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# Some topics on wave interaction with coastal structures: experiment and numerical modeling

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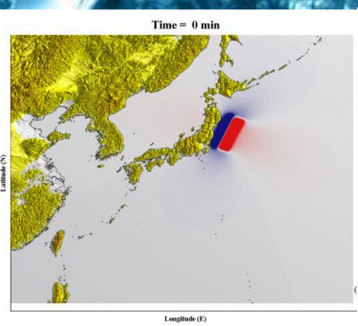


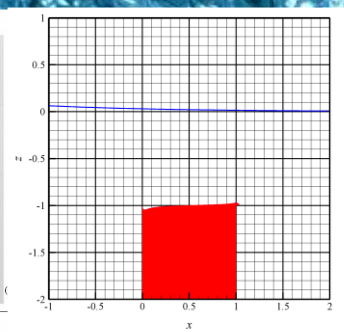

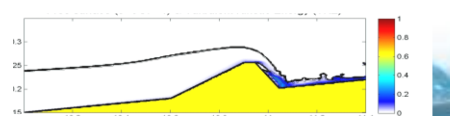

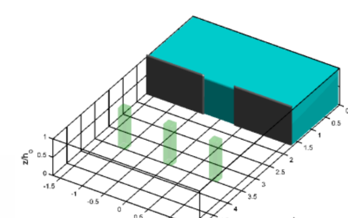

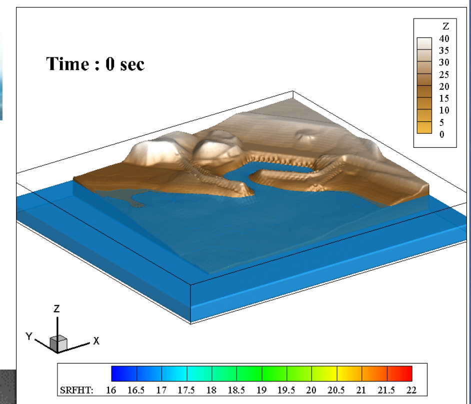


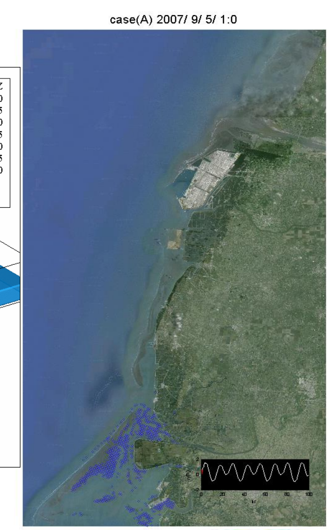


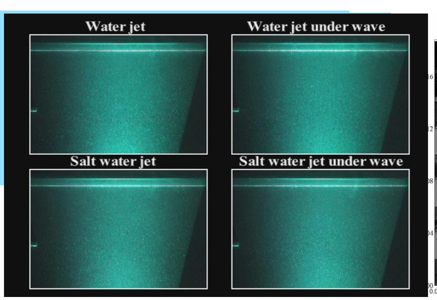


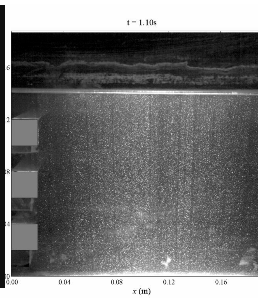

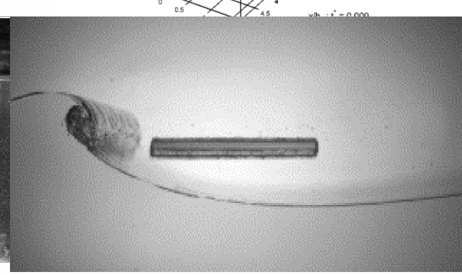

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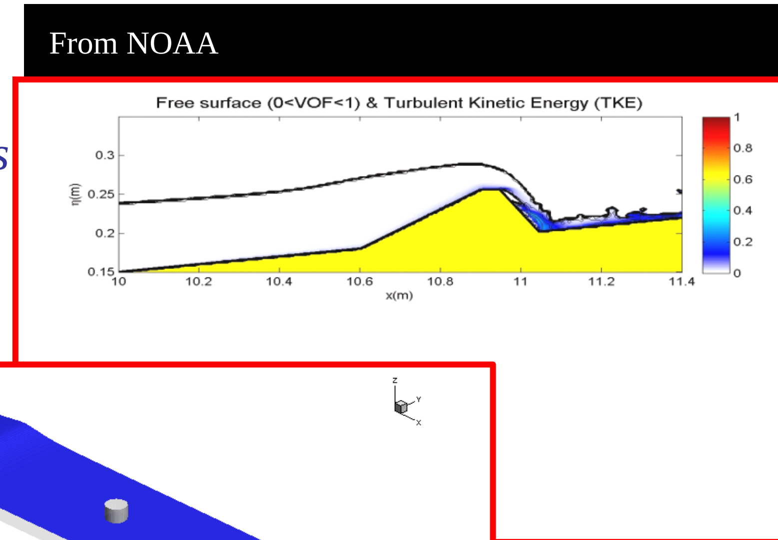
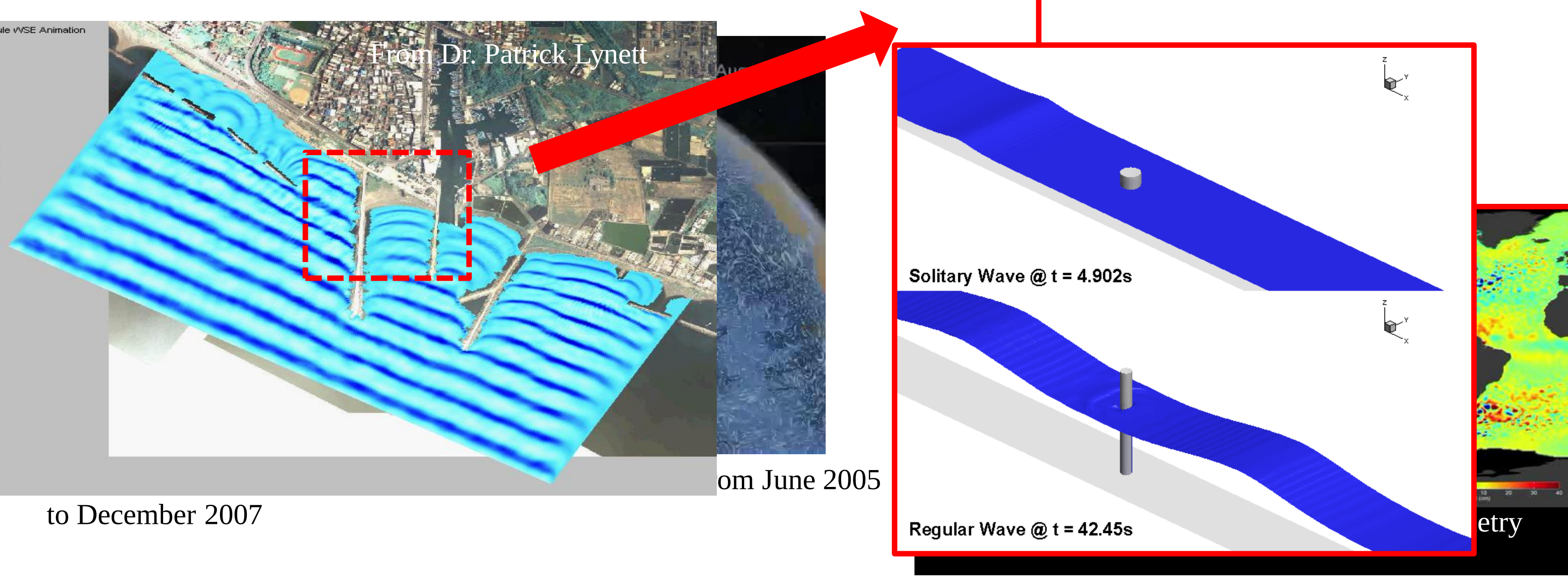
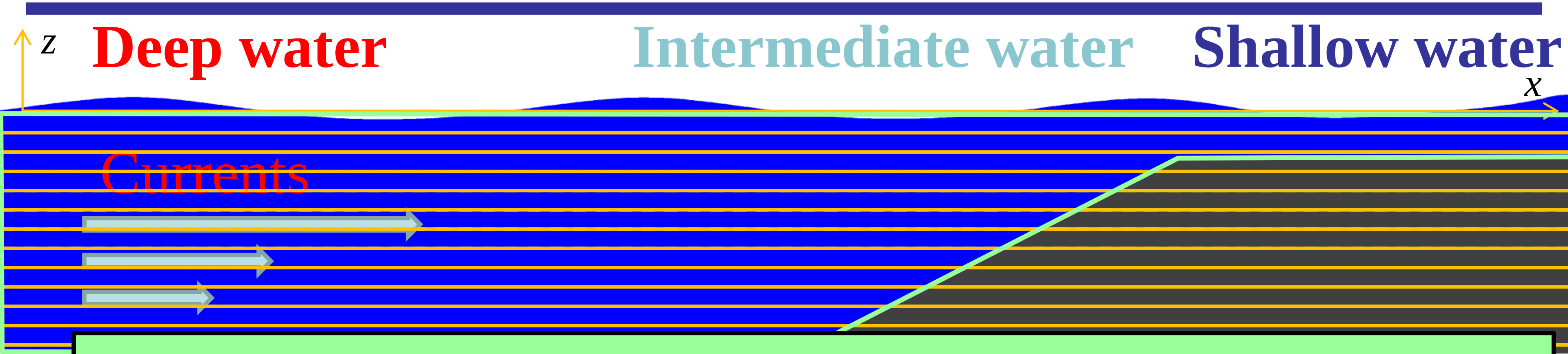
# Outline

- ***Water Wave & Current Models***
- ***Wave Dynamics Laboratory***
- ***Wave Interaction With Coastal Structures: Experiment and Numerical Modeling***
  - ✓ *Background on Tsunami Hazards*
  - ✓ *Numerical Modeling on Tsunami-like Long Waves*
- ***Conclusion and Ongoing Works***



# *Water Wave & Current Models*




- ✓ Large scale
- ✓ Limitation of water depth and nonlinearity

- ✓ Shallow water equation
- ✓ Boussinesq equation
- ✓ Mild-Slope equation

- ✓ MOST, COMCOT
- ✓ CULWAVE, FUNWAVE
- ✓ REF/DIF

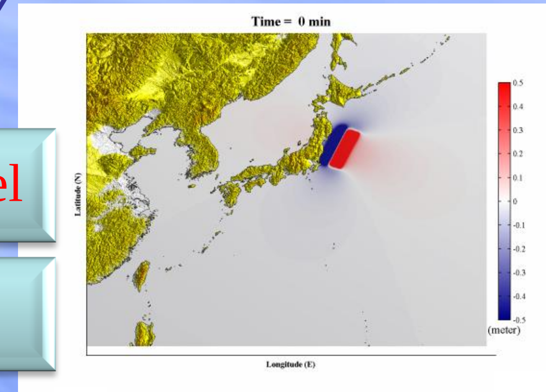
**Potential flow theory**

- ✓ all types of waves
- ✓ efficiently simulating waves
- ✓ cannot solve turbulent flow wave, wave propagation with rotation, and energy dissipation

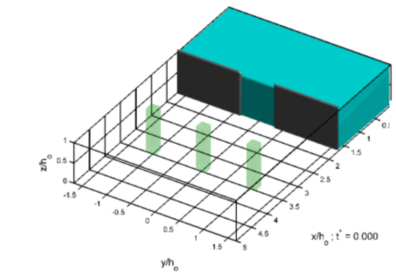
**Depth-averaged models**

# *Wave Dynamics Laboratory*

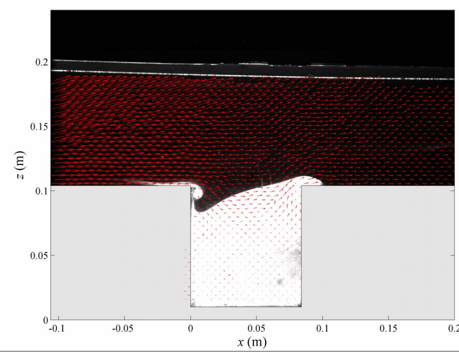
**Numerical Modeling (Large-scale)**
- Nonlinear Shallow Water Model
- Boussinesq Model




\+ → Coupling Model



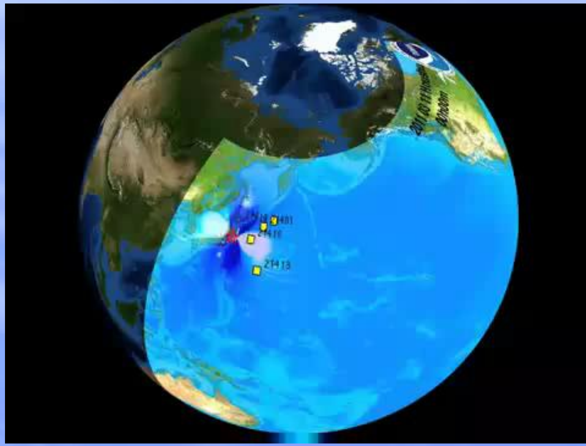

**Numerical Modeling (Small-scale)**
- Meshless Potential Flow Model
- 2D RANS Model
- 3D Model ( LES Model & FLOW-3D)




**Physical Experiment**
- Non-Intrusive Measurement (ex: Particle Image Velocimetry & Laser-Induced Fluorescence)
- Intrusive Measurement (ex: wave gauge & pressure transducer)

Numerical Modeling (Large-scale)

