Experimental and Numerical Modeling of Storm Surge and Tsunami Effects on Structures

by

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ABSTRACT

The joint research work at Oregon State University and the University of Hawaii at Manoa on experimental and numerical modeling of storm surge and tsunami interaction with structures for both model basin test and prototype scenarios are described in this paper. The numerical modeling capabilities for storm surge, and storm waves as well as tsunami propagation and runup using a nested-grid approach are presented first. Modeling capabilities at Oregon State University for coupled fluid-structure interaction using the computational fluid dynamics and computational structural dynamics approaches are then delineated. A roadmap to combine the computational and experimental capabilities for the analysis and design of prototype structures in future research is finally presented.

KEYWORDS: Storm surge, storm waves; tsunami; structures; numerical modeling; coupled; fluid; structure; interaction.

1.0 INTRODUCTION

Natural disasters caused by hurricanes and tsunamis, notably Katrina in 2005 and the India Ocean Tsunami in 2004 in the last couple of years, are vivid evidence that the design codes of coastal infrastructure, including those in the inundation zone, need to take into account these extreme events. However, current design codes (FEMA, CEM, UBC, etc.) in the US rarely mention hydrodynamic effects due to storm surge and waves or tsunami. In an effort to mitigate the effects of tsunami on coastal cities, the US government is implementing a series of measures including installation of additional tsunami measurement buoys in the Pacific and Atlantic oceans by NOAA. A number of conferences and workshops on the survey of the devastating effects of tsunami and hurricane have been held worldwide in the past decade, and much more frequently in 2005 to present. The 100th Anniversary San Francisco Earthquake Conference held this April attracted approximately 4,000 scientists, engineers and academicians from many countries (see web site in reference).

Recently, intense research activities on various aspects of storm surge and waves, and tsunamis as well as their effects on coastal infrastructure are underway. A complete account of these events is necessary to link the statistics of their occurrences to the mitigation efforts or design code revisions. These include modeling of generation at the source, propagation across the ocean, near-shore transformation, and fluid-structure interaction. In support of the experimental research at the Hinsdale Wave Research Laboratory at Oregon State University, 2-D and 3-D numerical models including tsunami runup and inundation effects on coastal structures are being developed. In the following sections, numerical modeling and its challenges are discussed.

2.0 STORM SURGE AND WAVES

Complete and accurate modeling of coastal overwash due to hurricanes requires simultaneous simulation of physical processes that include surface winds and pressure, storm surge, astronomical tides, swell and seas, surf-zone processes, and wave runup onto dry land. These processes, with different time and length scales, have been modeled separately with reasonable accuracy. Cheung *et al* (2003) described linkages

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of the processes to produce a forecast package for storm-induced coastal flooding. The package produces good agreement with measured wind velocity, wave conditions, and storm-water levels in the Pacific and Atlantic basins as well as the overwash evidence in Hawaii and Southern New England.

The coupling of the four model components and their interface with supporting models and utilities is illustrated in Figure 1. Each simulation covers three levels of nested geographic regions of increasing resolution: ocean, coastal, and nearshore. Hurricane wind and pressure fields, which can be generated by a parametric or numerical model, provide the environmental forcing over the ocean and coastal regions. A third-generation spectral wave model generates and propagates the waves in the ocean region. The simulation results define the boundary conditions for another spectral wave model to describe transformation of the storm waves as well as the subsequent wave setup in the coastal region. A shallow-water model simulates the storm surge and astronomical tides, while a Boussinesq model provides wave-by-wave simulation of the surf and swash zone processes at the coastline. The four-layered nested grid for the New England area for a model of the 1991 Hurricane Bob is shown in Figure 2. The grid size ranged from the coarsest of 10 Km for the ocean scale to the finest of 10 m for the runup on land (with 1 Km and 100 m in between).

