Measuring The Magnitude of Earthquakes

ME 226: Mechanical Measurements Project

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***Abstract*—A natural disaster is a major adverse event caused due to natural phenomena and leads to widespread destruction, loss of life and property. Various natural calamities include earthquakes, hurricanes, volcanic eruptions, floods, etc. These events happen every year all over the world and are out of the control of us human beings. This makes it crucial for us to study these phenomena in-depth and devise ways to quantify their magnitude, intensity and energy in order to counter their effects.**

One of the Geological disasters is an earthquake. Every year, around 50,000 earthquakes happen. While most of them are either of very low amplitude or go unnoticed due to them being away from populated areas, some have been the cause of unimaginable havoc for mankind.

In order to study the relations between earthquakes and the local geology, identify the most vulnerable areas and help in preparations and emergency response, we need to be able to detect and measure even the slightest and biggest of the earthquakes happening anywhere on the globe. In this project, we'll go over the methods and scales used for measuring magnitude of earthquakes, how they have matured over time and why it matters.

I. Introduction

A. Earthquake

An Earthquake is the shaking of the surface of the Earth which results when two blocks of the Earth suddenly slip past each other. The earth's lithosphere is divided into 7 large plates and several smaller plates referring to the tectonic plates are used to study the tectonic processes which happen here on our planet. The underlying layers of the earth's surface which often feel very quiet and static are very dynamic, and alive. These tectonic plates are always slowly moving, but they get stuck at their edges due to friction. When the stress on the edge overcomes the friction, a lot of energy stored in Earth's crust is suddenly released, it gives rise to seismic waves that travel through the earth's crust and cause the shaking that we feel. The energy can be released by elastic strain, gravity, chemical reactions, or even the motion of massive bodies. Of all these the release of elastic strain is the most important cause, because this form of energy is the only kind that can be stored in sufficient quantity in the Earth to produce major disturbances. Earthquakes associated with this type of energy release are called tectonic earthquakes. This usually happens when large rocks beneath the earth's crust straining against each other suddenly fracture and 'slip'. The surface where they slip is called the fault or fault plane. The major fault lines of the world are located at the fringes of the huge tectonic plates that make up Earth's crust. The location below the earth's surface where the earthquake starts is called the hypocenter, and the location directly above it on the surface of the earth is called the epicenter.

An earthquake may be preceded by foreshocks. These are earthquakes of lesser magnitude that happen in the same place as the larger earthquake that follows. Scientists still can't tell that an earthquake is a foreshock until the larger earthquake happens. The largest, main earthquake is called the mainshock. Mainshocks always have aftershocks that follow. These are smaller earthquakes that occur afterward in the same place as the mainshock. Depending on the size of the mainshock, aftershocks can continue for weeks, months, and even years after the mainshock!

B. Seismograph

Seismology is the study of earthquakes and seismic waves that move through and around the earth. These seismic waves can be classified into two types based on where they propagate, namely body waves and surface waves. Body waves can travel through the earth's inner layers, but surface waves can only move along the surface of the planet like ripples on water. Earthquakes radiate seismic energy as both body and surface waves.

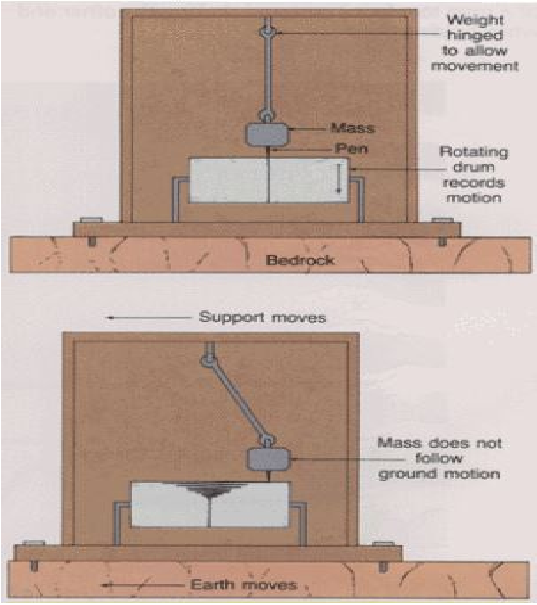
Seismographs are instruments used to record the motion of the ground during an earthquake. All seismographs operate on the principle of inertia. A seismographic network is maintained throughout the globe in which seismographs are installed in the ground to record the shocks in an event of an earthquake. A seismograph is securely mounted onto the surface of the earth so that when the earth shakes, the entire unit shakes with it *except* for the mass on the spring, which has inertia and remains in the same place. As the seismograph shakes under the mass, the recording device on the mass records the relative motion between itself and the rest of the instrument, thus recording the ground motion.