- Nonlinear Shallow Water Model
- Boussinesq Model



## ➢ Coastal hazard prevention and mitigation:

✓ **Tsunami** **( generation, propagation, amd inundation)**

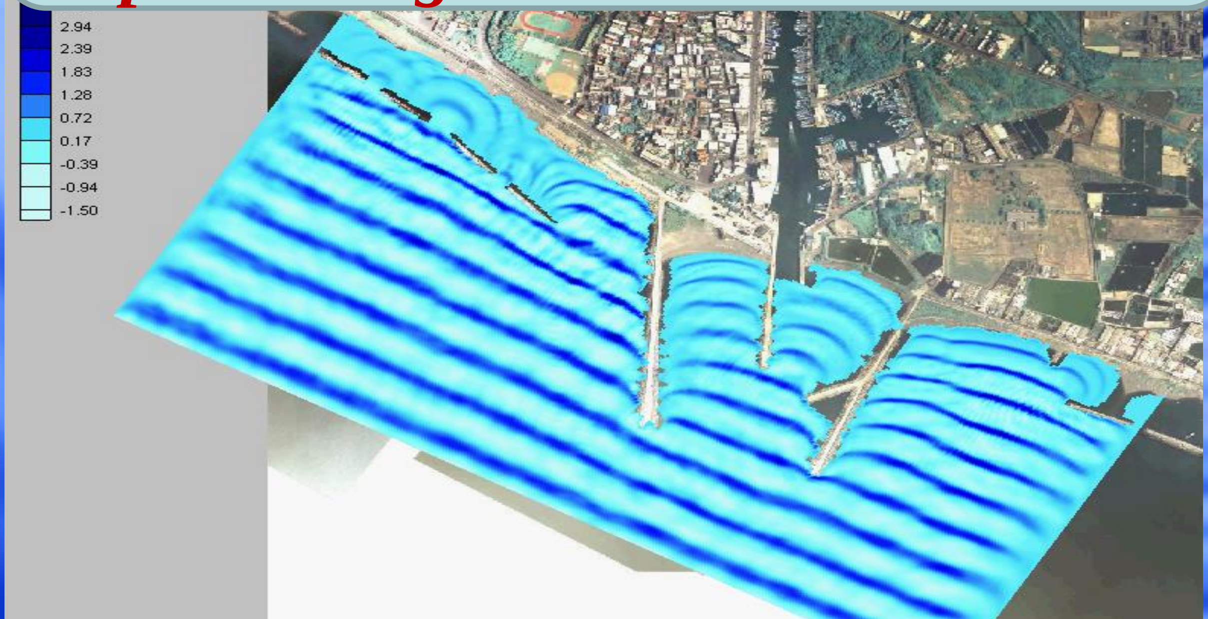
✓ **Wave field in large scale** **(wave reflection, diffraction, and refraction, etc.)**

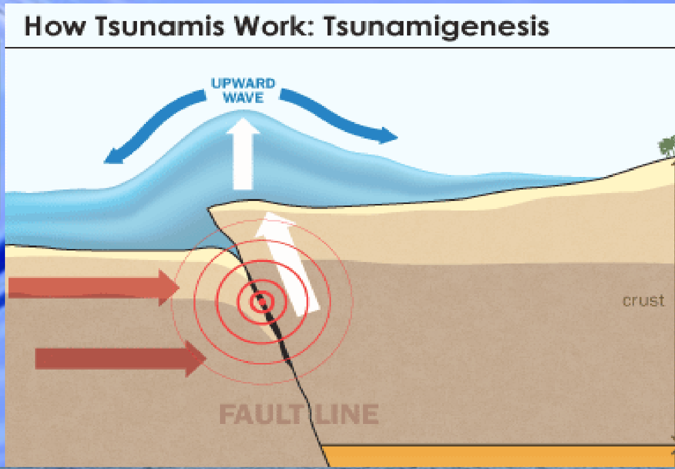
Modeling requirement:

✓ Large computational domain

✓ High efficiency

***Depth-averaged Model***




Numerical Modeling (small-scale)

- Meshless Potential Flow Model
- 2D RANS Model
- 3D Model ( LES Model & FLOW-3D)

➢ **Fluid-structure interaction problems:**

✓ **Stationary structures**

✓ **Porous structures**

✓ **Muti-phase**

Modeling requirement:

✓ Detailed flow field and pressure distribute

✓ Fully nonlinear and fully dispersive

***Depth-resolving Model***



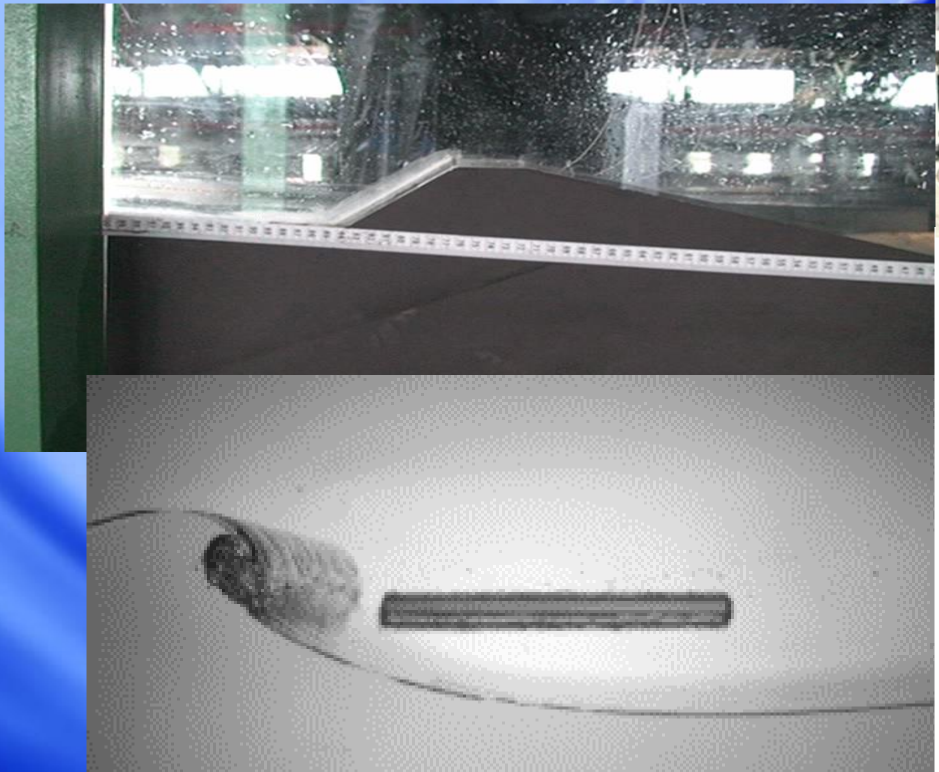


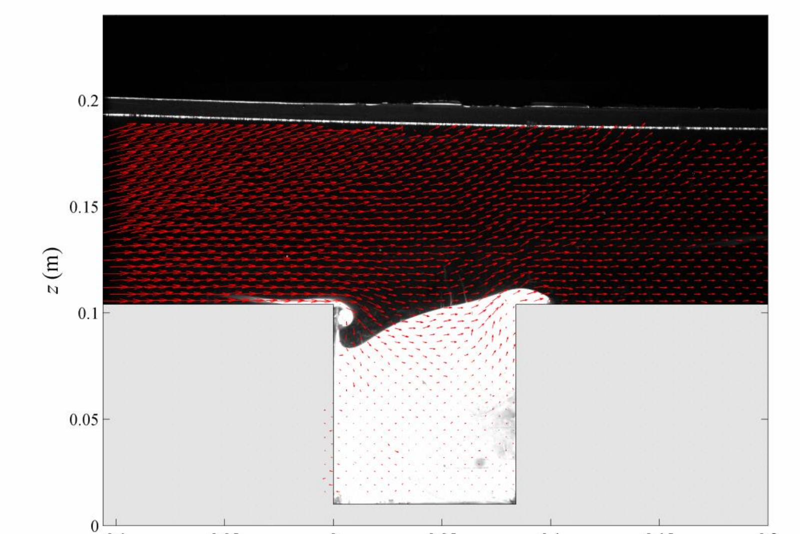


Physical Experiment

- Non-Intrusive Measurement (ex: Particle Image Velocimetry & Laser-Induced Fluorescence)
- Intrusive Measurement (ex: wave gauge & pressure transducer)

- **Free surface measurement**
- **Flow field measurement**
- **Fluid transport capture**
- **Pressure measurement**





# *Solitary Wave Interaction With Coastal Structures: Experiment And Numerical Modeling*

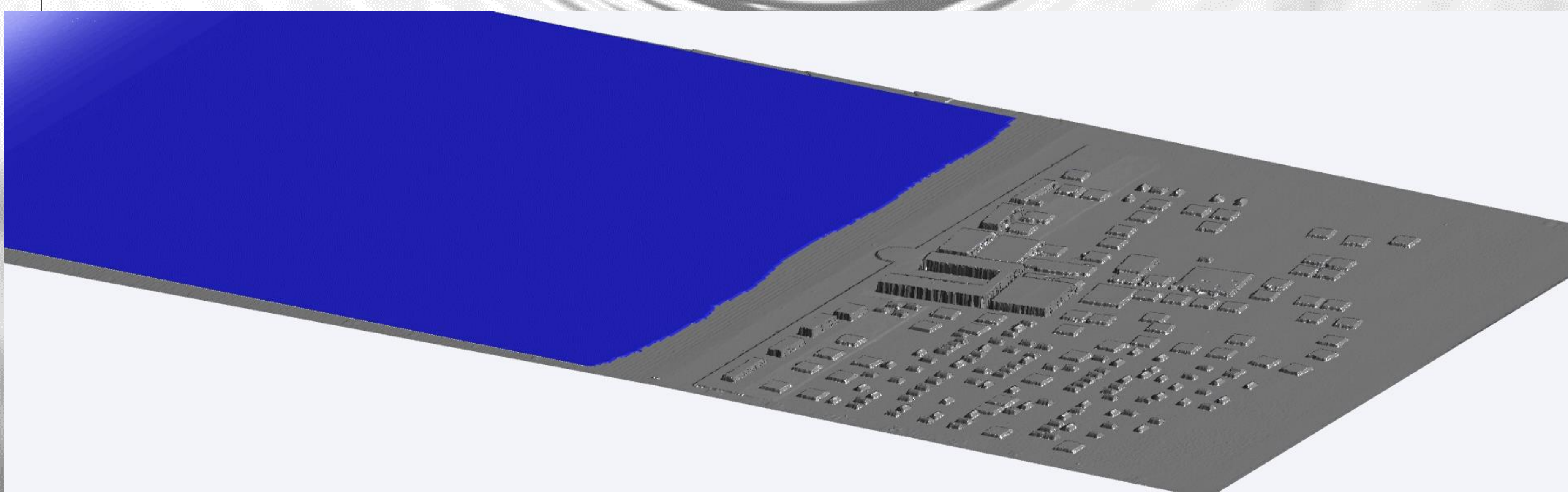
- *Background  on Tsunami  Hazards*
- *Numerical Modeling on Tsunami-like long waves*

✓ *Large-scale tsunami experiments-*

*On the evolution and run-up of breaking solitary waves on a mild sloping beach*

✓ *Small-scale tsunami experiments—*

*Solitary wave interaction with a submerged vertical barrier*



# *Background on Tsunami Hazards*

- Tsunami calamity has a evident relevance to the shoreline movement on the nearshore beach (run-up & run-down).
- Understanding a detailed evolution course and shoreline properties of tsunami-like waves are essential and urgent even for the East-Asia countries.

Significant impact by tsunami waves accompanied run-up & run-down (Sri-Lanka; Science paper, 2005)


Tsunami-induced underlying bore propagation along the Iwaki River (Yatsumori, Japan 1983)

**Inundation Evidence**

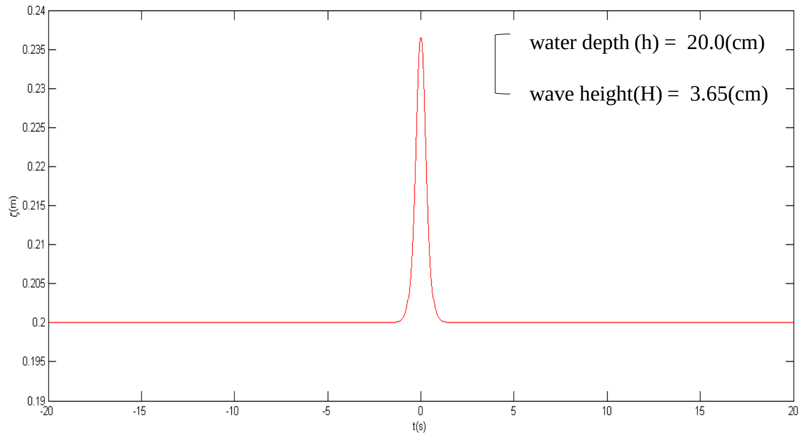
**# Photos by Prof. Philip Liu and Prof. Lynett (2005, Science paper)**

# ***Background on Tsunami Hazards***

➢ ***The solitary wave of Boussinesq (1872)***

$$\eta = \mathrm{Hsech}^2 \sqrt{\frac{3H}{4h^3}}(x - ct)$$

$$c = \sqrt{g(H+h)}$$




✓ A tsunami may be generated by a seaquake , landslide , volcanic eruption , or similar phenomena causing a large displacement of water.

✓ Traditionally, solitary waves are often utilized to investigate the characteristic of tsunami behaviors because of their hydrodynamic similarities.

# *On the Evolution and Run-up of Breaking Solitary Waves on a Mild Sloping Beach*

- *Large-scale tsunami experiments*
- *Numerical modeling on tsunami-like long waves*

  *- Boussinesq Model*
- *Model Validation*
- *Numerical experiments*

# *Large-scale Tsunami Experiments*

- Laboratory animation of tsunami wave propagation (THL)


- Tainan Hydraulic Laboratory (THL)
- ✓ Equipped with an unique supertank (300m×5m×5.2m) which is capable of simulating the tsunami-like solitary wave propagation with long distance and deep water condition.

