13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1517

A SHARED-USE LARGE-SCALE MULTIDIRECTIONAL WAVE BASIN FOR TSUNAMI RESEARCH

Solomon YIM[1], Harry YEH[2], Daniel COX[3], and Cherri PANCAKE[4]

SUMMARY

Oregon State University has expanded its multidirectional wave basin to create a shared-use experimental facility for tsunami research, supported by the US National Science Foundation's Network for Earthquake Engineering Simulation (NEES) program. The Tsunami Wave Basin – whose expanded dimensions are 48.8m (length) by 26.5m (width) by 2m (depth) – addresses the unique requirements posed by the tsunami research community. The wave generator is designed to generate a solitary wave 0.8m high in a water depth of 1m. Its waveboards are controlled on an individual basis, making it possible to generate arbitrary wave profiles and arbitrary wave directions. The basin supports high resolution, large-scale experiments with dense instrumentation, making it possible for researchers to test and validate both analytical and numerical models of tsunami phenomena induced by sub-sea earthquakes, and supporting a full range of coastal studies. A key focus of the project is the exploitation of advanced computing and networking technologies to enhance the research experience. Researchers located at distant sites can participate actively in experiments at the facility, viewing data and images in real time and participating in decision-making. Both remote and on-site researchers enjoy the ability to view the data/video displays in instant-replay, slow-motion, or freeze-frame modes. A "virtual wave laboratory" based on video gaming technology makes it possible to design experiments and plan the layout of instruments with just a web browser. A comprehensive, shared databank provides the broader research community with access to complete histories of all experiments and the ability to download experimental data for use in validating numerical models. This paper provides a detailed description of the Tsunami Wave Basin and offers examples of the types of collaborative experiments that will be made possible by this unique shared facility.

INTRODUCTION

[1] Professor of Civil Engineering, Oregon State University, Corvallis, Oregon, USA. Email: solomon.yim@orst.edu
[2] Professor of Civil Engineering and Computer Science, Oregon State University, Corvallis, Oregon, USA. Email: harry@engr.orst.edu
[3] Assoc. Professor of Civil Engineering and Director of O.H. Hinsdale Wave Research Laboratory, Oregon State University, Corvallis, Oregon, USA. Email: dtc@engr.orst.edu
[4] Professor of Electrical Engineering and Computer Science, Oregon State University, Corvallis, Oregon, USA. Email: pancake@nacse.org

Tsunamis are classified as “long” waves, Their runup and landward inundation cause potentially damaging effects along the coastal shorelines, including significant loss of human lives. Because the economic costs of strengthening local infrastructures and evacuating coastal areas are very high, a clear understanding of tsunami runup behavior is critical in order to develop appropriate warning systems and evacuation strategies. Systematic methods are needed for evaluating both the long-wave events themselves and the wave-structure interaction they are likely to precipitate.

The research community increasingly relies on computational simulations for predicting tsunami runup, landward inundation, and wave-structure interaction effects. Physical experimentation is costly and slow and requires high-resolution, real-time capture of multi-dimensional data; there is also only a brief opportunity to capture suitable data for a particular run. Numerical experiments offer an attractive alternative. Recently, concerted efforts by the tsunami community have resulted in several two- and three-dimensional numerical models that quantify the interaction of tsunamis with shorelines [1]. The predictive capabilities of these numerical models, however, have not been fully validated due to the lack of suitable field or laboratory data. Although field measurements of runup of several recent tsunamis exist, they are insufficient because of the nature of after-the-event field surveys. Very little information about temporal variations can be obtained and the data are often extremely spatially sparse. Furthermore, the source of tsunami generation cannot be accurately specified, since any information in deep water is difficult to obtain.

Laboratory experimentation has also been unsatisfactory. In order to accurately scale laboratory long-waves to full size, it is important to preserve the ratios of the most important forces relative to inertia. Most previous laboratory tests for long waves were conducted at relatively small scale, however, resulting in non-essential forces (surface tension and viscous forces) being exaggerated in comparison to essential forces (gravity, pressure and inertia). A large-scale laboratory facility is needed to obtain usable data for the validation of numerical models.

In 2000, the US National Science Foundation (NSF) initiated a program called the George E. Brown, Jr. Network for Earthquake Engineering Simulation, or NEES. This is a Major Research Equipment and Facility Construction program, intended to develop a national system of shared-use, next-generation experimental research facilities. The goal of the NEES program is to shift the emphasis of earthquake engineering research, including tsunami studies, from its current reliance on physical testing to integrated experimentation, theory, and model-based simulation.

