Numerical Simulation of Complex Tsunami Behavior

Field observations alone rarely offer a complete picture of a tsunami's nearshore impact, and they're useful mainly in areas where tsunamis have already hit. Tsunami modeling is thus crucial to understanding and preparing for tsunami inundation. Recent research offers compelling examples of how basic modeling approaches can enhance our understanding of tsunami generation and propagation.

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On 26 December 2004, the boundary between the Indo-Australian and Eurasian plates off the northern Sumatra coast ruptured in a great (Mw 9.3) earthquake at 00:58:53 Universal Time. Up to 15 meters of thrust on the plate interface[1] displaced tens of cubic kilometers of seawater and propagated a tsunami across the Indian Ocean. The earthquake was widely felt throughout South Asia and was locally destructive in Sumatra and the Andaman and Nicobar islands, but it was the tsunami that caused widespread damage to densely populated coastal communities both nearby and thousands of kilometers away. Multimeter runup elevations were experienced from Thailand to Oman, with widespread values in excess of 5 meters (see http://eqs.eeri.org/resource/1/easpef/v22/iS3 for a complete set of survey data). The observed damage was frequently staggering, with entire towns washed away. Figure 1a shows an image of the town of Kalmunai in Sri Lanka. In this photo taken by the International Tsunami Survey Team,[2] the sandy areas in the image were packed with brick houses prior to the tsunami; after the tsunami only the largest structure in the town's center remained partially upright.

There have been numerous significant tsunami events in the past few years, such as the Samoan tsunami of 2009 (see Figure 1b) and the wave generated by the huge Chilean earthquake of 27 February 2010. Most recently, the tsunami created by the Japan earthquake on 11 March 2011 took the lives of tens of thousands and reached runup elevations of an astonishing 38 m. Immediately after a tsunami impacts a site, teams such as the International Tsunami Survey Team are deployed to those locations to provide a comprehensive set of observations and measurements of the tsunami's nearshore impact and to help unravel the mystery of the tsunami-generation mechanism. However, it's difficult if not impossible to put together a complete picture of the event with field observations alone. Additionally, in parts of the world that haven't seen a tsunami in recent times, there are often no field observations on which to develop safety procedures and protect residences from future tsunamis. It's for these purposes—understanding the detail of tsunami inundation and to estimate tsunami hazard—that we must rely on tsunami modeling.

With this in mind, we describe the basic modeling approaches for tsunami generation and propagation, offering examples from recent research results. We also discuss simulation of wave generation from earthquakes and landslides, and their relatively small-scale coastal impacts, such as wave-structure interaction. Our goal is to offer background on state-of-the-art tsunami simulation research, as well as how numerical tools are being practically applied.