**#Totally 54 trials were carried out in this study**

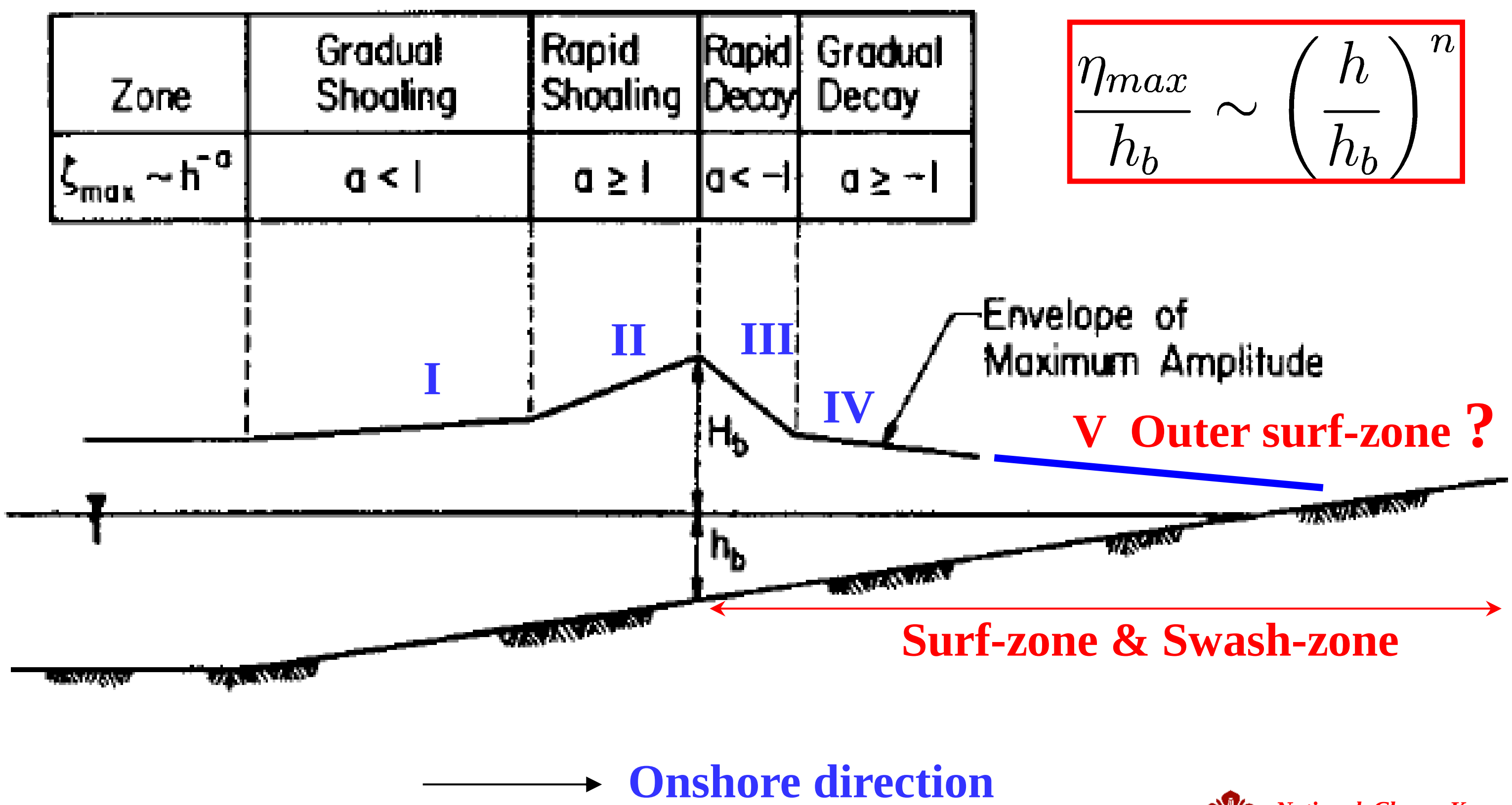
$$\epsilon = H_\circ / h_\circ = 0.011 \sim 0.338 \qquad h_\circ = 1.2m, 2.2m, 2.9m$$

# *Large-scale Tsunami Experiments*

- Synolakis & Skjelbreia (1993) -

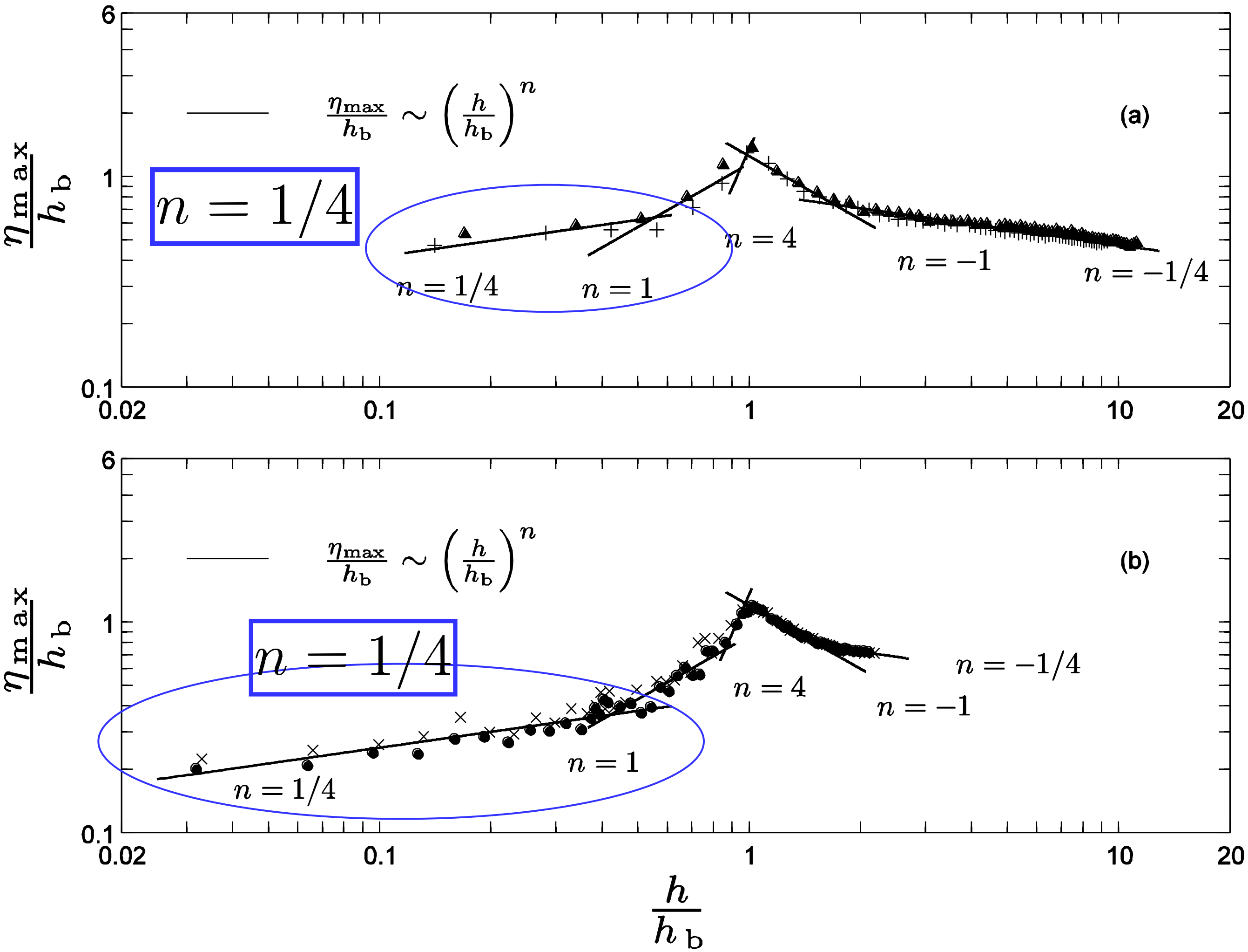
Amplitude evolution of a breaking solitary wave on a plane slope

$$\frac{\eta_{max}}{h_b} \sim \left(\frac{h}{h_b}\right)^n$$



# *Large-scale Tsunami Experiments*

- Amplitude evolution




$\epsilon = 0.041(\blacktriangle)$

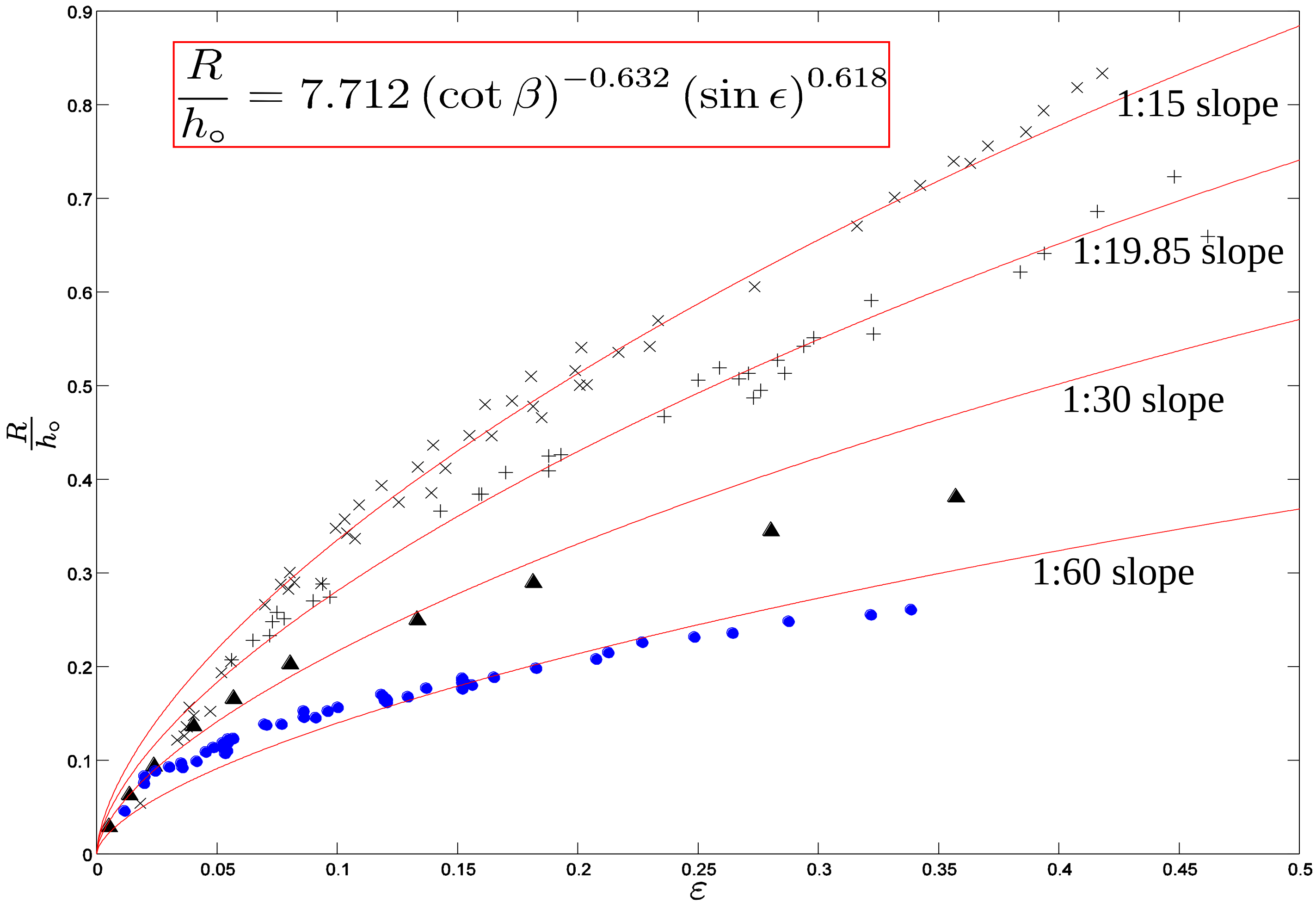
$\epsilon = 0.052(+)$

$\epsilon = 0.322(\times)$

$\epsilon = 0.338(\bullet)$

# *Large-scale Tsunami Experiments*

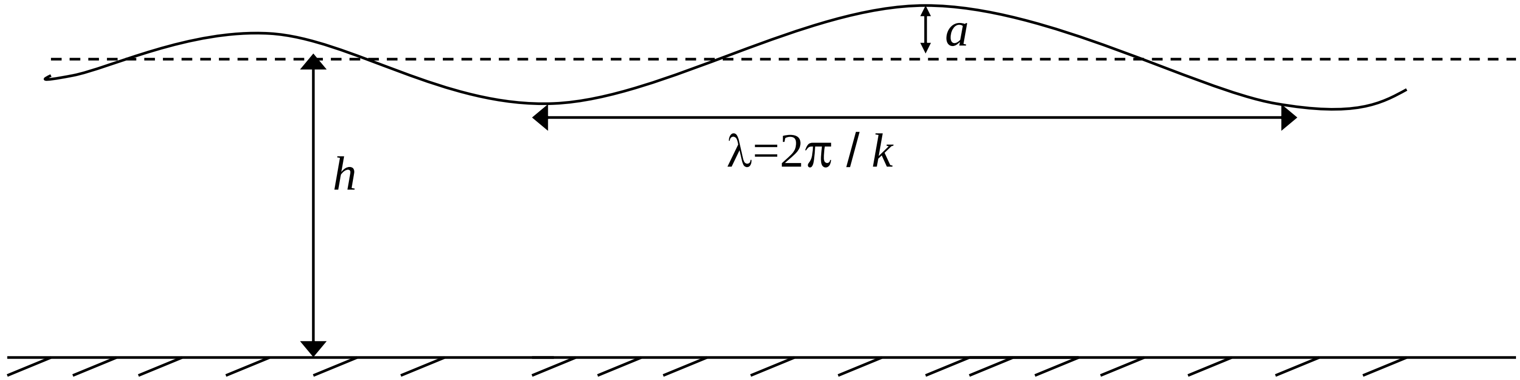
- Maximum Run-up



# *On the Evolution and Run-up of Breaking Solitary Waves on a Mild Sloping Beach*

- *Large-scale tsunami experiments*
- *Numerical modeling on tsunami-like long waves*
  - *Boussinesq Model*
- *Model Validation*
- *Numerical experiments*

