Anil K. Chopra Symposium

UC Berkeley

October 2-3, 2017

Analytical, Experimental and Numerical Simulation of Nonlinear Waves, Hydrodynamics Load and Fluid-Structure Interaction Problems in Large-Scale Wave Basins

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Introduction

- OSU NEES/NHERI 3D Tsunami Wave Basin and 2D Wave Flume
- Large-Scale Wave Basin Physical Experiments
  - Tsunami Engineering (NSF, ODOT, Caltrans)
  - Naval and Ocean Engineering (ONR, Coastal and Offshore Industry)
  - Wave Energy Conversion (DOE and Hydro Power Industry)
- Virtual Large-Scale Wave Basin Numerical Experiments
- Nonlinear Wave Theory and Make-to-Order Wave Field Simulations Based on Nonlinear Wavemaker Theory
- Professor Chopra's Influence on Fluid-Structure Interaction Research

Oregon State 3-Dimensional “Tsunami” Wave Basin

Specifications:

- 49.4 m long
- 26.5 m wide
- 2.1 m deep
- 29-segment 30-actuator directional wavemaker
- maximum stroke 2 m
- maximum velocity 2 m/s

Oregon State 2-Dimensional Large Wave Flume

Specifications:

- 104 m long
- 3.7 m wide
- 4.6 m deep

- Single-piston-type wavemaker with
  maximum stroke 4 m
  maximum velocity 4 m/s

- Maximum wave height
  1.7 m at T = 2.5-5.0 sec

NEES/NHERI NSF Tsunami Research Facility

- 2000 – 2004 Design and Construction of OSU 3D Tsunami Wave Basin and 2D Large Wave Flume
- 2004 – 2014 NEES Operation of NSF Tsunami Research Facility
- 2014 – 2015 Transition Year
- 2015 – 2020 NHERI Operation of NSF Tsunami Research Facility
- Naval, Costal, Offshore and Wave Energy Research Communities

- A Scientific Challenge – Demand from experimental researchers on generation of specific wave fields and profiles at various locations of the 3D Wave Basin and 2D Large Wave Flume

Representative Large-Scale 3D Wave Basin Experiment

Tsunami Impact on Multiple Vertical Cylinders

Desired Scaled Waves:

- Tsunami
- Rogue Waves
- Random Waves
- Hurricane Storm Surge

Representative Large-Scale 3D Wave Basin Experiment

Ocean Wave Energy Conversion Device Dynamic Response

Desired Scaled Waves:

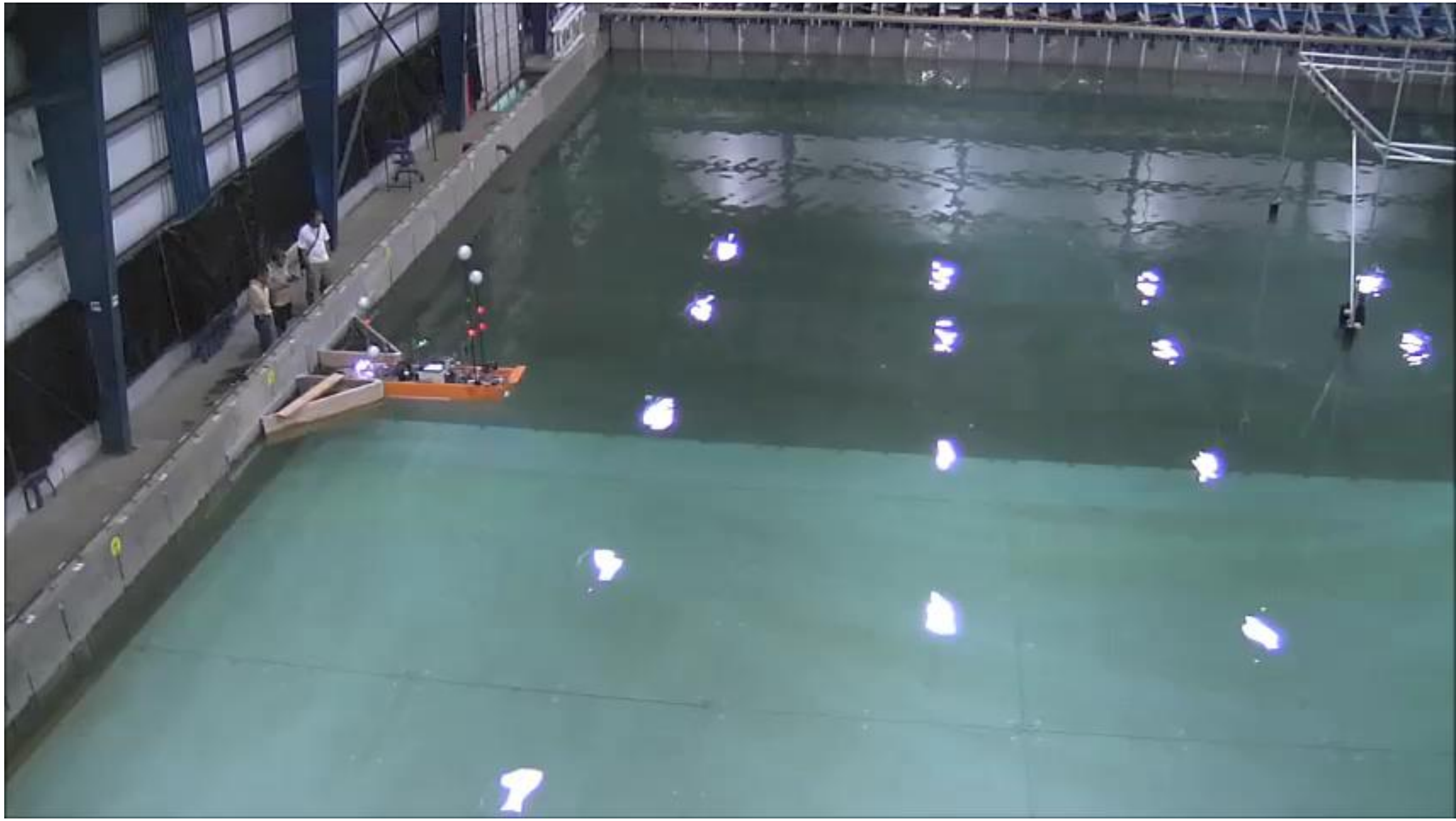
- Tsunami
- Rogue Waves
- Random Waves
- Hurricane Storm Surge