3.0 TSUNAMIS

A number of the numerical nonlinear long-wave models currently used do not conserve flow volumes and underestimate runup when breaking occurs. However, a fully conservative model with shock-capturing capability is a prerequisite to producing sensible runup results. Wei *et al* (2006) makes use of the surface-gradient method and a Godunov-type scheme with an exact Riemann solver to track directly the moving waterline and to capture flow discontinuities associated with bores or breaking waves, which are essential for runup calculations. This provides accurate descriptions of the conserved variables and small flow-depth perturbations near the moving waterline. The computed surface elevation, flow velocity, and runup show very good agreement with previous asymptotic and analytical solutions as well as laboratory data. The model accurately describes breaking waves as bores or hydraulic jumps and conserves volume across flow discontinuities.

A nested grid is employed in the numerical simulation with four levels of nested grids. As an example, the nested-grid model of a tsunami inundation simulation of the northshore of Oahu due to the 1946 Alaska tsunami is shown in Figure 3. The largest is ocean grid, with a size of approximately 10 Km. (top left, Figure 3). It contains the regional grid, with a size of 1 Km (top right, Figure 3). Within the regional grid is the island grid, which has a size of approximately 100 m (bottom left, Figure 3). Finally, the finest grid is used in the area, where runup calculations are performed. It is nested within the island grid and has an approximate grid size of 10 m (bottom right, Figure3).

Accurate modeling of tsunamis from seismic sources to runup is a challenging task. Deformation of the earth surface due to internal faulting is an idealization based on elastic theory of dislocation, in which the earth is treated as an isotropic and elastic material. The determination of the initial tsunami waveform from the seafloor deformation is not trivial and depends on a number of factors. The most important is the rupture time, which affects the transfer of energy from the seafloor deformation to the water. The standard approach is to assume a short rupture time, as a result, the initial tsunami waveform is identical to the vertical component of the seafloor deformation due to faulting. In recalibration of the seismic source intensity is necessary to reconcile errors from tsunami source modeling to match historical runup records.

4.0 TSUNAMI WAVE BASIN FACILITY

The multidirectional tsunami wave basin (TWB) at OSU is 48.8m long by 26.5m wide by 2m deep (Figure 4). It is a reinforced concrete reservoir with unistrut inserts placed in rows at 2.1m spacing to affix models, instrumentation, and the wave generator throughout the basin. The wave generator consists of 29 wave-board segments, each paddle 0.9m wide by 2m high. Each wave board is capable of a 2m displacement and a maximum velocity of 2m/sec. It is able to generate a clean solitary wave approximately 0.8m high in a water depth of 1m. Each wave board is powered by an AC electric motor. The wave generator digitally controls the paddles on an individual basis, making it possible to generate arbitrary wave profiles and arbitrary wave directions. Control of the wave board is achieved through displacement and velocity feedbacks. Velocity control utilizes a wave profile measurement at the front of the wave board, comparing it to the desired long-wave profile; board velocity is adjusted via an algorithm that relates wave profile and board velocity. This velocity control has the capability of absorbing reflected waves in the basin and optimizing the wave shape beyond that available by means of the displacement control. The 3-D TWB creates a unique large-scale experimental testing laboratory for tsunami-hazard mitigation research. This basin, together with the existing directional (2-D) large wave flume (LWF), supports high resolution, unprecedented-scale experiments with very dense instrumentation. The OSU WRL facility provides coastal, offshore, earthquake and tsunami researchers with critical means to conduct large-scale experiments and validate advanced analytical and numerical models.

5.0 FLUID-STRUCTURE INTERACTION

Storm surge and waves, and tsunami models define the boundary conditions at the coastline for more detailed analysis of fluid-structure interaction. The environmental loads on a structure include hydrostatic pressure, fluid impingement, form and viscous drag, and impact due to waterborne debris. These loads often induce large structural deformation, yielding, fracture, and collapse or dislodgement. Accurate modeling of coupled fluid-structure interaction is therefore a very challenging problem. Traditionally, the study of coastal waves and structures belong to two separate disciplines and their analysis and numerical techniques usually cannot be coupled. Since the inception of the Tsunami Wave Basin (TWB) construction project in FY2000, researchers at OSU have been developing computational fluid-structure interaction software suitable for use by both environmental and structural engineers (Yuk *et al* 2006). Selected on-going developments related to this goal are briefly summarized here.