II. Evolution and Working of Seismographs

- The earliest *seismoscope* was invented in 132 A.D. by the Chinese astronomer and mathematician Chang Heng. It was then called an *earthquake weathercock*. It had sculptures of 8 dragons mounted on a pot each having a bronze ball having in its mouth. It was designed in such a way that a slight earth tremor would open the mouth of one of the dragons causing the bronze ball to fall into the open mouth of one of the toads making a noise to alert someone that an earthquake had just happened. Additionally, the direction of the earthquake could be inferred by observing which dragon's mouth was opened. This did not, however, record earthquakes; it only indicated that an earthquake was occurring. This did not, however, in any way could record or depict the magnitude of the earthquake.

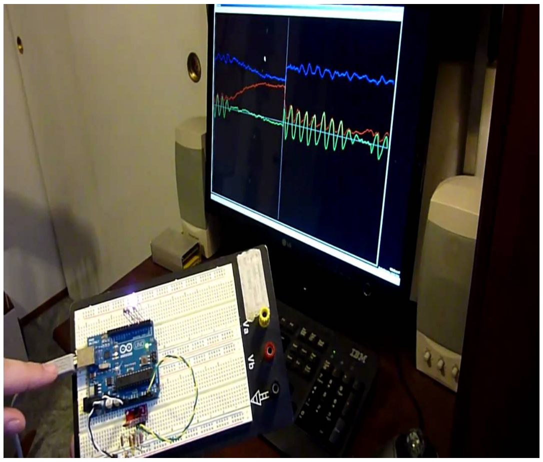
Earliest Seismoscope dubbed as "Earthquake Weathercock"

- Today, a basic seismograph can be made with a lot simpler design, using a small drum with paper on it, a bar or spring with a hinge at one or both ends, a weight, and a pen. The one end of the bar or spring is bolted to a pole or metal box that is bolted to the ground. The weight is put on the other end of the bar and the pen is stuck to the weight. The drum with paper on it presses against the pen and turns constantly. When there is an earthquake, everything in the seismograph moves except the weight with the pen on it. As the drum and paper shake next to the pen, the pen makes squiggly lines on the paper, creating a record of the earthquake. This record made by the seismograph is called a seismogram. Then by studying the seismogram, one can tell how far the earthquake propagated and how strong it was. However, the epicenter can't be located using just one seismograph. This is what makes creating a seismographic network so important. To locate the epicenter, at least 3 such seismographs are required. More the no. of seismic stations, the greater is the accuracy of locating the epicenter and recording the magnitude of the earthquake.



A simple seismograph

- Modern day seismographs are much more accurate and detect ground motion in all three axes. They make use of electronic microcontrollers, ground motion detection sensor or an accelerometer coupled with a recording and graphing system, usually on a computer.



A modern seismograph prototype

III. RICHTER MAGNITUDE (OR LOCAL MAGNITUDE) ML SCALE

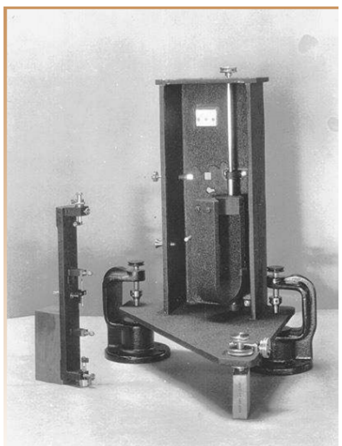
The Richter scale is a measure of the strength of earthquakes, developed by **Charles F. Richter** and presented in his landmark 1935 paper, where he called it the "magnitude scale". This was later revised and renamed the local magnitude scale, denoted as ML or ML.

A. Definition:-

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

$$ML = logA - logA_0(\Delta) \qquad (1)$$

where **A** is the maximum amplitude in millimetres recorded on the Wood - Anderson seismograph for an earthquake at epicentral distance of Δ km, and $A_0(\Delta)$ is the maximum amplitude at Δ km for a standard earthquake.



Wood-Anderson seismograph

Three arbitrary choices are made in the above definition:

1) the use of standard Wood-Anderson seismograph,
2) the use of standard Wood-Anderson seismograph,
3) selection of the standard earthquake whose amplitudes as a function of distance are represented by $A_0(\Delta)$.

