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Size of Earthquakes

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Abstract

Earthquake size is one of the most fundamental source parameters used in seismic catalogs. A reliable measure of the "size" of an earthquake is essential for seismological, geological, engineering, and scientific research. The size of a seismic source is measured using two parameters; damage caused (intensity) and energy released (magnitude). Intensity describes the strength of a seismic event in terms of human recognition, affected region, damage to structures. Intensity scales are valuable not only for the pre-instrumental period for historical earthquakes but also for seismic risk analysis. The intensity scale is classified by macroseismic scales. Intensity depends on local geological conditions, distance from the source that make the objective estimates difficult. The concept of magnitude was introduced by Richter to provide an objective measure of earthquake size. The advent of seismic recording systems made it possible to determine the strength of a seismic event from instrumental data. The magnitude of an earthquake provides quick information on the strength of a seismic event for the public and are essential for cataloging. Changes in instrumentation and magnitude formulation resulted from the calculation of different magnitude scales. In order to obtain a non-saturating uniform magnitude scale, seismic moment magnitude (Mw) is developed based on source parameters.

1. Introduction

Macroseismic intensity scales represent the intensity of ground-motion in terms of human observation, damage to buildings, or other observed effects at a certain location. Felt reports and damage in an area are sources of intensity estimation of an earthquake. Macroseismic intensities are important for historical seismicity and assessment of seismic hazard risk studies. Intensity depends on many factors such as local geological conditions, distance, and depth of the earthquake. The energy released from a seismic source may be may be amplified or diminished by ground motion. Macroseismic intensity classifies the severity of earthquakes depending on damage at different locations and felt shaking records. These factors are affected by the quality of construction and the density of the population [1].

An instrumental scale was necessary to characterize the size of a seismic event based on instrumental records. According to Richter (1935) "In the course of a historical or statistical study of earthquakes in a given region, it is frequently desirable to have a scale for rating these shocks in terms of their original energy, independently of the effects which may be produced at any particular point of observation" [2].

The advent of seismic recording instruments led to quantifying the strength of a seismic event by the amplitude of the recorded signal. The magnitude concept was first proposed in the 1930s by Wadati in Japan and Richter in California. The magnitude of an event is a number that characterizes the relative size or amount of energy released by an event which is independent of the place of observation. Magnitudes are derived from ground motion amplitudes and periods or from signal duration obtained from instrumental records and source parameters of the earthquake including seismic waves.

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2. Macroseismic Intensity Scales

The size of seismic sources is characterized by the macroseismic intensity scale before the advent of seismic recording instruments. The intensity or macroseismic intensity is an integer quantity that depends on earthquake distance, ground conditions, and strength of shaking. Intensities are defined in macroseismic scales.

The first studies took place in Italy at the end of the 18th century. The Ten-degree Rossi-Forel scale (1883) was the first scale to be used internationally. The first 12-degree scales were introduced by Sieberg, and Mercalli, Cancani and Sieberg (1912, 1923, 1932, MCS scale). The Modified Mercalli Scale (MM scale) was revised by Richter in 1956 (MM56 scale) and used in the USA. In Europe, MSK-scale is developed by Medvedev, Sponheuer, and Karnik (1964) was widely used. In 1988 MSK-scale is revised by European Seismological Commission and European Macroseismic Scale (EMS-98) is released in 1998 and widely adopted all over the world. Earthquake intensities in Japan contain 7–degree (later upgraded to 10-degree) by Japan Meteorological Agency (JMA). Macroseismic intensity is dependent on the local geological conditions, the distance from the source, quality of the construction and, density of the population.

The intensities generally decrease with distance from the source and are site-dependent. They represent the severity of ground-motion during a seismic event on the basis of observational effects of the region, human perception, and damage to buildings.