A key component of NEES is the use of advanced networking capabilities to support teleparticipation – the active, real-time involvement of researchers located at physically distant sites. Further, NEES is a collaboratory, meaning that it integrates not just research activities but also communication and data sharing to support collaborative research. NEES includes 15 major earthquake engineering experimental facilities. The sites are linked by a communications infrastructure based on the high-speed Internet2 network in order to facilitate shared use and teleparticipation and provide remote access to computational resources. NEES will also provide researchers with remote access to an organized repository of databases, software, and simulation models. This integrated system will encourage interdisciplinary collaboration among earthquake engineering researchers, opening participation to a much broader community than in the past. Oregon State University was chosen as the tsunami basin site for NEES in 2000. This paper describes the key features of the facility and instrumentation available at Oregon State and how they fit into the vision for this unique community-based research laboratory.

NEED FOR LARGE-SCALE TSUNAMI EXPERIMENTAL FACILITIES

Two- and three-dimensional numerical models are being developed to identify regions along coastlines where long waves can cause damage due to runup and overland flow. Some of the models are computationally complex and incorporate movable and deformable surface piercing objects as well as submerged boundaries associated with subaqueous landslides [2-4]. To validate them, one cannot rely on post-event field observations because of the inability to prescribe the causal waves. Further, field measurements of tsunamis cannot obtain sufficiently detailed spatial and temporal data for model validation. Consequently, laboratory modeling becomes the expedient alternative to field observation. It must be undertaken at a scale that reproduces prototype behavior, however. In small-scale experiments, the forces due to viscosity and surface tension can become appreciable compared to inertial, pressure and gravity forces. For ocean wave phenomena, on the other hand, gravitational and pressure forces generally dominaate; this condition will occur only in moderate- to large-scale physical models. The divergence between prototype behavior and small-scale physical models has led the tsunami and coastal engineering communities to conclude that large-scale laboratory experiments are needed.

The problem of scaling is exacerbated by the condition of wave breaking. Long waves shoaling up a beach slope will reach a water depth where the water-particle velocity will exceed the wave celerity, causing the wave to overturn. Surface tension affects the shape of the wave and the impact with coastal structures [5]. In some developed coastal areas, it will be desirable to strengthen critical structures so that they can survive some severe events, but evaluating the wave forces requires the proper representation of real flow properties [6]. Drag, inertia, and impact force modeling necessitates proper representation of the fluid kinematics and dynamics as well as the coupling mechanism between the relative motion of the fluid and the force on the object. This can be approximated in large-scale physical models, where all forces scale geometrically, facilitating extrapolation of measured results to prototype scale. Another reason for requiring a large-scale experimental facility in long-wave research is that the horizontal scale involved in the investigations is usually much larger than the vertical scale. If the wave basin size is limited, it is necessary to employ a distorted model, in which the model-to-prototype ratio is different in the vertical and horizontal directions, resulting in undesirable fluid scaling effects.

OREGON STATE'S MULTIDIRECTIONAL AND UNIDIRECTIONAL WAVE BASINS

Multidirectional Tsunami Wave Basin -- As part of NEES, Oregon State University has upgraded its existing multidirectional wave basin to become the largest laboratory facility in the Nation for tsunami research. Since real tsunamis have much greater horizontal dimensionality (tens to hundreds of kilometers long) than depth (just a few kilometers deep), they are categorized as long, or shallow-water, waves. Therefore, the primary component of the new facility is a large-scale, long-wave basin.

Figure 1 shows a plan view of the Wave Research Laboratory at Oregon State University, including the expansion. The multidirectional wave basin has been expanded to 48.8m long by 26.5m wide by 2m deep (see Figure 2). It is constructed as a reinforced concrete reservoir, with a 0.25m wall and floor thickness. Unistrut inserts are placed in rows at 2.1m spacing to affix models, instrumentation, and the wave generator throughout the basin.

The wave generator consists of 29 piston-type waveboards, each 0.9m wide by 2m high. Each waveboard is capable of a 2m displacement with a maximum velocity of 2m/sec. It is designed to generate a solitary wave 0.8m high in a water depth of 1m. Each waveboard is driven by a pre-tensioned high-strength belt, powered by an AC electric motor. The use of the belt drive enables efficient and adequate power transfer to the board. Unlike a traditional hydraulic powered system, it is also clean and quiet. The wave generator digitally controls the waveboards on an individual basis, making it possible to generate arbitrary wave profiles and arbitrary wave directions. Control of the waveboard is achieved through displacement and velocity feedbacks. Velocity control utilizes a wave profile measurement at the front of the waveboard, 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 shapes beyond that available by means of the displacement control.

Figure 3 demonstrates the capability of the wavemaker generating a solitary wave of 0.24m wave height in a 0.6m water depth.