The **zero level** of $A_0(\Delta)$ can be fixed by choosing its value at a particular distance. Richter chose the zero level of $A_0(\Delta)$ 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 $-logA_0$ = 3 at Δ = 100 km so 1 that the earthquakes do not have negative magnitudes. In other words, to compute ML a table of $-logA_0$ as a function of epicentral distance in kilometres is needed.

TABLE 1

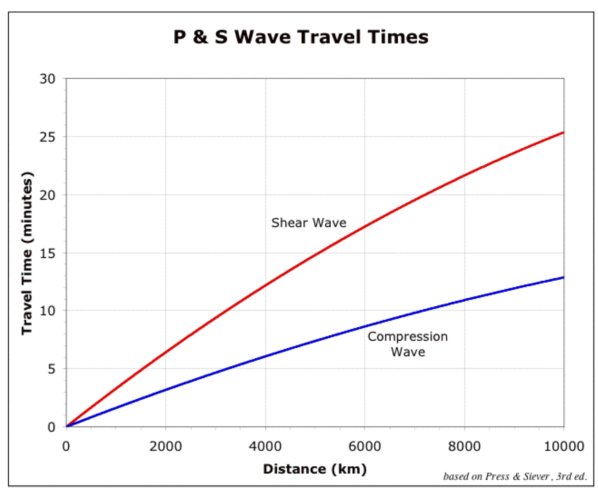
LOGARITHMS OF THE AMPLITUDES B (IN MM.) WITH WHICH THE STANDARD TORSION SEISMOMETER SHOULD REGISTER A SHOCK OF MAGNITUDE ZERO

Δ	$-\log B$	Δ	$-\log B$	Δ	$-\log B$
0	1.4	100	3.0	330–340	4.2
10	1.5	110–120	3.1	350–370	4.3
20	1.7	130–140	3.2	380–390	4.4
25	1.9	150–160	3.3	400–420	4.5
30	2.1	170–180	3.4	430–460	4.6
35	2.3	190–200	3.5	470–500	4.7
40	2.4	210	3.6	510–550	4.8
45	2.5	230–240	3.7	560–590	4.9
50	2.6	250–260	3.8	600	5.1
60–70	2.8	270–280	3.9	700	5.2
75–85	2.9	290–300	4.0	800	5.4
90	3.0	310–320	4.1	900	5.5
				1,000	5.7

Table of $-logA_0$ as a function of epicentral distance in kilometres

B. Measuring Procedure:-

- ☐ We need to know the approximate epicentral distance of an earthquake, which can be estimated from S-P time difference.
- ☐ The maximum trace amplitude on a standard Wood-Anderson seismogram is then measured in millimetres, and its logarithm to base 10 is taken.
- ☐ This number is then added to the quantity tabulated as $-logA_0$ 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 the average of all the station magnitudes is an estimate of the local magnitude ML for the earthquake.



Measuring Approximate Epicentre distance from P and S wave travel times

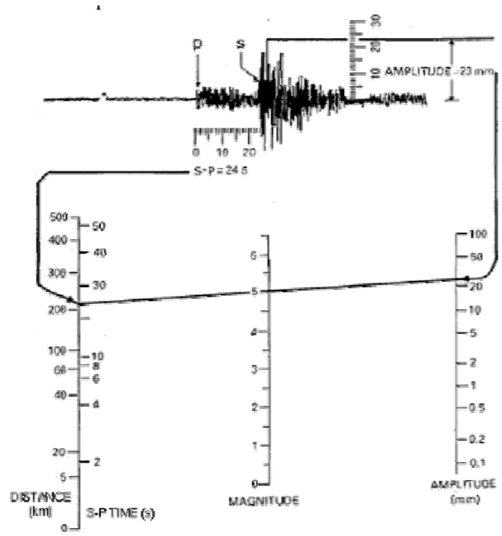


Fig.1: Estimation of Richter Magnitude.

Graphical procedure for estimating the Richter magnitude (ML)

C. Calibration of Scale for different regions:-

- In practice, the scale requires different calibration curves for regions such as stable continental interiors, as compared to the Southern California region for which the scale was originally defined.
- This is because the attenuation of seismic waves with distance can be very different for different geological provinces.
- The scale for Southern California is defined by:

$$ML = logA + 2.76log\Delta - 2.48 \quad (2)$$

D. Earthquake Energy and Richter Magnitude:-

Gutenberg and Richter's elaborate calculations (1954) produced the formula which relates energy release with magnitude as follows:

$$logE = 12 + 1.8M \quad (3)$$

This relation is fair enough for the earthquakes of magnitude range $4 < M < 7$, but for the large earthquakes, energy given by this formula is too high.

