BY ROBERT A. DALRYMPLE, STEPHAN T. GRILLI, AND JAMES T. KIRBY

TSUNAMIS AND CHALLENGES FOR ACCURATE MODELING

After lying dormant for hundreds of years, a seaside volcano erupts, splitting its cinder cone, plunging hundreds of tons of material into the sea. The splash from the debris impact flies hundreds of meters into the air and then falls back to the sea as nearly semi-circular water waves begin to radiate away from the volcano. Within minutes, the nearby coastal towns are obliterated by the towering walls of water that wash over them. Hours later the waves arrive at distant shorelines that surround the sea. These waves have evolved in form, being far different than those near the volcano due to radial spreading, frequency dispersion, and nonlinear effects. Their destructive nature has been reduced over the thousands of kilometers the waves have traveled; nonetheless, the shallow coastal water depths have caused the incoming waves to slow, increasing in height sufficient to overrun the shoreline, overtop breakwaters, and to smash into the coastal communities, killing thousands.

The volcanoes on the islands of Stromboli (Tinti and Bortolucci, 2001) and La Palma in the Canary Islands (Ward and Day, 2001) could provide such a scenario. Alternatively, tsunamis can be generated by an earthquake triggering a landslide on a mountain side, resulting in a large soil mass impacting into a water body; examples include the immense 524-m-high wave triggered at Lituya Bay, Alaska in 1958 (Miller, 1960), and the dam overtopping at the Vajont, Italy, reservoir in 1963 that drowned several thousand people downstream of the dam (Semenza, 2001).

Although these mechanisms for tsunami generation present a real hazard, their potential for destruction is likely small when compared to large earthquake-induced tele-tsunamis, such as in the Indian Ocean in 2004. For each of these types of tsunamis, the ability to predict the wave magnitudes, arrival times to shorelines, and inundation levels is critical to public safety. Here we discuss the modeling issues, from deep-ocean propagation to shallow-water and onshore aspects of the waves. In particular, we will point out the importance of modeling each of the wave fronts and the effects of wave amplitude, bathymetry, and topography on the waves.

SUBMARINE-EARTHQUAKE-GENERATED TSUNAMIS

Tsunamis are long waves created by the sudden displacement of a large amount of water. In addition to the subaerial landslides mentioned above, the other common mechanism for this sudden displacement is the seismically induced vertical motion of the ocean bottom. As the recent Indian Ocean tsunami painfully reminded us, very large "megathrust" earthquakes occurring in major subduction zones can generate giant tsunamis that are devastating and felt worldwide. In these zones, one tectonic plate is slowly moving under another, pushed by motions in Earth's asthenosphere. In the case of the Indian Ocean earthquake, the Indian-Australian plate is subducting beneath the Eurasian/Andaman plate at 5–6 cm/year, with a largely east-west direction of convergence. On December 26, 2004, the locked fault between the plates ruptured at the earthquake's hypocenter, located 160 km west of Sumatra, liberating strain that had accumulated since the last large earthquakes occurred in the area. The rupture then proceeded to literally unzip the fault over 1,200 km, from south to north. The rupture propagation took about 10 minutes, liberating a total accumulated elastic energy estimated by seismic inversion models at $M_o=10^{23}$ J, or a $M_w=9.2$ magnitude earthquake, making it the second or third largest earthquake ever recorded (Stein and Okal, 2005). The earthquake caused the seabed to uplift by as much as 6 m or subside by up to the same amount, slightly more in some areas, over a region 100–150 km wide around the ruptured fault. Maximum seafloor uplift of about 10 m occurred directly west of Banda Aceh, in Northern Sumatra (Ammon et al., 2005). The uplift displaced vertically an estimated 30 km^3 of water, which deformed the water surface, approximately mirroring the seafloor deformation (Kawata et al., 2005). This displaced water then began to flow away from the uplift region, propagating as long waves in directions mostly orthogonal to the fault.

Because of the (usually) large cross-fault width of seafloor deformation, initial earthquake-induced tsunami waves have similarly long wavelengths, on the order of 100 km or more—much greater than ocean depths. Furthermore, the seafloor uplift and subsidence due to an earthquake will typically be asymmetrical, with uplift on one side of the fault and subsidence on the other. On December 26th, the generated tsunami had a leading depression wave propagating eastward and a leading elevation wave propagating westward, both followed by trains of a few larger waves and then many smaller ones. People at the coastlines in Indonesia and Thailand first experienced a withdrawal of the ocean, followed by the arrival of a giant wave, in places described as a moving wall of water. Unfortunately, many people lost their lives because they came to witness this strange withdrawal, rather than fleeing to high ground. On the other hand, in the western Indian Ocean, the first wave was positive—there was no prior withdrawal of water that could have provided a warning to some.