The multidimensional long-wave basin allows repeatable, high-resolution, large-scale experiments with dense instrumentation. The facility is designed to provide a proper environment for implementation of state-of-the-art, non-contact instrumentation (e.g., optical and acoustic devices).

Although tsunamis behave differently from wind-generated sea waves, the basin is capable of modeling nearshore waves in general. Wind waves generated in deepwater transform to long waves as they approach the shore, due to the decrease in water depth. Consequently, we anticipate that the facility will also be attractive to coastal engineering and nearshore-oceanography as well as tsunami researchers.

Unidirectional Large Wave Flume -- The unidirectional large wave flume (Figure 4) is 106m long, 4.7m deep, and 3.7m wide. The wave generator is a hydraulically driven, hinged flap, aluminum weldment. The waveboard is hinged at the bottom of the channel in an overall depth of 5.6m. The bottom shoals 1m over a distance of 12.3m to the 4.7m depth of the basin test section. A false bottom, fabricated from 3.7m square, 0.15m thick, reinforced concrete panels, can be configured to simulate various seabed bathymetries. For example, the panels may be placed at a 1:12 slope to act as a beach that will cause waves to break, lose their energy to turbulence, and minimize wave reflection back to the test area.

The wave board is servo-hydraulically driven with direct digital controls. A 150-horsepower electric motor powers a 2×10^7 N/m^2 oil hydraulic pump that is the prime mover for a 0.2m diameter actuator. The actuator ram has a semi-stroke of 0.8m and is oriented horizontally, 3.1m above the channel floor. The backside of the wave generator is dewatered, reducing the power requirements by one-half. The still water hydrostatic head is overcome by applying nitrogen gas pressure to the back face of the actuator, creating static equilibrium between the still water pressure and the gas spring. The sides of the wave board are sealed to the sides of the channel via a polypropylene wiper, sliding on stainless steel cladding that is epoxied to the concrete walls. Two feedback loops are used to control the waveboard. The primary loop is a displacement control that minimizes the error between the measured waveboard position and the computed position, the latter based on an algorithm appropriate to the desired wave shape. A secondary loop measures the profile at the center of the waveboard and corrects the board velocity to yield the desired profile. This loop provides the capacity for active reflected wave cancellation. Monochromatic, random and solitary waves up to 1.52 m high can be generated in water depths of 3.5m, for wave periods of 3.5 seconds or less. Larger wave heights are limited by the stroke of the wave generator; however, long breaking waves can be achieved by shoaling the waves with the movable, false bottom.

ADVANCED INFORMATION TECHNOLOGY AND DATA SHARING CAPABILITIES

To broaden the community that can benefit from large-scale long-wave experimentation, recent advances in information and networking technology are leveraged through NEES program to support the vision of geographically distributed, collaborative use. The teleparticipation environment allows remote users to take active roles in experiments performed at Oregon State. The instrumentation data acquired during experiments are accessible through a Web observation interface that exploits high-speed networking capabilities to present information and to relay the responses of remote users back to the facility, both in real-time. Video cameras positioned both above and below the water surface allow remote participants to select from a number of views as the experiment unfolds. These multimedia data streams are converted to formats suitable for long-distance transmission and synchronized with a range of numerical and graphical representations of the instrument data; making it possible for users to start with an overall perspective on what is occurring, then “narrow-in” on those aspects of most interest to them. Tsunami experimentation requires a variety of instrumentation to support a research mode that is exploratory in nature. Therefore, the basic IT functions provided by NEES have been augmented by the Northwest Alliance for Computational Science and Engineering (NACSE), also based at Oregon State.

Some of the additional functionality addresses the difficulty of observing experiments in a physically large facility (even when the researcher is on-site). The multimedia data streams are captured and synchronized to provide freeze-frame, instant replay, and slow-motion capabilities such as those typically employed during telecasts of sporting events. These capabilities are available, through a web interface, to both on-site and remote researchers.

Another example is the availability of a three-dimensional "virtual laboratory" based on video gaming technology. Using just a web browser, tsunami researchers can take a virtual tour of the facility, view the types of camera and instrumentation setups used for past experiments, and plan their own experiments. Graphical replicas of cameras and instruments can be positioned in the virtual wave basin; to verify the positions, the user can "look through" the camera lens and see what will be visible. Once an experiment plan is complete, the information is saved automatically in a databank (see below). A complete setup list is automatically generated to direct lab technicians about which instruments to use and exactly where they should be positioned.

