TSUNAMIS

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Tsunamis are gravitational oscillations of the entire body of water of an ocean basin, following a disruption in the bottom (or exceptionally the surface) of the ocean. They differ from more conventional swells by their much longer periods (typically from 10 min to 1 hr) and relatively faster speeds over deep ocean basins (typically 220 m/s, or the speed of a modern jetliner). Tsunamis are capable of exporting death and destruction across entire ocean basins, their propagation being limited only by continental masses.

TSUNAMI SOURCES

Although tsunamis were once called "tidal waves," they are not caused by tides. Most tsunamis are generated when very strong earthquakes deform the ocean floor. Such a mechanism can move extremely large amounts of water (the fault rupture reached 1200 km in the 2004 Sumatra event), but only over relatively short distances (at most 20 m in the largest earthquakes), resulting in long waves of considerable energy (> 10^{22} erg for the Sumatra tsunami). Secondary, less frequent, tsunami sources include landslides, which can be either submarine (e.g., Papua New Guinea, 1998; Storrega, Norway, 6000 BC) or aerial, falling into the water (e.g., Stromboli, 2002; Aysen, Chile, 2007). Finally, catastrophic volcanic eruptions in the marine environment (e.g., Santorini, 1630 BC; Krakatau, AD 1883) and bolide impacts at sea (Yucatan, 65 million years ago) can also give rise to major tsunamis. However, non-earthquake sources obey different source scaling laws, which in lay terms means that they displace water over considerable distances (up to hundreds of km), but involve more contained volumes (rarely exceeding 50 km in linear dimensions). As a result, their tsunamis, which can be devastating in the near field (less than 1000 km from the source), feature shorter wavelengths and experience more efficient dispersion while propagating over large distances, resulting in generally benign amplitudes in the far field.

As the floor of the ocean has finite rigidity, it reacts to the passage of the tsunami by deforming elastically, resulting in a small, but significant, coupling of the tsunami to the solid Earth. Conversely, an earthquake source embedded in the solid Earth can excite a tsunami in an overlying ocean, but because the coupling is weak, appreciable transoceanic tsunamis are generated only by truly great earthquakes (of moments $\geq 5 \times 10^{28}$ dyn cm or so-called "moment magnitude" ≥ 8.7). The resulting tsunami wave remains in all cases relatively small on the high seas: Even for the catastrophic 2004 Sumatra tsunami, satellite altimetry provided a direct measurement of only 70 cm zero-to-peak in the Southern Bay of Bengal. Such low amplitudes are also spread over considerable wavelengths (~300 km), giving the tsunami a flat aspect ratio and rendering the wave undetectable on the open sea by classical (visual or optical) means.

THE INTERACTION OF TSUNAMI WAVES WITH COASTLINES

When approaching a shoreline, a tsunami undergoes shoaling; that is, the wave slows down in the shallower water, while its amplitude increases considerably, with run-up heights at the shoreline having reached, during the Sumatra event, 32 m in the near field and up to 12 m in the far field. If the structure of the wave remains stable at the shoreline, it can continue to propagate over initially dry land and inundate the coastal areas in the form of a progressively rising swell over distances having reached, again in 2004, 10 km in the near field and 3 km in the far field. Otherwise, the wave breaks like surf and hits the shore as a wall of water or "bore," particularly destructive but unable to propagate far inland.

In very general terms, tsunamis with shoreline run-up of decimetric amplitudes (< 1 m) are generally benign; amplitudes of a few meters will result in significant destruction of individual structures and in instances of loss of life; and dekametric amplitudes ($\geq$ 10 m) in total eradication of infrastructure and population.

The exact run-up amplitude at a given shore location is a very complex function of the shape of the coastline and of the small-scale bathymetry and topography at the receiving beach. In particular, bays, harbors, and coves can resonate at typical tsunami frequencies, and their nonlinear responses can locally increase the wave amplitude. While such effects can be successfully modeled, they must be addressed on a case-by-case basis. In this general context, the following properties have been regularly observed, and justified theoretically.

