Unique Large-Scale Wave Basins for NEES Collaborative Research

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Abstract

Under the Network for Earthquake Engineering Simulation (NEES) program at the National Science Foundation, the multidirectional (3-D) wave basin at Oregon State University is expanded to create a unique large-scale experimental testing facility for tsunami hazard mitigation research. When completed in 2004, this 3-D basin, together with the other existing directional (2-D) and circular wave basins, will support high resolution, unprecedented-scale experiments with very dense instrumentation. The facilities will provide earthquake engineering and tsunami researchers with critical means to test and validate advanced analytical and numerical models such as models for tsunami inundation, impact forces, fluid-soil-structure interactions, and submarine landslides. Detailed descriptions of the three large-scale wave basins, as well as potential research programs to be performed are discussed.

Introduction

Around the US, coastal shorelines are exposed to potential damages from severe natural hazard conditions including earthquakes and the associated tsunamis, which lead to wave runup and landward inundation. The devastation at any particular location is a function of the velocity, acceleration, and elevation of the water as it interacts with natural and man-made coastal objects. The economic costs of strengthening the local infrastructures and evacuating coastal areas are very high; and more importantly, severe tsunamis can cause significant losses in human lives. A clear understanding of tsunami runup behavior is critical if we are to develop appropriate warning systems and evacuation strategies to save human lives. Decisions affecting human safety require systematic methods for evaluating both tsunami events themselves and the wave-structure interaction behavior they are likely to precipitate.

To predict tsunami run-up, landward inundation, and wave-soil-structure interaction effects on coastal structures and infrastructures, the research community turns increasingly to computational models. Physical experimentation is costly and slow, and requires high-resolution, real-time capture of multi-dimensional data. It is also ephemeral, in that there is only one brief opportunity to capture suitable data for a particular run. Numerical experiments offer an attractive alternative. Recently, as a result of a strong effort by the tsunami community, several two- and three-dimensional numerical models have been evaluated to quantify the interaction of tsunamis with shorelines (Yeh, *et al.* 1996). Unfortunately, the predictive capabilities of these numerical models have not been fully validated, however, due to the lack of suitable field or laboratory data. Although field measurements of run-up 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 (except tide gage data) and the data are often extremely spatially sparse. Furthermore, the source of tsunami generation cannot be

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accurately specified, since any detailed information in deep water is difficult to obtain (Synolakis et al., 1997).

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

As a part of NEES experimental facilities, the O. H. Hinsdale Wave Research Laboratory (WRL) will upgrade its multidirectional wave basin, together with the existing directional and circular wave basins, to become the largest laboratory facility in the Nation for earthquake engineering and 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.

The objectives of this paper are to describe the key features of the facility under construction as well as the existing two-dimensional and circular wave basins at Oregon State University, present a vision for this unique, community laboratory, and discuss future experimental research work it will engender.

The Wave Research Laboratory

Figure 1 shows a schematic plan view of the WRL, including the planned expansion. The existing facility (below the dashed line) includes a 105.6m long by 3.7m wide by 4.6m deep (two-dimensional) wave basin, a 15.4m diameter by 1.5m deep circular wave basin, and a 26.5m long by 18.3m wide by 1.5m deep multidirectional wave basin. Technical information on these three basins is presented in this section.

Multidimensional (3-D) Wave Basin -- The multidirectional wave basin is being expanded to 48.8m long by 26.5m wide by 2m deep. It will be constructed as a reinforced concrete reservoir, with a 0.25m wall and floor thickness. Unistrut inserts will be placed in rows at 2.1m spacing to affix models, instrumentation, and the wave generator throughout the basin. The existing wave generator in the multidirectional basin (Figure 2) consists of 30 wave-board segments. Each paddle is 0.6m wide by 1.5m high, with a 1m/sec maximum velocity and a maximum stroke of 0.9m. The new wave generator will consist of 29 wave-board segments, each paddle 0.9m wide by 2m high. Each wave board will be capable of a 2m displacement and a maximum velocity of 2m/sec. It will be able to generate a clean solitary wave 0.8m high in a water depth of 1m. Each wave board will be powered by an AC electric motor with a peak power rating of approximately 30kW. The wave generator will digitally control the paddles on an individual basis, making it possible to generate arbitrary wave profiles and arbitrary wave directions. Control of the wave board will be achieved through displacement and velocity feedbacks. Velocity control will utilize a wave profile measurement at the front face of the wave board, comparing it to the desired long-wave profile; board velocity will be adjusted via an algorithm that relates wave profile and board velocity. This velocity control will have the capability of absorbing reflected waves in the basin and optimizing the wave shape beyond that available by means of the displacement control.