A Tsunami Experiment Databank has been created to preserve in electronic form a complete history of each experiment's procedures, data, and results. Leveraging almost a decade's experience in web-to-database interfaces to improve researcher productivity, NACSE has developed a databank capable of accommodating at least 15 years of experimental data. A wide variety of data formats are supported (e.g., experiment designs, instrumentation plans, video and still images captured during experiments, a wide range of sensor data, visualizations, comparative or predictive results from computational models, textual summaries, etc.) and are accessible through self-explanatory, web-based search interfaces. Once a user has identified the experiment(s) of interest, an "electronic lab notebook" interface supports browsing through the materials, "replaying" the experiment in simulated time, and scanning/fast-forwarding through the experiment's data streams to find the portions that offer the most relevant content. Experimental data can be extracted and downloaded in spreadsheet form, for use in fine-tuning and validating numerical simulations. For example, a modeler can extract data representing the initial conditions of the physical experiment, use them as input to the numerical models, and then compare the outputs predicted by the simulations with those actually obtained in the laboratory.

Metadata tools assist researchers to create higher-level information about their experiments, so that it will be possible to identify experiments that share particular characteristics, that led to particular types of results, etc. Thus, future users will be able to draw comparisons or analyses that span entire series of experiments, conducted by different researchers and perhaps over widely separated periods of time. Usability engineering methods – the application of human factors research to improve system safety and productivity [7] – have been applied throughout development of the information architecture to ensure that all user interfaces are simple to understand and operate.

Finally, to enhance the development of analytical models and numerical algorithms and directly support the validation of computer simulation codes, a web-based numerical codes repository will be hosted in conjunction with the Tsunami Experiment Databank. This community repository will include two classes of numerical simulation codes. The first comprises "open" numerical codes that owners are willing to make available to the public, such as the TUNAMI code developed by researchers at Tohoku University [8]; the owners will be responsible for code maintenance and periodic updates. The benefit of making these codes generally available is that more researchers can become familiarized with them, suggest improvements to the codes, and conduct laboratory and numerical experiments to validate them. In addition, the repository will maintain a director of information about "proprietary" simulations, offered by commercial entities on a license or fee basis; researchers and practitioners interested in using the codes will need to contact the code owners directly. In both cases, the repository will maintain complete descriptions of the underlying mathematical models, assumptions, numerical algorithms, range of applicability, and limitations of each model. Typical sample results will be posted to provide examples of the application and usefulness of the codes. A web-based community forum will also be provided for technical discussions concerning the development and use of numerical simulations in tsunami research.

INSTRUMENTATION

A workshop was held in April 2001 at Oregon State University to discuss the planned construction of the Tsunami Wave Basin. Recognizing that the Tsunami Facility would need a major upgrade in instrumentation, a session was devoted to this topic (a summary is available at http://nees.orst.edu/wkshop_apr2001/. The final report recommended a required set of instrumentation. Based on that information, it is anticipated that the following will be acquired and made available for researchers as of October, 2004:

- 128-channel data acquisition system with appropriate filters
- 50 wave gauges with automated calibration systems
- 14 acoustic Doppler velocimeters (ADV) with 5 remotely controlled positioning systems
- 5 high-resolution video cameras, 1 submersible camera, and 5 video cameras
- Photo lighting system
- 20 pressure transducers
- 2 6-degrees-of-freedom load cells with in-situ calibration
- 1 multiple acoustic transducer array for bed deformation measurement

EXAMPLES OF FUTURE LARGE-SCALE EXPERIMENTS

The large-scale, multidirectional wave basin enables a wide range of laboratory experiments, addressing the needs for understanding long-wave phenomena, as well as providing adequate data for model validation. These will support research in areas such as the following:

- quantitative evaluation of scale effects
- wave breaking and turbulence
- wave structure interaction
- precision measurements of runup and velocity in a highly three-dimensional flow domain
- tsunami generation and propagation behavior caused by subaqueous and subaerial landslides

As discussed earlier, a common scale effect is that viscous forces are exaggerated in small-scale physical models. The effect can be reduced if the model size is increased – although scale effects can never be entirely eliminated – hence a proper scale-effect evaluation is essential for laboratory experiments. Scale effects can be evaluated quantitatively by comparing identical experiments but using a wide range of model scales. Such investigations require a facility, like the new tsunami basin, that is equipped with a precision wave generator and precise basin bathymetry. For example, if the scaling hypothesis is to be examined with runup motion onto a plane beach at a variety of scales, both wave profiles and velocities must be measured at the same scaled positions relative to the beach toe. Dimensionless profiles and velocities should be identical at the same relative position in the absence of scale effects. Because the distance between the wave generator and the beach toe is physically fixed, the generated wave must be stable to provide identically scaled incident waves. Our tsunami basin can be used for this type of experiment because its large size can cover a broad range of scales and the wavemaker system is capable of generating a clean, stable wave such as solitary or cnoidal waves in a variety of water depths.