Near-Field Scaling

In the near field, the maximum run-up observed from a nearby seismic source along a smooth, linear coastline featuring no substantial indentation does not exceed twice the amplitude of the seismic slip on the fault. This simple rule of thumb (known as "Plafker's law") expresses a general scaling of the near field to the seismic source, verified by numerical simulations and in the field during the 2004 Sumatra tsunami: its local run-up, exclusive of splashes on cliffs, reached 32 m for a seismic slip estimated at 15 to 20 m. Any departure from the Plafker law is a proxy for the presence of an ancillary source, such as a submarine landslide, as was the case in Papua New Guinea (1998), Riangkroko, Flores, Indonesia (1992) or Unimak, Aleutian Islands (1946).

Effect of Island Geometry

The response of an island to a distant tsunami depends crucially on the geometry of its structure, from the ocean floor up. In this respect, atolls, characterized by small dimensions, and steep underwater structures (with slopes reaching 40°) offer an overall smaller cross-section to the onslaught of the tsunami than do traditional islands sloping more gently to the ocean floor. As a result, all other parameters being equal, run-up on atolls has generally been smaller than on high islands. In practical terms, the tsunami is able to flow unimpeded around the structure, largely ignoring it, while the gently dipping, and necessarily larger structure of a high island would provide a physical barrier against which the wave has to abut, leading to a substantial transfer of momentum. This property was observed during the 2004 Sumatra tsunami in the Maldives, where the run-up was relatively contained (≈ 2 m), while it reached 9 m along the coast of Somalia, essentially in the same azimuth but at double the distance along the same ray paths. These results are a scaled-up expression of the well-known value of pillared structures (houses, etc.) in tsunami mitigation: the water flows effortlessly around the pillars whereas it would take down a continuous wall at the same location.

Effect of Fringing Reefs

Coral structures fringing high islands provide some degree of protection to the shorelines. Although a tsunami can penetrate a lagoon and reach the shore of a reefed island, it propagates very inefficiently over the irregular and extremely shallow topography of the lagoon, resulting in a significant loss of energy before it reaches the high ground. As a result, the type of island most vulnerable to a tsunami is the unreefed high island. Numerous examples exist of this difference in vulnerability; for example, in Polynesia the Marquesas Islands, which are young, reefless volcanic high islands, have traditionally suffered much larger run-ups from distant tsunamis (Aleutian, 1946; Chile, 1960) than the nearby Society or Austral Islands, of comparable geological structure and age, but protected by substantial reef systems. Similarly, Mauritius (reefed) was much less affected by the 2004 Sumatra tsunami than its sister island of Réunion (unreefed).

Effect of Small-Scale Topography

Small-scale island topography also plays a significant role in controlling the run-up of a tsunami wave at a coastline. In this respect, river beds and gulches are known to function as efficient channels of tsunami flow, often doubling or trebling the local amplitude of run-up. For example, the river valleys in the Marquesas Islands recorded up to 20 m of run-up during the 1946 tsunami, while nearby overland locations were typically 5 to 7 m. Similarly, during the 1993 Japan tsunami, run-up at a gulch on the West Coast of Okushiri Island reached 32 m, in rough numbers double its values along most of the nearby coastline. Numerical modeling at Okushiri has explained such high run-up as a result of the concentration of tsunami energy in the cove formed by the estuary of the gulch. Unfortunately, human settlement usually favors estuaries, which provide freshwater and communication routes to the hinterland, as well as locales featuring gaps in coral reefs, which provide easy access to the high seas, but considerably restrict the mitigating effect of the reef.

Refraction Around Islands

Circular island structures with dimensions comparable to tsunami wavelengths can result in refraction of the wave along the island and focusing on the lee side of the island. This situation, which may go against common-sense intuition, was demonstrated dramatically at Babi Island during the 1992 Flores, Indonesia, tsunami. Even though this local tsunami approached the island from the north, the southern shore of the island suffered more devastation. This "Babi Island effect" was later both reproduced in the laboratory and explained theoretically.

