EXPERIMENTAL AND COMPUTATIONAL ACTIVITIES AT THE OREGON STATE UNIVERSITY NEES TSUNAMI RESEARCH FACILITY

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ABSTRACT

A diverse series of research projects have taken place or are underway at the NEES Tsunami Research Facility at Oregon State University. Projects range from the simulation of the processes and effects of tsunamis generated by sub-aerial and submarine landslides (NEESR, Georgia Tech.), model comparisons of tsunami wave effects on bottom profiles and scouring (NEESR, Princeton University), model comparisons of wave induced motions on rigid and free bodies (Shared-Use, Cornell), numerical model simulations and testing of breaking waves and inundation over topography (NEESR, TAMU), structural testing and development of standards for tsunami engineering and design (NEESR, University of Hawaii), and wave loads on coastal bridge structures (non-NEES), to upgrading the two-dimensional wave generator of the Large Wave Flume. A NEESR payload project (Colorado State University) was undertaken that seeks to improve the understanding of the stresses from wave loading and run-up on residential structures. Advanced computational tools for coupling fluid-structure interaction including turbulence, contact and impact are being developed to assist with the design of experiments and complement parametric studies. These projects will contribute towards understanding the physical processes that occur during earthquake generated tsunamis including structural stress, debris flow and scour, inundation and overland flow, and landslide generated tsunamis. Analytical and numerical model development and comparisons with the experimental results give engineers additional predictive tools to assist in the development of robust structures as well as identification of hazard zones and formulation of hazard plans.

KEYWORDS: Tsunami, structure, sediment, experiment, computation, research

1. INTRODUCTION

Oregon State University (OSU) is home to the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Tsunami Research Facility (TRF), one of the world's largest facilities for studying the effects of large waves. Of the 15 experimental sites supported by NEES, OSU is the only facility that supports the study of the hydrological effects of earthquakes, specifically tsunamis. The OSU experimental site is housed at the O.H. Hinsdale Wave Research Laboratory (HWRL), which was established in 1972 with the construction of a large wave flume (LWF) designed to study the stability of coastal structures. In 1989, the Office of Naval Research funded the construction of a wave basin to study complex, 3-dimensional fluid flow. In 2000, the HWRL was designated by the National Science Foundation (NSF) as a site for tsunami research as part of its NEES Program. Under the NEES support, the HWRL expanded the original wave basin, significantly increasing the physical dimensions of the basin, and at the same time, installed a state-of-the-art wave maker capable of 3-dimensional tsunami wave generation. This new expanded basin and wave maker are collectively known as the Tsunami Wave Basin (TWB), which together with the existing 2-dimensional Large Wave Flume (LWF), constitute the majority of experimental components utilized at the Tsunami Research Facility. In 2004, the operations and maintenance phase of the NEES facility began. By summer of 2008 (year 4 of operations), the facility has a full schedule of activities and has been fully occupied supporting six NEES research (NEESR) projects most of which are multi-year and multi-phase. In 2009, a new piston wave maker will be installed in the LWF funded by NSF under the MRI initiative.

2. OVERVIEW

The NEES mission is to improve the research and practice communities' understanding of earthquakes and their effects on structures and human safety by, in part, providing the most advanced experimental facilities for performing earthquake-engineering experiments. The United States has experienced major tsunamis that caused significant damage in Hawaii, Alaska and the West Coast, and research at the NEES OSU TRF is focused on improving the communities' understanding of earthquake generated tsunamis as they affect people's lives. The Indonesian earthquake and resulting tsunami in December 2004 increased awareness and concern about the possibility of a large magnitude event of this type occurring in the US. The US Office of Science and Technology Policy released a report in December 2005 entitled "Tsunami Risk Reduction for the United States: A Framework for Action (National Science and Technology Council, 2005)", which called for scientists to review the existing state of tsunami research and also to develop a strategic plan for tsunami research in the US. An organizing committee developed a framework which was then refined at a workshop that took place in July 2006. Experts from academic institutions, governmental agencies and the private sector contributed to a report that was released in December of 2006 entitled "National Tsunami Research Plan: Report of a Workshop Sponsored by NSF/NOAA" (Bernard et al., 2006).

A summary of the report recommendations that included all areas of tsunami risk assessment and mitigation identified three major areas of research:

- Hazard Assessment

  How and where tsunamis are created, how often tsunamis reoccur, an estimation of the impact of tsunamis on community infrastructure and natural environment using field, laboratory and model data, and how lives are threatened.

• Warning Guidance Research and Recommendations
Monitoring systems for detection, real-time forecasting, information dissemination and warning systems.

• Preparedness, Response and Mitigation
Program development, education of communities, and legislative and incentive policies designed to reduce risk to human life and property based on hazard assessment.