The numerical modeling of tsunamis caused by the seafloor displacement involves understanding the seismology and geology of the earthquake event in order to design a realistic tsunami source for a numerical model. This source, which takes the form of an initial ocean surface displacement surrounding the fault, must be specified, along with bottom topography representing the ocean basin. If the earthquake rupture occurs rapidly and covers a small horizontal area, this source will just constitute an initial condition for the model, but if the rupture covers a large area, as in the December 26th tsunami, the bottom motion should be specified as a function of time, with the corresponding free surface displacement similarly specified with time. For real-time tsunami prediction, the interpretation of the seismic record to infer the bottom displacement needs to occur rapidly so that the numerical modeling can take place in time for adequate warning (e.g., Ammon et al., 2005).

To simulate future tsunamis for hazard mitigation and planning, the geology of a subduction zone provides an estimate of the fault length and its linear orientation, and the fault plan orientation (described by three angles: dip, rake, strike). The subduction speed of the plates and number of years since the last large event occurred give an average potential fault slip Δ. For instance, for the Indian Ocean tsunami, one might have expected a 7–8 m slip for the part of the fault that moved 125 years ago and more for other older parts. Finally, an estimate of the earthquake depth can be obtained by comparing to other known events. To create a tsunami source, one has to assume an earthquake magnitude M_o, an epicenter location, a length L and width W of the ruptured area, and a Coulomb modulus μ (usually about 4 x 10^{10} Pa); parameters that are related by $M_o \approx \mu\, LW\, \Delta$. The seafloor—deformation/tsunami—source can then be predicted based on these parameters, in the simplest manner, using a half-space elasticity solution for a dislocation on an oblique plane (Okada, 1985). (Liu [2005] provides another description of tsunami source modeling.)

LANDSLIDE-GENERATED WAVES

In addition to volcano collapse, other *subaerial* mass failure, including landslides, avalanches, and pyroclastic (lava) flows, are tsunamigenic. Another source is a *submarine* mass failure, which refers to all submerged reef and slope failures. One such slope failure is believed to be responsible for a devastating tsunami in 1998 at Papua New Guinea (Tappin et al., 2001; Borrero, 2003). Once triggered, any such mass failure displaces water proportional to the transformation of its potential energy into kinetic energy, which is then imparted to the water.

The initial water motion representing the tsunami source is a function of the moving soil mass: volume, density, and cohesiveness; geometry; and location of the center of mass (i.e., initial height/depth of emergence/submergence). As the submerged soil mass begins to move, a depression of the water surface occurs; this depression then propagates away from the source area with a leading negative wave. The mass-failure motion can be simply represented by that of its center of mass, with an additional possible deformation about the center of mass. Center-of-mass motion itself is simply governed by a balance of gravity, inertia, and friction/dissipation forces. Underwater, the latter forces will typically include added mass and drag forces, in addition to basal friction. Predicting "landslide tsunami" sources thus requires modeling the mass failure motion in a hydrodynamic model, typically three-dimensional with bottom, free surface, and lateral boundaries (Grilli and Watts, 2005; Liu et al., 2005; Grilli et al., 2002).

Although initial wave generation by an accelerating mass failure is very complicated and can involve intense breaking in the most extreme subaerial cases, once the soil mass reaches sufficient depth, it ceases to generate waves. For large mass failures, able to generate large tsunamis, waves created in the initial stage will also be fairly long, although not as long as for "earthquake tsunamis" and likely more dispersive. Consequently, just as for "earthquake tsunamis," "landslide tsunami" sources can also be specified as an initial condition in long-wave propagation models, in the form of surface elevation and depth-averaged water velocity (because of the longer generation time for "landslide tsunamis," the source can no longer be assumed instantaneous and of zero velocity) (Watts et al., 2003). "Landslide tsunami" sources also will usually be fairly directional, about the direction of motion of the mass failure (i.e., made of waves propagating in a fairly narrow angular direction). Because tsunamigenic mass failures typically occur near a shoreline, where sediments accumulate, the onshore moving part of such directional waves will often impact the coast over a narrow section in a very concentrated manner, thus causing large local runups. The offshore moving part of "landslide tsunami," by contrast, lacking the huge energies imparted by earthquakes, will rarely propagate over large oceanic distance before being reduced to small oscillations through directional spreading and dissipation. Nevertheless, the typical proximity of "landslide tsunami" sources to shore and the possibility for mass failures to be triggered by moderate earthquakes that are quite frequent make for some of the most dangerous mechanisms for tsunami generation in coastal areas. In particular, very little warning time will be afforded the local populations, making evacuation almost impossible.