Intensity is a measure of the strength of the seismic source and a description of common observations of an earthquake. Instead of describing the effect of an earthquake-like "the event was felt by very few people indoors", the shaking is shortly defined as "intensity 2". Each intensity degree is expressed by a series of diagnostic that describes the effects of ground motion. Intensity data are mapped in contour lines for different degrees called isoseismals. The largest observed intensity is the epicentral intensity I_0 near to the epicenter or barycenter of the highest intensities. The most recent scales are the Modified Mercalli Scale (MMI) and European Macroseismic Scale (EMS-98) which are easily adaptable for the use to building stock anywhere in the world. In Table 1, MMI Scale of Stover and Coffman edited by Musson is shown as an example for the intensity scale [3].

Table 1. MMI Scale of 1993 (Stover and Coffman, after Wood and Neumann, edited by Musson).

I	Not or rarely felt under especially favourable circumstances. Under certain conditions, at and outside the boundary of the area in which a great shock is felt: sometimes birds, animals, reported uneasy or disturbed; sometimes dizziness or nausea experienced; sometimes trees, structures, liquids, and bodies of water may sway, doors may swing very slowly.
II	Felt by few sensitive, or by nervous persons indoors, especially on upper floors. Also, as in grade I, and often more noticeably: sometimes hanging objects may swing, especially when delicately suspended; sometimes trees, structures, liquids, bodies of water may sway; doors may swing very slowly; sometimes birds, animals reported uneasy or disturbed; sometimes dizziness or nausea experienced.
III	Usually rapid vibration motion felt indoors by several people. Sometimes not recognized to be an earthquake at first. Continuity estimated in some cases. Vibration occures due to the passing of light, or lightly loaded trucks, or heavy trucks some distance away. Hanging objects may swing slightly. Movements may be appreciable on upper levels of high structures. Rocked standing motor cars slightly.
IV	Felt by all. Many get frightened. Trees and bushes shake slightly. Buildings shake moderately to heavily. Walls creak loudly. Observers described the shaking as "strong." Few get awakened, especially light sleepers. No one is frightened, unless apprehensive from previous experience. Vibration happens due to the passing of heavy or heavily loaded trucks. Sensations like heavy body striking building or falling of heavy objects are seen inside. Rattling of dishes, windows, doors; glassware and crockery clink and clash. Hanging objects swung, in numerous instances. Liquids in open vessels disturb slightly. Standing motor cars rock noticeably.

Table 1. (Cont.) MMI Scale of 1993 (Stover and Coffman, after Wood and Neumann, edited by Musson).

V	Buildings tremble during the quake. Dishes, glassware break to some extent. Windows crack - in some cases, but not generally. Vases, small or unstable objects overturne in many instances. Hanging pictures fall. Doors, shutters, open, or close abruptly. Pendulum clocks stop, start or run fast, or slow. Small objects, furnishings, move the latter to a slight extent. Trees, bushes, shake moderately to strongly. People have difficulty in standing or walking. People feel moderately in moving vehicles.
VI	Damage is slight in poorly built buildings. Fall of plaster is seen in a small amount. The plaster layer cracks somewhat, especially fine cracks in chimneys in some instances. Dishes, glassware, in considerable quantity, also some windows break. Fall of knickknacks, books, pictures. Furniture overturne in many instances. Furnishings of moderately heavy kind move. Small bells ring - church, chapel, school, etc. The intensity can only be assessed as VI if damage to buildings is observed, unless many small objects fall from shelves or many glasses or dishes break.
VII	Damage neglected in buildings of good design and construction, from slight to moderate in well-built ordinary buildings, considerable in poorly built or badly designed buildings, adobe houses, old walls (especially where laid up without mortar), spires, etc. Chimneys get cracked to a considerable size, and walls to some extent. Fall of plaster in considerable to large amount, also some stucco. Numerous windows and some furniture break. Loosened brickwork and tiles shake down. Weak chimneys break at the roofline (sometimes roofs damaged). Fall of cornices from towers and high buildings. Bricks and stones dislodge.