Wave Energy Spectrum

Even though the most perceptible energy in a tsunami is usually in the millihertz (mHz) frequency range (typical periods from 10 minutes to one hour), large earthquake sources contribute tsunami energy throughout a broad spectrum. Higher frequencies (typically in the 5–15 mHz range) have shorter wavelengths and no longer qualify as shallow-water waves. As a result, they are considerably dispersed; that is, their velocities across the ocean basins can be reduced to as little as 70 m/s, and this portion of the tsunami can reach distant coastlines as much as five hours after the main components of the tsunami. This "tail" to the tsunami wave was identified for the first time on hydrophone and seismic records of the 2004 Sumatra tsunami. While it carries comparatively less energy than the more traditional (and more rapidly propagating) components at longer periods, it can trigger oscillations of large amplitudes in specific harbors when the tsunami spectrum matches their resonance frequencies. During the 2004 Sumatra tsunami, this has led to incidents in which large vessels broke their moorings in harbors of the Western Indian Ocean (Réunion, Madagascar) *several hours* after the passage of the more traditional tsunami waves. Although these phenomena can be simulated numerically given an adequate model of the harbor, they raise very sensitive issues regarding the duration of tsunami alerts and, in particular, the issuance of an "all clear" message to harbor communities.

TSUNAMI WARNING

Because tsunamis propagate much more slowly than seismic waves (typically 220 m/s rather than 3–10 km/s), it is possible, at least in principle, to issue a warning to coastal communities, based on the interpretation of seismic waves in terms of earthquake source, and on the evaluation of the potential of the source for tsunami genesis. The full description of tsunami warning procedures transcends the scope of this article; however, the remaining challenges in this field are fundamentally of two kinds.

First, it remains difficult to accurately quantify truly gigantic earthquakes in real time. In the case of the 2004 Sumatra event, the true size of the earthquake took about six weeks to assert, through a study of the free oscillations of the Earth. The major problem in this respect is that all real-time evaluation algorithms were by necessity (and to a large extent, continue to be) designed, implemented, and tested on earthquakes of lower magnitude, and the adjustment of their parameters to mega-events is far from a trivial task. Note, however, that the triggering of a tsunami alert is fundamentally a matter of overcoming a threshold, beyond which the exact size of the earthquake source is not crucial. In this respect, the Sumatra earthquake had been evaluated as having widespread tsunami potential within about 40 minutes of its source; the failure to issue adequate warnings for the far field had more to do with communications than with pure science.

A second challenge is that of anomalous earthquakes disobeying scaling laws, whose rupture proceeds more slowly than in conventional sources, resulting in a significant deficiency of seismic release at the high frequencies (1 Hz) typical of shaking and damage to property (and to some extent at the intermediate frequencies (0.1 to 0.01 Hz) traditionally recorded on seismometers), while low-frequency waves such as tsunamis are vigorously excited. The geological context in which these so-called "tsunami earthquakes" can take place remains obscure, and while we are making progress toward identifying their anomalous character in real time from their seismic waves, they remain a formidable challenge, notably because they are poorly felt by the local population, which may then not be receptive to the issuance of a tsunami alert. Such a dramatic scenario occurred in Java on July 17, 2006, where waves ran up to 20 m and 700 people were killed despite a warning issued by the Pacific Tsunami Warning Center in Hawaii, which remained largely ignored by authorities along a section of shoreline where the earthquake, distant only 200 km, had hardly been felt.

TSUNAMI MITIGATION

Efforts to minimize the effect of tsunamis can take several forms. Passive mitigation relies on the building of structures designed to absorb or reflect the wave's momentum before it can reach coastal infrastructure, houses, or individuals. Among them, tsunami walls have long been used, as in Japan, and are now engineered to optimize the reflection of the wave back towards the sea. However, they remain only as good as their height in relation to that of the incoming wave. The role of vegetation (mangroves or forest) has also been researched both in situ and through scaled experiments in the laboratory. The relocation of critical facilities (hospitals, schools, fire houses) is also necessary in low-lying areas prone to inundation during a tsunami. Finally, building construction can lessen tsunami damage, in particular through the use of stilts or pillars that provide a free flow through an empty first floor offering no cross section to the wave's momentum.