Another important factor in the scale effects phenomena is associated with wave breaking. Tsunamis often break near the shore, and the approaching flows toward the shore can be violently turbulent. Note that turbulence is a problem that remains to be solved, even at a fundamental level. While turbulence of a simple flow in a small domain can be simulated reasonably well with high-end numerical models, the modeling of turbulence in long-wave phenomena near the shore is far from being even casually approximated. Since turbulence behavior and characteristics are very sensitive to length scales, they cannot be analyzed correctly with small-scale laboratory models. Furthermore, turbulence is intrinsically three-dimensional; therefore the data taken in a narrow wave tank cast uncertainty on the results. The tsunami wave basin is sufficiently wide to play an important role in experimental efforts to understand turbulent flow behavior and characteristics.

Another critical research area is the investigation of wave forces exerted on structures, especially forces associated with breaking or broken waves. Impact wave loads on a structure are affected by the scale effect due to viscous and surface tension forces associated with entrapped air bubbles. Experiments at scales realizable in small laboratory basins produce exaggerated bubble sizes that are almost of the same order of magnitude as that of the impacted body. The size of the Oregon State facility makes it suitable for testing detailed models to obtain more accurate measurements and representation of the fluid dynamics. A preliminary experiment was already performed in the tsunami basin (see Figure 5). The tsunami impact forces were measured with an array of pressure transducers embedded in the cylinder surface; the temporal and spatial variations of tsunami runup onto the vertical cylinder wall will be obtained by analyzing the video images quantitatively.

Investigation of the tsunami forces on structures is a critical simulation endeavor that can be validated through collaborative experiments involving the new basin and other NEES components, such as shake tables, centrifuge equipment, and reaction walls. As an example, suppose a hypothetical earthquake occurs near a port facility where oil storage tanks are located. Deflection and material damage assessment for the tanks will first be made with a NEES shake table, while liquefaction and foundation damage will be investigated utilizing a NEES centrifuge facility. Weakened and partially damaged tanks will be subject to testing in the tsunami basin. The tsunami impact force measurements will serve as inputs for further testing of tank damage at a NEES strong-wall facility and to evaluate secondary damage assessment. If a tank material discontinuity is indicated, oil spill patterns will then be analyzed at the tsunami basin to identify potential environmental and fire hazards. Moreover, the tsunami simulation can provide information for water-borne objects that may collide into other structures; those data will be used for further damage simulations. We emphasize that all simulations will be performed in conjunction with complementary numerical and laboratory efforts, a mode of investigation made possible by the advanced information architecture developed at Oregon State. This type of collaborative simulation capability will be critical to the development of integrated assessment and mitigation strategies for earthquake hazards.

Validating computational models in terms of water-surface elevations alone is insufficient, since elevation is relatively insensitive to errors in other parameters. Therefore, it is essential that accurate velocity data be provided in order to validate models adequately. Predicting coastal long-wave kinematics is difficult in practice, however, because many coastal bathymetries and topographies are highly complex and three-dimensional. This, in turn, means that dense instrumentation patterns and accurate data for water-surface elevations and the velocity field must be obtained.

The new tsunami basin can also be used to explore the mechanisms of landslide wave generation in collaboration with the geotechnical engineering community. Landslide generated tsunamis are known to cause significant impacts locally. While these events have been documented in the past (such as the Lituya Bay event in 1958, discussed in [10], the topic has received more attention recently due to the 1998 Papua New Guinea event (although the cause of this tsunami is still controversial; see [11-13]). The topic involves many uncertain factors including the behavior of the landslide itself. The generated wave is highly three-dimensional and dispersive (i.e., the wavelength is not as long as that of tsunamis of tectonic origins), calling for the specialized capabilities of the new facility.

The experimental programs discussed previously are visually dynamic flow phenomena (e.g., wave breaking and wave interaction with structures). Nevertheless, a large-scale three-dimensional basin such as the new tsunami facility is also useful for investigating very subtle tsunami-induced flow phenomena. A typical tsunami generated from tectonic origins has a large horizontal scale (tens to hundreds of kilometers long), but very small wave amplitude at the origin (a few meters). Such a linear and very weakly dispersive wave is extremely difficult – almost impossible – to simulate in a laboratory facility and is not visually dynamic: there is no splash and no noise. Yet this is a typical tsunami characteristic. When such a tsunami enters a continental shelf, the wave may experience soliton fission. Further, the wave becomes more nonlinear near the shore and where runup occurs onto the beach. At least a portion of such a transformation process can be investigated using the new basin. It requires the precise motion control of the wavemaker to generate a clean, linear and very long wave; the movement is slow and short. The generated wave in the laboratory may be 10-20m long and less than a few centimeters in wave amplitude, so water-surface elevations must be measured accurately to sub-millimeter precision. Since it is a long wave, the basin floor and beach must also be constructed precisely. Clearly, fundamental simulations such as this, while key to understanding the behavior and characteristics of real tsunamis, will only be achievable in the unique large-scale facility at Oregon State.