Representative Large-Scale 3D Wave Basin Experiment

Maneuvering of Fast Ship in Shallow Water and Surf Zone

Desired Scaled Waves:

- Tsunami
- Rogue Waves
- Random Waves
- Hurricane Storm Surge



Representative Large-Scale 2D Wave Basin Experiment

Wave Impact on Breakwater

Desired Scaled Waves:

- Tsunami
- Rogue Waves
- Random Waves
- Hurricane Storm Surge

Representative Large-Scale 2D Wave Basin Experiment

Wave Impact on Bridge Section

Desired Scaled Waves:

- Tsunami
- Focused Waves
- Random Ocean Waves
- Hurricane Storm Surge

Representative Large-Scale 2D Wave Basin Experiment

Wave Overtopping Levee

Desired Scaled Waves:

- Tsunami
- Rogue Waves
- Random Ocean Waves
- Hurricane Storm Surge

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Experimental Wave Field Simulations

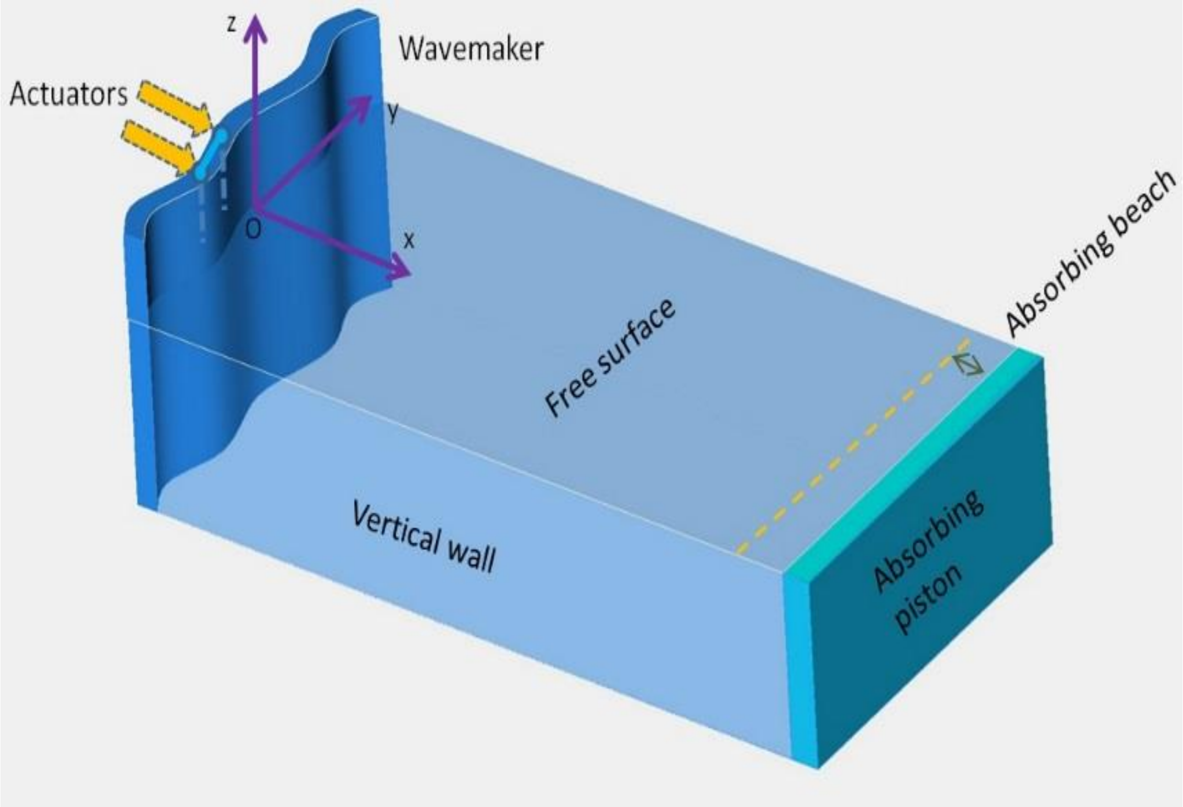
The US Navy Maneuvering and Seakeeping (MASK) Basin:

Virtual Wave Basin for Numerical Experiments

- Numerical models available are:
  - Compressible Navier-Stokes solver – a finite-element based model with fluid structure interaction capabilities
  - Incompressible Navier-Stokes solver – a finite-element based model with fluid structure interaction capabilities
  - Fully nonlinear potential flow (FNPF) solver – a boundary-element based model
  - Coupled FNPF – incompressible flow solver
  - Improved free surface capturing by using Strong stability-preserving Runge-Kutta nodal discontinuous Galerkin level set method
- A nonlinear wavemaker theory software needs to be developed to enhance wave making capabilities for both physical and numerical models