The software package LS-DYNA, which contains modules for very large strain deformation, nonlinear materials, fracture, shearing detachment, contact and impact, appears to be a suitable computational structural dynamic (CSD) code for the structural analysis needs. It also contains a fluid module based on the NS equations to model wave impact as well as surface piercing and re-submergence of multiple flexible bodies. Recently, a finite-element based formulation to model the fluid domain; called the particle finite element method (PFEM) (Del Pin 2003) shows promising signs of unifying the simulation of fully coupled fluid-structure interaction. In PFEM method, the continuity and momentum balance equations in the fluid domain are modeled using the Lagrangian formulation and discretized using particle finite-elements. The boundaries at the free surface and at the interface between the fluid and the structure can be modeled exactly with a moving FE grid that is remeshed at every time step.

A combination using the CSD and CFD (computational fluid dynamics) codes from the industry for their proven robustness and nonlinear capabilities for the analysis of structural behavior and the PFEM methods for modeling fluid motions in Lagrangian form may provide the best solution for the development of a robust code for simulation of storm wave and tsunami basin experiments and prototype events. This choice allows a unified Lagrangian formulation and computation for both fluid and structural domains. More importantly, it allows for exact means of tracking the fluid-structure interfaces that determines: (1) the energy input to the wave field by the wave generator; (2) the wave forces on the coastal structures and floating debris; and (3) energy dissipation at the bottom boundary and the beach that may contain porous media and/or movable sediments.

A glimpse of the current capability of LS-DYNA for modeling the US National Science Foundation supported Network for Earthquake Engineering Simulation Tsunami Wave Facility at Oregon State University is shown here. Figure 5 shows the physical 3-D wave basin and the LS-DYNA numerical model with the exact dimension and number of wave paddles. The numerical model accepts prescribed motions of each individual paddle. Using the same prescribed motions as those of the physical wave generator, the subsequent wave motions in the basin are observed to be predicted accurately when appropriately fine grids are employed.

LS-DYNA is also capable of modeling a complex system by first modeling the components of the system as individual modules and then assembling them together to form the system. With this capability, we are able to model an experiment to be conducted at the NEES Tsunami Wave Facility as follow. We first model the wave basin including wave paddles and water as a single module (Figure 6a), and separately an instrumented cylinder including its components as another module (Figure 6b), and then insert the cylinder module inside the tsunami wave basin module to form the experimental model (Figure 6a). Once the system is in place, we can simulate a test run and compute the strains inside the cylinder (Figure 6c). Thus, LS-DYNA is used as a design and simulation tool for experiments at the NEES Tsunami Wave Basin Facility.

An issue that needs to be addressed is computational resources. To model a fluid-structural interaction experiment at the TWB using 1cm^3 elements would lead to the number of fluid and structural elements approximately 3 x 10^9. Using 20-node solid element with 3 degrees of freedom (d.o.f.) at each node would lead to approximately 4 x 10^{10} d.o.f. An explicit computation of the numerical model for a typical transient experimental test of approximately 20 seconds would exceed the capability of many existing parallel computer clusters. The use of high-end vector supercomputer is necessary.

6.0 FUTURE RESEARCH

We are currently conducting research to develop a methodology to couple the numerical simulation capabilities at both universities and to extend the LS-DYNA capability to model fully coupled fluid-structure interaction. The key piece to be developed is the transfer of information at the boundary of the environmental domain containing the fluid and structure. The boundary conditions have to take into account the incoming wave (runup) from the ocean side and the out-going wave (rundown). When the research is complete, we expect to utilize the resulting software for practical applications to study the effects of storm surges and tsunamis on coastal infrastructure including bridges and buildings. For these cases, an existing finite-element model of a full-scale bridge (e.g., Figure 7) or a building, if available, may be directly inserted into the model of the coastal environment subjected to storm surge or tsunami boundary conditions. The resulting finite-element model will likely contain hundreds of thousands to millions of nodes and elements. Parallel and supercomputing will be needed. Results of this joint research will be reported in future workshops.