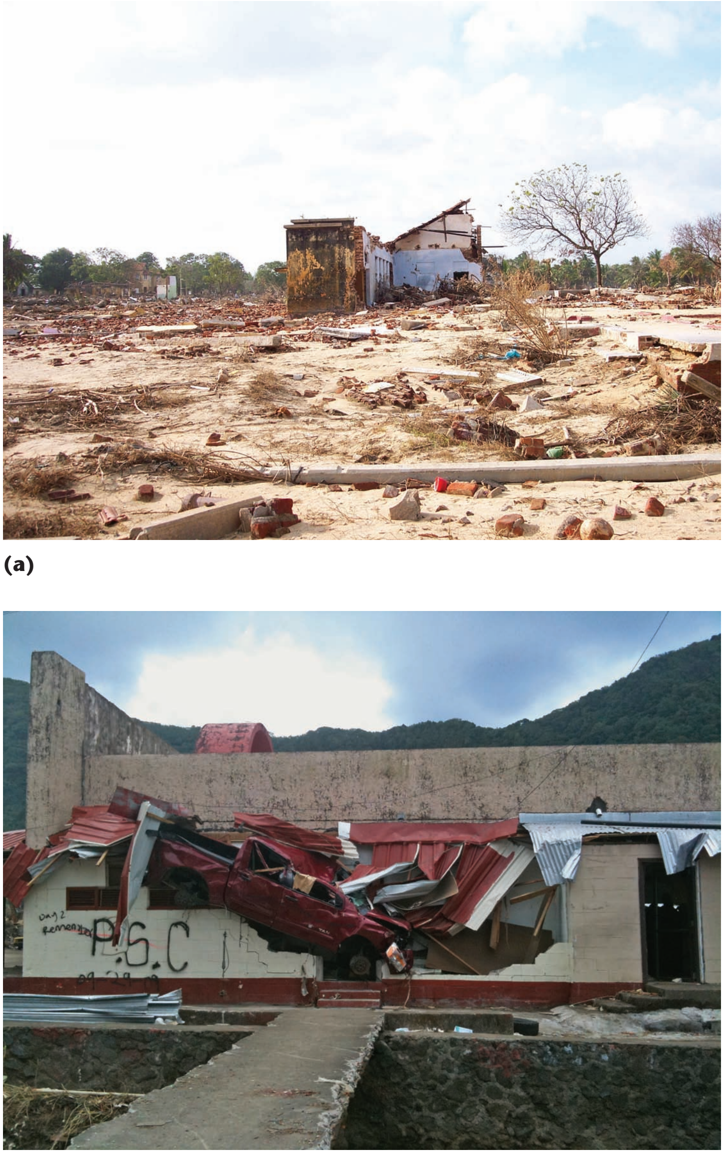
Tsunami Modeling

There are two primary modeling approaches—physical and numerical. The physical, or experimental, approach uses scaled-down models to look at a particular aspect of a phenomenon. While this approach is integral to the fundamental understanding of waves, because of tsunamis' huge wavelengths, experiments are limited due to scaling issues. Numerical modeling doesn't suffer from this scaling problem, and can generally accommodate any type of arbitrary wave and ocean depth profile.

Numerical simulations of tsunami propagation have made great progress in the past 30 years. Several tsunami computational models are currently used in the US National Oceanic and Atmospheric Administration's National Tsunami Hazard Mitigation Program to produce tsunami inundation and evacuation maps for the states of Alaska, California, Hawaii, Oregon, and Washington. The various numerical models employed in these efforts solve the same depth-integrated and 2D horizontal (2DH) nonlinear shallow-water (NSW) equations with different finite-difference algorithms. For a given source region condition, existing models can simulate tsunami propagation over a long distance with sufficient accuracy, provided that accurate bathymetry data exist.

Typically, shallow-water equation models can't simulate dispersive waves, which can be the dominating features in both landslide-generated tsunamis[3] and certain localized shallow-water phenomena. Several high-order depth-integrated wave hydrodynamics models (Boussinesq models) are now available for simulating nonlinear and weakly dispersive waves. These models often come with a significant additional computational cost compared to NSW solvers, but can provide a more physically robust prediction of nearshore wave mechanics, particularly when interaction with local bathymetry and topography features (such as shoals and embayments) are important to a tsunami's evolution.

Being depth-integrated and horizontally 2D, NSW and Boussinesq models can't simulate the vertical details of many coastal effects, such as strong wave breaking/overturning and the interaction between a tsunami and irregularly shaped coastal structures. To address this deficiency, researchers have developed several 2D and 3D computational models based on Navier-Stokes equations, with varying degrees of success. An example is the Cornell breaking waves and structures model (Cobras),[4] which describes the interactions between breaking waves and structures that are either surface piercing or submerged. Cobras adopted the volume-of-fluid (VOF) method to track free-surface movement along with a large-eddy simulation (LES) turbulence closure model; several other computational models using different free-surface tracking methods are also



(a)

(b)

Figure 1. Photos from post-tsunami field surveys. (a) The village of Kalmunai in Sri Lanka after the 2004 Indian Ocean tsunami. (b) The town of Pago Pago in American Samoa after the 2009 Samoan tsunami; note the red pickup truck pushed through the structure's outer cinder block wall.