FUTURE COLLABORATION OPPORTUNITIES

Oregon State University's tsunami basin facility, together with the large wave flume, will become available as a NEES equipment site for research use by October of 2004 and will be operated under the NSF-supported NEES Consortium,Inc. for at least ten years. It is envisioned that the tsunami research community will meet periodically to identify critical research topics and priorities for tsunami research in general, and experimental research in particular. Researchers in coastal science and engineering and other related communities are encouraged to take a similar approach for planning and prioritizing experiments in order to take advantage of this unique laboratory for longwave research.

CONCLUSIONS

The construction of the unique large-scale, three-dimensional tsunami basin at Oregon State University has been completed. The facility will enable a new genre of research studies on long waves, including tsunamis and storm surges. Nearshore wave characteristics and behavior can also be explored for coastal engineering problems. The large surface area and depth of the basin, coupled with its precision wavemaker, will make it possible to conduct detailed experiments for critical long-wave problems (e.g., scale effects and turbulence). By accommodating a full range of state-of-the-art instrumentation, the tsunami wave basin will also provide the analytical and numerical modeling community with a high-resolution tool for validating predictive models.

Through the application of advanced networking and computing technologies, the facility will be available to the international research and development community, including those at remote locations. Researchers will have real-time access to data from instruments and cameras, with simple web-based interfaces that make it possible to control both the timing and the granularity at which data are viewed. The Tsunami Experiment Databank will make it possible to share data, visuals, and results with additional collaborators, students, and the broader community. Specialized interfaces support searching through archives of past experiments, experiment re-play, and extraction of experimental data for use in validating numerical models. By providing comprehensive support for the tsunami research community, Oregon

State's NEES facilities will promote multi-disciplinary and collaborative research with researchers across the globe.

ACKNOWLEGEMENT

We gratefully acknowledge the financial support by the National Science Foundation (CMS-0086571) for upgrading and expansion of the Oregon State tsunami wave basin and the 2001 community workshop on research using the NEES tsunami facility (CMS-0116898), and by the Office of Naval Research for the original construction of the multidirectional wave basin and continuing research (N00014-86-K0687, N00014-92-J1221 and N00014-04-10008).

REFERENCES

1. Yeh, H., Liu, P., and Synolakis, C. (1996). *Long-Wave Runup Models,* World Scientific Publishing Co., Singapore, 403 pp.

2. Rzadkiewics S. A., Mariotti, C., and Heinrich, P. (1996.) "Numerical simulation of submarine landslides and their hydraulic effects", *J. Waterway, Port, Coastal, and Ocean Engrg.*, ASCE, Vol.123, pp. 149-157.

3. Grilli, S.T. and Watts, P. (1999). "Modeling of waves generated by a moving submerged body: applications to underwater landslides." *Engineering Analysis with Boundary Elements*, Vol.23, No.8, pp. 645-656.

4. Lynett, P. J., Liu, P. L.-F., Losada, I. J. and Vidal, C. (2000) "Solitary wave interaction with porous breakwater", *J. Waterway, Port, Coastal and Ocean Engrg.*, ASCE, Vol.126, pp. 314-322.

5. Peregrine, D.H. (1995). "Water wave impact on walls and the associated hydrodynamic pressure field," *Wave Forces on Inclined and Vertical Wall Structures*, Kobayashi and Demirbilek, eds., ASCE, pp. 259-281.

6. Sarpkaya, T. and Isaacson, M. (1981). *Mechanics of Wave Forces on Offshore Structures,* Von Nostrand Reinhold Co., New York, 651 pp.

7. Pancake, C.M. (1998). "Improving the usability of numerical software through user-centered design," in *The Quality of Numerical Software: Assessment and Enhancement*, ed. B. Ford and J. Rice, Chapman & Hall, London.

8. Imamura, F. (1995). "Tsunami numerical simulation with the staggered leap-frog scheme," manuscript for TUNAMI code, School of Civil Engineering, Asian Inst. of Tech., 45 pp.