Research at NEES OSU TRF coincides with the framework identified in the National Tsunami Research Plan (described above). Research projects at the site include experiments aimed at furthering our understanding of these scientific objectives and will be described in more detail below. Much of the work is concentrated in the "hazard assessment" area as the facility is uniquely constructed to specifically support many of these objectives. However, as pointed out in the National Tsunami Research Plan, there is inherent overlap in the three areas described above and some aspects of research and activities at the site also address "Warning Guidance" and "Mitigation".

3. ACTIVITIES

The research activities described below have been organized around the framework established by the National Tsunami Research Plan as described in the overview.

3.1 Hazard Assessment

The coupling between landslide motion and generated tsunami waves in three dimensions is of critical importance given the local source mechanism with a strong directionality and the characteristic trans-critical landslide versus tsunami velocity Froude numbers. Nearly a half-century after the Lituya Bay mega-event, Hermann Fritz from the Georgia Institute of Technology has successfully replicated a fully three dimensional scale model of a tsunami created by a deformable landslide. Using a unique landslide-generated tsunami simulator that was installed at the OSU NEES TWB, the researchers simulated the impact of landslides that occur both above and below the water's surface, generating simulated tsunamis in a three-dimensional environment. Fritz and a team of researchers have constructed the landslide tsunami generator—"an open box" that is mounted on a steel slide and filled with up to 1,350 kg of gravel (Figure 1a). The box accelerates down the slide by means of four pneumatic pistons. The granular mass is accelerated inside the box, and released while the sled is slowed down pneumatically. The box is 2.1 by 1.2 by 0.3 m with subdivisions to adjust initial slide length and thickness and is placed on a slide that can vary in length. The box itself is able to travel approximately 2 m before the gravel is released down the 2H: 1V slope at initial velocities of up to 5 m/sec. The researchers tested two types of landslides: those that fall into the water and those that occur beneath the surface. Sensors were placed on the simulator to measure the velocity of the gravel. Using cameras placed above and within the water, the researchers measured the shape, length, and thickness of the gravel masses while they were in motion. The granular landslide deposits were scanned with an acoustic multi-transducer array (Figure 1b). Wave gauges were placed to measure the size and shape of the waves that were generated including the lateral onshore run-up. The recorded wave profiles were extremely directional, unsteady, non-linear and located mostly in the intermediate water depth wave regime. Among the principal differences between a tectonic-generated tsunami and a landslide-generated tsunami is that the latter has a strong directional component that can be devastating to the immediate area. However, because it has a shorter wavelength, it dissipates quickly over a short distance. Landslide tsunamis exhibit a more dispersive and strongly directional propagation than tectonic tsunamis. Planar PIV was applied to the tsunami surface and revealed the fully 3D tsunami generation. Currently more than 60 successful runs are completed and the main tsunamigenic parameters determined which would serve as a key benchmark for the numerical models.

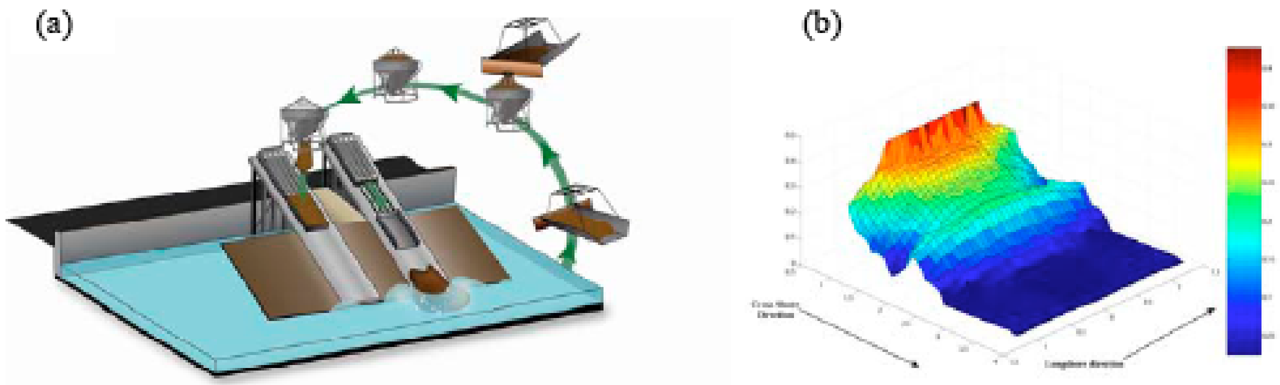

Figure 1. 3-Dimensional landslide tsunami experiments: (a) Landslide tsunami generator deployed in the NEES Tsunami Wave Basin at OSU in the winter 2006/2007; (b) granular landslide deposit scanned with an acoustic multi-transducer array.

