Experimental and Numerical Simulations of Tsunami-Structures Interaction

by

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ABSTRACT

Recently, with the support of the Network for Earthquake Engineering Simulation Program of the National Science Foundation in the US, Oregon State University (OSU) has completed the upgrading of a Tsunami Wave Basin Facility to support experimental and computational tsunami research. This paper briefly describes the physical experimental facility and selected experimental and numerical models at OSU for tsunami structure interaction modeling testing and simulation, provides a discussion on the development of comprehensive experimental and some challenges in experimental and numerical simulations of large-scale tsunami structure interaction is presented.

KEYWORDS: Experiment, numerical simulation, tsunami effects, coastal structures

1.0 INTRODUCTION

Devastating tsunamis occur periodically around the world (e.g., 1946 Alaska, 1993 Japan, and 1998 Papua New Guinea, to name a few), although none captured people's attention as vividly as those generated by the magnitude-9.0 earthquake occurred on the offshore of Banda Aceh, Indonesia on December 26, 2004. The total death toll suffered by countries around the Indian Ocean including Indonesia, Sri Lanka, India and Thailand now stands at more than 273,000. It is anticipated that earthquakes of similar magnitude and subsequent tsunamis might occur in the Cascade Subduction Zone offshore of the North America coast along Northern California, Oregon, Washington (U.S.) and British Columbia (Canada) within the next one hundred years. In an effort to mitigate the effects of tsunamis on coastal cities, the US government is implementing a series of measures including the installing of additional tsunami measurement buoys along the US coasts in the Pacific and Atlantic oceans by NOAA. Intense research activities in the study of tsunami propagation and tsunami effects on coastal structures are underway.

In 2000, Oregon State University (OSU) was selected as the "Tsunami Wave Basin Site" under the Network for Earthquake Engineering Simulation (NEES) Program of the National Science Foundation (NSF) in the US. A three-dimensional (3-D) Tsunami Wave Basin (TWB) at the Wave Research Laboratory (WRL) was expanded to create a suitable experimental environment for tsunami and tsunami-structure interaction research. In addition, the existing two-dimensional (2-D) large wave flume (LWF) is also an integral part of the "NEES Tsunami Facility". The two wave basins are supported by NSF for operate and maintenance for the next ten years (FY2004-2014) and available for experimental use by US and international researchers. In support of the experimental research at the Lab, 2-D and 3-D numerical models of the wave basins including tsunami runup, inundation and tsunami effects on coastal structures are being developed at OSU. In the following sections, the physical effects, experimental modeling in the wave basins, numerical modeling and it challenges are discussed.

2.0 TSUNAMI-STRUCTURE INTERACTION

A typical tsunami often contains several waves each separated by several minutes. The characteristics of the wave form as it approaches a coastal structure depend on the local bathymetry of the surrounding region. As video footage shown on television around the world indicates, the wave is usually intact far away from the shore. As it approaches the shore, the wave amplitude increases

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significantly due to shoaling, then the wave starts to break due to nonlinear kinematics and the turbulence caused by shear stresses at the sea floor. When the wave reaches the beach and impact a structure, the wave is usually already broken, thus turbulence and energy dissipation are important. The structure considered can be a breakwater, a seawall, or a building. The tsunami loads on a structure include hydrostatic pressure, fluid impingement, fluid flow drag, and impact due to waterborne debris. These loads often induce large structural deformation, yielding, fracture, and collapse and/or dislodgement.

The effects of a tsunami on a structure can be simulated experimentally in the 3-D TWB and the 2-D LWF with scaled models. Although the typical tsunami may contain a few waves, usually there is a single dominant wave that is much larger in magnitude than the rest. Thus the tsunami effects on a coastal structure can often be characterized by a solitary wave, the characteristics of which may be assumed identical to those of the largest wave measured in the field. A typical "tsunami-structure interaction" experiment will include the generation of a representative solitary wave which propagates towards a structure, or an array of structures that may be submerged, surface piercing, or aerial. The "structures" may also be floating objects such as boats, or parts of land debris flow such as vehicles.