VIII	Slight damage in structures (bricked) built especially to withstand earthquakes. Partial collapse considerable in ordinary substantial buildings. Wooden houses rack, tumble down in some cases, panel walls in frame structures thrown out, and decayed pilings break off. Fall of walls. Solid stone walls crack and break seriously. Chimneys, columns, monuments, also factory stacks, towers fall or twist. Very heavy furniture move or overturn conspicuously. Trees shake strongly - branches, trunks, break off, especially palm trees.
IX	Damage considerable in (masonry) structures built especially to withstand earthquakes: break of some plumb wood-frame houses built especially to withstand earthquakes; great extent damage in substantial (masonry) buildings, some collapse in large part; or wholly shifted frame buildings off foundations and racked frames.
X	Damage serious to dams, dykes, embankments. Severe to well-built wooden structures and bridges, some destroyed. Dangerous cracks develop in excellent brick walls. Most masonry and frame structures, as well as their foundations, destroy.
XI	Damage severe to wood-frame structures, especially near shock centres. Great to dams, dikes, embankments often for long distances. Few, if any (masonry) structures remained standing. Destroyed large well-built bridges by the wrecking of supporting piers, or pillars. Less affected yielding wooden bridges.
XII	Total damage - practically all parts of construction wholly damage or destroy.

The simplified short form of EMS-98 (abstracted) [3] is shown in Table 2.

Table 2. Short Description of EMS-98 (Abstracted).

I	Not felt	Not felt
II	Scarcely felt	Felt only by very few individuals at rest in their homes.
III	Weak	Felt indoors by a few people. People at rest feel a swaying or light trembling.
IV	Largely observed	Felt by many people indoors, but by very few outdoors. A few people are awakened. Windows, doors and dishes rattle.
V	Strong	Felt by most indoors, by few outdoors. Many sleeping people wake up. A few are frightened. Buildings tremble in the meantime. Hanging objects swing considerably. Small objects are shifted. Doors and windows swing open or shut.
VI	Slightly damaging	Many people are frightened and run outdoors. Some objects fall. Some houses suffer slight non-structural damage like hair-line cracks and fall of small pieces of plaster.
VII	Damaging	Most people are frightened and run outdoors. Furniture is shifted 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 chimneys fall down; older buildings may show large cracks in walls and failure of fill-in walls
VIII	Heavily damaging	Many people find it difficult to stand. Many houses have large cracks in walls. A few well-built ordinary buildings show serious failure of walls, while weak and older ones may collapse.

Table 2. (Cont.) Short Description of EMS-98 (Abstracted).

IX	Destructive	General panic. Many weak constructions collapse. Even well-built ordinary buildings show very heavy damage: serious failure of walls and partial structural failure.
X	Very destructive	Many ordinary well-built buildings collapse.
XI	Devastating	Most ordinary well-built buildings collapse; even some with good earthquake resistant design are destroyed.
XII	Completely devastating	Almost all buildings are destroyed.

Macroseismic data is gathered by several methods. The main source of the data is the collection of the questionnaires. The questionnaires are important to collect data from a large number of observations. A web-based program called "Did you Feel It?" by USGS [4] is an international questionnaire. Field studies should be held to collect information on earthquake damages of the buildings. [5]. In Figure 1, the intensity map of 24 January 2020 Sivrice-Elazığ earthquake is given as an example [6].
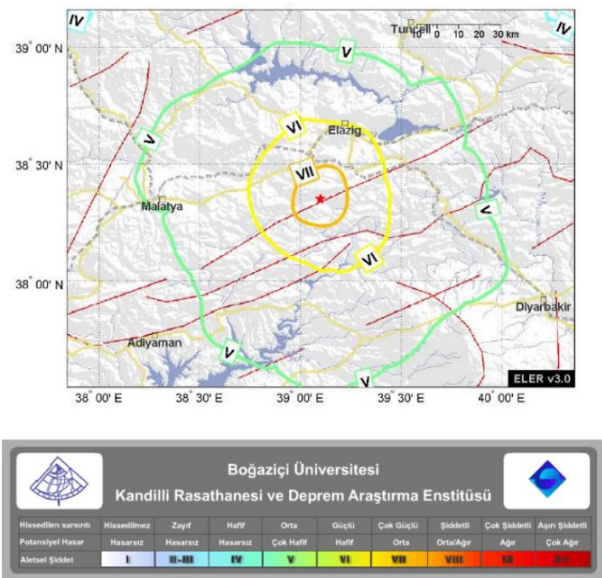

Figure 1. Screenshot from the KOERI website, showing a macroseismic display of 24 January 2020 Sivrice-Elazığ earthquake.