Pre-NEES shared-use principle investigator Philip Liu of Cornell University and his research group conducted two sets of experiments on wave impact on cylinders. The scientific objectives were to understand the dynamic interactions among tsunamis, rigid and flexible structures and to develop benchmark problems with high quality experimental data for validating numerical simulation models. Figure 2 shows a focused wave impacting a single cylinder with design wave breaking right at the cylinder. A variety of wave conditions and water depths were used to collect benchmark data of wave force run-up on structures. Experimental results are used to calibrate the predictive capability of numerical models including a nonlinear-coupled fluid-structure interaction code, LS-DYNA (see description below for details), which specializes in accurate contact and impact modeling. A typical comparison of the numerical prediction and experiment results is shown in Figure 3. Figure 3a shows good agreement between measured and predicted results, while Figure 3b shows consistent estimates of the time history of the free-surface elevation at the front of the cylinder, which was obtained, using the numerical model at variable depth below the mean water level.

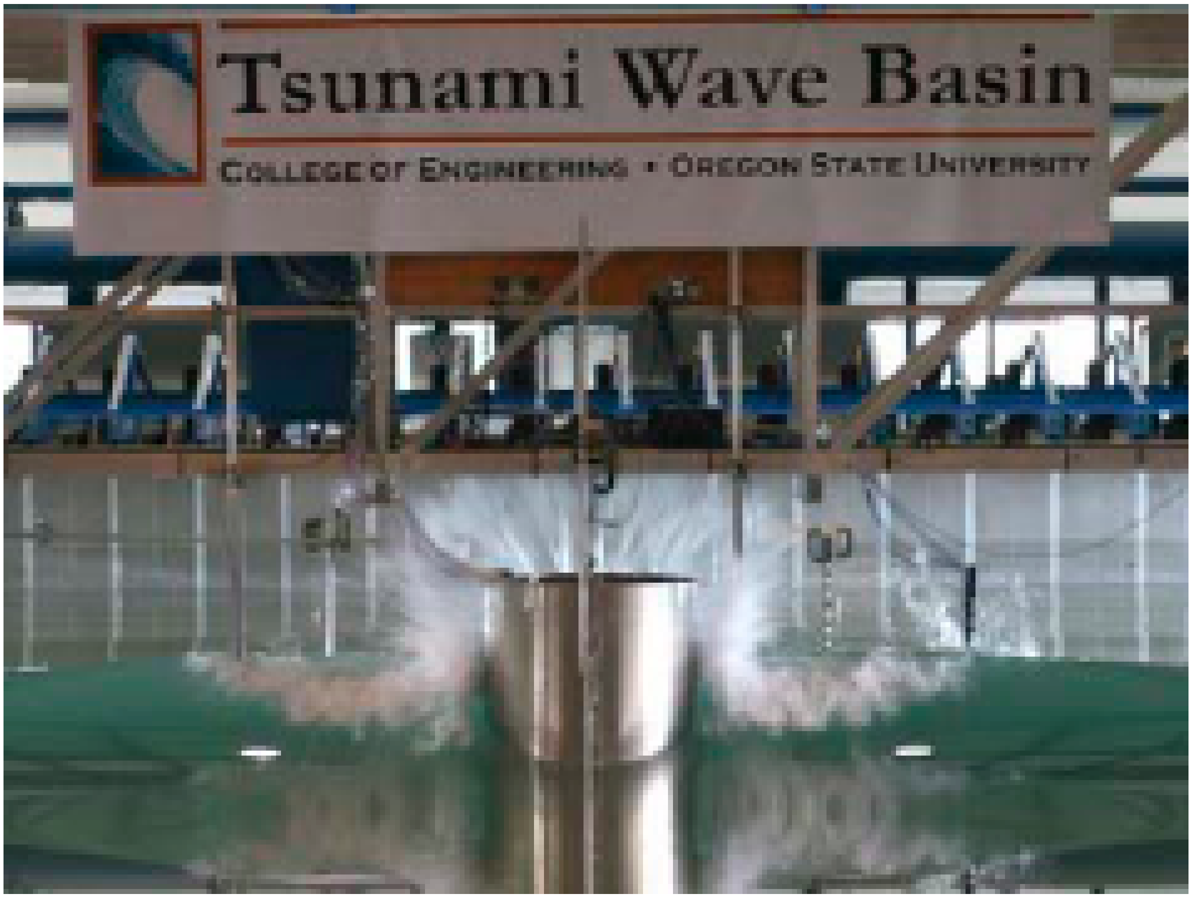

Figure 2. Tsunami wave impact on cylinders.

3.2 Warning Guidance Research and Recommendations

NEESR principal investigator Patrick Lynett of Texas A & M University conducted phase I of a multi-year project in the TWB for 25 days in the spring of 2007, and phase II is beginning in July 2008. The proposed scientific objectives are to: (1) improve understanding of near shore, 3 dimensional tsunami evolution through an extensive set of physical experiments; (2) create an extensible framework to provide a systematic structure for validating computational models with experimental and field data; (3) refine modeling capabilities and couple the various components together to create a multi-scale simulation tool; and (4) develop a sustainable education and outreach program that educates the general public about tsunamis and appropriate responses to them. Concurrent to the experimental effort, a comprehensive tsunami simulator, TSUNAMOS (Tsunami Open Source Community Model), will be developed (Lynett et al., 2006).