Consistent Virtual and Physical Test Basin Modeling Methodology

- A virtual marine basin consistent with large-scale physical test basin using domain decomposition models



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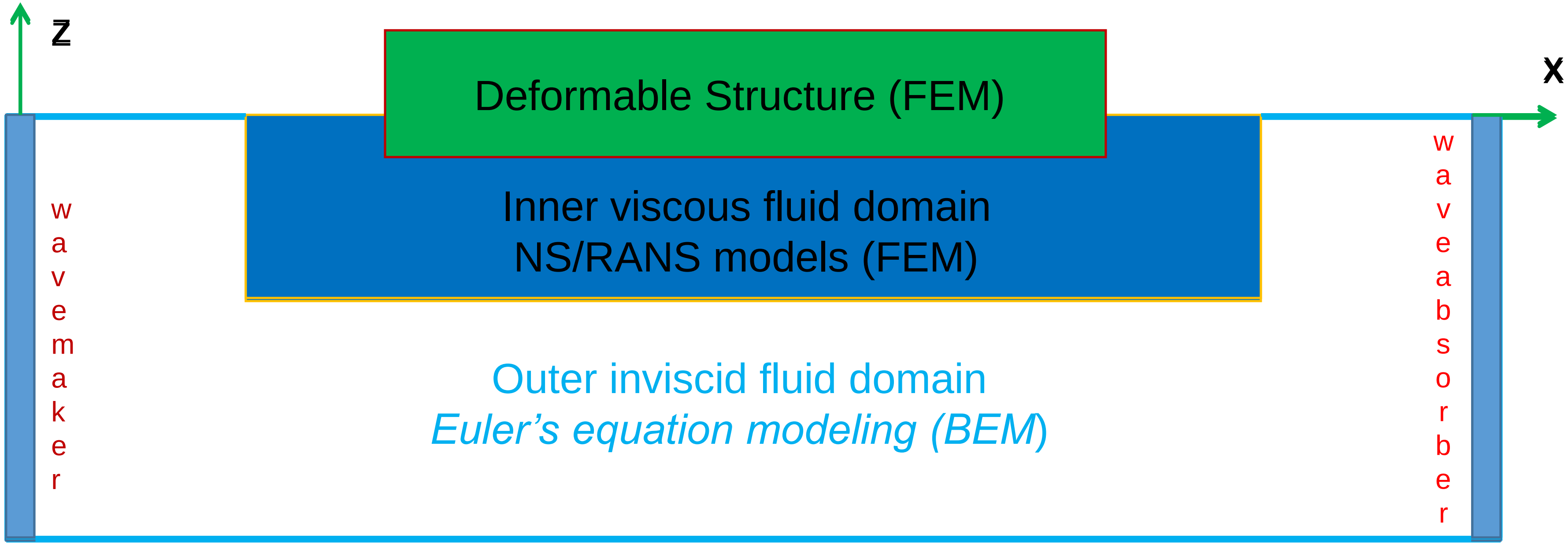
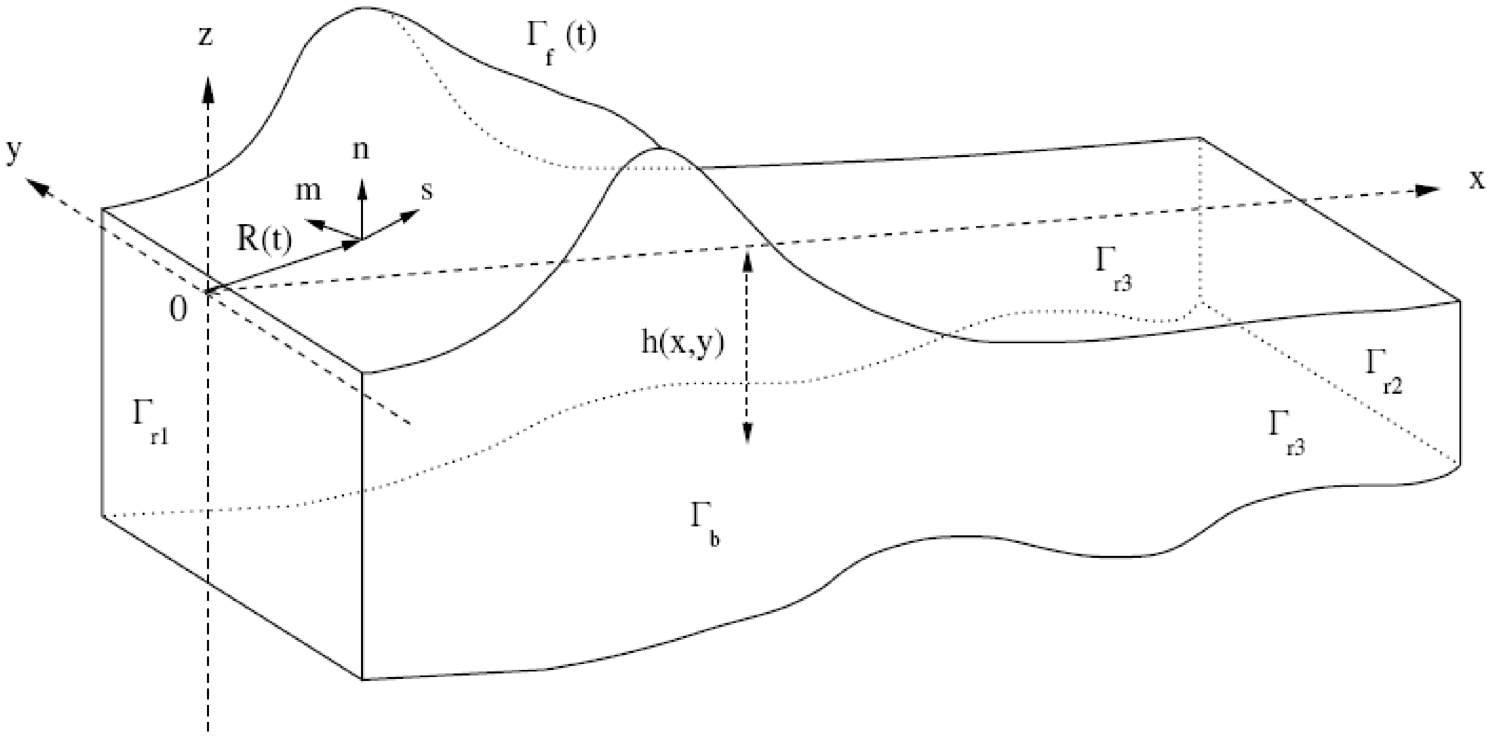