9. Landau, L.D., and Lifshitz, E.M. (1959). *Fluid Mechanics*, Pergamon Press. 536 pp.

10. Miller, D.J. (1960). "Giant waves in Lituya Bay, Alaska." U.S. Geological Survey Professional Paper 354-C, 83 pp.

11. Matsuyama, M., Walsh, J.P., Yeh, H. (1999). "The effect of bathymetry on tsunami characteristics at Sissano Lagoon, Papua New Guinea," *Geophysical Research Letters*, Vol. 26, No. 23, pp. 3513-3516.

12. Tappin, D.R., Watts, P., McMurty, G.M., Lafoy, Y., Matsumoto, T. (2001) "The Sissano, Papua New Guinea tsunami of July 1998 – offshore evidence on the source mechanism," *Marine Geology*, Vol. 175, pp. 1-23.

13. Synolakis, C.E., Bardet, J.-P., Borrero, J.C., Davies, H.L., Okal, E.A., Silver, E.A., Sweet, S., and Tappin, D.R. (2002) The slump origin of the 1998 Papua New Guinea Tsunami. *Proc. R. Soc. Lond. A* **458**, 763-789.

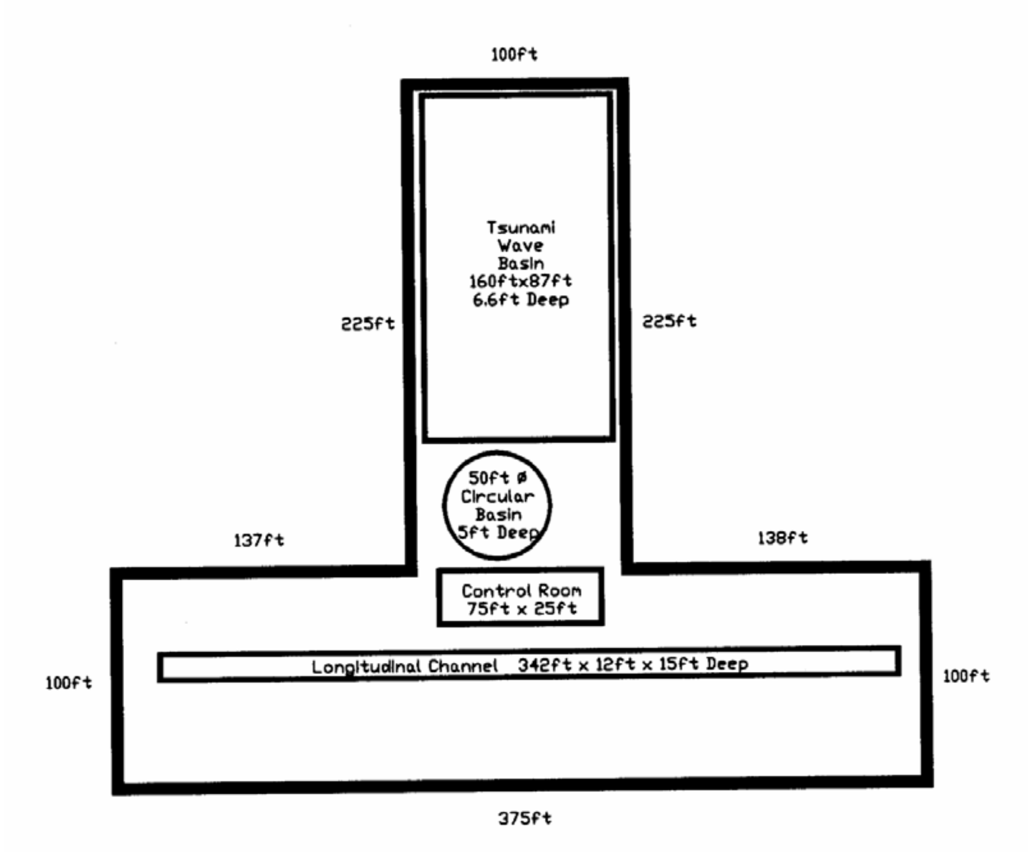

Figure 1. Plan view of the Oregon State Wave Research Laboratory.

Figure 2. The Oregon State Wave Research Laboratory NEES Tsunami Wave Basin.