BASIN-SCALE TSUNAMI MODELING

As we are now fully aware, tsunami-warning systems for coastal areas provide a vital tool for saving lives by alerting people to the imminent arrival of a tsunami. This warning, coupled with proper education about tsunamis, provide people with time to get safely to higher ground. The efficacy of these systems is highly improved if numerical or physical modeling has provided information about the possible destructive effects of a tsunami making landfall. On the Pacific Coast of the United States, we have a NOAA-maintained warning system that is triggered by tide gages and pressure sensors in and around the Pacific Ocean. Given that an earthquake occurs, the location and magnitude can be estimated rapidly (within minutes) and then the probable shoreline impact of this tsunami, in terms of arrival times and wave heights, can be determined by either real-time modeling of the wave, or

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by pre-computing the trajectory of waves from that site and obviously many others (Titov et al., 2005).

In contrast to the problems associated with tsunami generation in the vicinity of the source, modeling the propagation of a tsunami in the ocean, a semi-enclosed sea, or lake is relatively simple. A model must be able to deal with wave propagation in an irregularly shaped water body with a spatial variation of water depth. In the event that propagation occurs over scales of one or more ocean basins, the model must account for Earth's sphericity. The accuracy of the modeling effort is principally limited by uncertainty in specification of the source, inaccuracies in bathymetry and its mapping onto a computational grid, and possible under-resolution of the propagating wave fronts in the numerical simulation.

Theories and Models: Linear Shallow Water

Tsunamis propagating in the open ocean are basically linear, nondispersive long waves. Linear waves are waves whose evolution is not influenced by the amplitude of the motion. Nondispersive waves are not affected by frequency dispersion, which alters wave speed depending on wavelength, and which causes waves with shorter wavelengths to travel more slowly. In the long wave limit, all waves travel at the speed $C = \sqrt{(gh)}$, where g is the acceleration of gravity, and h is the local water depth. (This relationship leads to the surprising result that tsunamis in the open ocean can travel at speeds comparable to that of a jetliner—although it is only the waveform and the wave energy that travel at these speeds, the water itself is only slightly displaced.) This wave speed relationship makes it relatively easy to make travel-time estimates for a tsunami event, because only the distribution of water depth along a great-circle arc would be needed to estimate time of travel from a source to a target area. For long waves, linearity follows from the fact that the ratio of water surface displacement to water depth is small. As a consequence of these limits, tsunami modeling is often performed using the linear long wave equations. These linear models are capable of making useful leading-order assessments of tsunami propagation over ocean-basin scales, and, in particular, their prediction of initial arrival time can be quite accurate because the leading wave in a real wave train is the longest and propagates at the long wave speed.

Tsunami modeling is the application of numerical methods to the equations governing long wave propagation over basin-scale bathymetries.

Nonlinearity

The assumption of linearity breaks down as tsunami wave fronts shoal into shallow water and build in height as they approach shore. In this rapid phase of wave evolution, tsunami wave fronts take on properties similar to other long waves approaching shorelines, such as wind-generated swell with wave periods on the order of 10 seconds. The waves steepen and either break before arriving at the still water shoreline or surge over the nearshore bathymetry without breaking. Figure 1 shows the runup of a tsunami, represented by a solitary wave, on a uniform slope. This phase of wave evolution, still neglecting effects of frequency dispersion, is governed by the nonlinear shallow water equations (NLSW), which also form the basis of the study of unsteady open channel hydraulics. NLSW-based models can provide good predictions of runup heights and inundation over coastal terrain. The principal limitation to their accuracy in predicting shoreline inundation in tsunami applications stems from factors not covered by the basic theory: frequency dispersion and the interaction with fixed obstacles with sizes that are small relative to the wave-crest geometry, and the interaction with the mass of transported debris resulting from destruction of structures, uprooting of trees, and entrainment of objects, including vehicles.

Frequency Dispersion

The second principal deviation from linear long wave theory results from the effect of frequency dispersion, which causes shorter waves to propagate at a slower speed and thus causes an initial packet of waves to disperse as it propagates. Frequency-dispersion effects are always present, but can be quite subtle in the case of most seismically generated tsunamis, where the effect is manifested in the details of, for example, a sequence of wave crests in the tsunami wave packet.

Landslide tsunamis, on the other

hand, can be generated in regions with spatial extents that are not excessively large relative to the water depths in which the motions are generated. The resulting waves are often dispersive in nature; as a particular example, scenarios that are presently being investigated for the Stromboli volcano (A. DelGuzzo, University of L'Aquila, Italy, personal communication, 2005) lead to initial tsunami waveforms that are effectively in intermediate or deep water immediately after generation. Adequate modeling of these events is not within the capabilities of the long wave theory. A more comprehensive theory is needed. The need for this extension to the theory, even to account for the slow accumulation of dispersive effects in long wave propagation over ocean basin scales, has long been recognized.