3. Earthquake Magnitude Scales

Earthquake magnitude is a parameter used in seismology to quantify the size of an earthquake based on

the measurement of the maximum ground motion recorded by a seismograph. There is no scale limitation to magnitudes as in macroseismic intensity scales. Magnitudes are commonly derived from ground motion amplitudes and periods or from duration of seismic signals measured on instrumental records. The same earthquake might have different magnitude values on different scales. The magnitude scales above are dependent on a certain signal frequency.

The magnitude of an event is based on and corrected for the decay of amplitudes with epicenter distance and source depth.

Charles F. Richter (1935) introduced Richter magnitude [7] or local magnitude (M_L) and defined it as:

"The magnitude of a shock is defined as the logarithm of the calculated maximum trace amplitude, expressed in microns, with which standard short-period torsion seismometer (T0=0.8, V=2.8000, h=0.8) would register that shock at the epicentral distance of 100 km)."

Richter scale termed as ML and applicable local earthquakes are formulated as:

$$M_L = \log A_{max} - \log A_0 (\Delta) \qquad (1)$$

where A_{max} is the seismogram amplitude measured on a Wood-Anderson record and the distance Δ to the source. Generally all magnitude scales are a form of

$$M = \log \left(\frac{A}{T}\right) + f(\Delta, h) + C_{source} + C_{receiver} \qquad (2)$$

where T is the period of the signal, $f(\Delta, h)$ is a correction for epicentral distance and hypocenter depth. Empirical correction values for the source region and the receiver site are added. In Richter's formula, as all the seismographs were of the same type dependence on T was missing, maximum amplitude always had the same dominant period.

For global earthquake size calculations, the local magnitude scale is not practical. Gutenberg and Richter designed magnitude scales for global magnitude scales. Body-wave magnitude (m_b) is calculated by maximum ground-motion amplitude of P, PP, or S body waves, and defined as

$$m = \log \left(\frac{A}{T}\right) + Q(\Delta, h) \qquad (3)$$

where Q is an empirically determined distance and depth correction, depending on the phase used. If the body-wave magnitude is determined from P wave at a period of 1s, it is generally abbreviated as m_b. When determined from long-period instruments at periods between 5-15 seconds, it is noted as m_B.

Surface wave magnitude scale uses the maximum ground motion amplitude of surface wave at a period of 20s. In general, Rayleigh wave amplitude is used for the calculation of M_s. The formula for this surface-wave magnitude is defined as

$$M_S = \log A_{20s} + 1.66 \log \Delta + 2.0 \qquad (4)$$

As the size of the earthquake increases, the low-frequency part of its spectrum relative to the higher frequencies is stronger. This will cause magnitude saturation for large earthquakes. Seismic moment calculation was introduced by Kanamori [8] to provide a non-saturating magnitude scale for large earthquakes termed as moment magnitude (M_w) based on seismic moment (M_0). The seismic moment M_0 can be determined by seismic data, geodetic data or geological data [9].

Seismic moment can be found accurately from seismic data [9]. The seismic moment calculation constitutes the fault area, slip, and strength of the material which represents the physical measure of an earthquake. It can be obtained from amplitudes of seismic waves or from the field estimations of the slip and fault area of the earthquake. For a finite source with area of fault plane (S), on which the averaged slip is D (offset, in km) and μ (Gpa) is shear or the rigidity modulus of the material surrounding the fault, the M_0, scalar seismic moment is given as

$$M_0 = \mu DS \qquad (5)$$

In cgs units, the seismic moment is given in dyn cm and in SI units it is in Nm.
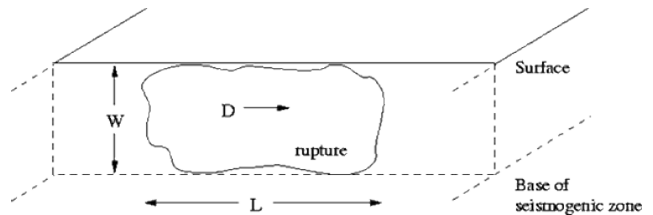

Figure 2. Diagram of an area of the fault rupture on earthquake area [10].