# *Boussinesq Model -*
# *Water Wave Modeling Efficiency*

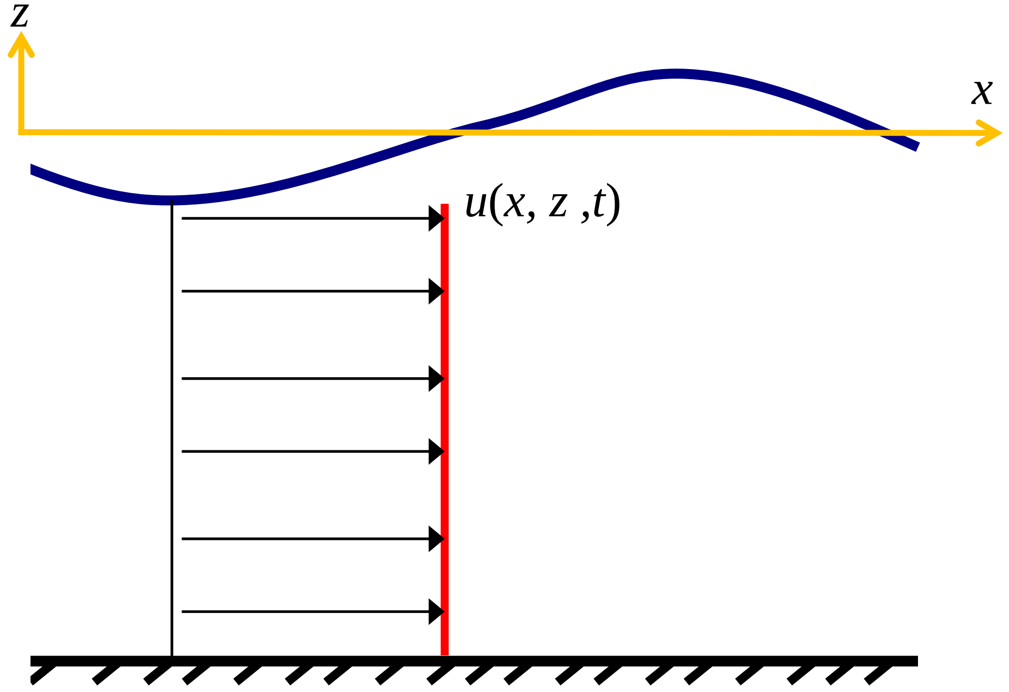



Increasing
Computational
Time

| **Solving Approach** | **Nonlinearity restriction** | **Frequency dispersion restriction** |
|---|---|---|
| Linear / Analytic | $a/h \sim 0$ | $kh$ unbounded – fully dispersive, in the linear sense |
| Depth-Integrated / Numerical | $a/h \sim O(1)$ – highly nonlinear | $kh \sim 0$ NLSW<br>$kh < \pi$ Boussinesq |
| Potential Flow & Navier Stokes / Numerical | Fully nonlinear | Fully dispersive |

# *Boussinesq Model-*
# *History of Depth-Averaged Approach*

- What is a "depth-averaged" equation?
  - ✓ A quick derivation:
  - ✓ Shallow water wave equations: $u(x, z, t) = A\,(x, t)$

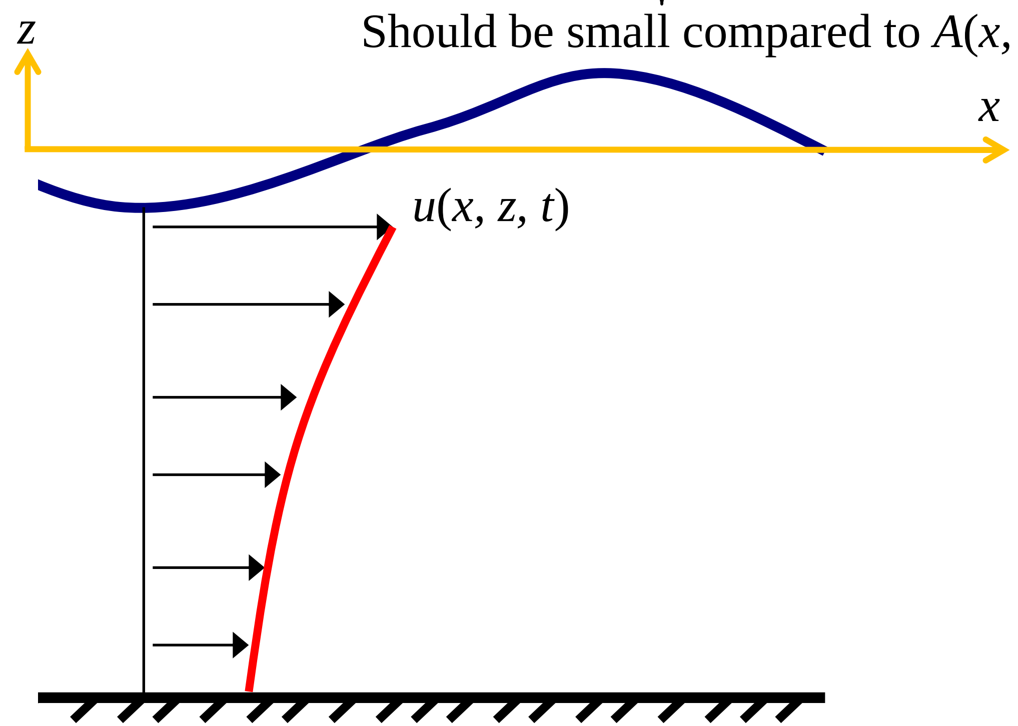



  - ✓ Accurate only for very long waves, kh<~0.25 (wavelength > ~ 25 water depths)

# Boussinesq Model-
# History of Depth-Averaged Approach

- ✓ Boussinesq Equations (Peregrine, 1967; Ngowu, 1993):

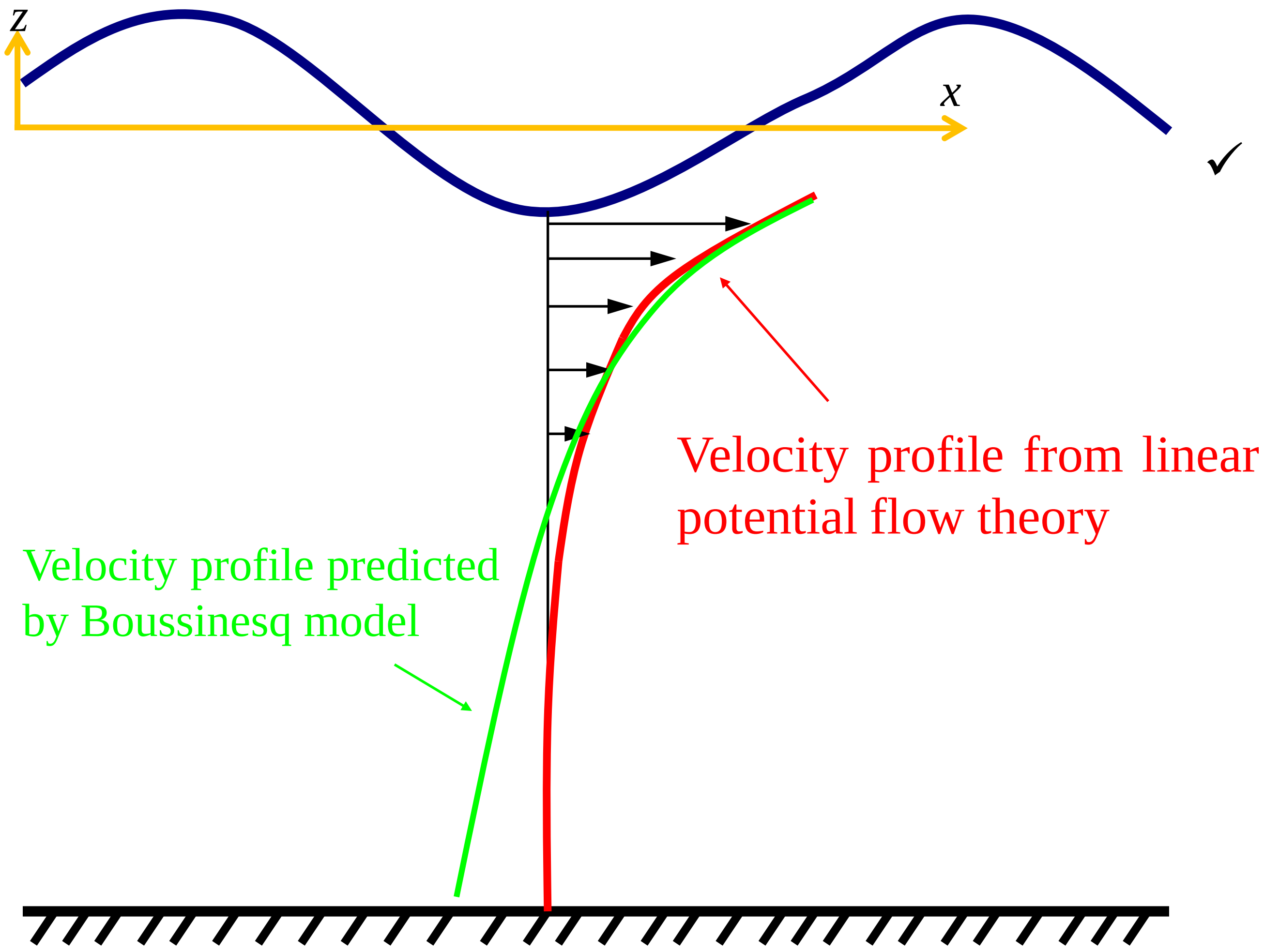
$$u(x,z,t) = A(x,t) + \underbrace{\left[ z * B(x,t) + z^2 * C(x,t) \right]}_{\text{Should be small compared to } A(x,t)}$$




- ✓ Functions *B*, *C* lead to 3rd order spatial derivatives in model (eqns)
- ✓ Accurate for long and intermediate depth waves, kh<~3 (wavelength > ~ 2 water depths)

# *Boussinesq Model-*
# *Limitations of Boussinesq Models*

- ✓ Velocity profile of deep water waves looks like an exponential ($e^{-kz}$) in the vertical
- ✓ Boussinesq models yield a very poor approximation of this shape




- ✓ Approaches employed to overcome this problem include the High-Order velocity profile ……

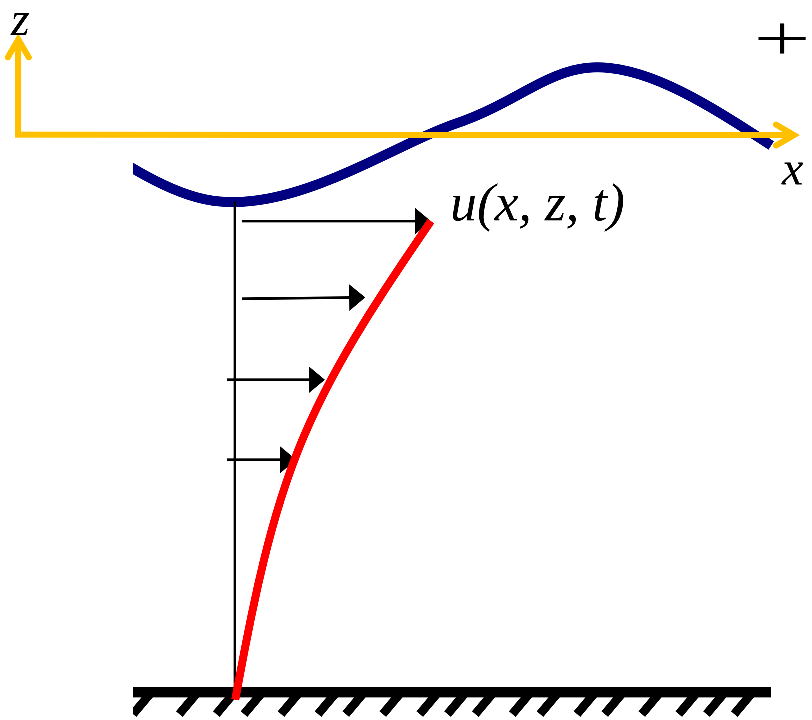
# *Boussinesq Model - History of Depth-Averaged Approach*

✓ High-Order Boussinesq Equations (Gobbi *et al*., 2000):

$$u(x,z,t) = A(x,t) + \left[ z * B(x,t) + z^2 * C(x,t) \right]$$

$$+ \underbrace{\left[ z^3 * D(x,t) + z^4 * E(x,t) \right]}$$

Should be small compared to B,C group




✓ Accurate for long, intermediate, and moderately deep waves, kh<~6 (wavelength > ~ 1 water depth)

✓ Functions *D*, *E* lead to 5th order spatial derivatives in model

# Boussinesq Model - History of Depth-Averaged Approach

- Difficult to solve the high-order model
- ✓ Momentum equation:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+....+C_1\frac{\partial^5 u}{\partial x^5}=0$$

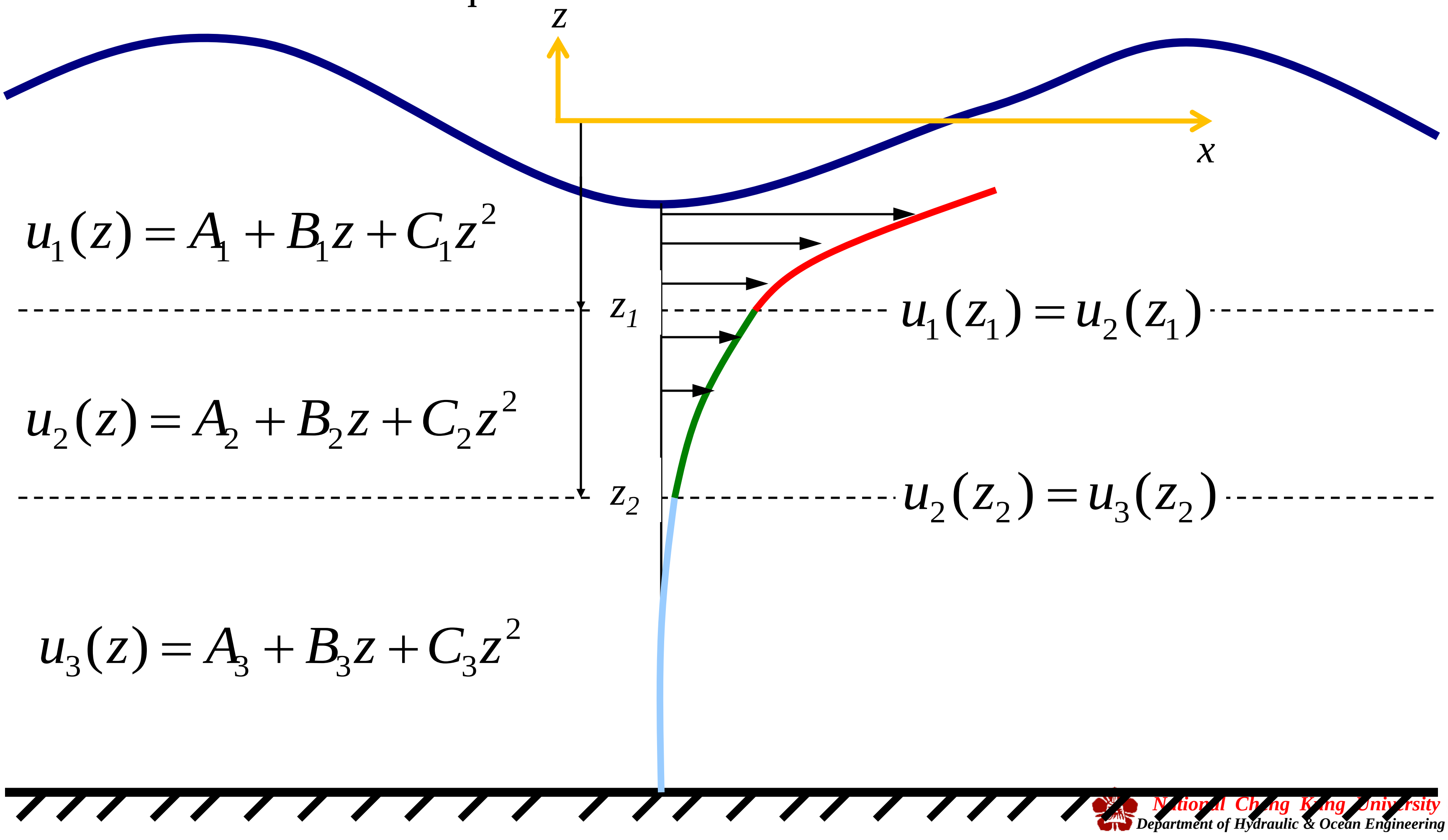
- ✓ To solve consistently, numerical truncation error (Taylor series error) for leading term must be less important than included terms.
- ✓ For example: 2nd order in space finite difference:

$$\frac{\partial u(x_o,t)}{\partial x}=\frac{u(x_o+\Delta x,t)-u(x_o-\Delta x,t)}{2\Delta x}-\frac{\Delta x^2}{6}\frac{\partial^3 u(x_o,t)}{\partial x^3}$$