Two-Dimensional Wave Basin -- The large, two-dimensional wave basin (Figure 3) is 106 m (342 ft) long, 4.7 m (15 ft) deep and 3.7 m (12 ft) wide. The wave generator is a hydraulically driven, hinged flap, aluminum weldment. The wave board is hinged at the bottom of the channel in an overall depth of 5.6 m (18 ft). The bottom shoals 1 m (3 ft) over a distance of 12.3 m (40 ft) to the 4.7-m (15-ft) depth of the basin test section. A false bottom, fabricated from 3.7-m (12ft) square, 0.15 m (6-in) 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 x 10^{7} N/m² (3000 psi) oil hydraulic pump that is the prime mover for a 0.2-m (8-in) diameter actuator. The actuator ram has a semi-stroke of 0.8 m (30 in) and is oriented horizontally, 3.1 m (10 ft) 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 wave The primary loop is a displacement control that minimizes the error between the board. measured wave board 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 wave board 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 (5 ft) high can be generated in water depths of 3.5 m (11.5 ft), 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.

<u>Circular Wave Basin</u> -- The circular wave basin (Figure 4) is 15.2 m (50 ft) in diameter and 1.52 m (5 ft) deep. A 16 segment, spiral wave generator, 3.35 m (11 ft) in diameter, is located at the center of the basin. Each segment is edge driven by a direct digital controlled AC motor with ball screw drives. Both random and simple periodic waves can be generated with wave heights up to 0.61 m (2 ft). One mode of wave generator operation simulates a cylinder orbiting eccentrically about its center and produces spiral shaped waves that propagate with a tangential component at the periphery of the wave basin. A cone shaped beach is constructed at the outer perimeter of the circular wave basin. The tangential wave component drives littoral processes along the beach and non-linear wave interactions generate infragravity waves. Littoral processes continue around the basin as if along an infinite beach, uninterrupted by the end effects of rectangular wave basins. One of the applications is to model tsunami edge bores, which were visually observed during the 1983 Nihonkai-Chubu Earthquake event (Shuto, 1985). Other example applications include modeling of edge waves and far-infragravity waves, long shore sediment transport rates and the impacts of coastal groins and jetties.

These three basins allow repeatable, high-resolution, large-scale experiments with dense instrumentation. The facilities are designed to provide a proper environment for implementation of state-of-the-art, non-contact instrumentation (such as optical and acoustic devices) and sensors such as MEMS (micro-electro-mechanical systems). They will enable researchers to validate analytical and numerical models of a variety of tsunami phenomena including long-wave/structure interactions for a full range of ocean, coastal, and harbor studies. By controlling changes in bathymetry, surface permeability, roughness, and material erodibility, the effects on

tsunami runup and attenuation can be measured.

Although larger wave facilities exist elsewhere, most of them are narrow wave tanks similar to Oregon State University's two-dimensional wave channel (see Fig. 3). For example, the FZK Hanover wave tank is 330m long by 5m wide by 7m high, with a 4m-stroke wavemaker. Wide wave basins similar to the new tsunami basin also exist, but their wave generation capabilities are much smaller. Those facilities are used primarily for studies of coastal wind-generated waves and are not suitable for tsunami studies. The Cedex Basin in France, for example, is 34m x 26m x 1.6m in size and has a wavemaker with a peak-to-peak stroke of less than 0.6m, while the US Army Corps of Engineers basin in Vicksburg, MS, is 60m x 40m with a wavemaker stroke of 0.7m. The multidirectional wave basin at Oregon State University will be the first tsunami-scale facility anywhere in the world.