The moment magnitude (M_w) and seismic moment (M_0) relation is defined as by the following [9]. M_0 is a static parameter that does not represent dynamic properties of the source unless the use of scaling relations exist. M_0 or M_w can be used as a useful parameter for the earthquake damage effects [9].

$$M_w = \frac{\log_{10} M_0}{1.5} - 6.07 \quad (M_0 \ in \ Nm) \qquad (6)$$

Magnitude scales are affected by not only

observational errors but also fault geometry, size and source depth of the earthquake. The magnitude scales determined at different periods represent different parts of the seismic source spectrum. Various magnitude scales [M_s, m_b, M_L, M_w) calculated for earthquake catalogues will be useful for research purposes [9]. As the range of period for different magnitude scale change, magnitude scales saturate differently. The relations between various magnitude scales are summarized in a graphical form representing the saturation of m_b, m_B, M_L, M_s by [11-12] in Figure 2. and Figure 3.
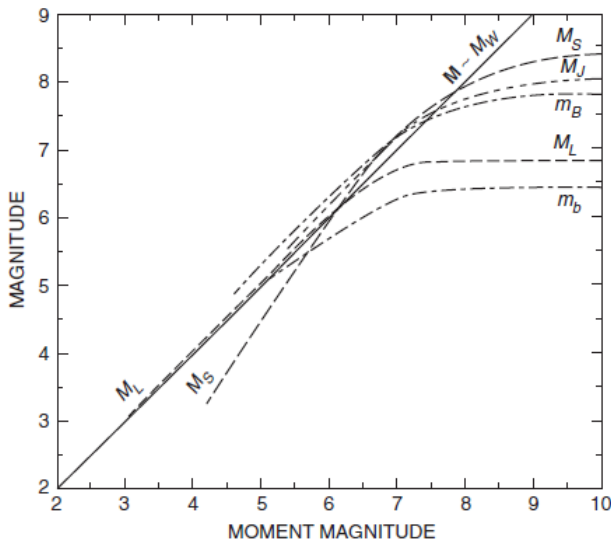

Figure 3. Relations between magnitude scales.

The range of periods of different magnitude scales is: for mb:~1 s; for M_L: ~0.1-3 s form mB: ~ 0.5-15 s; for M_s: ~ 20s and for Mw: ~10 - ∞. For shorter periods, early saturation occurs. For instance, m_b saturates around 6.5, M_L around 7, mB at 8 and M_s at about 8.5. Mw magnitude does not saturate [13].

3. Conclusions

Size of an earthquake is one of the most fundamental earthquake source parameters of seismic catalogs. A reliable size of an earthquake is essential for engineering, tectonic studies, seismic hazard and risk assessment applications. Earthquake size is the basis of a variety of scientific research. The size of earthquakes are characterized in two different ways; macroseismic intensity scale (I) and magnitude (M).

Macroseismic intensity represents strength of the event in terms of human perception, damage to buildings and changes in the surrounding environment.

Magnitude scale is a logarithmic measure of the size of an event derived from instrumental records. The size estimates of different magnitude scales may be different

for the same earthquake due to the magnitude calculation methods. There is no scale limitation to magnitudes whereas macroseismic scale is limited to 10 or 12-degree scale. Different macroseismic scales can be used in different countries depending on the regional properties. Earthquake magnitude scale is not uniform due to changes in instrumentation, the data reduction method and the magnitude formula. Various magnitude scales have been developed. The magnitude scales change with the range of period of the signal used during magnitude determination. Seismic moment magnitude is one the most reliable, uniform type of non-saturating magnitude for earthquakes derived from seismic moment that uses source parameters of the earthquake region.

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