3.0 TEST BASIN FACILITY

The multidirectional tsunami wave basin (TWB) at OSU is 48.8m long by 26.5m wide by 2m deep (Figure 1). 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.

4.0 EXPERIMENTAL MODELING

The large-scale TWB and LWF enable a wide range of laboratory experimentation to address the needs for understanding long-wave 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*

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 TWB, 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, 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, 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. This can be demonstrated by considering the Kolmogorov model. The ratio of the Kolmogorov dissipation length scale to the integral scale of turbulence is proportional to $R^{-3/4}$, where R is the Reynolds number. Hence the inertial range of turbulence, and kinetic energy, are sensitive to the scale of the model. Furthermore, turbulence is intrinsically three-dimensional; therefore the data taken in a narrow wave tank cast uncertainty on the results. The TWB is 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 on structures, especially forces associated with breaking and 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. Because of the size of the TWB, it is capable of testing detailed models for more accurate measurements and representation of the fluid dynamics.

Investigation of the tsunami forces on structures is 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 TWB. 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.

Validating numerical 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 experimental programs discussed previously are visually dynamic flow phenomena (e.g., wave breaking and wave interaction with structures). Nevertheless, a large-scale 3-D basin such as the

TWB 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 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, is only be achievable in the unique large-scale facility at OSU.

5.0 NUMERICAL MODELING

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. Such models are computationally complex and must incorporate movable and deformable surface piercing objects as well as submerged boundaries associated with subaqueous landslides (e.g., Lynett, *et al.* 2000; Grilli and Watts 1999).

The accurate numerical simulation of fluid-structure interaction is a very challenging problem since the study of coastal waves and structures have traditionally belonged to two different disciplines, namely, environmental hydrodynamics and structural mechanics. While the modeling of structures has been studied with success in the past, coupled wave-structure interaction is limited to special cases, mostly naval applications (e.g., Gorski *et al* 2002), with often highly simplified assumptions. While the research on each individual discipline is vast, the following sections briefly summarize the research on coastal waves and structures pertinent to this discussion.

5.1 Wave Model

To model a tsunami approaching a beach, as well as a tsunami over land, the wave may be assumed to be breaking and/or broken. In this case, the research work of Philip Liu's group at Cornell University using the Reynolds Averaged Navier-Stokes (RANS) equation is most applicable (Lin and Liu 1998). Liu's group incorporated the k-ε equations governing the turbulence intensity (k) and energy dissipation rate (ε) in the flow field computation of a LANL simulation code TRUCHAS (which solves the NS equations in 3-D) to take into account wave breaking and turbulence (Wu 2004). In the model, the RANS equations are obtained based on the Eulerian formulation and the resulting equations are solved numerically using the finite-volume (FV) method.

5.2 Structural Model

The structures considered for fluid-structure interaction may be breakwaters, seawalls, buildings, individual building components (columns, beams, shear walls, etc.), or non-structural objects like boats, vehicles or vegetation (trees). Typically, structures are modeled numerically using the FE method and Lagrangian formulation (Belytschko *et al* 2000) with various levels of refinement. The structural modeling ranges from the simplest case of rigid bodies to flexible bodies with large deformation including yielding and fracturing, or a combination where structures or structural components shear off from the foundation and become rigid body "debris" or floating "obstacles" in the wave field that may impact other structures.

5.3 Coupled Fluid-Structure Interaction

A comprehensive fully-coupled fluid-structure interaction model for tsunami effects on structures may be divided into two components, the wave domain and the structure domain. The coupling of the two domains is enforced via compatibility and equilibrium criteria at the multi-physics interface. Dynamic and kinematic variables in each domain are first solved independently using a CFD solver for the fluid and a CSD solver for the structure, with compatibility and equilibrium enforced at the interfaces using an iterative process (Lohner 2001). This substructuring technique is flexible and may be quite efficient since it allows the response in the fluid and structure domains to be computed independently using CFD and CSD solvers that take full advantage of their respective physical characteristics. The substructure method is quite popular and has been employed in a large number of coupled problems. A disadvantage of this method, though, is that because the two substructures usually employ different mesh techniques (e.g., FD or FV with structured grid for the fluid and FE with unstructured grid for the structure), compatibility and equilibrium have to be enforced at different grid points and values of dynamic and kinematic variables at the interface have to be approximated via an interpolation algorithm (Huang and Riggs 2004).