Phase I included dense measurements of free surface and velocity measurements for 3-dimensional wave breaking under five different wave conditions including solitary and N-waves. For each wave, ADVs provided 3D velocity data at 120 different x, y, z combinations clustered near the onset of breaking. Wave height was measured with wave gauges and the breaking envelope was tracked using overhead video. In all, 225 trials were conducted.

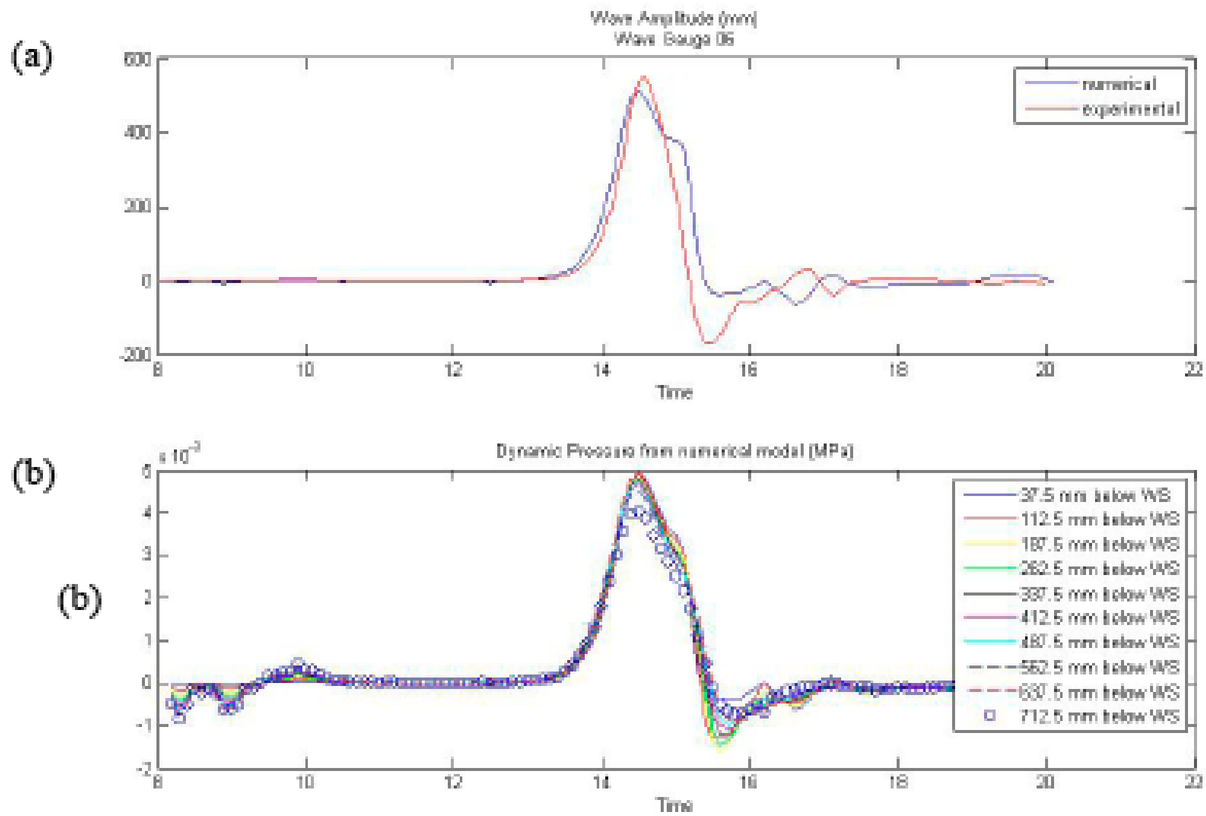

Figure 3. (a) Comparison of LS-DYNA numerical prediction and measured data; (b) Free-surface elevation predictions obtained from LS-DYNA at varying water depth.

Phase II of TSUNAMOS will make use of a longshore-variable sloping beach. This beach can be described as a triangular reef, where the largest shallow water extent (shelf) exists along the centerline of the tank, and linearly tapers to zero at the basin side wall (Figure 4). The purpose of this beach is to create a 3D, bathymetry-forced breaking pattern. A single solitary wave and depth condition will be investigated. Numerous ADV's will be used, with the goal of extracting turbulence (stress) information; many realizations with ADV's in the same location are needed. The free surface elevation will be mapped with approximately 170 resistance wave gage locations. Run-up will be recorded with video cameras. Additionally, dye studies will provide information on the mixing and transport by the solitary wave. Roughness studies will include both fixed and movable sand and gravel, stripes and wires (simulating bushes and trees), and small blocks (simulating small structures in the path of tsunami inundation). 2HD run-up time series will be digitized from overhead cameras, and the inundation limit will be manually traced after each experimental trial. These experimental settings will simulate situations closer to what tsunamis encounter on natural beaches. With this data, accurate bottom dissipation models will be developed for transient tsunami flow, improving significantly upon the traditional approach. The data collected in these two phases address the run-up and drawdown research identified as needed for hazard assessment. Development of TSUNAMOS will provide officials and communities with an important warning guidance tool.