Boussinesq Equations

The basis for modeling dispersive wave behavior of tsunamis is the Boussinesq equations, which originally included the effects of weak wave nonlinearity and frequency dispersion. Modern work has relaxed the restriction on nonlinearity, leading to the so-called fully nonlinear Boussinesq theory in which frequency dispersion is weak but nonlinearity may be as strong as it is in the NLSW theory (see Wei et al. [1995] for an example). The numerical model FUNWAVE, based on the fully nonlinear Boussinesq theory, was developed by Kennedy et al. (2000) and Chen et al. (2000) and has been applied successfully to a number of examples of wave propagation and, surprisingly, to nearshore wave-induced currents, including rip current dynamics (Chen et al., 1999), longshore current generation (Chen et al., 2003), and shear wave instability of the longshore currents (Kirby et al., 2003). The general applicability of the model to long waves makes its application to tsunami modeling quite natural. Recently, FUNWAVE has been combined with TOPICS, which provides a wide range of parameterized tsunami sources, to become GEOWAVE. Watts et al. (2003) have used this model in conjunction with a source based on a parameterized landslide to successfully model runup and inundation in the 1998 Papua New Guinea event. Day et al. (2005) have used the model to explain observed runup events associated with a small-scale tsunami event generated on the flank of the Kilauea volcano. The most extensive application of the model

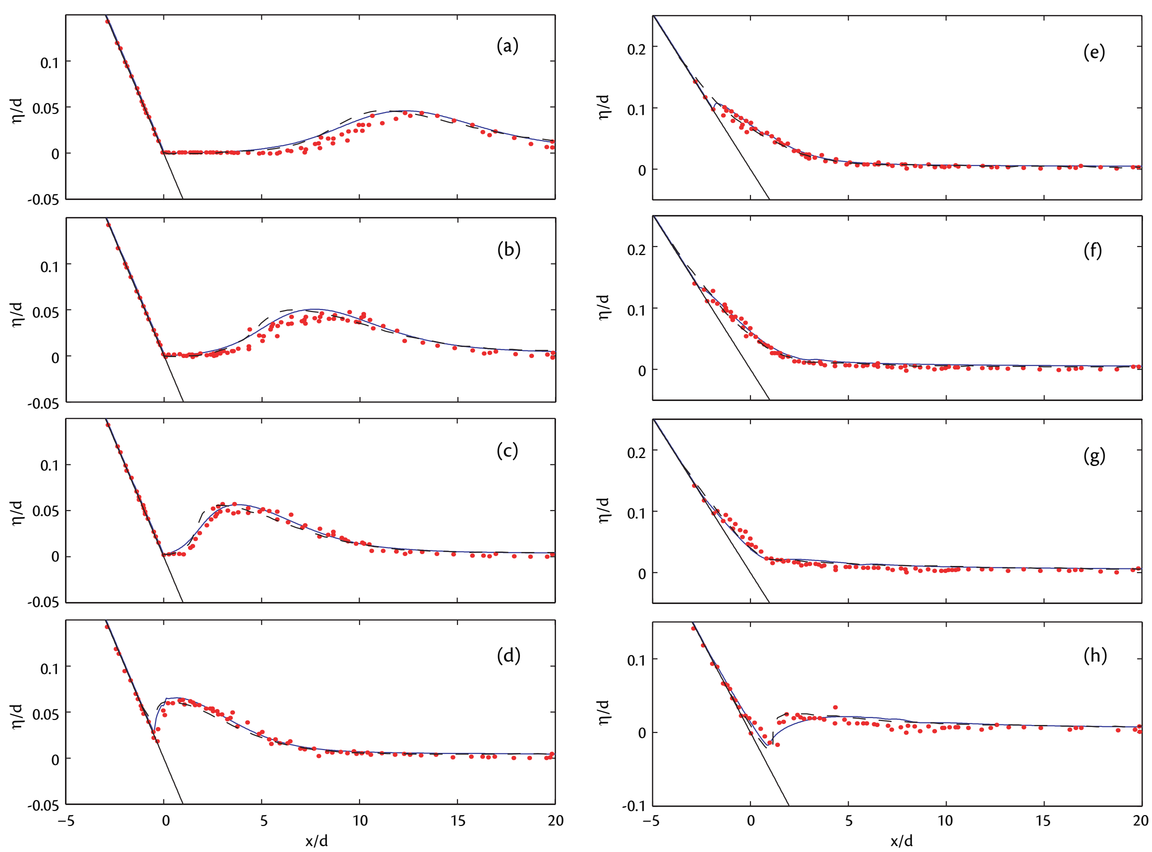

Figure 1. Sequence showing the approach and runup of a breaking solitary wave of initial height H/h = 0.040 on a beach with slope 1:19.85. The dots represent laboratory data obtained by Synolakis (1987). The dashed line is a nonlinear shallow water solution by Synolakis and the solid line represents numerical results of a Boussinesq wave model.

