Measuring the Size of an Earthquake

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Earthquakes range broadly in size. A rock-burst in an Idaho silver mine may involve the fracture of 1 meter of rock; the 1965 Rat Island earthquake in the Aleutian arc involved a 650-kilometer length of the Earth's crust. Earthquakes can be even smaller and even larger. If an earthquake is felt or causes perceptible surface damage, then its intensity of shaking can be subjectively estimated. But many large earthquakes occur in oceanic areas or at great focal depths and are either simply not felt or their felt pattern does not really indicate their true size.

Today, state-of-the-art seismic systems transmit data from the seismograph via telephone line and satellite directly to a central digital computer. A preliminary location, depth-of-focus, and magnitude can now be obtained within minutes of the onset of an earthquake. The only limiting factor is how long the seismic waves take to travel from the epicenter to the stations—usually less than 10 minutes.

Magnitude

Modern seismographic systems precisely amplify and record ground motion (typically at periods of between 0.1 and 100 seconds) as a function of time. This amplification and recording as a function of time is the source of instrumental amplitude and arrival-time data on near and distant earthquakes. Although similar seismographs have existed since the 1890's, it was only in the 1930's that Charles F. Richter, a California seismologist, introduced the concept of earthquake magnitude. His original definition held only for California earthquakes occurring within 600 km of a particular type of seismograph (the Wood-

Anderson torsion instrument). His basic idea was quite simple: by knowing the distance from a seismograph to an earthquake and observing the maximum signal amplitude recorded on the seismograph, an empirical quantitative ranking of the earthquake's inherent size or strength could be made. Most California earthquakes occur within the top 16 km of the crust; to a first approximation, corrections for variations in earthquake focal depth were, therefore, unnecessary.

Richter's original magnitude scale (M_L) was then extended to observations of earthquakes of any distance and of focal depths ranging between 0 and 700 km. Because earthquakes excite both body waves, which travel into and through the Earth, and surface waves, which are constrained to follow the natural wave guide of the Earth's uppermost layers, two magnitude scales evolved—the m_b and M_s scales.

The standard body-wave magnitude formula is

$$m_b = \log_{10}(A/T) + Q(\Delta, h) ,$$

where A is the amplitude of ground motion (in microns); T is the corresponding period (in seconds); and $Q(\Delta, h)$ is a correction factor that is a function of distance, Δ (degrees), between epicenter and station and focal depth, h (in kilometers), of the earthquake. The standard surface-wave formula is

$$M_s = \log_{10}(A/T) + 1.66 \log_{10}(\Delta) + 3.30 .$$

There are many variations of these formulas that take into account effects of specific geographic regions, so that the final computed magnitude is reasonably consistent with Richter's original definition of M_L. Negative magnitude values are permissible.

A rough idea of the frequency of occurrence of large earthquakes is given by the following table:

M_s	Earthquakes per year
8.5–8.9	0.3
8.0–8.4	1.1
7.5–7.9	3.1
7.0–7.4	15
6.5–6.9	56
6.0–6.4	210

This table is based on data for a recent 47-year period. Perhaps the rates of earthquake occurrence are highly variable and some other 47-year period could give quite different results.

The original m_b scale utilized compressional body *P*-wave amplitudes with periods of 4–5 s, but recent observations are generally of 1-s-period *P* waves. The M_s scale has consistently used Rayleigh surface waves in the period range from 18 to 22 s.

When initially developed, these magnitude scales were considered to be equivalent; in other words, earthquakes of all sizes were thought to radiate fixed proportions of energy at different periods. But it turns out that larger earthquakes, which have larger rupture surfaces, systematically radiate more long-period energy. Thus, for very large earthquakes, body-wave magnitudes badly underestimate true earthquake size; the maximum body-wave magnitudes are about 6.5–6.8. In fact, the surface-wave magnitudes underestimate the size of very large earthquakes; the maximum observed values are about 8.3–8.7. Some investigators have suggested that the 100–s mantle Love waves (a type of surface wave) should be used to estimate magnitude of great earthquakes. However, even this approach ignores the basic fact that the excitation level at any period is not truly related to the fundamental processes that determine earthquake size. Thus, modern seismologists are increasingly turning to seismic moment as such a measure.

Fault Geometry and Seismic Moment, M_o

The orientation of the fault, direction of fault movement, and size of an earthquake can be described by the fault geometry and seismic moment. These parameters are determined from waveform analysis of the seismograms produced by an earthquake. The differing shapes and directions of motion of the waveforms recorded at different distances and azimuths from the earthquake are used to determine the fault geometry, and the wave amplitudes are used to compute moment. The seismic moment is related to fundamental parameters of the faulting process.

$$M_o = \mu S \langle d \rangle \ ,$$

where μ is the shear strength of the faulted rock, S is the area of the fault, and $<d>$ is the average displacement on the fault. Because fault geometry and observer azimuth are a part of the computation, moment is a more consistent measure of earthquake size than is magnitude, and, more importantly, moment does not have an intrinsic upper bound. These factors have led to the definition of a new magnitude scale based on seismic moment, M_w, where

$$M_w = 2/3 \log_{10} (M_o) - 10.7 .$$

The two largest reported moments are 2.5×10^{30} dyn·cm (dyne·centimeters) for the 1960 Chile earthquake (M_s 8.5; M_w 9.6) and 7.5×10^{29} dyn·cm for the 1964 Alaska earthquake (M_s 8.3; M_w 9.2). M_s approaches its maximum value at a moment between 10^{28} and 10^{29} dyn·cm.

Energy

The energy radiated by an earthquake is a measure of the potential for damage to man-made structures. Many attempts have been made to relate earthquake magnitude to seismic energy as a convenient and meaningful interpretation of magnitude. By manually integrating many seismograms from a reference set of earthquakes, Beno Gutenberg and Charles Richter arrived at the following empirical relationship:

$$\log_{10} E = 11.8 + 1.5 M_s ,$$

where energy, E, is expressed in ergs. Thus, for every increase in M_s by 1 unit, the associated seismic energy increases by about 32 times. The press commonly makes misleading statements such as a "magnitude 7 earthquake is 10 times more powerful than a magnitude 6 earthquake." As can be seen from the magnitude formulas, a unit increase of magnitude implies only that seismograph trace amplitude should increase by a factor of 10 for the same wave period and for a given epicentral distance and earthquake focal depth. With digitally recording seismograph systems, computerized methods make accurate and explicit estimates of energy on a routine basis for all major earthquakes.