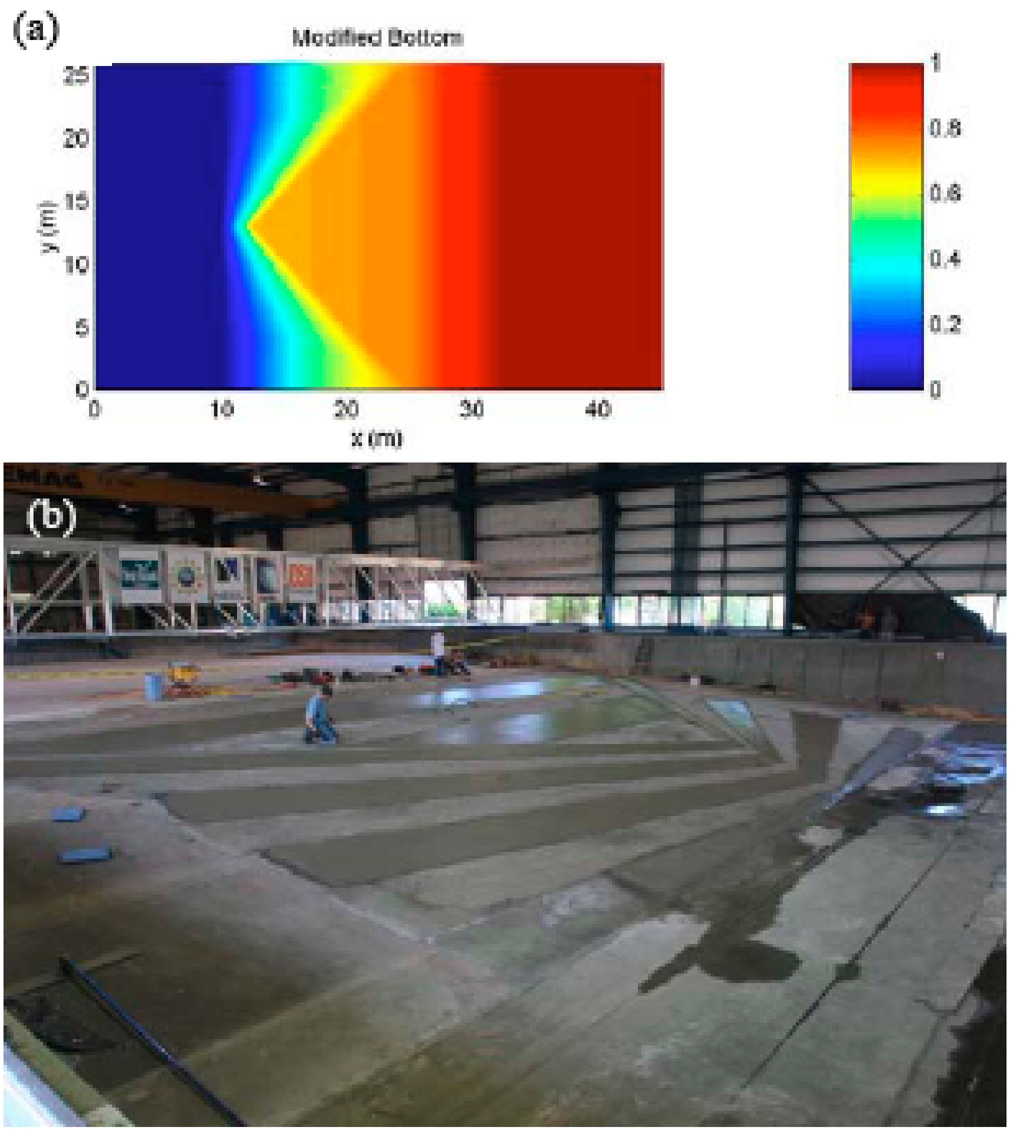

Figure 4. (a) Contours of the longshore-variable sloping beach in the TWB. Contour scale is vertical elevation in meters, and (b) Construction of the bathymetry.