Gutenberg and Richter (1956) revised the formula to reduce the values of energy for the larger shocks, after extensive study of strong motion seismograms, and preferred unified magnitude m derived from body waves recorded at teleseismic distances, and it took the form:

$$logE = 5.8 + 2.4m \quad (4)$$

where $m = 2.5 + 0.63Ms$, thus it is equivalent to

$$logE = 11.4 + 1.5Ms \quad (5)$$

Table 1
Magnitude versus ground motion and energy

Magnitude Change	Ground Motion Change (Displacement)	Energy Change
1.0	10.0 times	about 32 times
0.5	3.2 times	about 5.5 times
0.3	2.0 times	about 3 times
0.1	1.3 times	about 1.4 times

Magnitude vs Ground Motion and Energy

A magnitude 7.0 earthquake produces **10 times more ground motion** than a magnitude 6.0 earthquake, but it **releases 32 times more energy**.

E. Advantages of Local Magnitude (ML) Scale:-

- Magnitude is directly measured from seismograms without sophisticated signal processing.
- The estimates they yield are intuitively meaningful (magnitude 5 is moderate, magnitude 6 is strong etc).
- The local magnitude is a number characteristic of the earthquake, and independent of the location of the recording station, based solely on amplitudes of ground motion recorded by a seismograph, independent of the effects produced at a particular area.

F. Limitations of Local Magnitude (ML) Scale:-

- ✓ A scientific weakness is that there is no direct mechanical basis for magnitude as defined above. They are totally empirical, and thus have no direct connection to the physics of the earthquake.
- ✓ Amplitudes depend on the scalar moment, the azimuth of the seismometer relative to the fault geometry, the distance from the source, and the source depth.
- ✓ The source time function has a finite duration, depending on fault dimensions and rise time, the amplitudes vary with frequency.
- ✓ Richter magnitudes in their original form are no longer used because they only apply to Southern California and the Wood-Anderson seismograph is now rarely used for recording the seismic wave-field.
- ✓ Because of limitations imposed by seismographs and the emphasis on measuring a single peak amplitude, for magnitudes greater than 6.5, the values calculated after measuring very large seismic waves tend to cluster, or "saturate" near one another.
- ✓ The Richter scale underestimates the energy released in distant earthquakes (over 600 km) because of attenuation of the S-waves, and of deep earthquakes because the surface waves are smaller.

A number of different global and local magnitude scales have been produced since the original formulation of Richter. Some of these will now be discussed.

IV. Body - wave Magnitude (mb) Scale

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, P and S in the period range 0.5 to 12 s :

$$mb = log(A/T) - f(\Delta, h) \tag{6}$$

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

A. Advantages:-

- The amplitude of the P wave is not affected by the focal depth.
- The body-wave magnitude scale, with its approximately 1,000-km range, was viewed as accurate enough to measure the few relatively small earthquakes that occurred in eastern North America.

B. Limitations:-

- The equations used are not even dimensionally correct (A/T is not dimensionless, yet the logarithm of this quantity is still taken).
- Saturation occurs for approximately $mb > 6.2$.

V. Surface wave magnitude (Ms) Scale

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

$$Ms = logA_{Hmax} - logA_0(\Delta_0) \tag{7}$$

where A_{Hmax} is the maximum combined horizontal ground amplitude in micrometres for surface waves with a period (T) of 20 + 2 second, and $-logA_0$ 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.

For shallow focus earthquakes, an approximate relation between mb for P-waves and Ms is given by :

$$mb = 2.5 + 0.63Ms \tag{8}$$

A. Advantages

- The surface-wave magnitude scale had no distance restrictions between the earthquake epicentre and the location of the seismograph

B. Limitations

- It can be applied only for the shallow earthquakes that generate observable surface waves.
- Different magnitude scales also yield different values for large earthquakes.
- Scale saturates for approximately $Ms > 8.3$.

VI. Duration Magnitude (Md) Scale

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 A_max impossible. Therefore, an alternative magnitude scale such as Md was developed. This scale is based on signal duration. It is almost routinely used in micro earthquake surveys.

Lee et al. (1972) established an empirical formula for estimating signal duration magnitude (MD) for the local earthquakes recorded by the USGS Central California micro earthquake network using signal duration.

For a set of 351 earthquakes, they computed the MD equivalent to local magnitudes as defined by Richter (1958). Correlation of the local magnitudes with the signal duration measured by the USGS micro earthquake network is shown in below Figure. They obtained the following relation :

$$MD = -0.87 + 2.00log\tau + 0.0035\Delta \tag{9}$$

where MD is duration magnitude equivalent to Richter magnitude, τ is signal duration in seconds Δ is epicentral distance in kilometres.