- ✓ High-order model requires use of 6-point difference formulas ($Dx^6$ accuracy)
- ✓ Additionally, time integration would require a $Dt^6$ accurate scheme

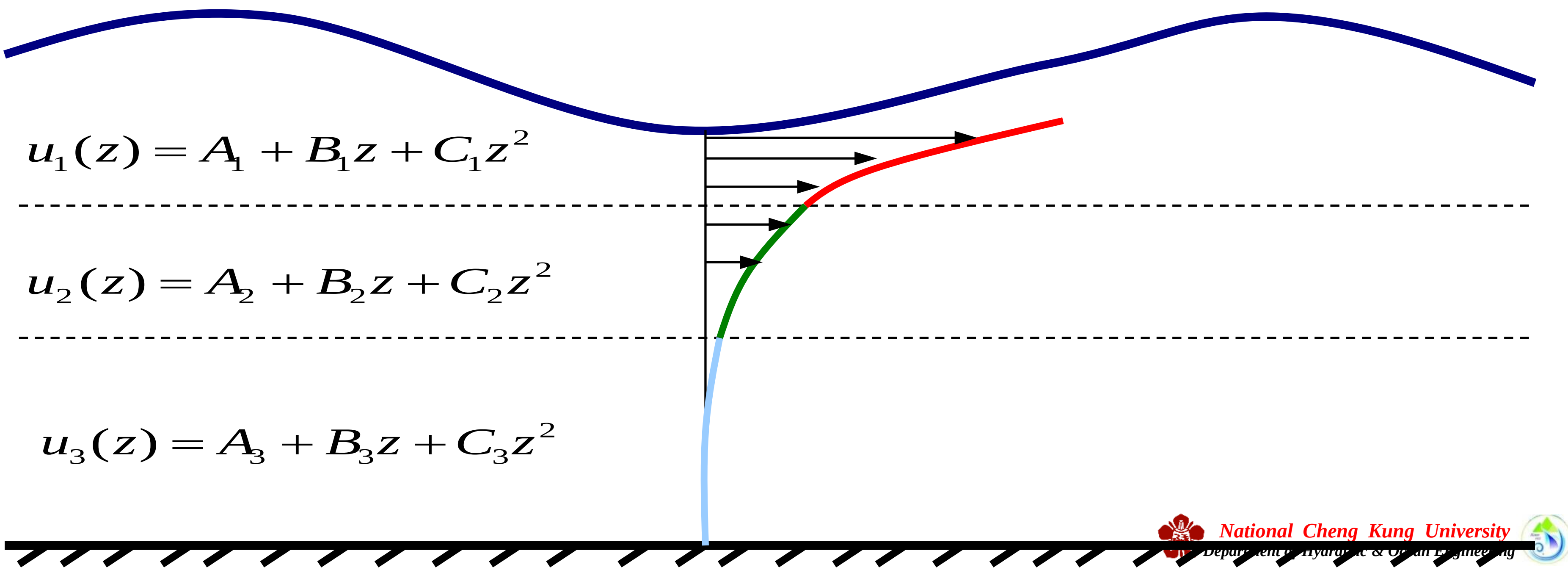
# *Boussinesq Model - Employing Multiple Layers (Lynett & Liu, 2002)*

- ➢ Divide water column into arbitrary layers
- ✓ Each layer governed by an independent velocity profile, each in the same form as traditional Boussinesq models:



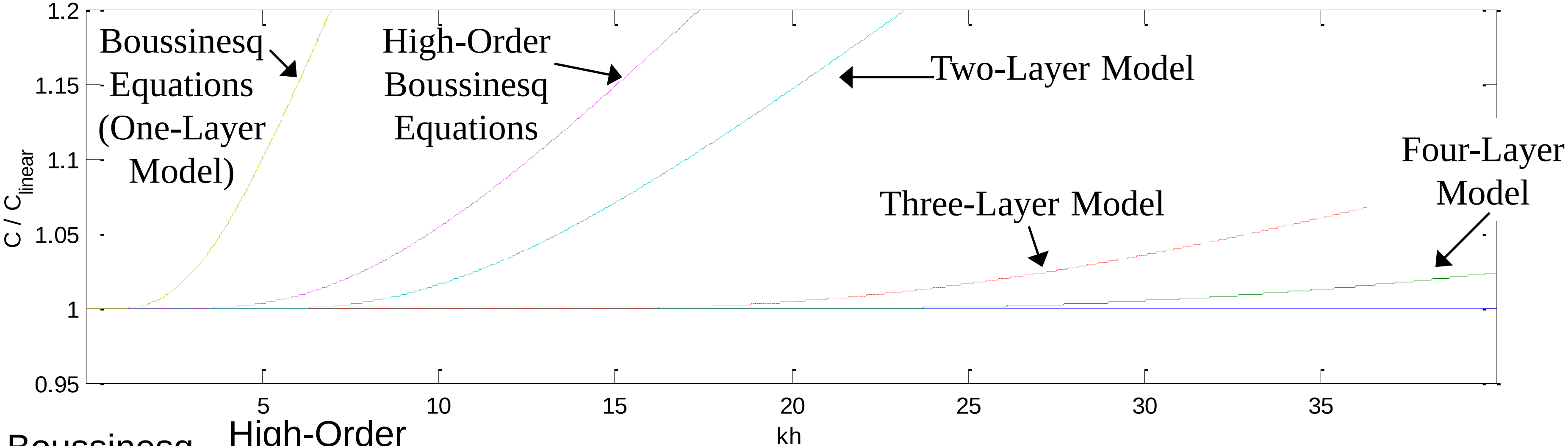
# *Boussinesq Model -*
# *Employing Multiple Layers (Lynett & Liu, 2002)*

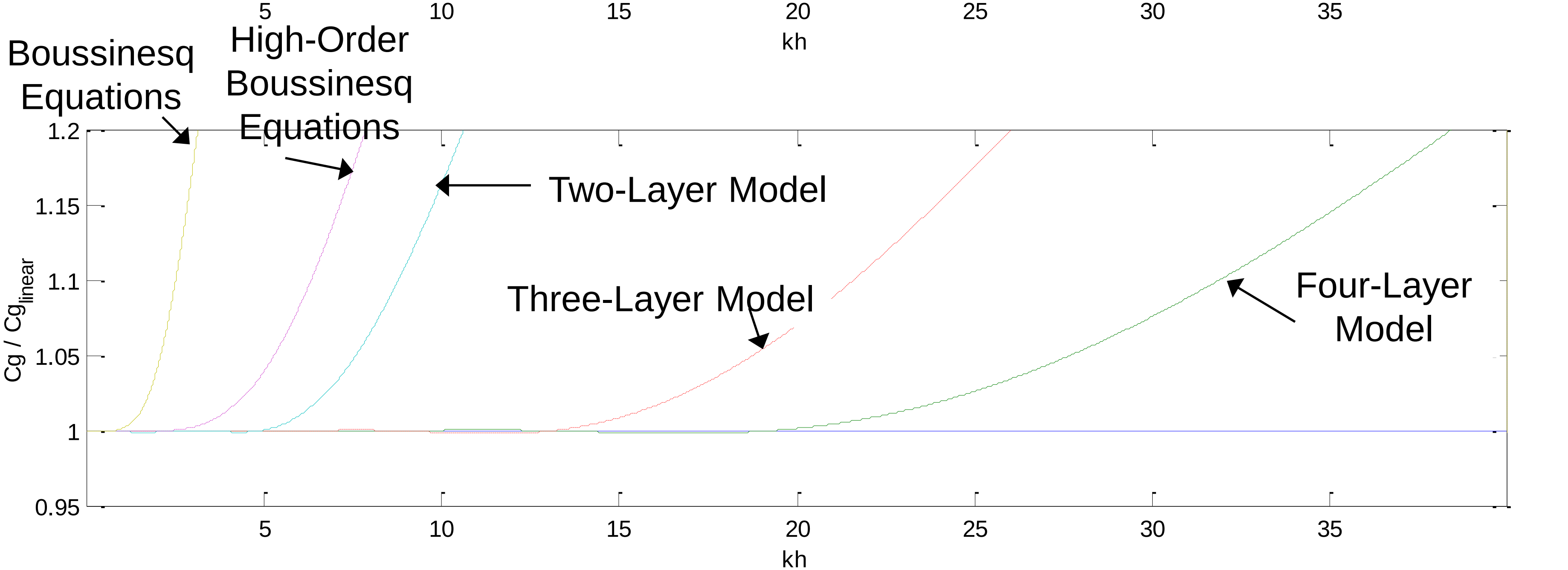
- ✓ Regardless of # of layers, ***highest order of derivation is 3***
- ✓ The more layers used, the more accurate the model
- ✓ Any # of layers can be used
  - – 1-Layer model = Boussinesq model
  - – Numerical applications of 2-Layer model to be discussed
- ✓ Location of layers will be optimized for good agreement with known, analytic properties of water waves



# *Boussinesq Model -*
# *Linear Dispersion Properties of Multi-Layer Model*

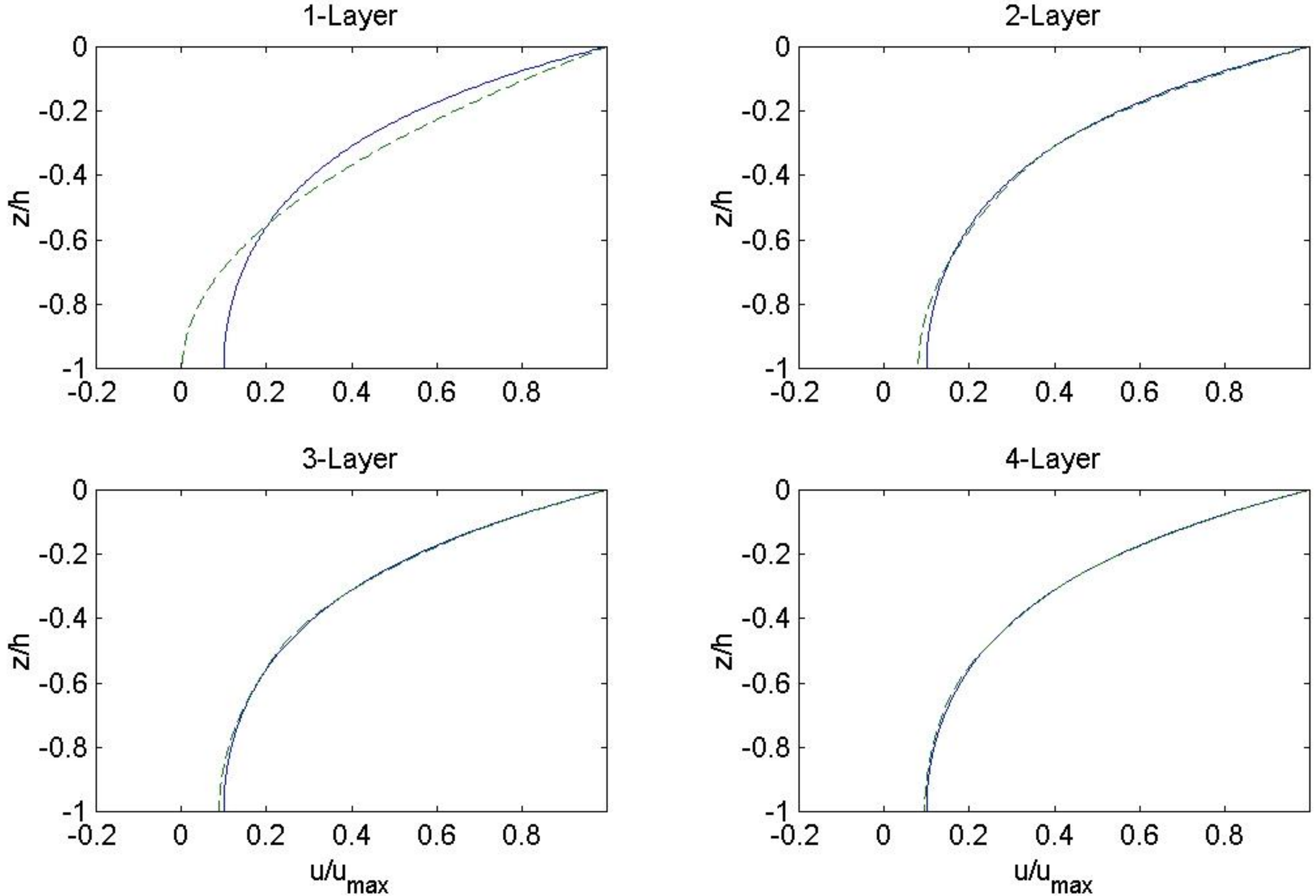
- Compare phase and group velocity with linear theory