An alternative to the substructure technique is the monolithic technique, in which case, the governing equations for the fully-coupled fluid and structure domains are solved simultaneously, with matching grids at the interface (Lohner 2001). Although the formulation and the numerical solution procedures for the fluid and the structure may be different, the grid points at the fluid-structure interfaces are matched exactly at all times. No approximation or interpolation algorithm is needed for the dynamic and kinematic variables at the interface. Although it has advantages over substructuring, the monolithic technique may require more computational effort and increased memory due to the large number of coupled equations, and it is often prone to ill-conditioning.

An ideal solution technique for fully-coupled fluid-structure interaction problems should take advantage of the efficiency of the substructure technique yet maintain the matching grids at the interface to preserve accuracy and eliminate the need for a mesh interpolation algorithm. The application of this type of solution technique to simulating fluid-structure interaction is a major focus of the proposed research.

6.0 RECENT DEVELOPMENTS

Since the inception of the TWB construction project, researchers at OSU have been developing computational fluid-structure interaction software and monitoring state-of-the-art developments in CFD and CSD in an effort to develop software that would be suitable for use by both tsunami and structural engineers. Selected developments related to the goals of this paper are presented here.

6.1 Fully-Coupled CFD-CSD Software

An NSF supported “pre-NEES” research project involving the development of 2-D fully coupled fluid-structure interaction simulation software, SFXC, to predict submarine landslide generated waves and fluid-structure interaction under waves is being conducted at OSU. This code extended the Cornell 2-D COBRAS finite difference, structured grid model (Lin and Liu 1998) by adding the capabilities of prescribed rigid boundary movements and fully coupled fluid-rigid structure interaction. Details of this research can be found in Yuk, *et al* 2005.

6.2 Latest Development in Particle FE Method

In the study of tsunami effects on structures including TWB experiments, a unified approximation procedure covering both the fluid and structural domains with an exact representation of the fluid-structure interface is essential. The exact representation of the interface is necessary because the kinetic energy of the entire fluid-structure system is generated by the wave maker and dissipated by the bottom boundaries and moving structures. The dynamic response of the structure is governed by the equilibrium and compatibility constraints at the fluid-structure interface (as mentioned earlier, moving structures are also “wave makers”). “Exact” modeling of the fluid-structure interfaces is needed to achieve numerical accuracy and to ensure energy is dissipated properly during a simulation.

Recently a finite-element based formulation of the fluid domain, called the particle finite element method (PFEM), has shown promising signs for unifying the simulation of fully-coupled fluid-structure interaction (Onate *et al* 2004). In this method, the continuity and momentum balance equations in the fluid domain are modeled using the Lagrangian formulation and discretized using the PFEM (Del Pin 2003). 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 with the computationally efficient Delaunay tessellation technique.

6.3 Commercial Software Applications

A number of commercial simulation software packages including ANSYS, Star-CD/COMET and LS-DYNA to determine their TWB experiment modeling capabilities have been examined. The study revealed that LS-DYNA (Hallquist 1998) is quite versatile and the most capable among the selected codes since it contains modules for very large strain deformation, nonlinear materials, fracture, shearing detachment, contact and impact. Recently, a fluid model using the NS equations has been added to LS-DYNA. This fluid model can handle wave impact on flexible bodies as well as surface piercing and re-submergence of multiple flexible bodies. There are versions for PC, parallel and supercomputing available for research, development and production runs. LS-DYNA has a feature USER MAT that allows researchers to develop their own modules for research and development while taking full advantage of the mesh generation, explicit and implicit computation, and graphics capabilities. An example application using the code to model fully-coupled fluid-structure interaction in the 3-D TWB with fluid-structure and structure-structure interaction including impacts is shown in Figure 2. A numerical model of the TWB with exact dimensions and prescribed wave generator movement has also been developed (Figure 3). The results appear to be quite reasonable for fluid flows with negligible turbulence.