Active mitigation by individuals consists essentially of taking refuge at a combination of altitude and distance from the shore that the wave is not expected to reach. This evacuation depends crucially on the amount of time available before the arrival of the tsunami. In the near field, this may be as short as a few minutes, and the value of a centralized warning becomes marginal; the responsibility for evacuation away from the shore must be borne by the individual, as soon as shaking is felt or an anomalous behavior of the sea, most notably a regression exposing a normally submerged beach, is observed. (Note, however, that automatic systems not requiring human intervention, including closing sluices and stopping trains, can be successfully implemented in the near field.) A generally appropriate rule of thumb is to evacuate to an altitude of 15 m and to remain there at least three hours after anomalous wave activity has ceased. Motorized vehicles should be avoided in the near field, as they will almost certainly contribute to traffic jams. In low-lying areas providing no adequate relief, vertical evacuation must be used. During the 1998 Papua New Guinea tsunami (2200 deaths), some villagers survived by quickly climbing trees; high-rise buildings can serve (and are occasionally built for) the same purpose in developed communities, but the use of elevators during evacuation should be avoided. Evacuation platforms standing on pillars have been built in Japanese ports to provide harbor workers with a means of vertical evacuation at the workplace. Tsunami evacuation drills are regularly conducted in countries at risk, such as Japan and Peru.

In the far field, tsunami alerts may benefit from several hours' advance notice, which can be used for a more profound level of orderly evacuation over greater distances. In both fields, a critical aspect of a successful evacuation is some advance knowledge of the geometry of the expected flooding. This is achieved by running, before the fact, numerical simulations of the extent of flooding for a given community under various scenarios of local or distal tsunamis. These simulations use models of expectable sources, and computer codes solving the equations of hydrodynamics under the relevant initial conditions to map the inundation of the wave down to the scale of a city block, based on available small-scale bathymetry and topography. Their output is made available to civil defense and law enforcement officials, who can then review zoning, optimize evacuation procedures, and conduct drills. For example, the entire west coast of the United States is presently undergoing a systematic program of inundation mapping for all coastal communities.

THE VALUE OF EDUCATION

Above all, a number of recent occurrences have repeatedly shown that tsunami fatalities can be significantly reduced among a population educated to this kind of hazard. For example, following the Papua New Guinea tsunami of 1998, an informative video was developed, translated into many local languages, and shown in neighboring countries, including on battery-operated televisions in remote villages. When a large earthquake hit the island of Pentecost in Vanuatu just a few months later in 1999, the village chief immediately ordered its evacuation. Minutes later, the village was destroyed by the tsunami, with all but a handful of residents unharmed.

In addition to formal education of children in the classroom, tsunami awareness can come as part of a community's cultural heritage through parental or ancestral education in regions regularly affected by tsunamis. For example, fishing communities in Southern Peru suffered no casualties during the 2001 tsunami, as the villagers took to the hills as soon as they felt the earthquake and noticed a down-draw of the sea. By contrast, farm workers hired from the hinterland shrugged off the earthquake and were swept by the waves as they tended to crops in the delta of the Camana River. Similarly, a number of tsunami-aware tourists, mostly from Japan, but also an 11-year-old British girl who had been taught about tsunamis at school, escaped the catastrophic 2004 tsunami on Thai beaches by recognizing anomalous down-draws as harbingers of disaster and immediately evacuating the beaches.

Unfortunately, tsunami awareness inherited from ancestral tradition will fade after an estimated four or five generations in the absence of a recurring event; it is estimated that the recurrence time of an event of the size of the 2004 one is at least 400 years in Sumatra, and thus the local populations were not educated to this hazard (with the possible exception of the Moken people of the Surin, Andaman Islands, who live in complete isolation and may have been able to preserve their heritage longer). In this context, it is crucial to emphasize both the value of, and the need for, permanent education of populations at risk. The fundamental messages are simple: (1) Tsunamis are a natural phenomenon associated with the dynamic nature of the Earth, as opposed to supernatural occurrences; hence they must and will recur. (2) Upon feeling any kind of shaking along a shore line, or noticing an anomalous behavior of the sea, and in particular a strong down-draw, one should immediately evacuate to higher ground. Such simple precautions have repeatedly been proved to save lives.

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FURTHER READING

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