Earthquake magnitudes

Earthquake magnitude is a measure of earthquake size based on the amplitude of the resulting waves recorded on a seismogram. The earliest magnitude scale, introduced by Charles Richter in 1935 for Southern California earthquakes, is the local or "Richter" magnitude. This scale has been replaced by other magnitude scales that use seismic waves of different periods. These give more information, because an earthquake radiates different amounts of seismic energy at different periods. All are derivative from Richter’s original scale.

Magnitude is based on the concept that the recorded amplitude reflects the earthquake size once it has been corrected for the decrease with distance due to geometrical spreading and attenuation.

\[ M = \log_{10} \left( \frac{A}{T} \right) + F(h, \Delta) + C , \]

where \( A \) is the amplitude of the signal, \( T \) is its dominant period, \( F \) is a correction for the variation of amplitude with the earthquake's depth \( h \) and distance \( \Delta \) from the seismometer, and \( C \) is a regional scale factor. Magnitude scales are thus logarithmic, so an increase in one unit, as from magnitude "5" to a "6", indicates a ten-fold increase in seismic wave amplitude. Measured magnitudes range more than 10 units because the displacements measured by seismometers span more than a factor of \( 10^{10} \).

Different magnitudes are used, each of which measures the seismic energy radiated at a different period. The body wave magnitude \( m_b \) is determined from the amplitude of waves that travel through the earth’s interior, with a period of 1 second. Similarly, the surface wave magnitude \( M_s \) is determined from the amplitude of waves that travel along the earth’s surface, with a period of 20 seconds.

**Figure 1:** Body and surface wave magnitude determination (K. Schramm, Ph.D. thesis)
As measures of earthquake size, magnitudes have two major advantages. First, they are directly measured from seismograms without sophisticated signal processing. Second, they yield units of order one which are intuitively attractive: magnitude 5 earthquakes are moderate, magnitude 6 are strong, 7 are major, and 8 are great.

However, magnitudes have two related limitations. First, they are totally empirical and thus have no direct connection to the physics of earthquakes. A striking illustration of this is that equations are not even dimensionally correct - logarithms can only be taken for dimensionless quantities, whereas these expressions involve ratios of displacement to period. A second difficulty is with the numbers that emerge. Magnitude estimates vary noticeably with azimuth, due to the amplitude radiation patterns, although this difficulty can be reduced by averaging results. The different magnitude scales yield different values. Moreover, body and surface wave magnitudes do not correctly reflect the size of large earthquakes.

To see why different measurements yield different magnitudes, consider the spectrum of the earthquake source, or how much energy is radiated at different periods. Figure 2 shows the logarithm of amplitude of the radiated waves versus the logarithm of the wave frequency (1/period). Ideally the plot is flat at low frequency (long period) and then decays for frequencies above (periods shorter than) “corner” frequencies proportional to 1 over the times needed for the rupture to propagate along the length of the fault and for slip to be completed at a point on the rupture. The larger the earthquake, the more the corner frequencies move to the left.

Figure 2: Illustration of earthquake spectra showing corner frequencies (dashed vertical lines) and different magnitude determinations. The earthquake whose spectrum is shown in red has larger moment magnitude than the one with spectrum shown in blue, even though they have the same surface and body wave magnitudes, as shown by the black part of the spectra that are the same for both earthquakes.
A problem with body and surface magnitudes is that they saturate or remain constant once earthquakes exceed a certain size. This happens because the added energy release in the very large earthquakes is all at longer periods than are measured by the 20 sec period surface waves. No matter how big an earthquake is, its body and surface wave magnitudes do not get above about 6.5 and 8.4, respectively. Hence for very large earthquakes these magnitude measurements underestimate the earthquake’s size. This issue is crucial for tsunami warning.

To surmount this difficulty, we use the *seismic moment* that can be calculated by measuring the energy in the longest periods of the seismogram. The seismic moment also relates directly to the physical properties of the fault, so the moment can be determined either from seismograms or from the fault dimensions. In terms of the fault dimensions, the seismic moment

\[ \text{Mo} = [\text{fault rigidity}] \times [\text{fault area}] \times [\text{fault slip distance}] . \]

The *rigidity* is the strength of the fault and is an approximate value determined from lab experiments. The moment magnitude \( M_w \) is calculated from the seismic moment using the relation

\[ M_w = (\log \text{Mo} / 1.5) - 10.73 . \]

The constants in the equation have been chosen so that the moment magnitude scale correlates with the other magnitudes when they do not saturate.
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