3.3 Preparedness, Response and Mitigation

NEESR principal investigator Ron Riggs of the University of Hawaii and his research group conducted a multi-phase, multi-investigator research project that utilized the TWB through late 2007, and will utilize the new wave maker installed in the LWF in 2009. The proposed research will develop a methodology and validated simulation tools for implementation of site specific Performance Based Tsunami Engineering (PBTE) for use in the analysis, evaluation, design and retrofit of coastal structures and facilities, and code-compatible provisions for tsunami resistant structural design. Coastal inundation modeling will be developed to redraft the inundation mapping for the Hawaiian Islands. The analytical simulation tools will be validated through extensive experimentation at the TRF at OSU. The project is separated into two distinct types of experiments; 1) sediment transport and scour; 2) run-up/inundation and structural loading. Phase I in the TWB began with the sediment transport and scour testing June and July 2007. In August 2007 the testing transitioned to run-up/inundation and structural loading tests (Figure 5). By the end of fiscal year 2007, this project had run seven separate experiments involving ~350 trails and collected ~400GB of data. Work in the LWF in 2009 will provide data at a significantly different scale, which will allow further comparison and verification of models and further refinement of PBTE. The TWB and LWF data will be used to develop and validate coastal inundation codes including the influence of coastal plane and bathymetric variations, and 3-D RANS (Reynolds-Averaged Navier Stokes) simulations of fluid-structure interaction. Design code for development of tsunami resistant structures directly addresses the need for research in how best to prepare communities for tsunami waves and how to mitigate damage and save lives.

Figure 5. A solitary breaking wave in one of two flume channels instrumented to measure run-up.

A NEESR payload project, led by John van de Lindt at Colorado State University, was funded to utilize the University of Hawaii experimental setup. Waves generated by tsunamis and hurricanes have cost hundreds of thousands of lives and millions of dollars in loss of infrastructure and property damage. Currently there are few guidelines for engineers to utilize when designing structures in wave prone areas. The research objective is to test typical residential structural models in order to investigate impact due to wave loading and run-up, and wind/pressure driven surge. A 1/6th scale two story wood framed structure was tested in the north side of the TWB opposite of the UH testing area, utilizing water and wave conditions being generated for the UH experiments. Several aspects of building configuration were analyzed to determine how loading properties were affected. Forces were measured at each corner and deflection was measured at the second story roofline. The experimental setup was determined to be effective at capturing the wave-induced loads. Significant uplift forces were generated when water was allowed to pass beneath the structure, while overturning moments were generated when the front face of the structure was impacted. Structural irregularities, an overhanging roof and a reentrant corner, were found to have impact on how loading was distributed throughout the structure. Pushover tests are planned to verify the results of our analysis. One of the 1/6th scale residential structures was tested to failure (Figure 6).

Figure 6. 1/6th scale residential structure that was tested to failure by wave impact.

3.4 Education and Outreach

The OSU Tsunami Research Facility conducts an extensive education and outreach program including tours and open houses, K-12 educational tours and programs, undergraduate education (Research Experience for Undergraduates site in 2003-2005, 2007, 2008), Research Experience for Teachers (RET) in 2008, and graduate research and teaching opportunities. In all, the site hosts over 3000 visitors a year. Improving the understanding of the public about the science of tsunamis and at the same time disseminating information about warnings and proper hazard response is crucial in saving lives. The site has educational posters, guided tours and hands-on activities all designed to address preparedness and response. The site also utilizes its telepresence cyberinfrastructure to provide public access to on-going research, off-site researcher participation in experiments, and as a teaching tool. A Tsunami Structures activity was developed and implemented with 200 local middle school students, and 40 UH civil engineering fluid dynamics undergraduate students (who participated remotely utilizing the telepresence system). The students studied, designed and constructed shelters scaled at 1:50 (Figure 7) that were bolted to the floor of the TWB, and tsunami waves were generated impacting the structures. A Tsunami Shelter Challenge project funded by NSF was undertaken in the TWB involving 40 middle school teachers and included supplied computers, modeling and visualization design and testing of constructed shelters (http://shelter.nacse.org/).

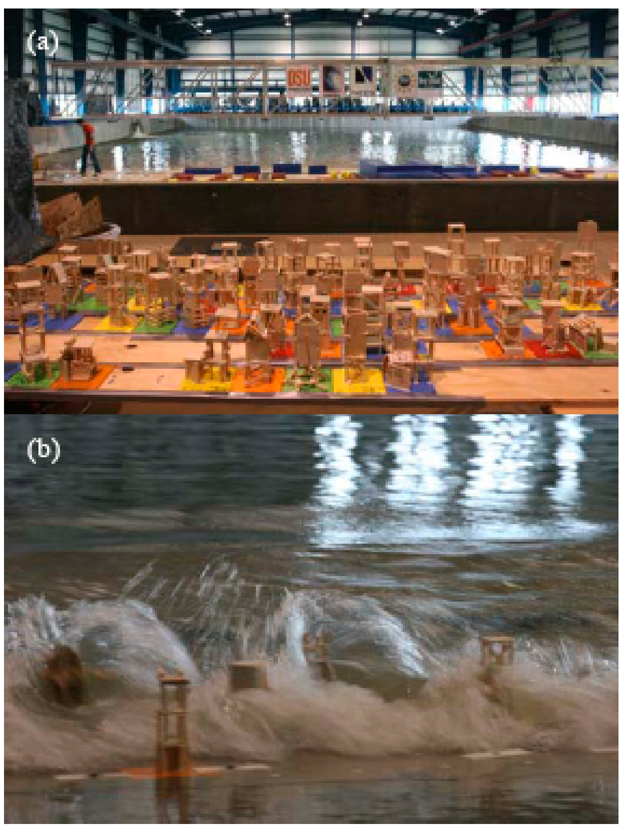

Figure 7. (a) Tsunami structures designed by middle school students waiting to be tested, (b) structures subjected to tsunami wave impacts.