to date has been in the context of the 2004 Sumatra event (Watts et al., 2005; Grilli et al., 2005, submitted). Ongoing work includes the development of a version of the model in spherical coordinates for application to ocean-basin scale or worldwide events; preliminary results are described by Kirby et al. (2004).

Although the use of fully nonlinear Boussinesq equations, with dispersive and large amplitude effects, can be considered overkill in the context of a general basin-scale tsunami model, the generality of the modeling framework provided by the model is advantageous in that it automatically covers most of the range of effects of interest, from propagation out of the generation region, through propagation at ocean-basin scale, to run-up and inundation at affected shorelines. Rather than switching from one model equation to another as we move through this range, we use a single comprehensive model that adapts automatically to cover each range. The main modeling challenge is to move across a sequence of spatial resolution needed to resolve wave crests as they move from the deep ocean into complex coastal environments. This hierarchical sequencing of cascading model scales has not been implemented as yet in a practical model and should be an important focus of future work.

Another justification for the use of Boussinesq equations is that there are records of events in the recent past that indicate that a reasonable prediction of the actual waveform would be a useful part of a prediction. In particular, the sequence of wave heights in the train of tsunami waves resulting from dispersion over long distance can be crucial. Figure 2 shows the difference in waveform for a tsunami when the dispersive terms are included and when they are not. Much of the loss of life associated with the arrival of the 1960 Chile tsunami in Hawaii (an event for which a warning system was in place and was used) resulted from reaction to the small size of the leading wave, and resulting lack of preparedness for the largest, third wave of the wave train that arrived two hours later. The fully nonlinear Boussinesq models hold out the possibility of making a more correct prediction of the history of individual wave crest arrivals in a dispersing train of tsunami waves.

HINDCASTING AND FORECASTING

The study of individual tsunami events still involves a great deal of detective work. Submarine and subaerial landslide events often leave an inadequate history of their properties, and the determination of even the leading order parameters needed for a wave prediction, such as total slide mass and its tra-