7.0 ACKNOWLEDGMENTS

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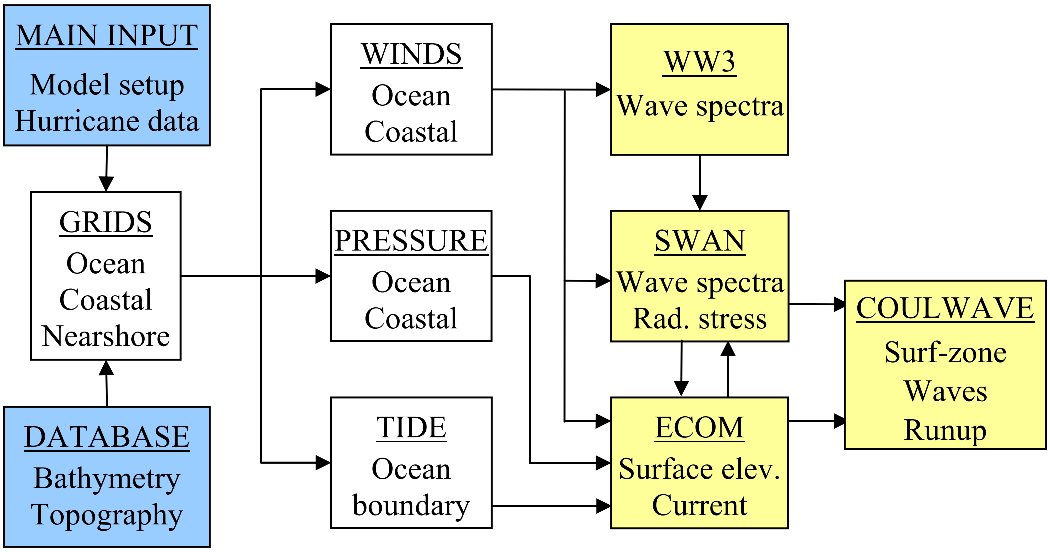


Figure 1. Storm Surge and Storm Waves Model Structure.