7.0 FUTURE RESEARCH

A combination using the CSD codes from the industry for their proven robustness and nonlinear capabilities for the analysis of nonlinear structural behavior and the PFEM methods for modeling fluid motions in Lagrangian form may provide the best solution for the development of a sophisticated and robust code for simulation of tsunami wave 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, which 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 which may contain porous media and/or movable sediments.

Another 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 on the order of 3×10^9. Using 20-node solid element with 3 degrees of freedom (d.o.f.) at each node would lead to approximately 4×10^{10} d.o.f.'s. 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 systems. The use of high-end vector supercomputer will be necessary. Efficient unstructured grids generation software with judicial choice of grid density and some combination of explicit-implicit integration schemes will be also needed.

8.0 ACKNOWLEDGMENTS

Financial support from the National Science Foundation (CMS-0086571) for upgrading and expansion of the Oregon State tsunami wave basin and NEESinc for operation and maintenance of the facility, and from the Office of Naval Research for the original construction of the multidirectional wave basin and continuing research (N00014-92-J1221 and N00014-04-10008) is gratefully acknowledged.

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Figure 1. The NEES Tsunami Wave Basin.

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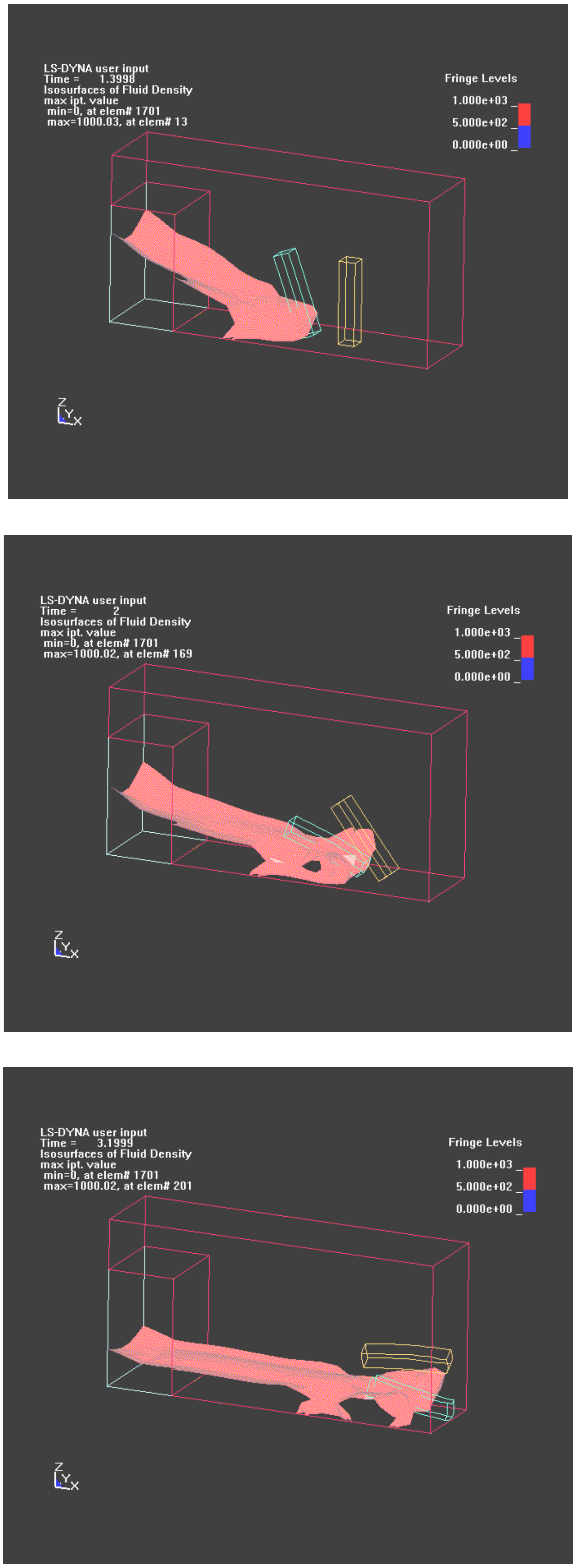

Fig.2. Fluid-Structure Interaction with Fluid-Structure and Structure-Structure Impact.