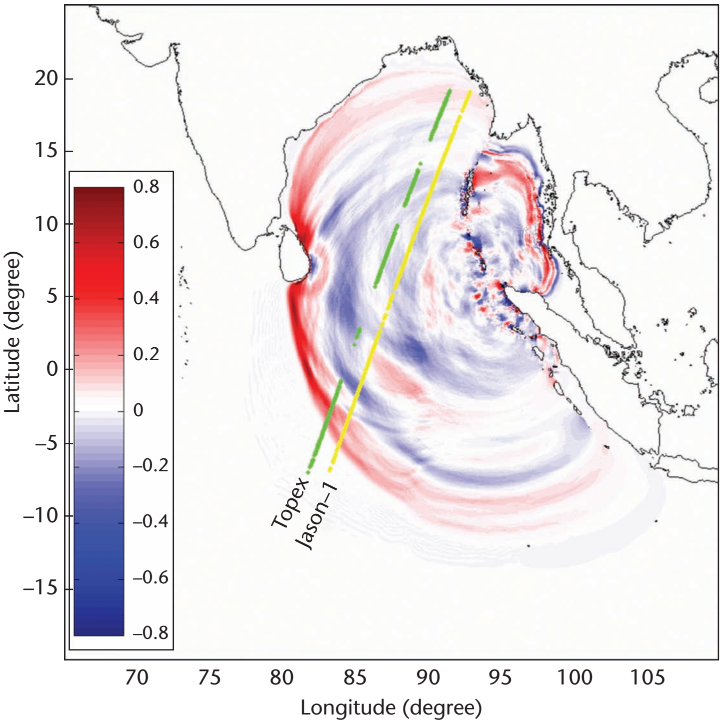


Figure 2. Satellite tracks for Jason-1 and Topex on 26 December 2004. The colors indicate the numerically simulated free-surface elevation (in meters) two hours after the earthquake struck.[7]

in use, including the microsurface cell technique and level-set methods.

Tsunami Generation, Propagation, and Nearshore Impact

Tsunamis are surface gravity waves generated in a water body when a large volume of the water is suddenly displaced. This displacement can be created by a submarine earthquake, a landslide falling into the water body, a submarine slope failure or slump, or—extremely rarely—a meteor impact. We can subdivide tsunami phenomenon modeling into three main phases, independent of the tsunami source:

- tsunami generation,
- propagation in the open ocean, and
- coastal inundation.

Researchers have generally studied these three phases using separate models. Such an approach might be suitable for earthquake-generated tsunamis, but not for landslide-generated tsunamis.

Earthquake-Generated Tsunamis

During earthquakes—the most common tsunami-generation mechanism—elastic deformation of the seafloor occurs in response to a slip within a fault rupture zone. A coseismic slip is strongly heterogeneous in both time and space, owing to a complex friction law that governs earthquake rupture, complexity in fault geometry, and other effects.

Conventional tsunami-generation models rely on different approximations for both fault slip and the elastic deformation of rocks surrounding the fault zone. Typically, the earthquake rupture is approximated by a linear elastic dislocation theory in a half space, which yields a simplified seafloor displacement.[5] Because the rupture time is usually brief (a few seconds) and the water's compressibility is small, it's plausible to assume that seafloor deformation caused by the earthquake provides the initial water surface displacement. In this case, tsunami waves are decoupled and computed separately from seismic waves. Researchers have also developed dynamic displacement models for the region near the earthquake, which provide the consistent prediction of seismic and tsunami waves.[6]

A slip/strike earthquake in an elongated subduction zone can create tsunamis with a leading depression wave propagating in one direction (perpendicular to the fault line), and a leading elevated wave in the opposite direction. The leading waves' wavelengths are usually in the same order of magnitude as the rupture zone's width. Thus, most tsunamis have long wavelengths (tens or hundreds of kilometers) when compared to the ocean depth (approximately 3 to 5 kilometers) at which they occur and are often referred to as *long waves* or *shallow-water waves*.

The initial amplitude of an earthquake-generated tsunami in a source region's vicinity is usually quite small—typically a meter or less—in comparison with the wavelength. When the tsunami propagates into the open ocean, the tsunami's amplitude decreases further as the wave energy spreads over a much larger area. Because the rate at which a wave loses its energy is inversely proportional to its wavelength, a tsunami will lose little energy as it propagates. Hence in the open ocean, a tsunami will travel at high speeds and over great transoceanic distances with little energy loss.