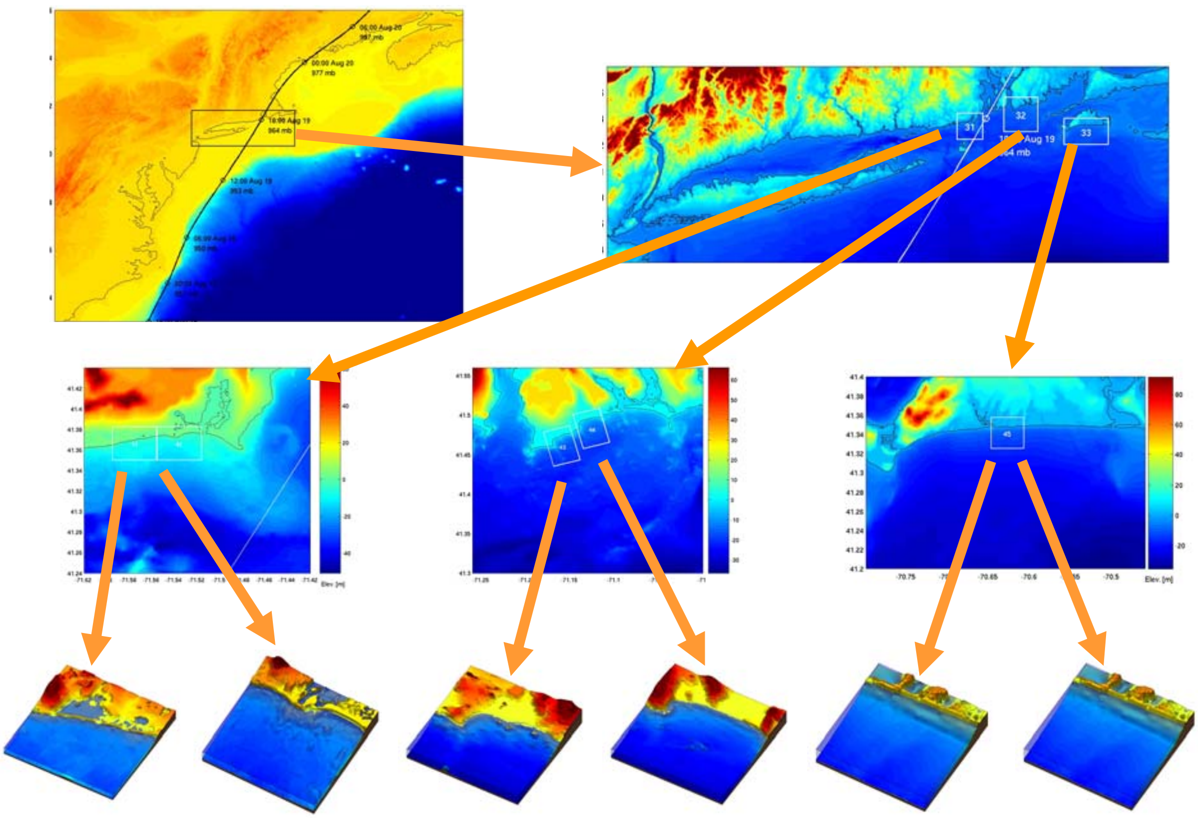


Figure 2. Nested Grid of Storm Surge and Storm Waves Model Structure for New England Area.

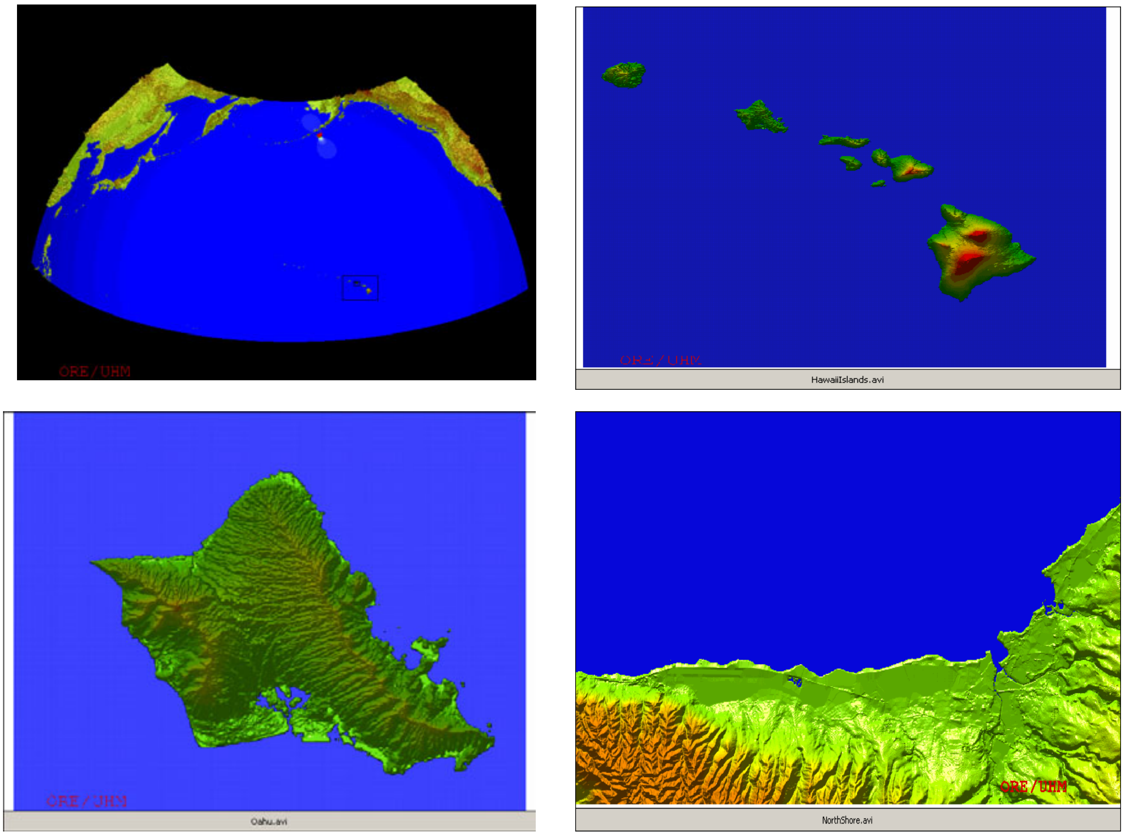


Figure 3. Nested grid with four scales and grid sizes.