Examples of Future Large-Scale Experiments

The large-scale, multidirectional wave basin, together with the 2-D and circular wave basins, will enable a wide range of laboratory experimentation. These will address needs for understanding tsunami phenomena as well as for providing adequate data for model validation in areas such as the following:

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

As discussed earlier, a common scale effect is that viscous forces are exaggerated in small 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 WRL expansion, 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 in a variety of scales (proportional to water depths), 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. This experiment therefore requires that the wave basin be sufficiently large to cover a wide range of scales, the basin floor be carefully constructed, and the wavemaker system be 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 approximated reasonably well with high-end numerical models (e.g. direct numerical simulations of the Navier-Stokes equations), the modeling of turbulence in tsunami 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. This can be demonstrated by considering the Kolmogorov model (e.g., Landau and Lifshitz 1959). The ratio of the Kolmogorov dissipation length scale to the integral scale of turbulence is proportional to $R^{-\lambda_1}$, where *R* is the Reynolds number. Hence the inertial range of turbulence, and kinetic energy, are sensitive to the scale of the model. Note that, unlike the friction effects, such turbulence characteristics do not appear to become independent of the Reynolds number as R becomes large. Furthermore, turbulence is intrinsically three-dimensional; therefore the data taken in a narrow wave tank cast uncertainty on the results. The WRL's new wave basin will be sufficiently wide to play a substantial 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 and/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 comparable to that of the impacted body. Because of the size of the expanded facility, it will be capable of testing detailed models in the basin for more accurate measurements and representation of the fluid dynamics.

Investigation of the tsunami forces on structures will be a critical simulation endeavor that will 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 WRL wave 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 WRL 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 effort, a mode of investigation becomes realizable by the advanced information architecture provided as part of Oregon State University's effort and the high-speed, high-capacity network system provided by the NEESGrid program (reference for NEESGrid). This type of collaborative and interactive simulation capability is 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. In fact, since the water-surface elevation is obtained by integration of the hydrodynamics equations, it is relatively insensitive to errors in other parameters. For adequate model validation, it is essential that accurate velocity-field data be provided. Predicting coastal long-wave kinematics is difficult in practice, however, because many coastal bathymetries and topographies are highly complex and three-dimensional. A highly three-dimensional bathymetry is needed as a benchmark for model validation, which means that dense instrumentation patterns and accurate data for water-surface elevations and the velocity field must be obtained. The new WRL wave 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 Miller 1960), the topic has received more attention recently due to the 1998 Papua New Guinea event (e.g., Matsuyama, *et al.* 1999; Tappin, *et al.* 2001; although the cause of this tsunami is still controversial). The topic involves many uncertain factors including the behavior of the landslide itself. The generated wave is highly three-dimensional and dispersive (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 threedimensional basin such as the new WRL 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 (Madsen and Mei 1969). 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 1cm 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 be achievable in the unique large-scale facility at Oregon State University.

Summary and Concluding Remarks

A unique large-scale, three-dimensional, long-wave facility is under construction at the O. H. Hinsdale Wave Research Laboratory at Oregon State University. The facility, together with the existing two-dimensional and circular wave basins, will enable a new genre of fluid-soil-structure interaction research studies including tsunami effects on coastal infrastructures. Because of the three wave basins' large surface area, great depth, and precision wavemaker, detailed experiments for critical fluid-soil-structure interaction problems (e.g., scale effects and turbulence) can be conducted. By accommodating a full range of state-of-the-art instrumentation, the basins will also provide the analytical and numerical modeling community with high-resolution tools for validating predictive models. By providing comprehensive support for the earthquake engineering and tsunami research communities, the facility will promote multi-disciplinary and collaborative research with researchers across the globe.

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Figure 2. Oregon State University's Existing Multidirectional (3-D) Wave Basin.



Figure 3. Oregon State University's Direction (2-D) Wave Basin.



Figure 4. Oregon State University's Circular Wave Basin.