The 2004 Sumatra-Andaman earthquake triggered one of the most devastating natural disasters in the last few decades.[2] One of the event's most important scientific records is the satellite altimeter data taken by Jason-1 and Topex over the Bay of Bengal (see Figure 2). This data provides, for the first time, snapshots of sea surface profiles associated with tsunami waves in an

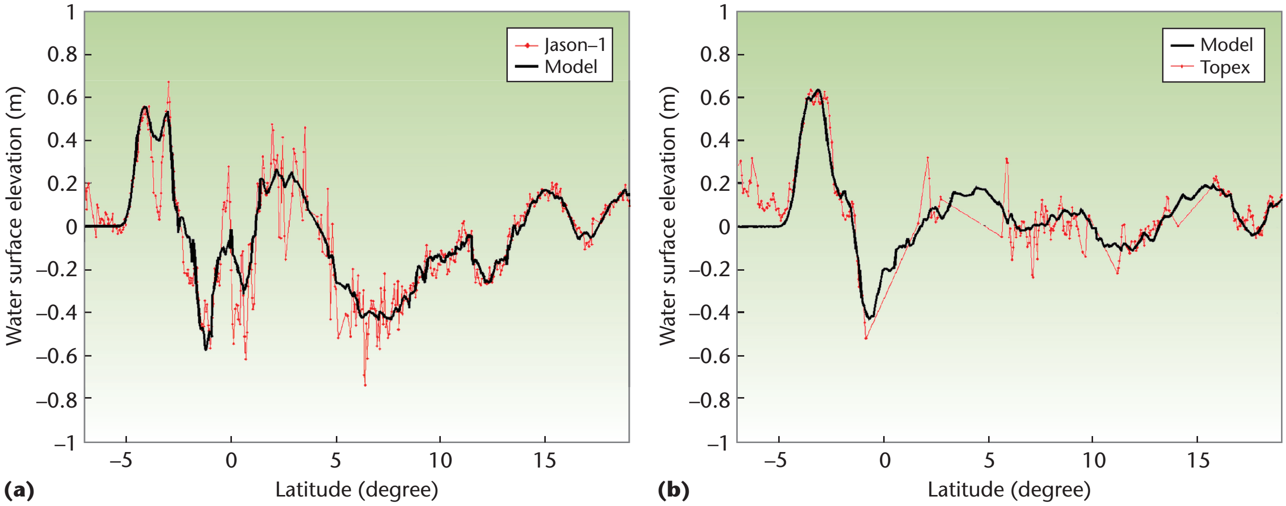


Figure 3. Ocean surface elevations. Comparisons between numerical model results[8] and (a) Jason-1 measurements, and (b) Topex measurements.

open ocean.[7] Figure 3 plots the ocean surface elevations along the tracks of Jason-1 and Topex. It also shows the corresponding numerical simulations, based on linear shallow-water equations (LSW).[8] Both the satellite data and the numerical simulation confirmed that the leading tsunami waves were small-amplitude long waves; the nonlinearity and frequency dispersion were unimportant as far as the leading tsunami wave propagation was concerned. Indeed, most of the important tsunami characteristics—such as the propagation's speed and direction, as well as the leading wave height and wave period—can be predicted reasonably well by the linear shallow-water wave theory once we've defined the earthquake source region's parameters.

As a tsunami propagates onto the continental shelf, it undergoes noticeable transformations. A leading tsunami wave's height must increase and the corresponding wavelength must decrease because the tsunami slows down due to decreasing water depth. Given this "shoaling" effect, a tsunami that was imperceptible in the open ocean might grow to be several meters or more in height on the continental shelf. However, the leading wave's wavelength is still very long (approximately several to tens of kilometers) and is independent of the wave height. As a tsunami travels far from the source, the effects of frequency dispersion, which are cumulative, might become important; the most appropriate model for simulating the leading tsunami wave far away from the source region is based on linear dispersive wave theory.

As a tsunami finally reaches the coastal region, reefs, bays, entrances to rivers, undersea features (including vegetation), and beach slope all play a role in modifying the tsunami. Tsunamis rarely become great, overturning breaking waves. Sometimes the tsunami might break far offshore and turn into a bore, which is a step-like wave with a steep breaking front and a long tail.