Figure 4. The Oregon State University NEES Tsunami Wave Basin Facility.

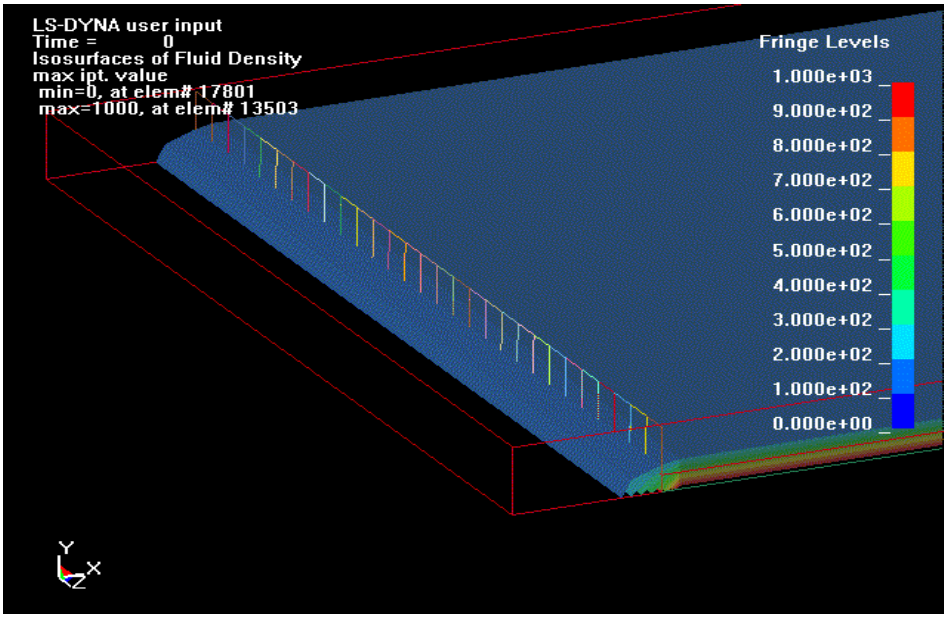
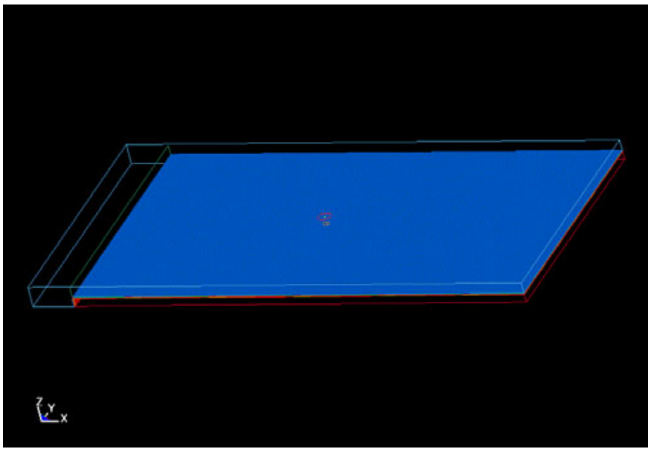
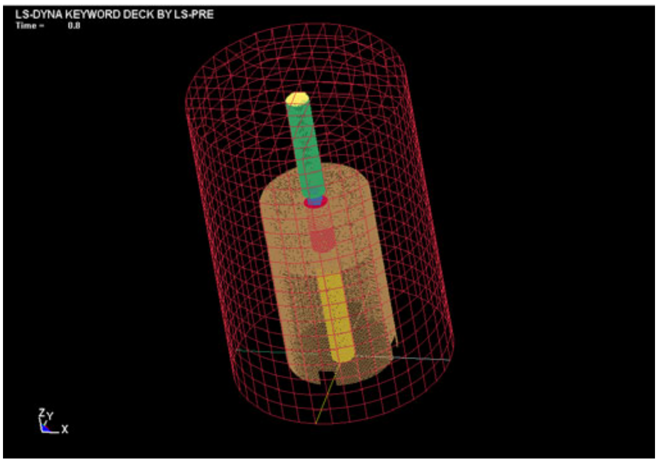