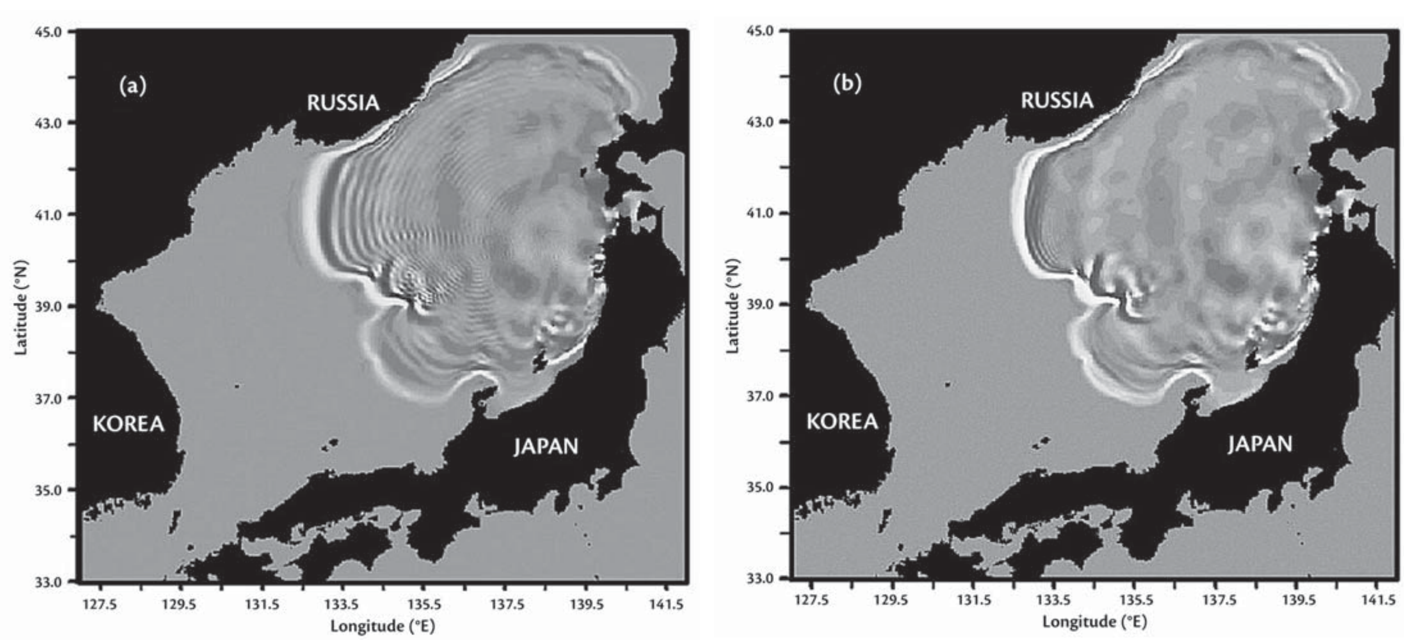

Figure 2. Simulation of Nihonkai-Chubu tsunami of May 26, 1983 in the Japan Sea. Numerical model results from Yoon (2002). Left frame shows simulated wave with dispersive effects included in the numerical model. Right frame shows results without dispersive effects. Clearly, the inclusion of the dispersive effects is important for the determination of the time history of the wave motion at a point. Figure from Yoon (2002). Copyright 2002 by the American Geophysical Union; reproduced with permission.

jectory, is troublesome. For the case of submarine earthquakes, it is likely that tsunami generation could be well modeled (or predicted) if a complete picture of the causative bottom motion were available. Inversion of seismic records to obtain ground motion models can miss displacements resulting from slow slip behavior, where a relatively slow faulting motion can lead to significant vertical bottom motion but leave very little record in the seismic data. As we have seen in the study of the December 2004 Sumatra event, an accurate, well-resolved propagation model can be used in conjunction with tide-gage data to effectively constrain the spatial and temporal characteristics of slow-slip ground motion, thus enhancing and in some instances significantly modifying the picture of the event deduced entirely from seismic inversions (e.g., Fujii and Satake, submitted; Grilli et al., submitted). These propagation model-based "inversions" are now performed in an ad-hoc, iterative forward method, which could potentially be made more automatic, given a good population of tide-gage data.

With increased dedication of computational capacity to direct modeling of highly resolved tsunami propagation, it is likely that even more effective forecasts of tsunami wave behavior could be made to aid in warning and rescue efforts. These forecasts would necessarily be based on rapid assessment of seismic inversions, and would require a strong, effective coupling between the organizations conducting seismic and hydrodynamic analysis. We also note that predictions of this type would necessarily omit the part of the tsunamigenic motion associated with slow slip. As we have seen in the study of the 2004 event, this would have led to a significant underprediction of damage in Thailand, which was strongly effected by waves generated by a portion of the overall source that was not well constrained by the seismic data.

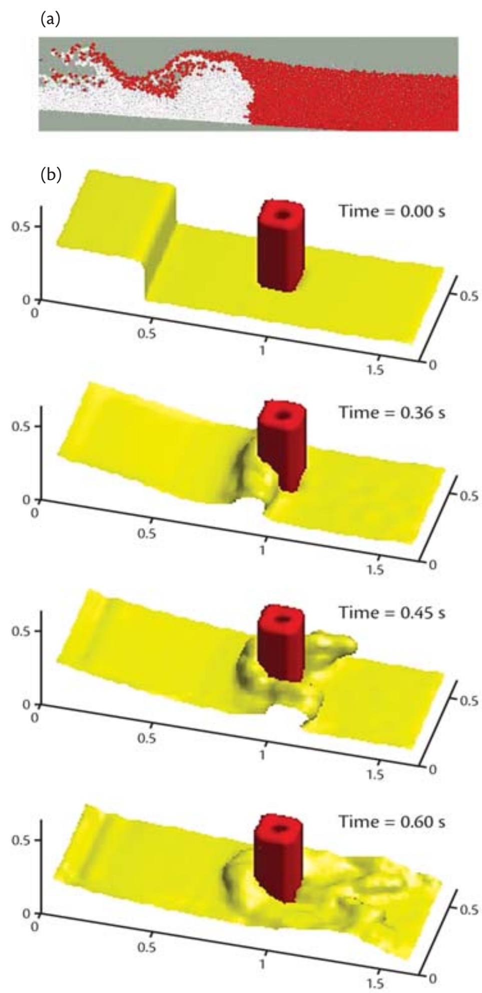

Figure 3. (a) Close-up of a breaking wave modeled by Smoothed Particle Hydrodynamics. The Lagrangian numerical method allows the tracking of individual particles; the red particles come from the offshore region on the right and have formed most of the plunger. The splash-up of the plunging jet in front of the wave is shown. (b) Time sequence of a wave attacking a structure, from the SPH modeling efforts of Gomez-Gesteira and Dalrymple (2004). The time sequence is top to bottom. The initial wave is due to a dam break. The wave wraps around the structure and collides at the back, resulting in a large wave height behind the structure.