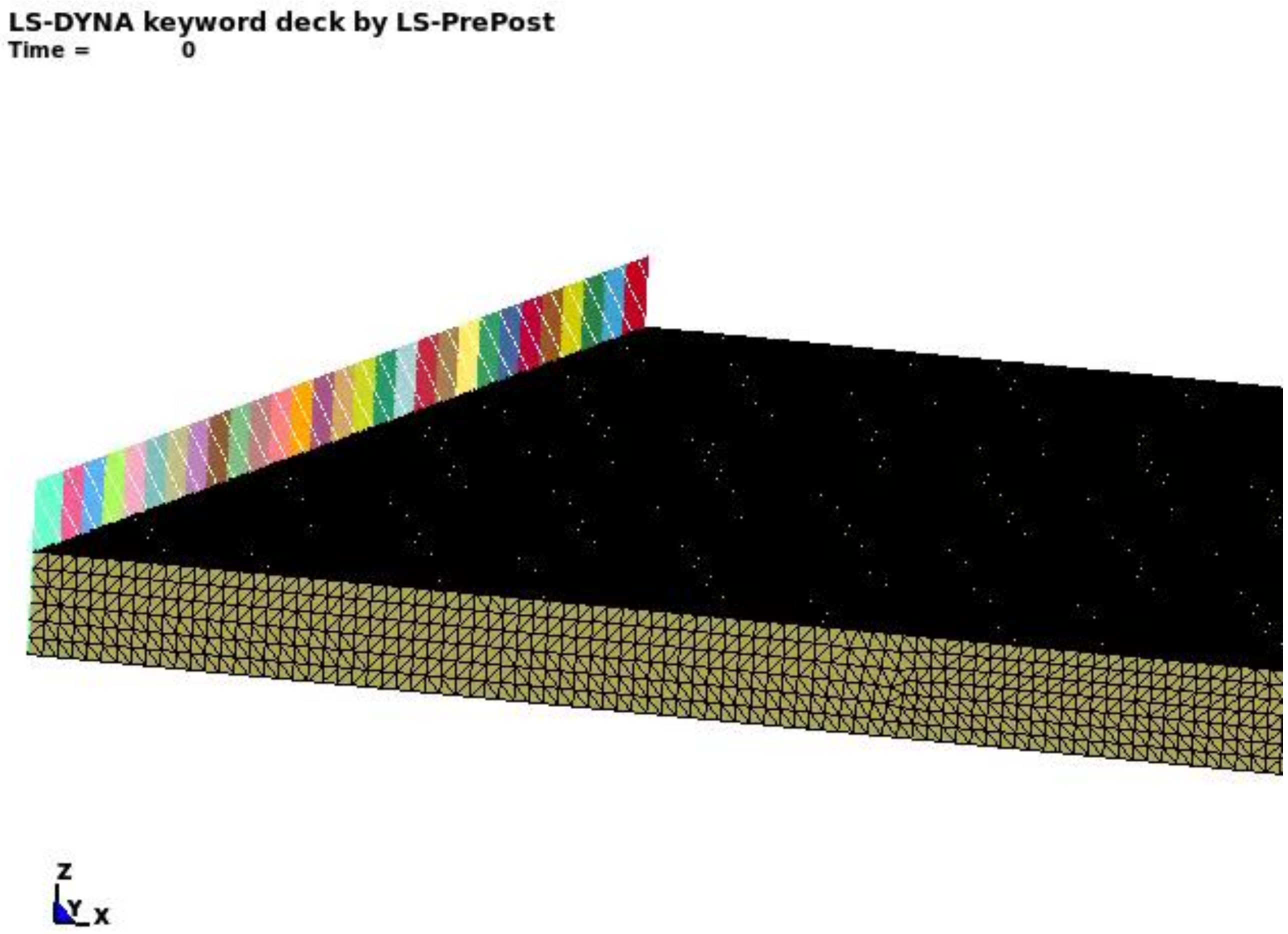
Numerical Wave Basin Models Cont’d

- Fully nonlinear potential flow (FNPF) solver :