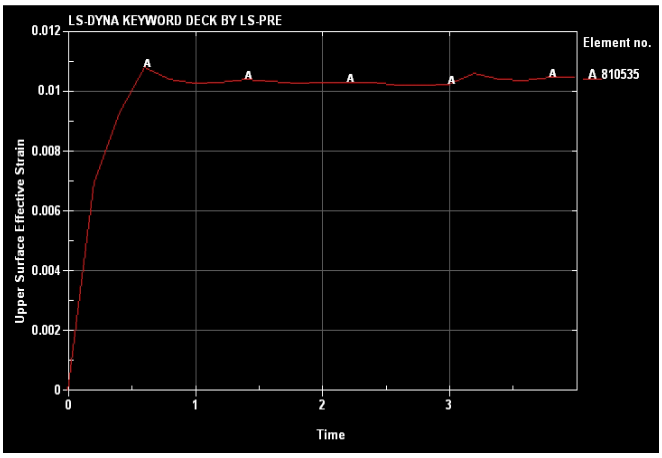
Figure 5. LS-DYNA model of tsunami wave generation at the OSU NEES 3-D basin.



(a)



(b)



(c)

Figure 6. Numerical modeling of tsunami wave effect on a cylinder.

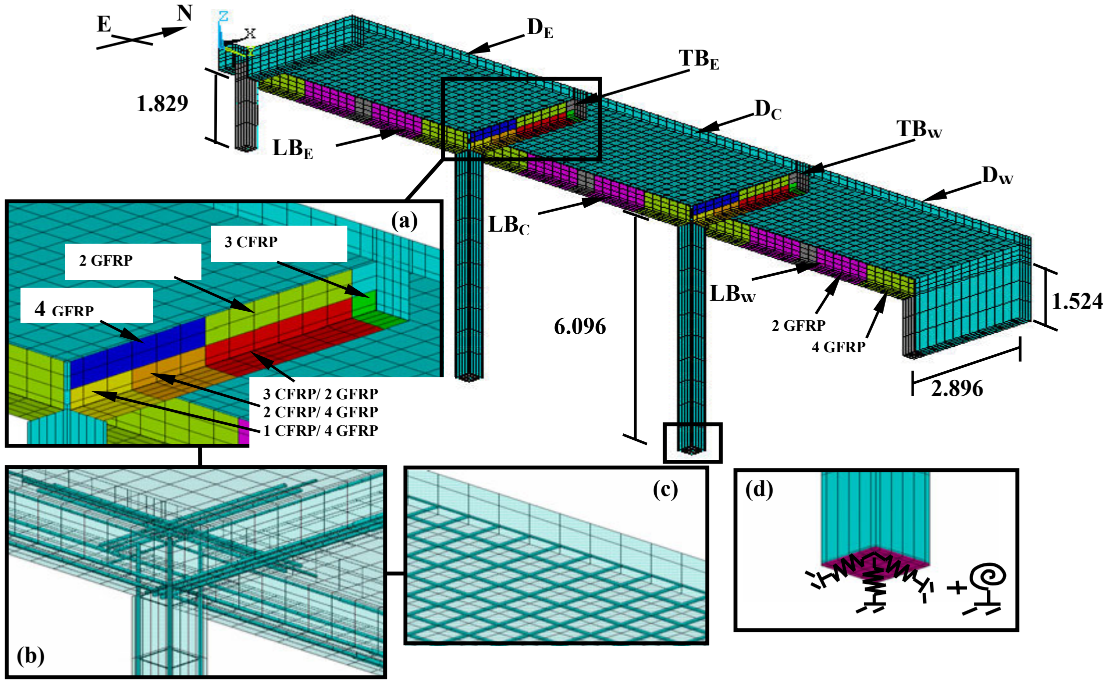


Figure 7. An example finite-element model of a coastal bridge.