On the other hand, in some cases we can characterize the tsunami-induced overland flows as a slow rise and fall of water, where the water level on shore can rise several meters. In extreme cases, water level can rise to more than 20 meters for tsunamis of distant origin and more than 30 meters for tsunamis generated near the earthquake's epicenter.

Also, the first wave might not always be the largest in the wave series. In some cases, the water level initially falls significantly, exposing the bottom of a bay or a beach, and is followed by a large positive wave. A tsunami's destructive pattern is also difficult to predict. One coastal area might see no damaging wave activity, while in a neighboring area destructive waves can be large and violent. The flooding of an area can extend inland by 500 meters or more, covering large expanses of land with water and debris. To simulate tsunami coastal inundation, researchers generally consider the NSW equations and Boussinesq-type equations as suitable, practical models.

Landslide-Generated Tsunamis

Landslides are the other tsunami-generation mechanism that has been of considerable interest. Unlike earthquakes, there's no routine monitoring of landslide occurrence or an observed evolution during failure. In terms of tsunami-generation mechanisms, two significant differences exist between landslide and coseismic

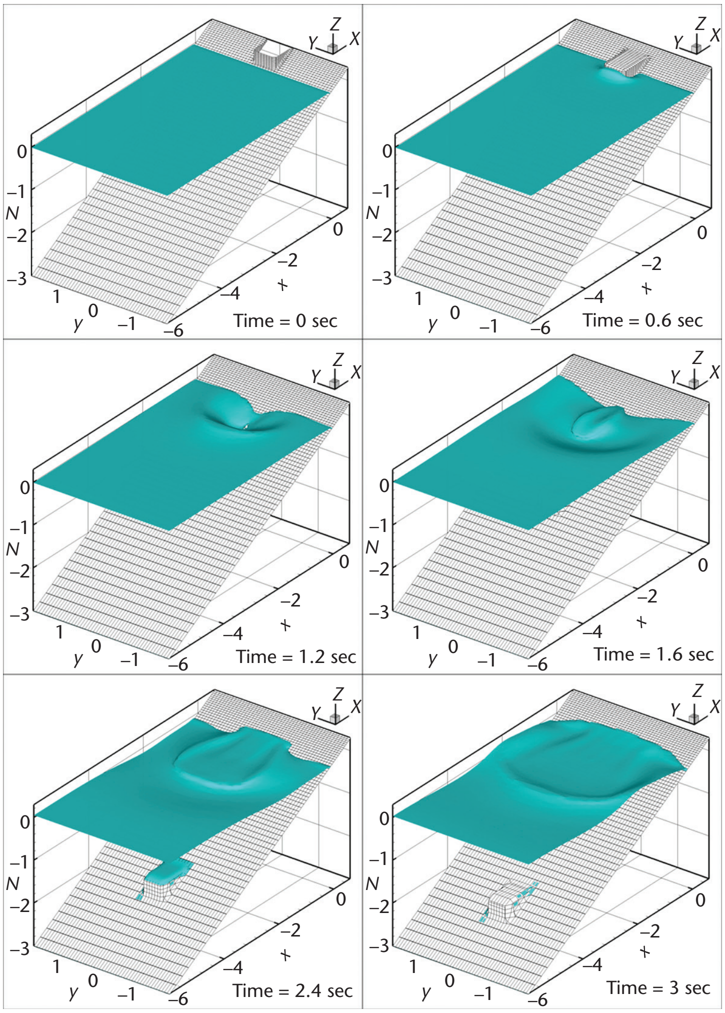


Figure 4. Snapshots of free-surface profile and runup generated by a sliding wedge. The simulations are obtained by solving 3D Navier-Stokes equations with a large-eddy simulation model.[9]

seafloor deformation. First, the landslide region's effective size is usually much smaller than the coseismic seafloor deformation zone. Secondly, a landslide's duration is much longer—in the order of magnitude of several minutes or more. The landslide movement's time history will affect the characteristics of the generated waves.