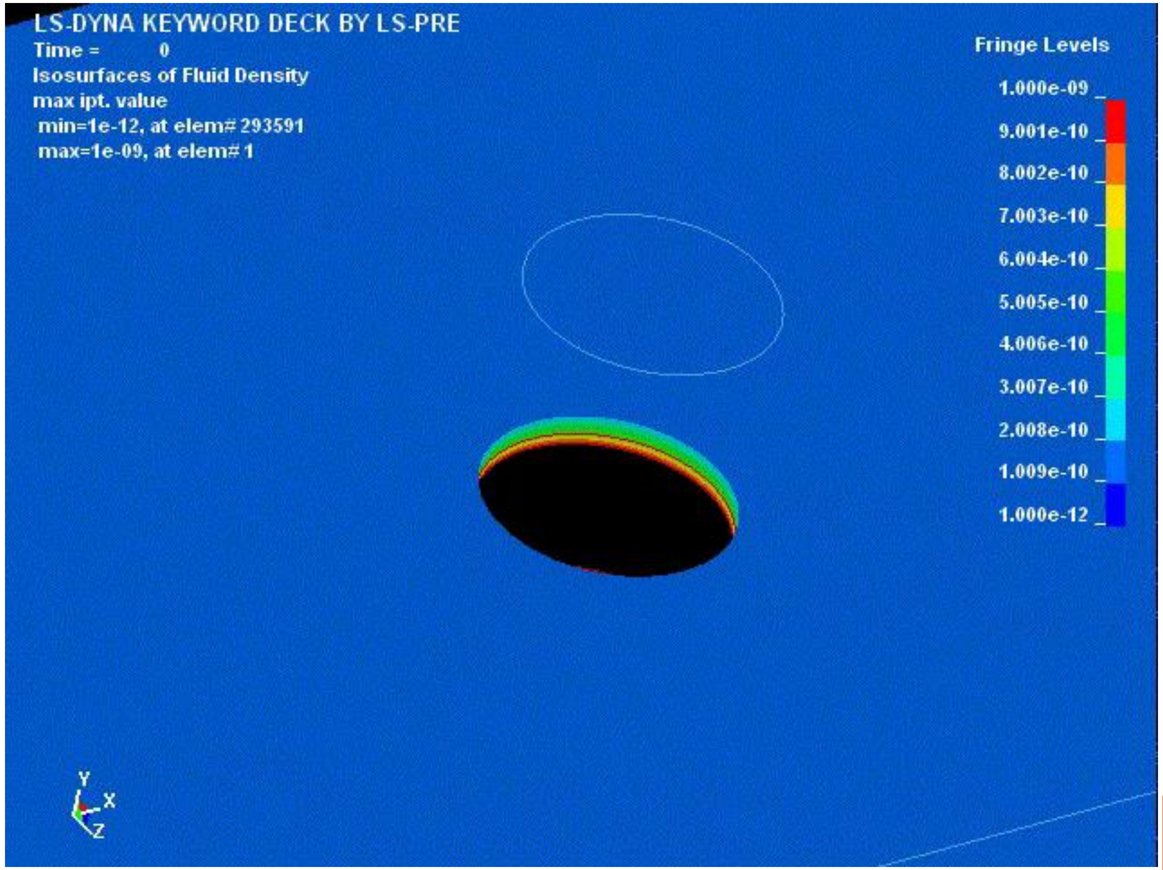
Numerical Wave Basin Models Cont’d

- Incompressible Navier-Stokes solver (LS-DYNA ICFD) Results for TWB modeling (snake wavemaker motion):



Numerical Wave Basin Models Cont'd

Sample model output in compressible solver: Solitary wave forces on cylinder



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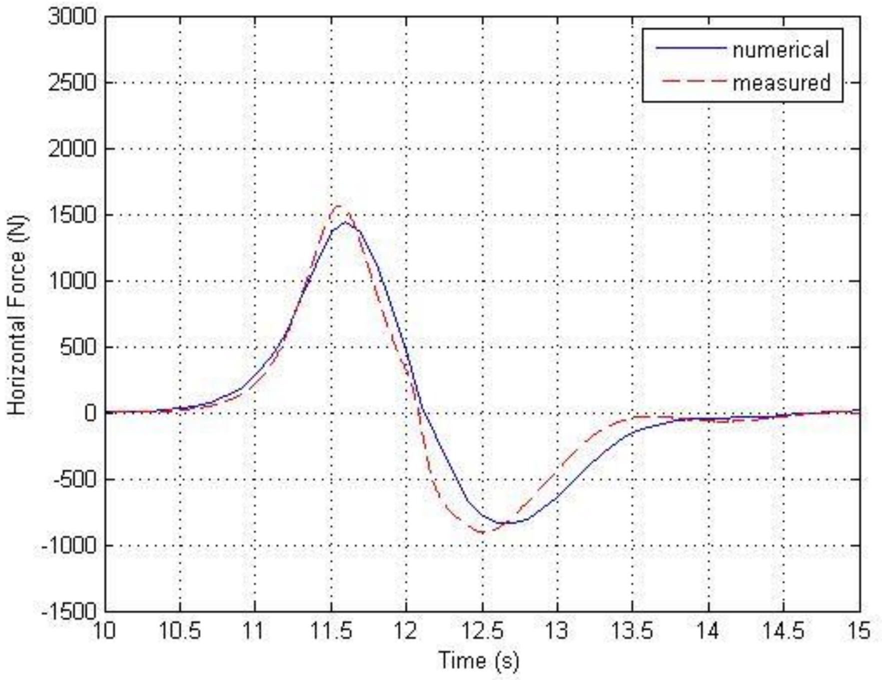
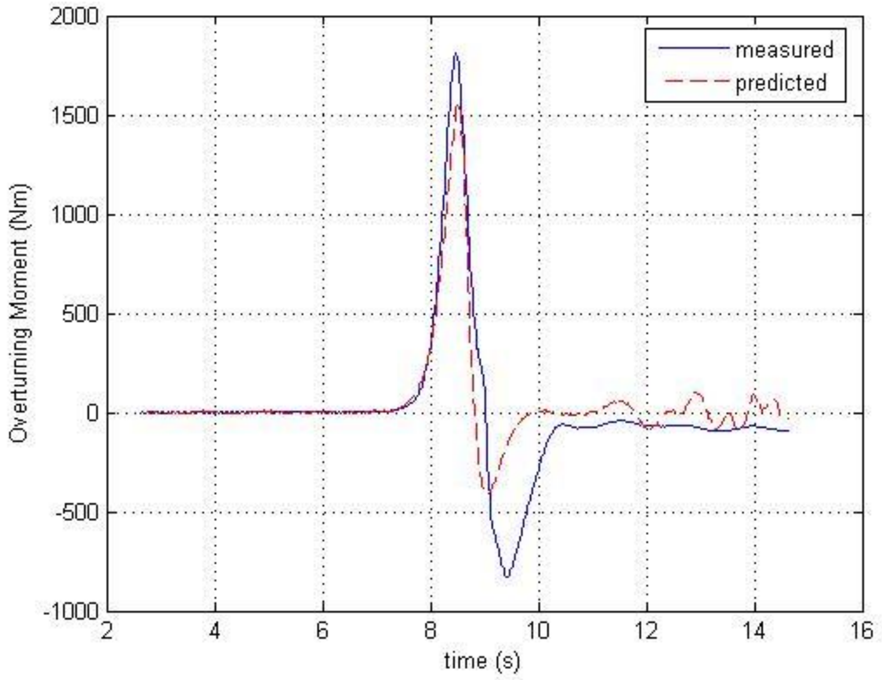