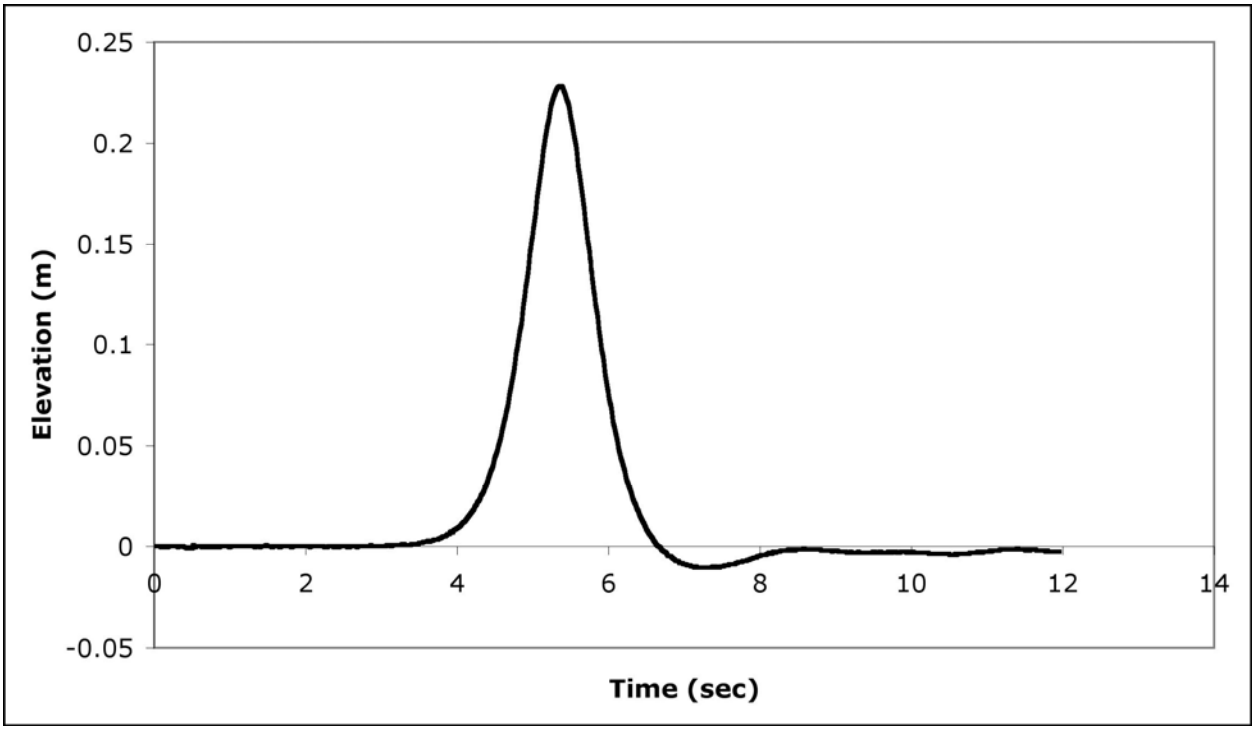

Figure 3. Generated solitary wave at 15.7 m from the waveboards. The targeted wave height is 0.24 m.

Figure 4. The Oregon State Wave Research Laboratory Large Wave Flume.

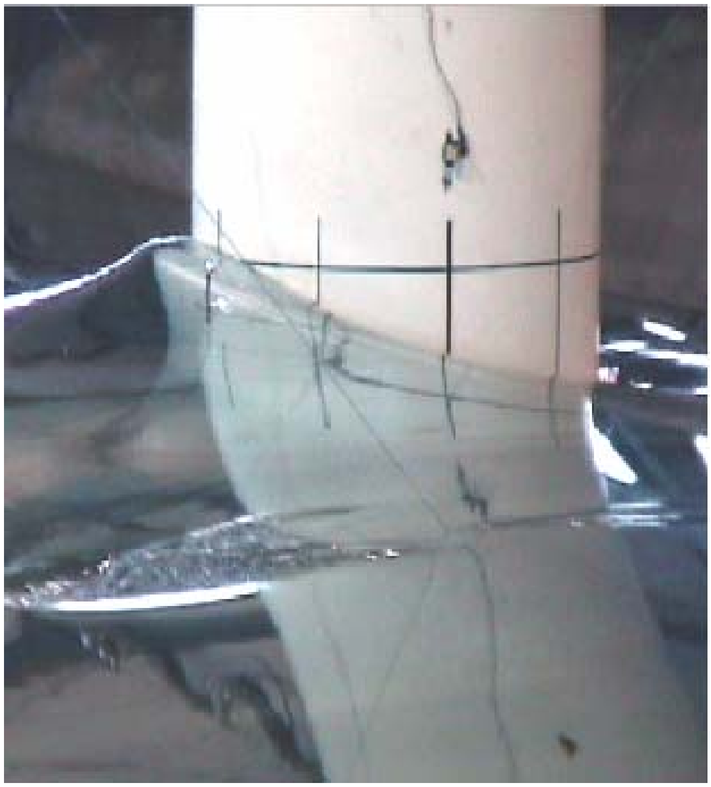

Figure 5 An image of the preliminary experiment for tsunami force on a vertical cylinder. The size of the cylinder is 50 cm in diameter in a water depth of 80 cm.