Tsunami generation, propagation, and coastal inundation phases locally coexist in landslide-generated tsunamis and can't be modeled independently. The first stage involves the wave-generation process with the landslide impact and the run-out along the water body's bed, the water displacement, and the tsunami wave formation. The second stage typically embraces the tsunami wave train's propagation, including lateral spreading and dispersion. However, for landslide-generated tsunamis, the wave-propagation stage is skipped by the dangerous onshore runup along the hill slope itself. The third stage is characterized by the wave runup along the shoreline. The transition between the different phases is irregular. In particular, in narrow fjords and bays, the forward and backward wave runup can begin even before the landslide motion has terminated.

Given the diversity of landslide types (rocks, debris flows, avalanches, and so on), researchers have considered a wide variety of non-Newtonian rheologies to simulate landslide dynamics. In the simplest model, the landslide is viewed as a solid block. It's then possible to use the 3D LES hydrodynamic model to describe the generated tsunamis and runup. Figure 4 shows snapshots of the free-surface profile and shoreline movements generated by a prescribed slide motion.[9]

Hybrid Simulation of Tsunami Evolution

Of the two typical depth-integrated models used in tsunami studies, researchers typically consider the Boussinesq a more physically complete approximation compared to the NSW. In coastal regions, where the water depth is shallow and thus amplitude and wavelength become high and short, nonlinear and bathymetric interactions across a wide range of frequencies occur. These interactions can locally generate various shorter-crested or dispersive wave components.

A well-known example here is the transformation of a tsunami front into an undular bore. Thus, the nearshore is expected to be nonlinear and (possibly) dispersive, and the Boussinesq model is appropriate. However, the additional physics included in the Boussinesq approximation come with a substantial computational cost, often making the model impractical for ocean-basin scale simulations. If we want the Boussinesq model's physical advantages for a local region in the nearshore zone, we must couple that Boussinesq model with some other source of wave information for its boundary conditions. The obvious coupling choice would be the NSW, which is proven for both efficient and accurate basin scale tsunami predictions.

Here, we offer an example that demonstrates the possible advantages of such a coupling. In the US, offshore of the Pacific Northwest, is the Cascadia Subduction Zone (CSZ) fault line, which is rather similar in its properties to the fault that ruptured in the 2004 Indian Ocean event. If the locked portion of the CSZ were to rupture in a single earthquake, the resulting tsunami would affect the entire Pacific basin, and would likely be devastating for the numerous coastal towns along the northern California, Oregon, and Washington coastlines. Thus it's of more than an academic interest to be able to predict the impacts of such a wave. While there are many towns in the high hazard zone here, in this discussion, we focus on just a single, hypothetical town.

Figure 5 provides background for this discussion. For this example, we modeled a hypothetical earthquake along the entire CSZ, creating a large wave in the deep water off the coast. Figure 5a shows the tsunami surface just minutes after the earthquake. The various "boxes" in this subplot show the different levels of nested computational grids. There are three levels of nested NSW grids, each with increasing spatial refinement, with the final, highest-resolution nested grid using the Boussinesq model. There are numerous challenges with this coupling, most notably that fact that the two approximations (NSW and Boussinesq) are different, which can create a physical mismatch across the coupling interface. Also, the NSW typically has a low-order numerical solution approach (hence its computational efficiency), while high-order partial derivatives in the Boussinesq model require a high-order scheme; matching these two schemes can also create numerical stability issues. Details regarding a coupling approach can be found elsewhere.[10]

Once we've constructed the nested grid system, the simulation can provide predictions across a wide range of spatial scales. For example, the outer NSW grid shown in Figure 5 uses a 2-kilometer resolution, while the Boussinesq grid uses a 2-m grid. Figures 5b and 5c show output from the Boussinesq domain, offering a visual example of the type of physical processes this model offers. Figure 5b shows a snapshot of the leading positive tsunami wave inundating the city; the simulation includes and resolves each building and road. In Figure 5c, the same surface is colored with the tsunami's instantaneous momentum flux, which is a good measure of the potential force the fluid might exert on structures. Clearly, we can see that the individual wakes created by each structure can create a complex flow field inside a city, and these wake interactions largely control the maximum fluid force.