AT THE BEACH

The runup of the waves at the shoreline depends on the shoaling history of the waves, the local bathymetry and topography, and the nature of any coastal structures. Clearly, a high-cliffed coastline would likely experience no damage from a tsunami while a low-elevation shoreline is easily overrun. Variations in wave characteristics can appear over very short distances along the coast due to differences in local refraction, diffraction (say, around offshore islands), and shoaling. In Thailand, plunging waves with heights of 4–6 m were experienced on Phuket Island, while 65 km away to the north, in Khao Lak, a moving wall of water came ashore with a height over 11 m (Kawata et al., 2005).

The modeling of tsunami flows at most types of shorelines remains a difficult but important problem. Inundation maps for communities, based on hypothetical and historical tsunamis, provide planners with information about areas that require evacuation and also safe havens. However, the full problem is very difficult to model. For coastal communities within the wave runup region, the tsunami flows around, through, and over buildings. This turbulent, fast-moving flow results in building damage, collapse, or floating away. People are drowned, due to the high water, the difficulty of withstanding the fluid forces, coping with the large turbulent eddies, or impact with debris. The amount of debris picked up in a tsunami depends on the distance of overland flow, the nature of the coastal construction, and the characteristics of the wave. As we saw in Banda Aceh, the wave front in overland flow can be dense with debris. As there are usually several waves striking the shoreline, this debris can be washed landward and seaward several times—with devastating effects as it impacts other objects.

Modern numerical techniques, such as Volume-of-Fluid and level set methods, which allow water surface tracking in Eulerian models, and Lagrangian particle methods, such as MPS (moving particle semi-implicit) and SPH (smoothed particle hydrodynamics; e.g., Monaghan and Kos, 1999; Gomez-Gesteira and Dalrymple, 2004; Panizzo and Dalrymple, 2004) will likely be useful tools for onshore flows. Figure 3a shows a two-dimensional breaking wave modeled by SPH, including the splash-up of the plunging breaker jet. Figure 3b shows a three-dimensional SPH result for a wave attacking a tall building.

In addition to water motions, particle methods also offer the capability of modeling large debris, such as logs or buildings (Gotoh et al., 2002), carried by the surging waves. However, this effort is far less advanced than the open ocean tsunami modeling and requires more research.

After the December 26th tsunami, many teams of field investigators traveled to many of the countries around the Indian Ocean to obtain runup and inundation data—these teams were from Japan (e.g., Kawata et al., 2005; Yamada et al. 2005), Korea (Choi et al., 2005), the United States (e.g., Earthquake Engineering Research Institute [EERI], 2005), Turkey (Yalciner et al., 2005a, b), and the home countries themselves. One purpose of gathering these data is to provide calibration data for future tsunami model development. As this tsunami was the most photographed, most videotaped tsunami in history, having both the video record and the actual elevation measurements at the same location taken shortly afterwards is important documentary work. Prompt reconnaissance is required as the traces that the tsunami leaves behind of its size are ephemeral. Although collapsed houses and building provide clues to the magnitude of the tsunami, high water lines (visible inside and on the outside of structures) due to the sediment and organics in the water, as well as signs of the limits of uprush on the sides of hills and mountains (downed trees, damaged or uprooted vegetation) provide the essential ground-truth. Rescue and repair activities, as well as the rapid recovery and growth of the flora, obliterates much of this evidence.

Early comparisons of field data with tsunami models show reasonable agreement. For example, Liu (2005) compares the Cornell Multigrid Coupled Tsunami Model (COMCOT) results to field data from Sri Lanka taken by EERI investigators. Grilli et al. (2005, submitted) used GEOWAVE to simulate the tsunami generation and propagation for the December 26, 2004 event. Tsunami elevations simulated using GEOWAVE (e.g., Figures 4 and 5) agree well with tidegage records, and predict coastal runup within the measured ranges (Table 1). Kulikov (2005) identified dispersive ef-