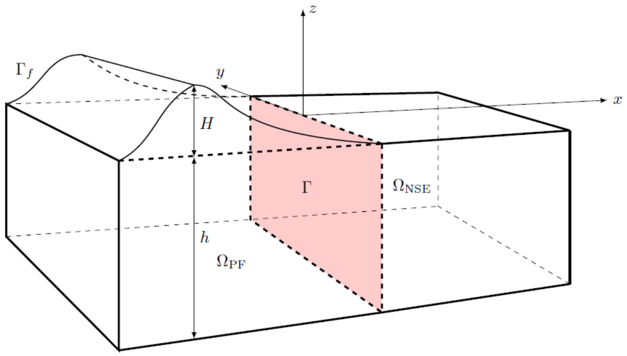
Forces on cylinder, numerical and measurements

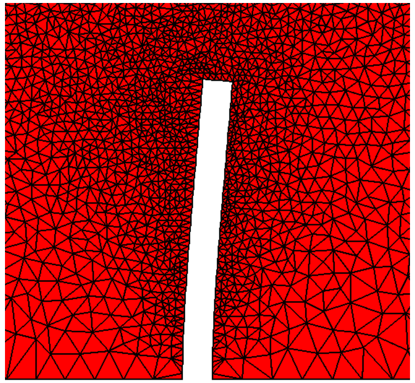


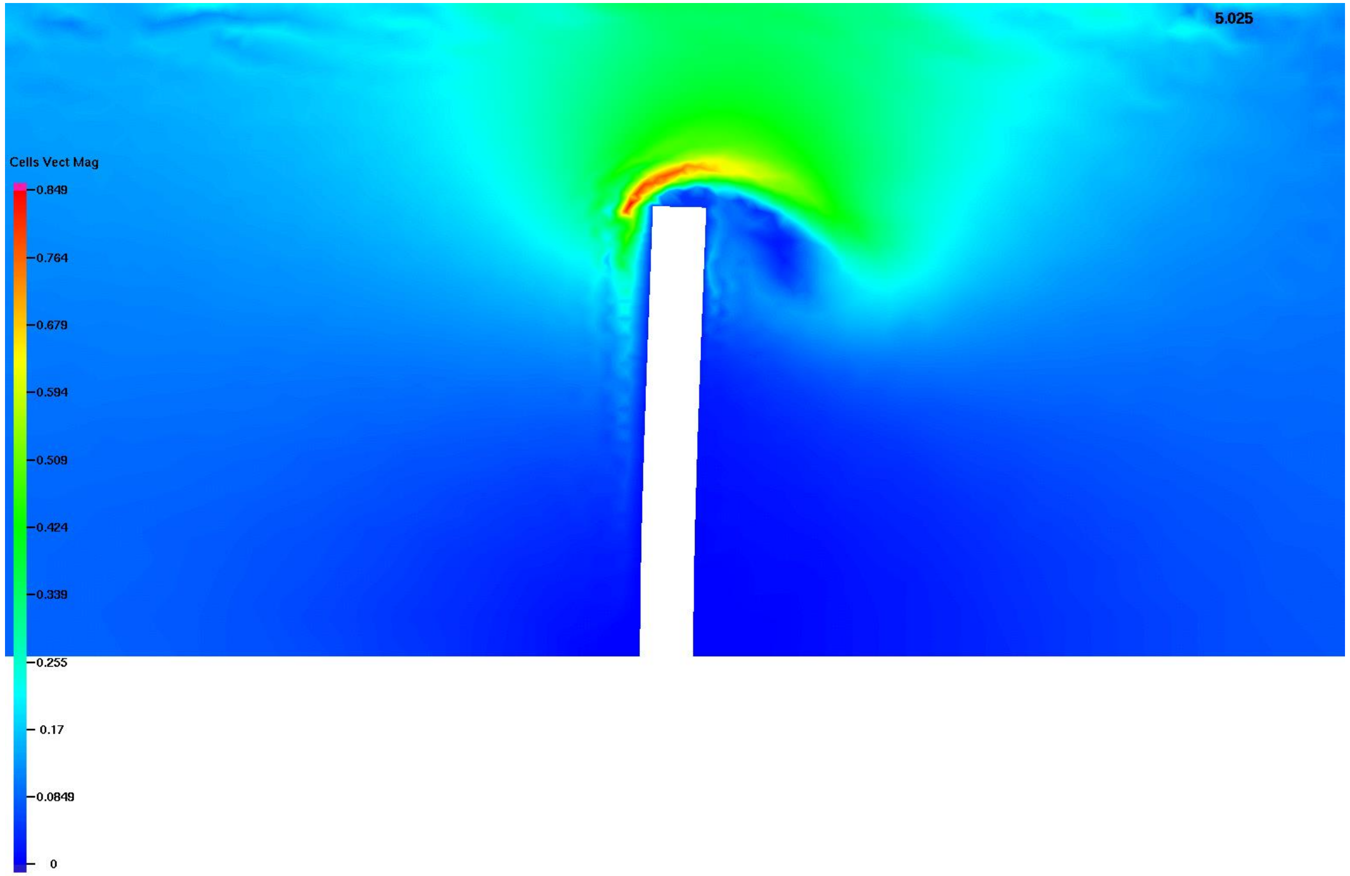
Over turning moment on cylinder, numerical and Morison results