Although Boussinesq models can provide a detailed description of a tsunami's flow, it can be necessary to use a model with even less restrictive physical approximations and the ability to resolve very small-scale (less than a meter) turbulent features, such as a 3D Navier-Stokes model. A coupling argument similar to the one we provided earlier for the Boussinesq applies for the fully 3D model. Because of their high computational costs, full 3D models are best used in conjunction with a depth-integrated 2DH model (that is, with NSW or Boussinesq). Although the 2DH model provides incident far-field tsunami information, the 3D model computes local wave-structure interactions. The results from 3D models could also provide a better parameterization of small-scale features (3D), which could then be embedded in a large-scale 2DH model. One-way coupling (such as using a NSW-generated time series to drive a 3D model, but not permitting feedback from the 3D model back into the NSW) is fairly straightforward to construct. Two-way coupling, however, is difficult and requires consistent matching of physics and numerical schemes across model interfaces.

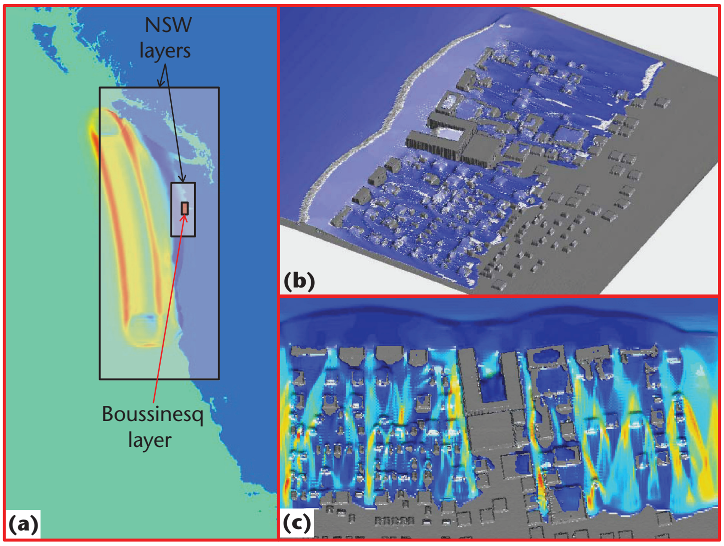


Figure 5. Example of a nonlinear shallow water (NSW)-Boussinesq hybrid simulation for a hypothetical Cascadia Subduction Zone tsunami. (a) The numerical grid "layers," with three NSW grids (two nested) and a single, fine-resolution Boussinesq grid. Snapshots from the Boussinesq simulation of the tsunami inundating a coastal town include those of (b) the sea surface and (c) the fluid's instantaneous momentum flux.

One of us (Lynett) along with Khairil Sittanggang previously presented work on coupling a Boussinesq model and a 2D NS model.[11] The two models are two-way coupled, thus acting as if they're a single model working on a continuous domain. In the coupling implementation, the Boussinesq model is applied in the nonbreaking zone and the Reynolds Averaged NS (RANS) model in the breaking/high-turbulence zone. The two models share a common domain interface for exchanging data that's used as boundary conditions in the models. By coupling the two models, it's computationally feasible to achieve accurate