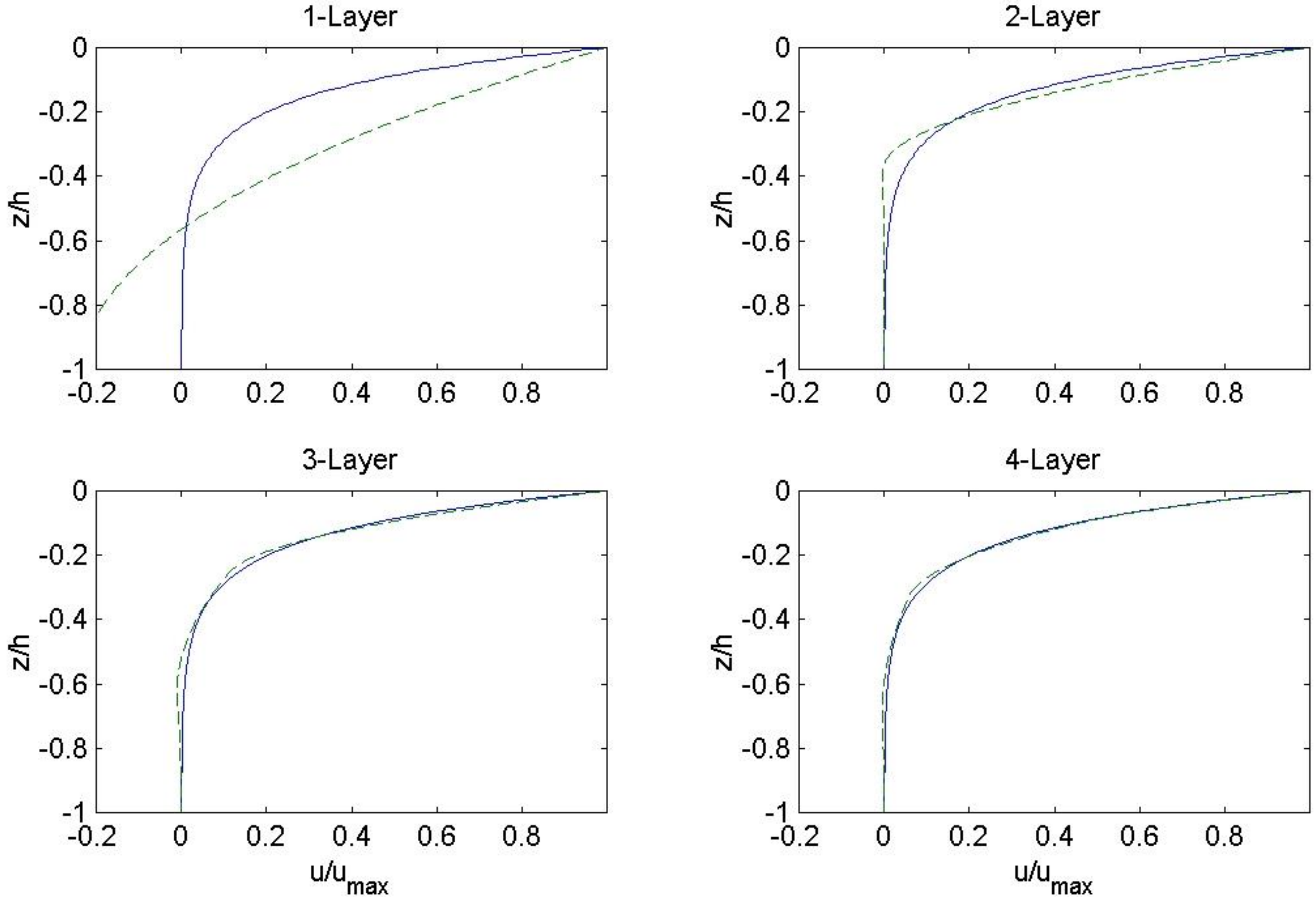
# *Boussinesq Model -*
# *Linear Dispersion Properties of Multi-Layer Model*

- Vertical profile of horizontal velocity for kh=3



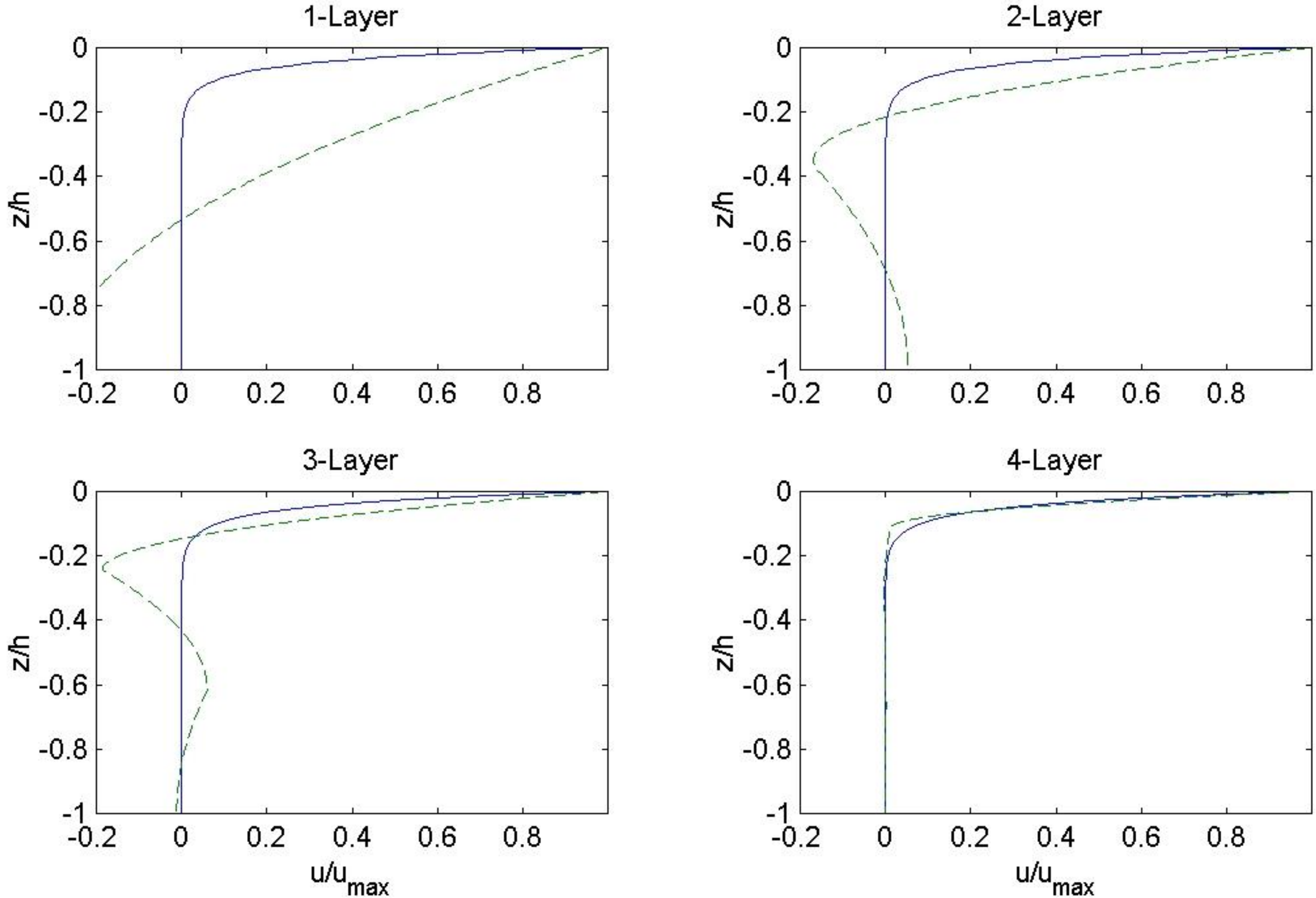
# *Boussinesq Model -*
# *Linear Dispersion Properties of Multi-Layer Model*

- Vertical profile of horizontal velocity for kh=8

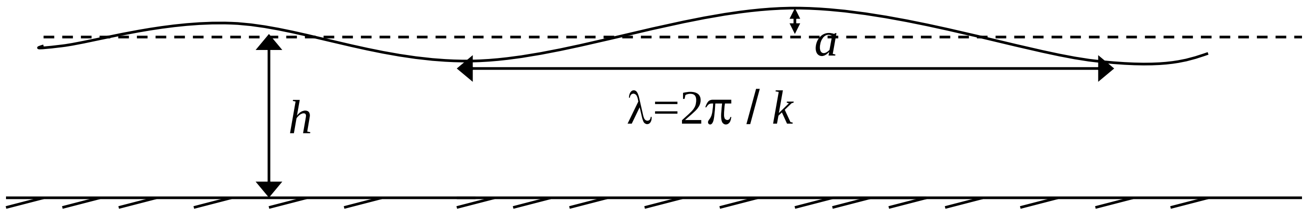


# *Boussinesq Model - Linear Dispersion Properties of Multi-Layer Model*

- Vertical profile of horizontal velocity for kh=25



# *Boussinesq Model -*
# *Back to Water Wave Modeling Efficiency*

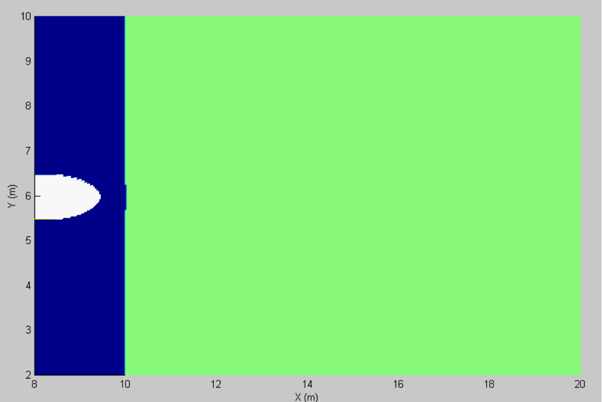



Increasing CPU Time

| **Solving Approach** | **Nonlinearity restriction** | **Frequency dispersion restriction** |
|---|---|---|
| Linear / Analytic | *a*/*h* ~ 0 | *kh* unbounded – fully dispersive, in the linear sense |
| Depth-Integrated / Numerical | *a*/*h* ~ O(1) – fully nonlinear | *kh* ~ 0 NLSW<br>*kh* < ~3 (λ/h>2) Boussinesq<br>*kh* < ~5 (λ/h>1.2) High-Order Bous. |
| *Multi-Layer Modeling* | *a/h ~ O(1) – fully nonlinear* | *kh < ~8 (λ/h>0.8) 2-Layer*<br>*kh < ~15 (λ/h>0.4) 3-Layer*<br>*kh < ~30 (λ/h>0.2) 4-Layer* |
| Potential Flow & Navier Stokes / Numerical | Fully nonlinear | Fully dispersive |

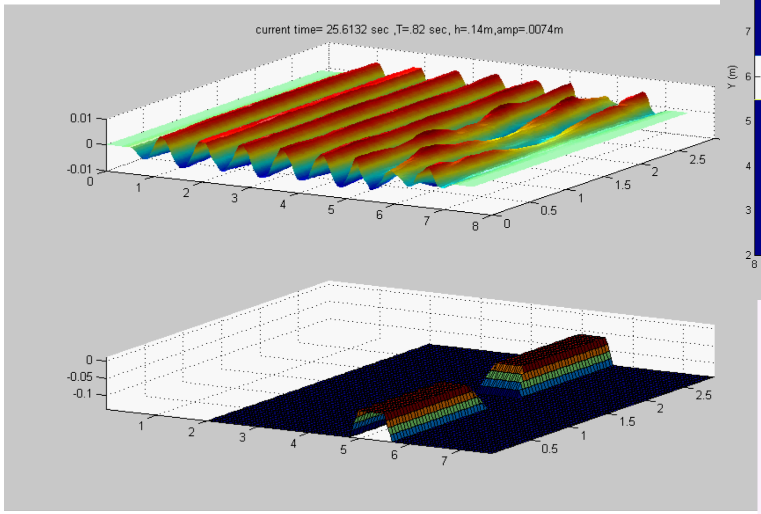
# *Boussinesq Model -*
# *Modeling in The Nearshore*

- ➢ Fundamentally, the Boussinesq model should not be used landward of the breaker zone due to its theoretical assumptions of irrotationality and no viscous effects
- ✓ However, we add ad-hoc breaking and turbulence models to approximate these phenomena
- ✓ Tuned empirically with experimental data to provide reasonable predictions for a range of setups

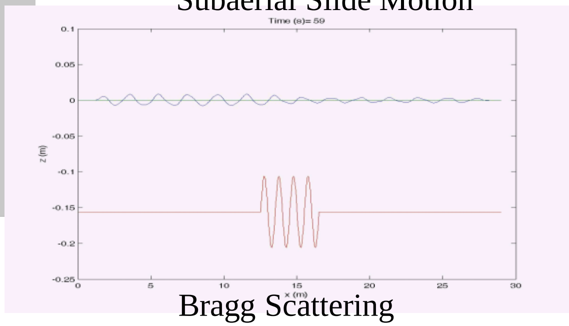


Subaerial Slide Motion


Large Scale Modeling



Submerged Porous Breakwater



Bragg Scattering

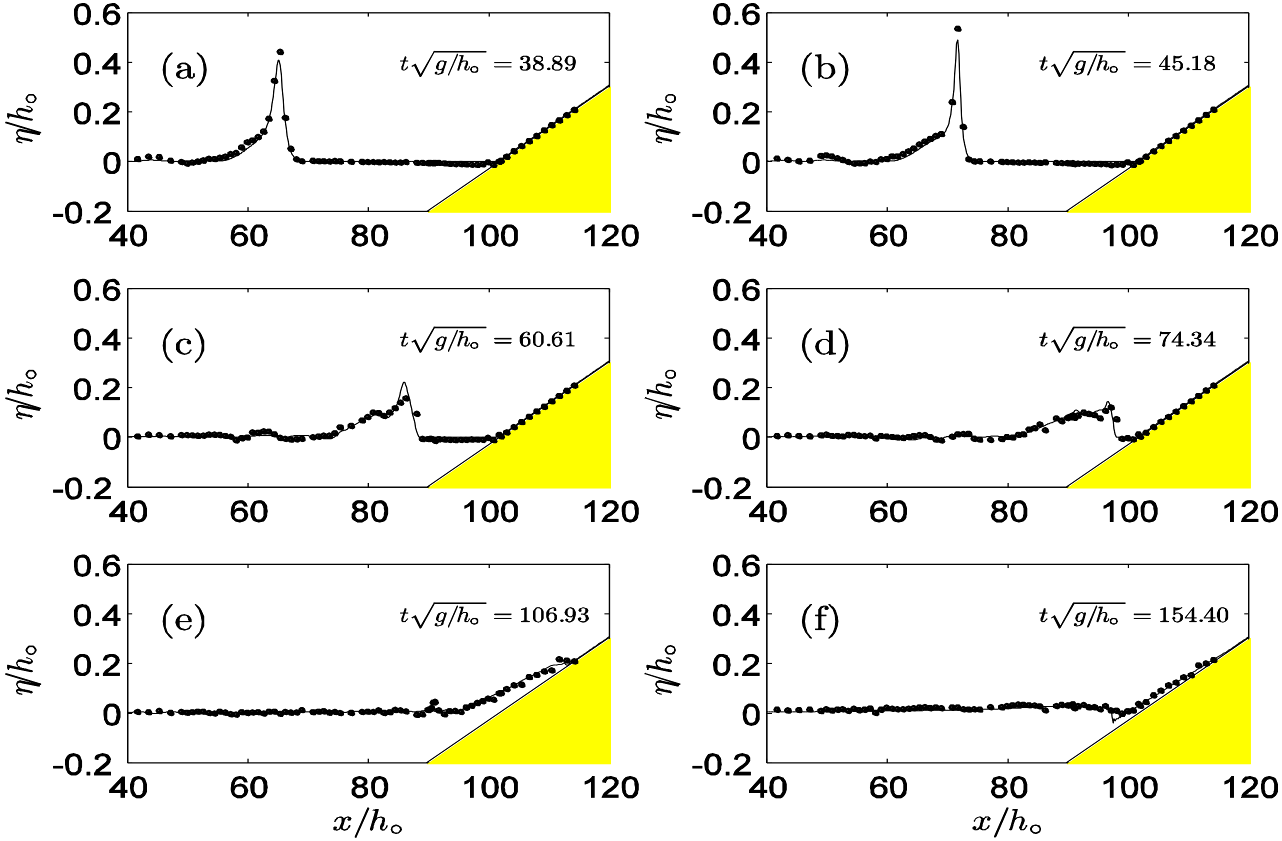
# On the Evolution and Run-up of Breaking Solitary Waves on a Mild Sloping Beach

