to represent the fundamental physical parameter of seismic waves: ENERGY.

They obtain the following relationship:

 $\log E = 1.5 Ms + 11.8$



This is a rapid estimate of the energy of seismic waves associated with an earthquake.

Energy Equivalents

Note that an increase of one magnitude unit corresponds to about 32 times increase in the amount of energy released

Earthquake frequency and destructive power

The left side of the chart shows the magnitude of the earthquake and the right side represents the amount of high explosive required to produce the energy released by the earthquake. The middle of the chart shows the relative frequencies.



Seismic Moment Recap

From elastic dislocation theory (Aki 1962) we recall the concept of scalar seismic moment:

$$M_0 = \mu A D$$

Seismic moment is one of the most reliable seismological parameters that represents the 'size' of an earthquake.

Mo does not saturate, it is therefore a more suitable parameter to represent the size of great earthquakes than the conventional magnitude scales such as Ms.

Moment Magnitude

Moment magnitude (Mw) was first introduced by Hiro Kanamori in 1977 as:

$$M_{w} = \frac{2}{3} \log(M_{0}) - 10.7$$



Mw measures the size of events in terms of seismic moment , and therefore of how much energy is released.

Mw can be easily compared to magnitude values for other events.

Comparing Scales to Mw

Scale type	Author	Earthquake size	Earthquake depth	Epicentre distance (km)	Reference parameter	Applicability	Saturation
$M_{\rm L}$	Richter (1935)	Small	Shallow	<600	Wave amplitude	Regional (California)	1
mb	Gutenberg and Richter (1956)	Small-to-medium	Deep	>1,000	Wave amplitude (P-waves)	Worldwide	1
$M_{\rm S}$	Richter and Gutenberg (1936)	Large	Shallow	>2,000	Wave amplitude (LR-waves)	Worldwide	1
$M_{\rm w}$	Kanamori (1977)	All	All	All	Seismic moment	Worldwide	n.a.

Key: n.a. = not applicable; \checkmark = saturation occurs.

Comparing Scales to Mw

Moment magnitude does not saturate because it is derived from seismic moment as opposed to an amplitude on a seismogram.



- The local magnitude ML and the short-period body wave magnitude mb are essentially equal to moment magnitude up to M = 6.
- The surface wave magnitude MS is essentially equal to moment magnitude in the range of M = 6 to 8.

Measuring Mw

Mo is proportional to the far-field earthquake spectrum at long periods. Mw can then be obtained by spectral fitting.