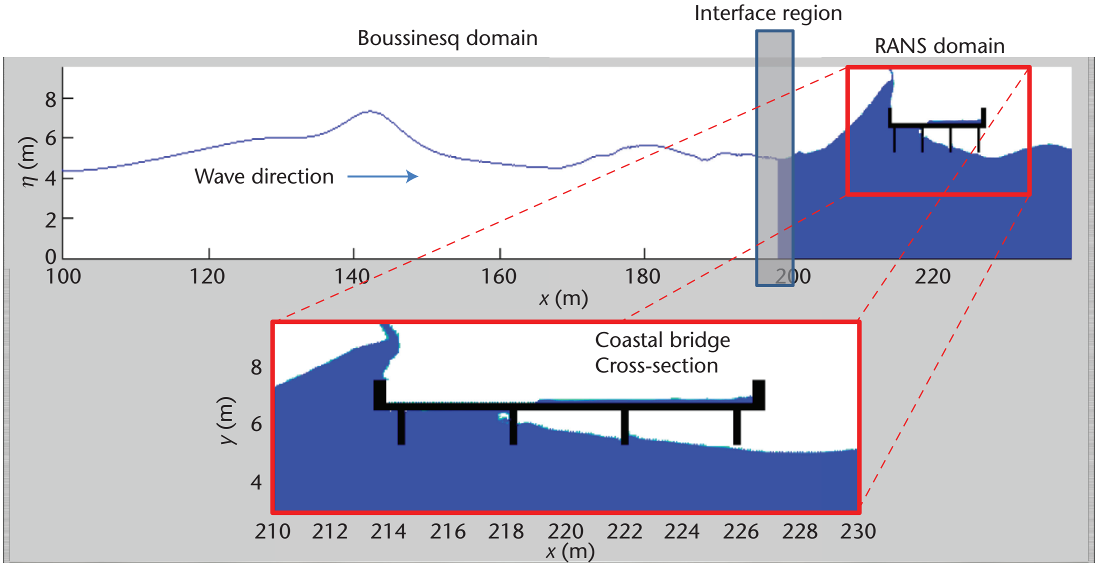


Figure 6. Example of a Boussinesq-Reynolds Averaged NS (RANS) hybrid numerical simulation. Long waves approach a coastal bridge. The Boussinesq domain predicts the wave evolution over the continental shelf. The RANS result yields the complex hydrodynamic response to the bridge's cross section, which includes both the bridge girders on top of the bridge platform and the four baffles underneath.

large-scale wave simulation using a coarse grid and "simple" physics in the deep-to-intermediate water region matched with a fine grid and detailed physics in the shallow, nearshore area.

Figure 6 shows an example application of this RANS-Boussinesq hybrid model. During extreme coastal events (such as tsunamis) and wind–wave events (such as hurricanes), coastal infrastructure can be at risk of failure. Such failure is often driven by local, small-scale flow phenomena, such as scour, turbulent bore impact, or floating debris impact. Thus, to predict the failure of these structures—or at least the forces acting on them—we need a fine-scale hydrodynamic model.

On the other hand, to properly predict this wave loading, we must use a realistic wave input near the structure. The coupled model is an ideal tool for such studies, where the relatively computationally inexpensive Boussinesq model propagates the waves to a location close to the target structure, and then the RANS model takes over. The Boussinesq model propagates the wave from far offshore—typically hundreds of meters to tens of kilometers—using a spatial resolution on the order of 1 meter. The RANS domain will generally be less than 100 meters in length, using a spatial resolution in the tens of centimeters and less. Figure 6 shows long-period ocean waves interacting with a coastal bridge. On the image's left side is the Boussinesq domain, which predicts the wave evolution over the continental shelf. The right side is the RANS result, yielding the complex hydrodynamic response to the bridge's cross section, which includes both the bridge girders on top of the bridge platform and the four baffles underneath. It's possible to predict forces, moments, and likely methods of failure using this computationally efficient and practical numerical tool, which also includes a state-of-the-art computational fluid dynamics capability. These results indicate that there's great potential for hybrid modeling in terms of more rapid simulation as well as the ability to approach a new class of problems.

To more robustly simulate tsunamis, a few major issues must be must addressed and investigated, including dissipation mechanisms and interaction with infrastructure. The hydrodynamic effect of common coastal vegetation, such as mangroves, must be better quantified, and we need to bring these effects into existing simulation tools. Currently, there's discussion of using such natural roughness as a tsunami defense.[12] However, we can't place confidence in such measures until we understand how they behave. In addition to bottom friction, which exists at all locations and times under an inundating tsunami, wave breaking can increase the total energy dissipation. Although breaking is generally confined to a tsunami's leading front, the front's characteristics are important for hydrodynamic loadings on beachfront structures, and might be significant to a tsunami's net sediment and debris transport.

Wave loadings and interactions with infrastructure aren't well understood. To tackle this problem, tsunami hydrodynamic models must be coupled with structural and geotechnical models. Ideally, these models should all be two-way coupled, such that the displacement of a structure—be it a single collapsed wall or an entire building—will change the flow pattern, and scouring underneath the foundation will change the structure stability. Additionally, the framework should include impacts of flow-transported debris (such as cars). Combined with ongoing research to use high-performance computing, our modeling ability's scale and scope will continue to increase. If such a modeling capacity existed, we could undertake the engineering design of coastal structures in a highly efficient manner.

Acknowledgments

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