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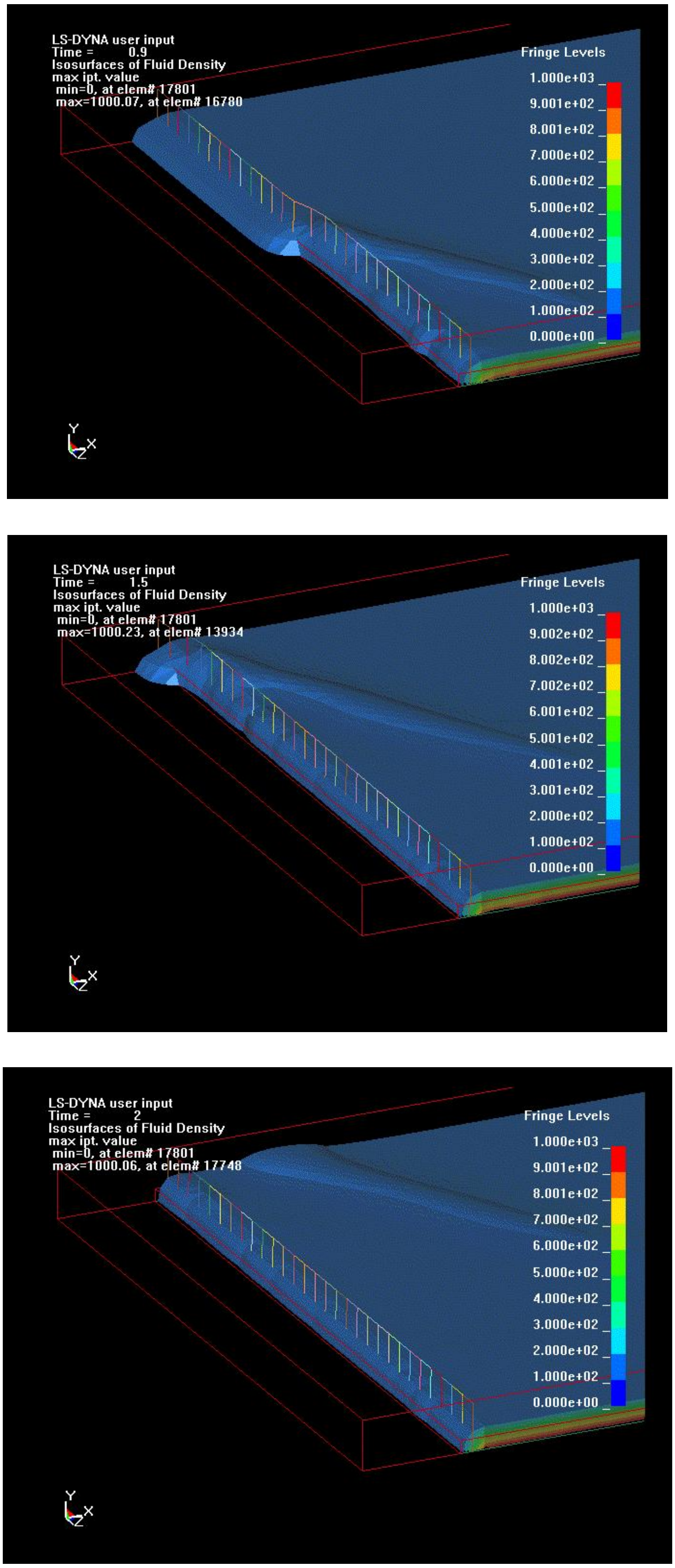

Fig.3. Simulation of the NEES TWB's 29–paddle wavemaker generating a directional wave.