4. NEW PISTON WAVEMER IN THE LARGE WAVE FLUME

The National Science Foundation Major Research Instrumentation program (CMMI-0723277) awarded OSU $1.1M to install a new 2- dimensional piston wave maker in the 342ft LWF in late 2008 (Figure 8). The new piston wave maker will replace the existing hinged-flap style wave maker currently installed. The large-stroke high performance piston wave maker will provide researchers with complementary capabilities due to the significantly wider range of scales available for testing.
The new wave maker will be able to produce tsunami type waves generated by earthquakes as well as extreme hurricane storms (Figure 9), an important step in understanding the impact these waves have on coastal infrastructure, and providing a national asset for precision, large-scale studies enabling safer and more cost effective design of offshore as well as coastal infrastructure including platforms, bridges, levees, buildings and lifelines. Outcomes include better practices for the repair and retrofit of existing structures and improved design codes for new construction.

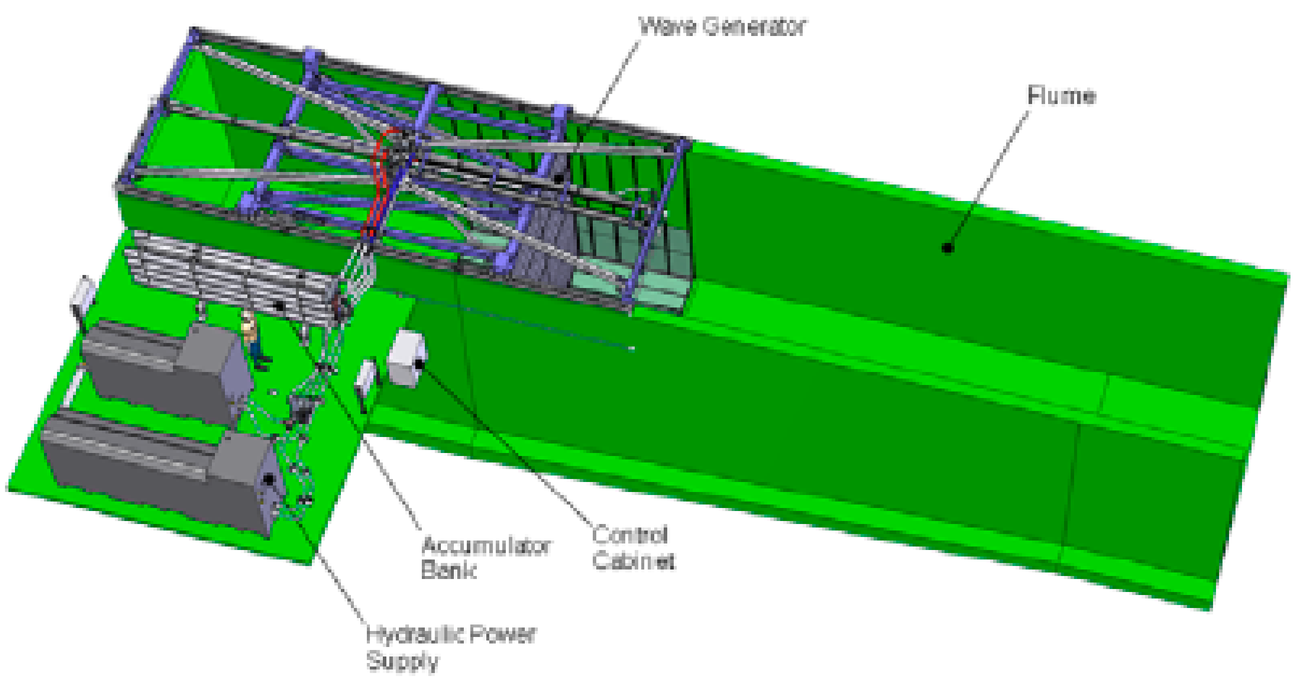

Figure 8. Conceptual rendering of the new piston wave maker installed in the Large Wave Flume. (Image courtesy of MTS Corporation).