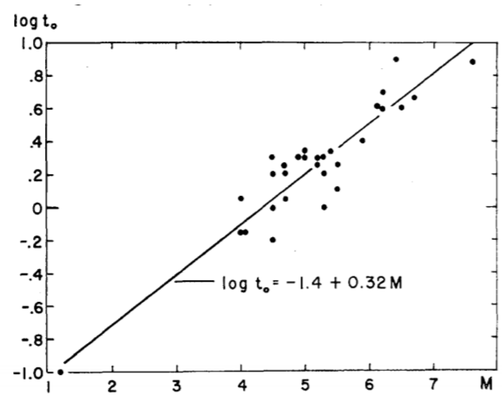


Fig. 1. Duration t_0 of strong motion at short distances, as a function of magnitude M.

Relation between Richter Magnitude and Signal Duration

Because of various shortcomings of the ML scale, most seismological authorities now use other scales, such as the moment magnitude scale (Mw), to report earthquake magnitudes. But much of the news media still refers to these as "$Richter$" magnitudes. All magnitude scales retain the logarithmic character of the original and are scaled to have roughly comparable numeric values.

However, local magnitudes are sometimes still reported, because *many buildings have resonant frequencies near 1 Hz*, which is close to that of a Wood-Anderson seismograph. Therefore, ML is often a good indicator of the potential for structural damage.

VII. Moment Magnitude(Mw) Scale

A. History

The Richter scale was developed on the basis of shallow, moderate-sized (~15 km deep) earthquakes at a distance of around 100 to 600 km where the surface waves are significantly active. But at greater depths. Lengths and magnitudes the surface waves are reduced also and Richter scale is unable to estimate the magnitude of earthquake and it saturates. Due to this some additional scales were also developed such as - Surface-wave magnitude scale, Body-wave magnitude scale etc. but all of them had their saturation limits and this problem wasn't efficiently solved. After this, Moment Magnitude Scale (Mw) came into the picture.

B. Development and Working mechanism

1) Seismic Moment (Mo) : It is a measure of the fault slip and area involved in earthquakes. Its value is the torque of each of the two force couples that form the earthquake's equivalent double-couple. Seismic moment is a measure of the work (more precisely, the torque) that results in inelastic (permanent) displacement or distortion of the earth's crust. It is related to the total energy released by an earthquake.

2) Moment Magnitude Scale (Mw) : Hanks and Thatcher pointed out that a magnitude scale based directly on an estimate of the radiated energy, rather than the converse, would not only circumvent the difficulties associated with characterizing earthquake source strength with narrow-band time domain amplitude measurements, specifically magnitude saturation, but had become practical with the increased understanding of the gross spectral characteristics of earthquake sources that developed in the early 1970's. Kanarnori [1977] realized this possibility by independently estimating the radiated energy E, with the relation:

$$E_s = \Delta\sigma * M_0/\mu \tag{10}$$

where $\Delta\sigma$ is the earthquake stress drop and μ is the shear modulus, reducing 10 to

$$E_s = M_0/2 * 10^4 \tag{11}$$

by taking advantage of the constancy of earthquake stress drops for shallow earthquakes, and using 11 in the Gutenberg-Richter relation between E_s and Ms

$$logE_s = 1.5Ms + 11.8 \tag{12}$$

where E_s is in ergs. The idea is that if Ms is bounded, so too is E_s as obtained from 12, but if E_s is known independently from 11, it may be used on the left-hand side of 12 to determine a magnitude Mw that will not saturate.

A significant feature of Kanarnori's definition of Mw by 12 through use of 11 is that he found that Mw so defined is quite similar to Ms for a number of earthquakes with $Ms <= 8$, that is, well below the saturation level of Ms. This agreement attests to the general validity of both the Gutenberg-Richter $E_s - Ms$, relation 12 for $Ms <= 8$ and the use of 11 to estimate E_s independently.
A second important feature of Mw as defined by Kanarnori is that it is intrinsically a moment magnitude scale. This moment magnitude relation is upon substituting 11 on the left-hand side of 12 and Mw for Ms on the right-hand side of 12,

$$logMo = 1.5Mw + 16.1 \tag{13}$$

which is remarkably coincident with the M_o-M_L relationship empirically defined by Purcaru and Berckherner for $5 <= Ms <= 7$

$$logMo = 1.5Ms + (16.1 \pm 0.1) \tag{14}$$

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