Measuring earthquakes

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Measuring the magnitude and intensity of earthquakes is subject to enormous misunderstanding; there are several basic methods and scales that can lead to confusion. What does it mean if someone says an earthquake had a magnitude of 7? Or a microseismic event generated by a hydraulic fracturing operation has a magnitude of –2?

There are two fundamentally different types of scales commonly used by seismologists to describe earthquakes. A magnitude scale measures the force or energy of an earthquake, but an intensity scale measures the level of shaking which occurs at an observation point on the Earth’s surface.

Historically, earthquakes were measured on the Richter scale (a magnitude scale) developed in the 1930s. Richter developed a scale based purely on local observations in southern California. The Richter scale is a logarithmic (each unit magnitude step indicates 32 times greater energy release), and is a relative scale based on an arbitrary small magnitude. Richter’s selected relative magnitude of zero was an earthquake that would show a maximum combined horizontal displacement of 1 µm (0.00004 in) on a seismogram recorded using a Wood-Anderson torsion seismograph 100 km (62 mi) from the earthquake epicenter. To set a standard based on a specific instrument, and distance might seem strange, but a magnitude “0” was the smallest earthquake that could be measured at the time and the magnitude scale was initially designed only to compare local earthquakes in California. Developments in instrumentation since the 1930s, including high-sensitivity geophones and digital recording, mean that “negative” magnitudes are now routinely measured. Richter’s local magnitude scale was not designed for distant earthquakes (greater than 600 km) or large earthquakes because the instrumentation saturated at around 6.5, so larger earthquakes don’t register as larger! Richter (in conjunction with Gutenberg) later developed magnitude scales based on surface wave magnitude and body-wave magnitude. However, both of these scales also saturate at around magnitude 8. Magnitudes are often designated with a subscript to indicate the method of measurement, $M_s$ indicates “Richter local magnitude,” $M_b$ designates body-wave magnitude, and $M_w$ is magnitude derived from surface waves.

Today, the Richter magnitude scale has largely been replaced by the moment magnitude scale, $M_w$, but for national and local seismological observatories, the original Richter magnitude scale is often used because magnitudes can be calculated quickly and because it allows comparison to older earthquake catalogs, which is important for historical comparisons.

The moment magnitude scale ($M_w$) is used to measure the size of earthquakes in terms of the released energy involved. The magnitude is based on the seismic moment of the earthquake, (the rigidity of the Earth multiplied by the average amount of slip on the fault and the size of the area over which slippage occurred). Even though the underlying measurements are different, the $M_w$ scale retains the familiar continuum of magnitude values defined by Richter. However, this does not mean the scales are the same. For example, some of the largest earthquakes recorded would have been ranked differently on the two scales. The May 1940 El Centro earthquake in California would have been a 6.4 on the Richter scale but a 7.0 on the moment magnitude scale (remember that both scales are logarithmic and moving from a 6 to a 7 represents an order of magnitude increase in size).

To further confuse, the 1933 Long Beach earthquake was a 6.3 on the Richter scale but only a 6.2 on a moment magnitude scale. Many government agencies use both scales interchangeably even for $M<4.0$.

Measurements of induced seismicity through hydraulic fracturing operations also can be confusing. Typically, the smallest magnitude events, which can be detected by downhole instruments, have moment magnitudes between –4 and –1, (far too small to be felt on the surface with an intensity scale). Underlying the $M_w$ is an assumption of pure slip without tensile component. Because a lot of fluid is pumped during hydraulic fracturing and disposal, you may wonder whether $M_w$ is a suitable measure, despite the fact that only a small fraction of the total strain energy is released as microseismic events.

However, the same microseismic events observed on the surface may be measured with different magnitudes because of transmission and boundary effects, and are sometimes an order of magnitude higher (i.e., increased by 1 on a magnitude scale). These differences may be the result of the local sensor coupling at a free surface; the upcoming waves getting a boost in the poorly consolidated near-surface layer, or the wavelet consisting of a primary pulse reinforced by many short-period multiples that are absent in a downhole scenario where waves propagate mostly parallel to the layering. Downhole measurements may suffer from a radiation pattern bias measured at only one raypath azimuth, compared to surface recording measurements, which are averaged over a variety of azimuths. Microseismic vendors may use different methods to obtain a magnitude estimate, or different parameters in the equations to calculate magnitude which can lead to different magnitude estimates for the same event.

While the Richter and moment magnitude scales attempt to measure the energy released by an earthquake, the Mercalli intensity scale classifies earthquakes by their effects, from detectable by instruments but not noticeable to cata-
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strophic. The magnitude and intensity of an earthquake are not necessarily strongly correlated; a shallow earthquake in a populated area with soil of certain types can be far more intense (for example, in the earthquake swarms experienced in Italy) than a much more energetic deep earthquake in an isolated area. There are many different intensity scales, and they do not usually relate to an absolute reference—for example, level “V” on the widely adopted Rossi-Forel scale is defined as “Felt generally by everyone. Disturbance of furniture, ringing of some bells.”

There is, however, an upper limit. Earthquakes cannot have a moment magnitude larger than around 9.5. There is only a finite amount of strain that a rock can store before it ruptures, so the size of a quake depends strictly on how much rock, or how many kilometers of fault can rupture at once. The largest recorded earthquake occurred in 1960 along the Atacama Trench in the eastern Pacific, which has a depth of 8065 m below sea level and is approximately 5900 km long; its mean width is 64 km and it covers an expanse of some 590,000 km² (228,000 mi²). The only way to get more energy into Earth movement would be through an asteroid impact.

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