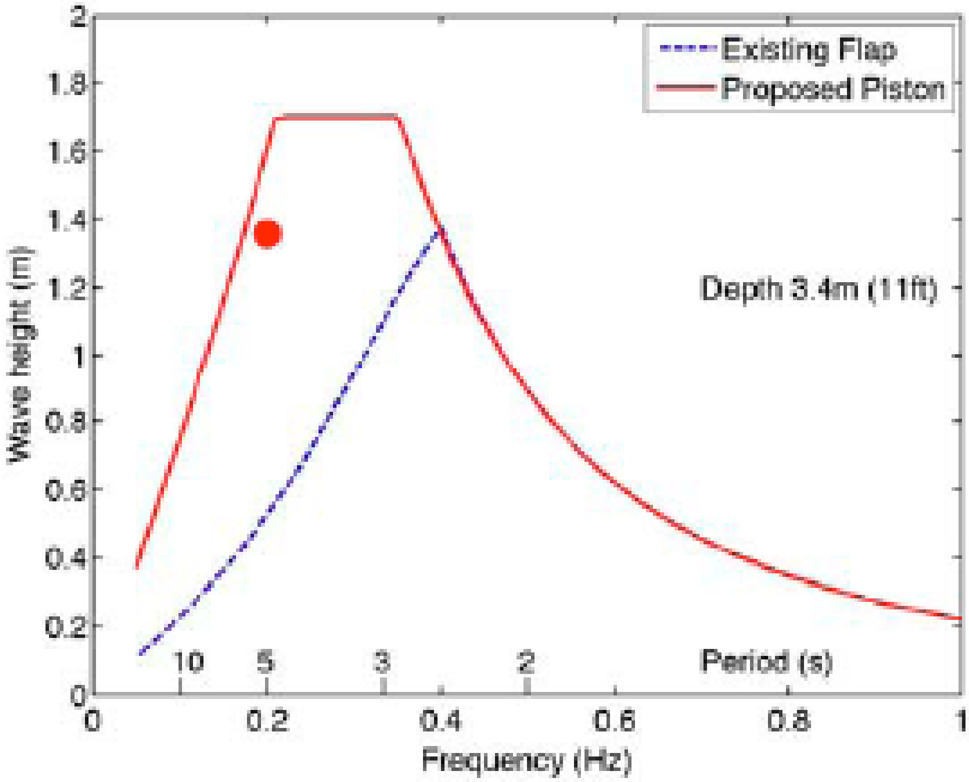

Figure 9. Theoretical performance curve comparing existing (dashed, blue) and proposed (solid, red) wave makers at design water depth d = 3.3 m. Figure shows increased maximum wave heights for lower frequencies (larger wave periods) and the ability to simulate large-scale coastal models under tsunami and hurricane wave conditions (red dot).

5. COMPUTATIONAL SUPPORT

Hydrodynamic models of storm and tsunami waves define the boundary conditions at the coastline for numerical models geared toward 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, some of which may induce large structural deformation, yielding, fracture, and collapse or dislodgement. Accurate modeling of coupled fluid-structure interaction is 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 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 structural analysis needs. It also contains a fluid module based on the Navier-Stokes equations used 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 the PFEM formulation, the continuity and momentum balance equations in the fluid domain are modeled using a 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 computational fluid dynamics (CFD) codes from industry with proven robustness and nonlinear capabilities for the analysis of structural behavior, and the PFEM formulation for modeling fluid motions in arbitrary Lagrangian-Eulerian (ALE) form, may provide the best solution for the development of a robust code for simulation of storm waves, tsunami basin experiments and prototype events. This choice allows a unified ALE formulation and computation for both fluid and structural domains. More importantly, it allows for exact means of tracking the fluid-structure interface 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.

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 OSU TRF as follows. We first model the wave basin including wave paddles and water as a single module, and separately an instrumented cylinder including its components as another module, and then insert the cylinder module inside the tsunami wave basin module to form the experimental model. Once the system is in place, we can simulate a test run and compute the strains inside the cylinder. This procedure was used to generate the numerical prediction of wave impact on a cylinder presented in a previous section shown above.

An issue with using a complex code like LS-DYNA is computational resources. To model the fluid-structural interaction experiment at the TWB shown above using 1cm3 elements would lead to the number of fluid and structural elements on the order of 3 x 109. Using a 20-node solid element with 3 degrees of freedom (d.o.f.) at each node would lead to approximately 4 x 1010 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 state-of-the-science high-end high-performance parallel computers is necessary.

5. CONCLUSION

Research underway at the NEES Tsunami Research Facility at Oregon State University reflects the NEES mission to further earthquake engineering research, with the ultimate goal to save lives and preserve property. Recommendations by the National Tsunami Research Plan suggest a research roadmap to further scientific understanding of tsunami processes and effects on human lives. The recommended research includes areas in (1) hazard assessment, (2) warning guidance and (3) response and outreach. It is shown that the research projects at the OSU TRF are not only furthering the NEES mission, but also aligned with the recommended areas of research in the roadmap report. The simultaneous development of numerical modeling tool at the TRF has shown promising results in assisting with the design of wave-basin experiments. These numerical models, both 2-D and 3-D, when matured, are anticipated to become integral parts of technical tools for future experiments at the facility.

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