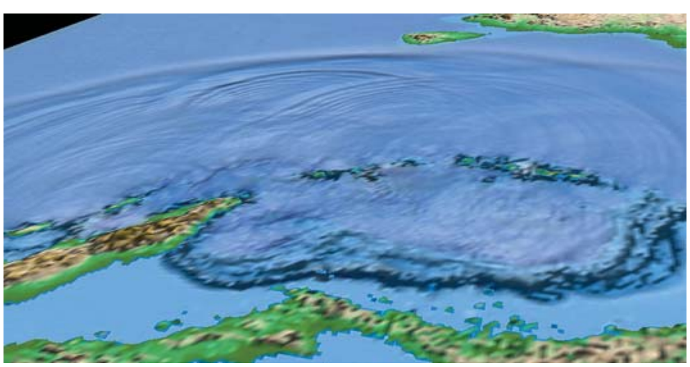

Figure 4. GEOWAVE computation of the December 26, 2004 tsunami in the Indian Ocean (Grilli et al., submitted). Waves are shown about 1h 45 min into tsunami propagation, as the waves approach Thailand and Phuket Island. Note the variation in wave direction along the wave front due in part to the offshore bathymetry. The dark area at the wave front is the leading depression wave that caused the drawdown of the water at the shoreline prior to the arrival of the destructive elevation waves. In the Indian Ocean, there are dispersive wave trains following the main tsunami wave front.

Figure 5. GEOWAVE computation show waves about two hours after the earthquake, when Sri Lanka and Phuket Island (Thailand) have just been hit by the tsunami. The leading elevation wave in the west is followed by series of smaller oscillations. There is a leading negative wave in the east, followed by two to three large waves.

fects in the tsunami wave train measured in deep water (west of the source) using satellite data. To estimate the importance of dispersive effects, Grilli et al. (submitted) also run a non-dispersive NSW version of GEOWAVE, using the same tsunami source and model grid. Dispersive effects led to changes of up to 20 percent in tsunami elevation, mostly on the west side of the Bay of Bengal, where deep water propagation occurred. By contrast, on the eastern side, likely because propagation was shorter and mostly took place in shallower water, dispersive effects were much smaller. This can be seen in the runup values in Table 1. Many more comparisons are sure to be made in the future with this extensive data set.

Beyond providing runup and inundation data for modelers, another purpose of post-tsunami field investigations is to examine and remind ourselves about the types of construction that are suitable for tsunami-hazard zones (Technical Council on Lifeline Earthquake Engineering [TCLEE], 2005; Dalrymple and Kriebel, 2005). Although the concepts of building tsunami-proof communities and the importance of siting critical civil infrastructure out of harm's way are well known, the perception of risk or the costs associated with retro-fitting structures and facilities has resulted in no action in many locales. In some cases, low-cost tsunami-prevention measures can and are being developed. In others, more expensive solutions are being implemented. However, most peoples' perception of hazard is short-term, and with time, people move back into harm's way. It is vitally important that the dangers associated with tsunamis be inculcated into subsequent generations of coastal dwellers and that competent and well-exercised tsunami warning systems be in place.

Table 1. GEOWAVE and NLSW simulation results at the shore and runup ranges measured in field surveys at a few key locations (simulations from Grilli et al., submitted, and field data from Kawata et al., 2005; Yalciner et al., 2005ab; Yamada et al., 2005).

Locations	Long. E, Lat. N	Boussinesq Model (m)	NLSW Model (m)	Field Surveys (m)
Aceh (N coast), Indonesia	95.323, 5.570	9.38	9.33	10–11
Aceh (N coast), Indonesia	95.284, 5.556	14.44	14.4	10–16
Aceh (W coast), Indonesia	95.247, 5.458	16.92	16.94	24–35
Galle, Sri Lanka	80.475, 5.974	2.97	3.23	2–3
SE coast, Sri Lanka	81.816, 7.427	6.71	8.13	5–10
Chennai, India	80.279, 13.021	2.45	2.43	2–3
Nagappaattinam, India	79.740, 10.865	4.98	4.67	2–3.5
Pulikat, India	80.333, 13.383	2.63	2.62	3.5
Kamala Bch., Phuket, Thailand	98.275, 7.973	3.46	3.47	4.5–5.3
Patong Bch., Phuket, Thailand	98.276, 7.900	2.46	2.48	4.8–5.5
Kho Phi Phi, Thailand	98.777, 7.739	3.67	3.68	4.6–5.8
Khao Lak, Thailand	98.268, 8.857	13.82	13.88	15.8

SUMMARY

Tsunami modeling is the application of numerical methods to the equations governing long wave propagation over basin-scale bathymetries. Open-ocean tsunamis are modeled quite successfully and a number of models were applied to the 2004 Indian Ocean tsunami within days. No models provided real-time modeling of the event. In the future, we should see accurate near real-time modeling of the actual highly resolved tsunami waveforms as they propagate across oceans, but before they strike land. Further inundation mapping will be able to include the effects of coastal construction/communities on the possible water levels associated with tsunamis.

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