Predicting large tsunamis

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IN 1992, two catastrophic tsunamis killed more than 2,000 people. These giant sea waves, generated by earthquakes or submarine landslides, can travel across the oceans and bring destruction to faraway shores: in 1960, an earthquake in Chile led to the deaths of more than 100 people in Japan. In the case of the Nicaraguan earthquake on 2 September last year, the death toll was high because the ground tremors felt by the coastal populations were deceptively mild. On page 714 of this issue[1], Kanamori and Kikuchi take a hard look at the seismic data available for this earthquake. The long-period seismic waves measured at the time should, they say, have conveyed the much-needed warning.

In the Nicaraguan event, there was an alarming disparity between the fairly low conventional magnitude (reported to be as low as $m_b = 5.3$) and the size of the tsunami generated: in some sections of the coast, the earthquake was not even felt by the local people who were swept away by the waves a few minutes later. The other major tsunami of 1992, on 12 December, completely destroyed the village of Riangkrok on Flores Island, Indonesia (see the accompanying box). The waves at some locations reached 26 metres in height, whereas along most of the shoreline the maximum amplitudes were only 3 to 4 metres.

Because tsunami waves cross the ocean comparatively slowly ($250\ \mathrm{m\ s^{-1}}$, or roughly the speed of a jetliner), early warning should be possible. The risk could be assessed either from reports of the size of sea waves at shorelines closer to the epicentre, or by evaluating the parent earthquake, whose surface waves travel about 15 times faster. Not surprisingly, tsunami generation is often directly related to the earthquake's size — in layman's terms, its magnitude. But the concept of magnitude was developed at a time when there was little theoretical understanding of the propagation and generation of seismic waves, or of the physical nature of the forces required to describe an earthquake source. The chief shortcoming of the conventional 'Richter' magnitude scale, traditionally based on the magnitude at a period of 20 seconds, is that it saturates around $M = 8$, just where tsunami generation can become substantial. (The body wave magnitude, m_b, is measured at a period of about 1 second, and saturates still earlier.) Far better as a measure of earthquake size is the seismic moment, a *bona fide* physical quantity associated with the earthquake source, and measured in physical units (dyn cm). This can be used to extend the concept of magnitude to much lower wave frequencies, thus avoiding the problem of saturation.

Thanks to developments in broadband seismic instrumentation in the 1980s, we can now estimate the seismic moment of a parent earthquake in quasi-real time. Distant coastal populations can then be warned if tsunamis seem likely. Several algorithms exist[2–4], one of which has been successfully tested down to a distance of 1.5° (about 170 km)[5]. If the quake is closer than this, however, there may be only a few minutes in which to assess the earthquake and deliver a warning. Many coastal communities in earthquake-prone areas rely on public education, which can be summarized as "If it shakes really strongly, run for the hills at once".

Enter the ominous 'tsunami earthquakes'. This term was coined by Kanamori in the 1970s to describe events whose tsunami was much larger than expected from their seismic waves[6]. Examples include the 1896 earthquake in Sanriku, Japan; the 1946 Aleutian earthquake (which unleashed possibly the strongest tsunami of the century in the Pacific, despite a Richter magnitude of only 7.2), and smaller events in the Kuriles (1963, 1975) and Peru (1960).

Part of the problem with tsunami earthquakes is that their size may be underestimated if the seismic energy is released exceedingly slowly. A slow source is inefficient at generating the high frequencies that rock buildings and alert their inhabitants (0.2 Hz and above) and even those used in conventional magnitude scales (0.05 Hz and above). But the vibrations can still interfere constructively at the mantle-wave

Disaster on Flores Island

THREE weeks after the tsunami hit Flores Island, Indonesia (see Okal's article above), an international tsunami survey team of scientists and engineers from five countries visited the location. They found that, at the site of the village of Riangkrok, located on the northern tip of the easternmost peninsula, the waves had caused devastation at enormous heights above sea level. The maximum height reached was measured as 26.0 m on the south hillside slope; the average of four different measurements was 19.6 m from sea level at the time of the tsunami onslaught. There is now no trace of the village at Riangkrok. It was destroyed and completely washed away. Almost all the coconut trees have been knocked down and washed away, leaving only their root marks still visible on the beach. The area engulfed by the tsunami is unmistakably identifiable as brown, bare ground. The size of the debris and coral rocks (dragged up from the sea floor) can be seen by comparison with the person to the right of the rock in the picture. This sort of destruction is very different from that observed at other tsunami-damaged locations in Flores Island, where the waves ran up to heights of only 3 to 4 m above sea level, and also at the sites of the Nicaraguan tsunamis, where most of the trees survived the tsunami flows, despite being swamped. All the signs indicate that the tsunami flow forces at Riangkrok must have been fiercely strong, as they ripped away everything that had stood in the area. At this small rural village, 137 people lost their lives to the tsunami.

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