Consistent Virtual and Physical Test Basin Modeling Methodology

- Completed development of coupled fluid-deformable structure interaction (FSI) using consistent finite-element method (FEM) for both fluid and structure
- Identical wavemaker theory for both virtual and physical wave basins







General Mathematical Theory for Nonlinear Wave Basin Wave-field Modeling and Simulation

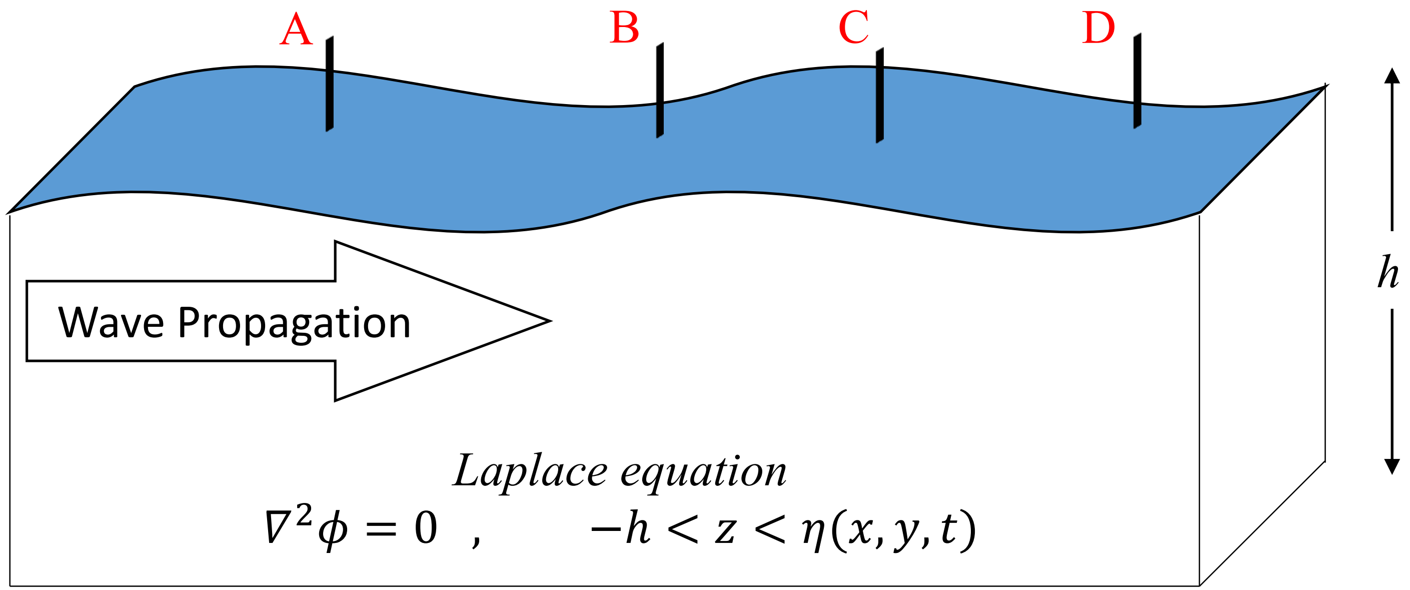
Open Ocean Wave Environment Model

$$\eta_t + \phi_x \eta_x + \phi_y \eta_y = \phi_z \quad \textit{Kinematic free surface BC}$$

$$\phi_t + \frac{1}{2}|\nabla\phi|^2 + g\eta = 0 \quad \textit{Dynamic free surface BC}$$

Lateral BCs one of the following:

- $Infinite - plane$: $|\nabla\phi| \to 0 \, , \eta \to 0$
- Periodic
- Semi-periodic



Lateral BCs one of the following:

- $Infinite - plane$: $|\nabla\phi| \to 0 \, , \eta \to 0$
- Periodic
- Semi-periodic

Bottom BC:

$$w = \frac{\partial\phi}{\partial z} = 0 \quad , \qquad z = -h$$

Multi-Point Evaluation of Competing Wave Theories

Linear wave equation

$$\eta_{tt} - c^2\eta_{xx} = 0$$

KdV equation

$$\eta_t + c_0\eta_x + \alpha\eta\eta_x + \beta\eta_{xxx} = 0$$

Nonlinear Schrödinger equation (NLS)

$$i(\psi_t + C_g\psi_x) + \mu\psi_{xx} + \nu|\psi|^2\psi = 0$$

Modified KdV equation

$$\eta_t + c_0\eta_x + \alpha\eta\eta_x + \beta\eta_{xxx} = \lambda_1\eta_{xxxxx} + \lambda_2\eta\eta_{xxx} + \lambda_3\eta_x\eta_{xx} + \lambda_4\eta^2\eta_x$$