- *Large-scale tsunami experiments*
- *Numerical modeling on tsunami-like long waves*
  - *Boussinesq Model*
- *Model Validation*
- *Numerical experiments*

# Model Validation

- Breaking solitary wave climbing up a slope (I)

Hsiao et al. (2008) – 1:60 gradual slope




$$\epsilon = H_\circ/h_\circ = 0.338$$

$$h_\circ = 1.9m$$

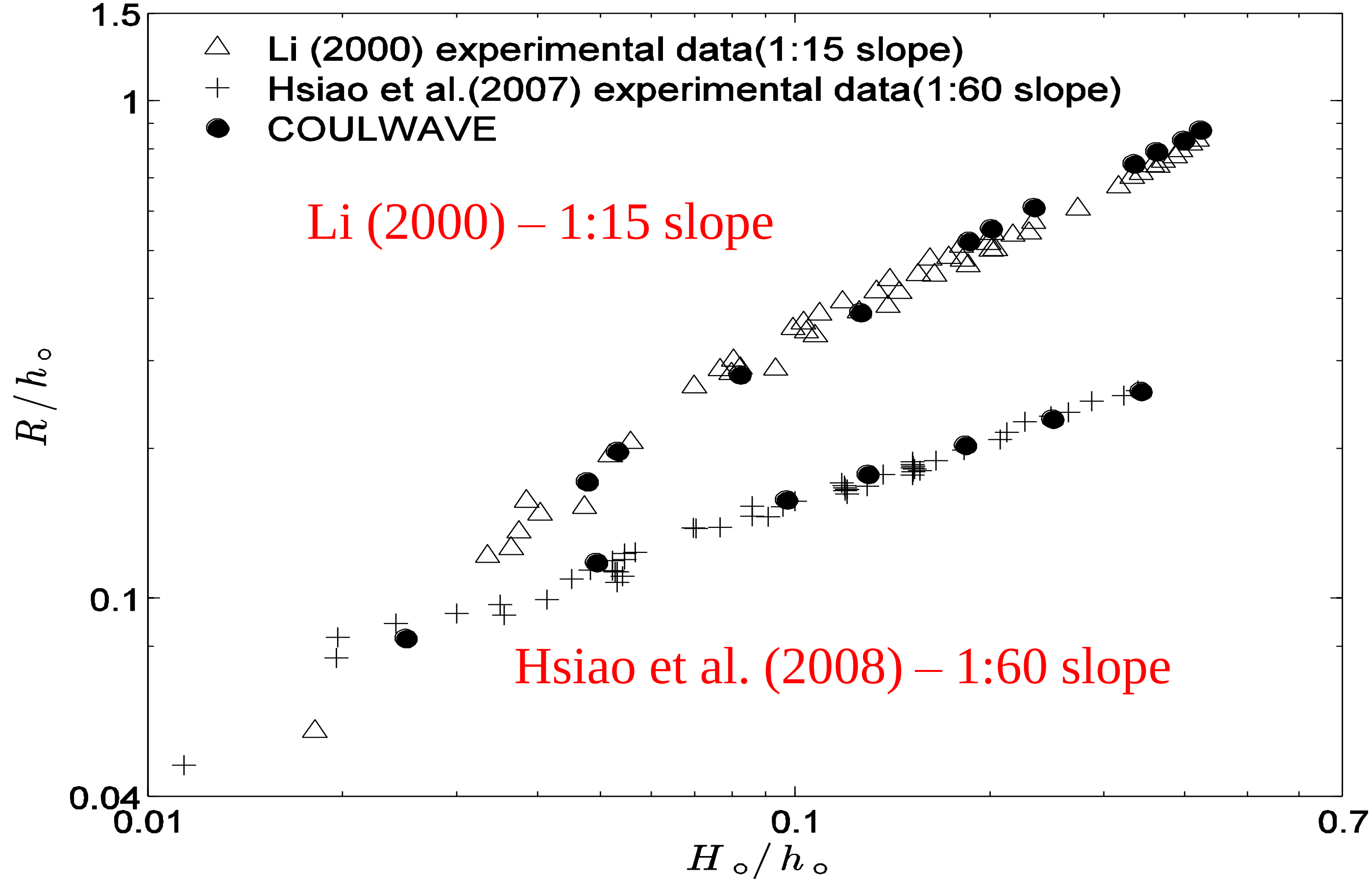
$$\boxed{f = 0.0025}$$

Breaking algorithm (ok)

# Model Validation

- Breaking solitary wave climbing up a slope (II)

Maximum run-up height




$f = 0.0025$

# On the Evolution and Run-up of Breaking Solitary Waves on a Mild Sloping Beach

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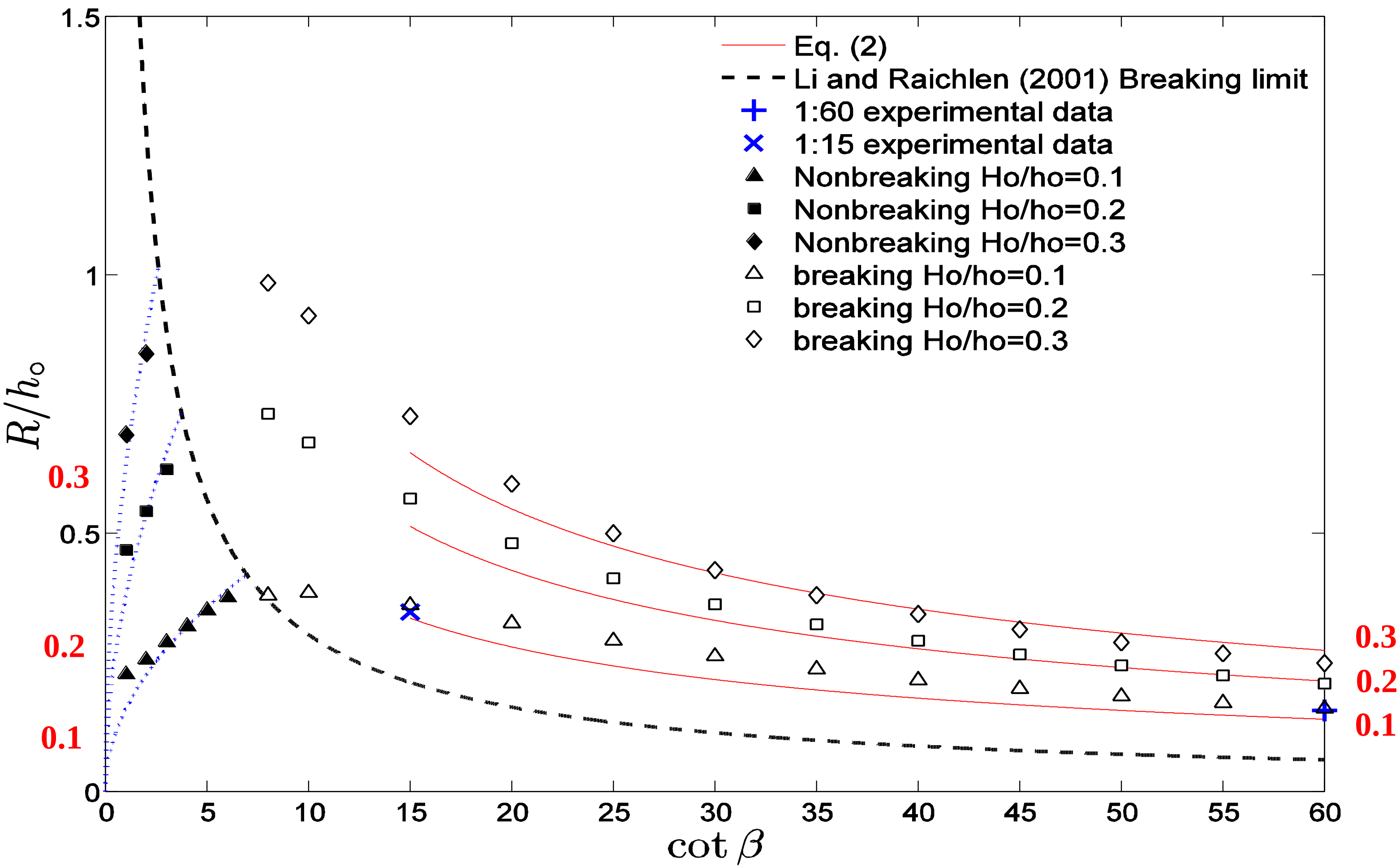
- Model Validation
- Numerical experiments

# Numerical Experiments

- Non-breaking waves: $R \propto \cot\beta$
- Breaking waves: $R \propto (\cot\beta)^{-1}$



# *Concluding Remarks - Experiments*

- Laboratory experiments are presented to study the tsunami-like solitary waves propagation and run-up on a gentle slope,
- ✓ A zone behind the gradual decay zone is demonstrated and it can be well-described by $\eta_{max} \sim h^{1/4}$
- ✓ An empirical formula for reasonably estimating the maximum run-up of a breaking solitary wave on a plane beach is proposed $(15 \leq \cot\beta \leq 60)$ ,

→ Present experimental results are in reasonable agreements with available data or methods, (Hsiao et al., 2008)

# *Concluding Remarks – Numerical Results*

- Numerical experiments are presented to simulate the properties of non-breaking & breaking solitary waves climbing up a sloping beach.
- ✓ For the non-breaking cases, the maximum run-up increases with the decrease of slope angle.
- ✓ For the breaking cases, the maximum run-up decreases with the growth of bed slope.

# Solitary Wave Interaction With a Submerged Vertical barrier: Experiment and RANS modeling

- *Motivation*
- *Small-scale tsunami experiments*
- *Numerical modeling on tsunami-like long waves*
  - *RANS Model*
- *Model Validation*
- *Wave Force and Pressure Fields*
- *Energy Dissipation*

# Motivation

- Protections of coastal regions from the attack of incident waves have been an important problem and deep interest for coastal engineers. Man-made structures are deployed to *dissipate wave energy, reduce beach erosion,* and *for sustainable development*.

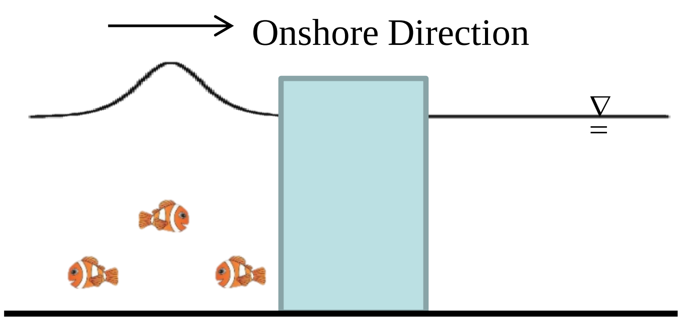
Seawall

**[ Chiting, 2007 ]**

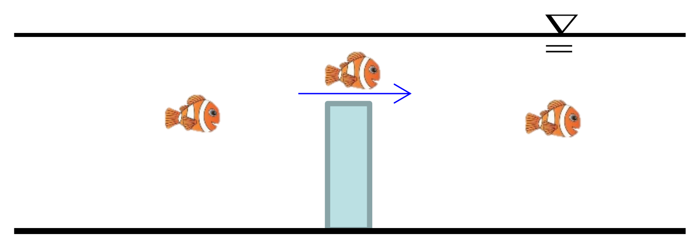
Artificial Reef

# Motivation

- ✓ Most of existing studies were focused on conventional hard structure made of large amount of concrete and rubble mound, which is not *cost-effective* and may cause *inevitable environmental impacts* to some extent.
- ✓ An alternative design of breakwater, *wave barriers*, is considered. A common type of barrier is thin and rigid as cost-efficient structures in reducing transmitted energy of long waves.