Zakharov equation

$$\frac{i\partial A(\boldsymbol{k},t)}{\partial t} = \iiint_{-\infty}^{+\infty} T(\boldsymbol{k},\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3)\delta(\boldsymbol{k}+\boldsymbol{k}_1-\boldsymbol{k}_2-\boldsymbol{k}_3)\times \exp\{i[\omega(\boldsymbol{k})+\omega(\boldsymbol{k}_1)-\omega(\boldsymbol{k}_2)-\omega(\boldsymbol{k}_3)]t\}\,A^*(\boldsymbol{k}_1)A(\boldsymbol{k}_2)A(\boldsymbol{k}_3)\,d\boldsymbol{k}_1 d\boldsymbol{k}_2 d\boldsymbol{k}_3$$

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Multi-Point Evaluation of Competing Wave Theories

- Nonlinear Fourier Analysis: Given a spatial array of measured time series of a wave field/basin, determine the exact free surface solution (Nonlinear Sturm-Liouville Problem) over certain domain of wave field/basin by the following procedure:

1. Select Nonlinear Wave Theory Equation for the Wave Field Model (e.g. NLS, KdV, Gardner, etc.)
2. Compute nonlinear Eigen-vector basis (Stokes/Cnoidal/Solitons) and wave parameters through appropriate wave theories
3. Decompose measured time series at given Location A via NLFT/IST and compute wave parameters (amplitude and phase of the Eigen-functions)
4. Propagate each Eigen-components in time / space
5. Compute nonlinear local interactions (base vectors are non-orthogonal)
6. Reconstruct time / space series at arbitrary locations by superposition and propagation of nonlinear Eigen wave components and nonlinear interaction terms as function of space x and time t over applicable wave field/basin
7. Exact analytical solution of nonlinear waves over wave field/basin domain at arbitrary selected Location B, C, D, …

Nonlinear Fourier Analysis of Wave Motions

Advantages of NLFA/Inverse Scattering Transform

- Explicit analytical representation for all nonlinear Fourier components including:
  - Sine waves
  - Stokes waves
  - Phase locked Stokes waves known as Breathers/Rogue Waves
  - Solitons/Tsunami/Solitary Waves
  - Vortices
- Means to combine these nonlinear components to obtain the nonlinear solutions to nonlinear wave equations.

Inverse Scattering Analysis of Wave Motions

- Start Nonlinear Fourier Analysis (NLFA) by selecting the Nonlinear Schrodinger Equation for deep water waves (Nonlinear Sturm-Liouville Problem):

$$i(\psi_t + C_g\psi_x) + \mu\psi_{xx} + \nu|\psi|^2\psi = 0$$

- Solve the associated spectral eigenvalue problem:

$$i\psi_{1x} + iu\psi_2 = \lambda\psi_1$$
$$-i\psi_{2x} + iu^*\psi_1 = \lambda\psi_2$$

where $\lambda_k, k = 1,2,\dots,2N$ are complex constants and the basis eigenvectors are permanent wave forms with nonlinear coherent structure: Stokes, Cnoidal, solitons, etc.

- Compute (specify) the system parameters and the amplitude and phase of components of the base vectors for a given measured time series (time series simulation)
- Compute (specify) local wave-wave interaction matrix ("B matrix") of wave components and reconstruct the exact solution of free surface (time series simulation):

$$\eta = \eta_{superposition\ of\ nonlinear\ wave\ modes} + \eta_{interaction}$$

Nonlinear Fourier Analysis of Wave Motions

Examples of exact solutions of NLS and their corresponding maximum amplitude ratios:

$$u(x,t) = A\left[\frac{\cos\left[\sqrt{2}Ax\right]\operatorname{sech}[2A^2t] + i\sqrt{2}\,\tanh[2A^2t]}{\sqrt{2} - \cos\left[\sqrt{2}Ax\right]\operatorname{sech}[2A^2t]}\right]e^{2iA^2t} \qquad \frac{u_{\max}}{A} = 2\frac{|\lambda_I|}{A} + 1 \cong 2.414$$

$$u(x,t) = A\left[1 + \frac{2\left(\cos[4\sqrt{2}A^2t] + i\sqrt{2}\sin[4\sqrt{2}A^2t]\right)}{\cos[4\sqrt{2}A^2t] + \sqrt{2}\cosh[2Ax]}\right]e^{2iA^2t}$$

Breathers - “blows up” once in a while. Stays near 1 at other times

$$\frac{u_{\max}}{A} = 2\frac{|\lambda_I|}{A} + 1 = 2\sqrt{2} + 1 \cong 3.828$$

$$u(x,t) = A\left[1 - \frac{4(1+4iAt)}{1 + 16A^4t^2 + 4A^2x^2}\right]e^{2iA^2t} \qquad \frac{u_{\max}}{A} = 2\frac{|\lambda_I|}{A} + 1 = 3$$

Rogue Wave - “blows up” only once near x=0. Lower amplitude oscillatory motions for large x and/or t.

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Professor Chopra's Influence on Research

Most Important Research Skills Gained from Working with Professor Chopra:

- Advanced background in mechanics, structures and mathematics
- A keen sense of identifying important fundamental problems that may appear simple but in fact are very complex and rich in mechanics
- Maturity in conducting research and analyzing engineering problems
- Insightful and detailed technical writing

- Thank you Professor Chopra for your guidance and patience over all those years
- Best wishes for a happy retirement / next phase of teaching and research