**Emerged Breakwater**



**Bottom-standing Barrier**
**(Impermeable Barrier)**

# Solitary Wave Interaction With a Submerged Vertical barrier: Experiment and RANS modeling

- *Motivation*
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- *Numerical modeling on tsunami-like long waves*

  *- RANS Model*
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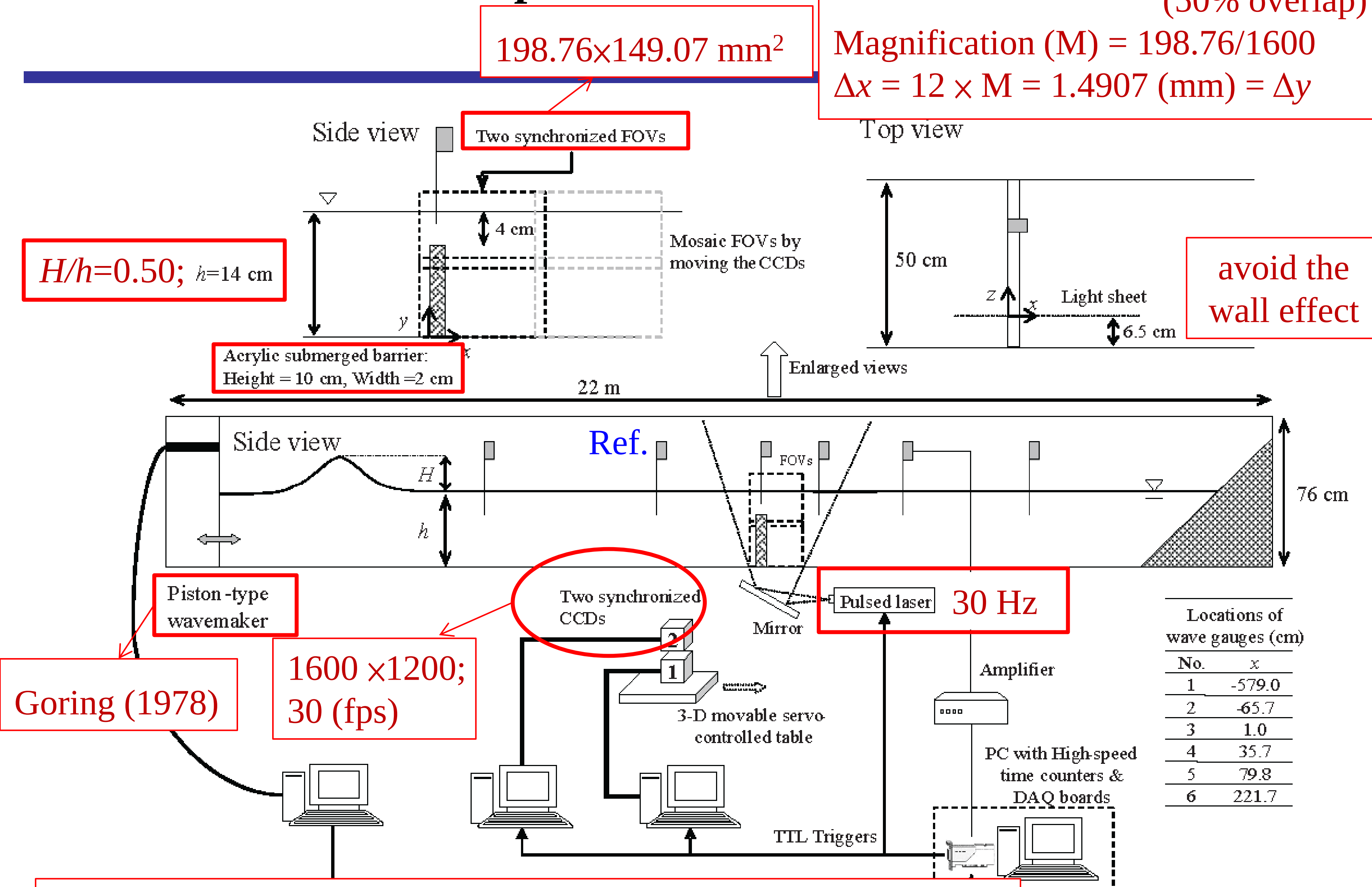
- *Energy Dissipation*

# *Small-scale Tsunami Experiments*

Interrogation window: 24×24 pixels (50% overlap)

Magnification (M) = 198.76/1600

$\Delta x = 12 \times M = 1.4907$ (mm) $= \Delta y$

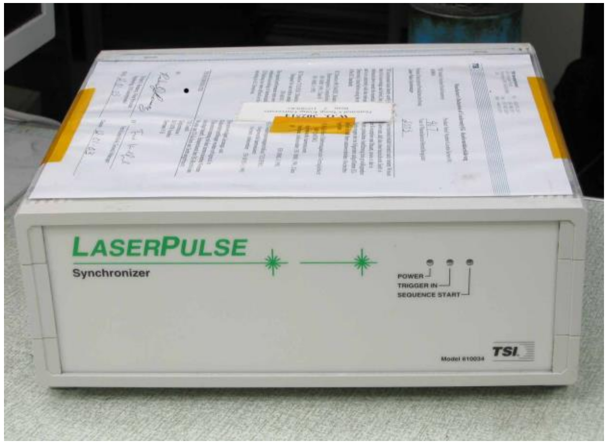



| Locations of wave gauges (cm) | |
|---|---|
| No. | $x$ |
| 1 | -579.0 |
| 2 | -65.7 |
| 3 | 1.0 |
| 4 | 35.7 |
| 5 | 79.8 |
| 6 | 221.7 |

✓ A total of 35 tests were conducted under identical experimental conditions for computing ensemble-averaged quantities.

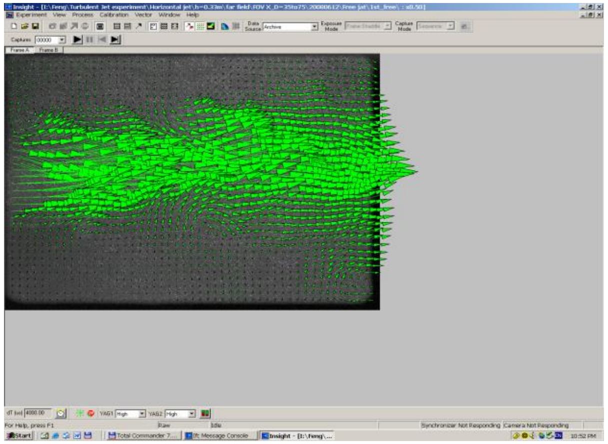
# *Small-scale Tsunami Experiments -Particle Image Velocimetry (PIV)*

Dual-head pulsed Nd: YAG laser system



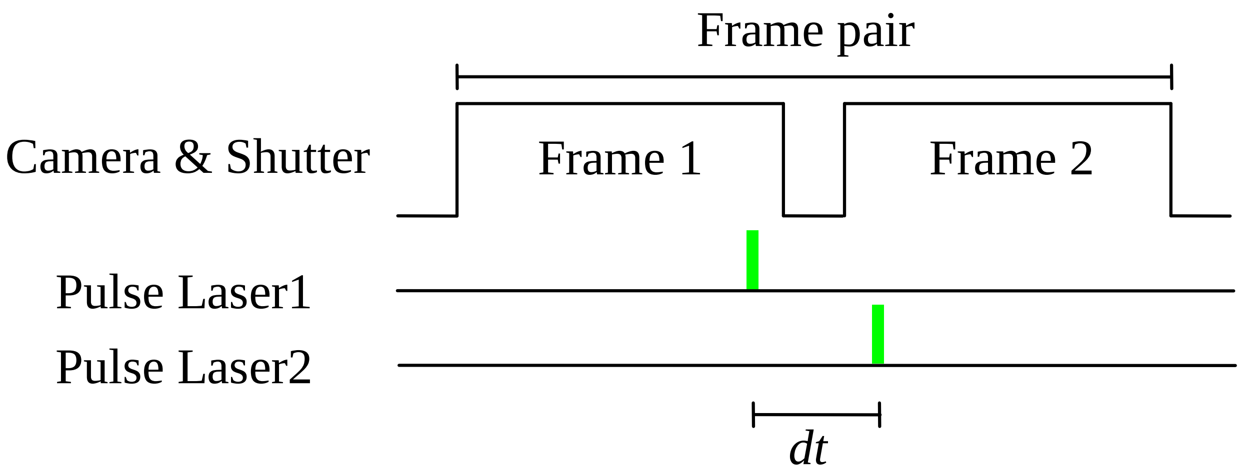

Synchronizer

PowerView™ 2M camera (CCD)

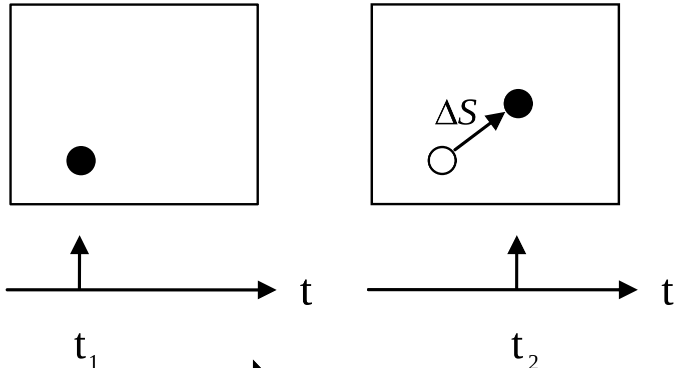


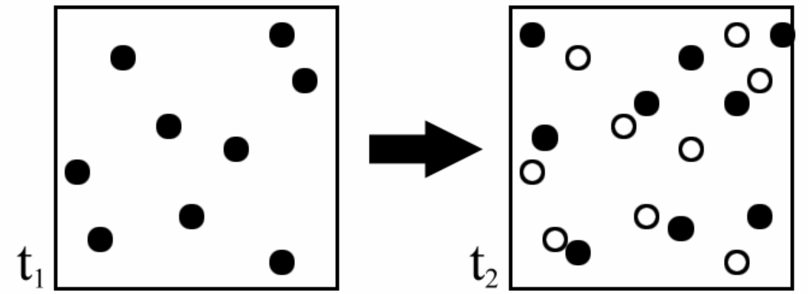
PIV analysis software

# Small-scale Tsunami Experiments -Image Data Acquisition Method




Two - frames / Single - pulse

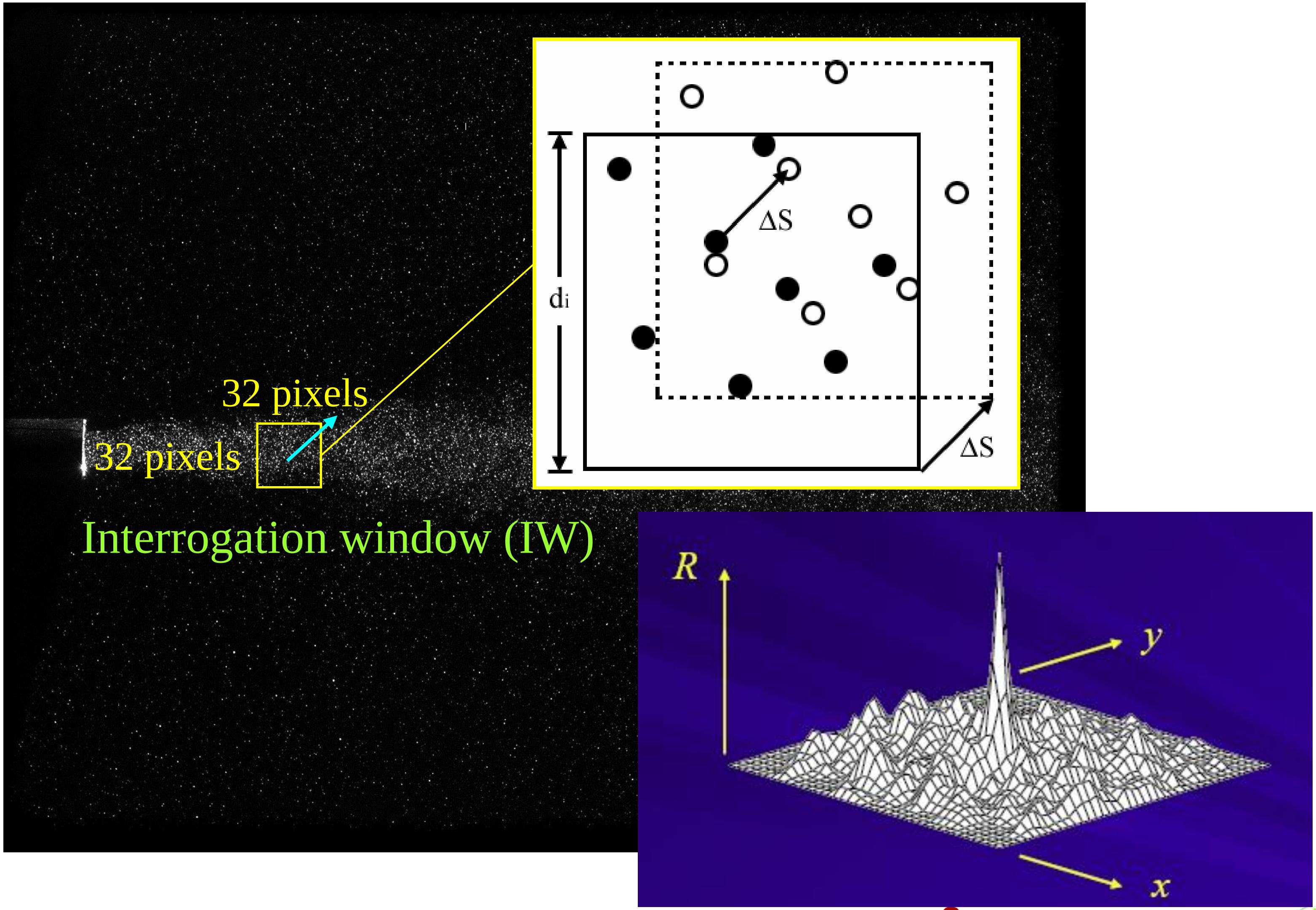



Flow velocity $\rightarrow$ $V_i = \dfrac{\Delta S}{t_2 - t_1}$

Flow velocity $\rightarrow$ Cross - correlation

# Small-scale Tsunami Experiments -Image Analysis



# *Solitary Wave Interaction With a Submerged Vertical barrier: Experiment and RANS modeling*

- *Motivation*
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  - *RANS Model*
- *Model validation*
- *Wave force and pressure fields*
- *Energy dissipation*

# RANS Model
# -Introduction of RANS model

- [COBRAS] COrnell BReaking And Structure (Lin & Liu, 1998 JFM)
  - ✓ Reynolds-Averaged Navier-Stokes Equation (RANS)
    - – ensemble averaged flow motions (mean flow motions)
  - ✓ Turbulence Kinetic Energy (TKE)
    - – Modified $k-\varepsilon$ closure model (Lin & Liu, 1997)
  - ✓ Free surface treatment-Volume of fluid (VOF) (Hirt & Nichols, 1981)
  - ✓ Target solitary wave is generated through the left boundary
    - – Lee et al. (1982) : Conventional Boussinesq eqs.c

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## A numerical study of breaking waves in the surf zone

By PENGZHI LIN AND PHILIP L.-F. LIU
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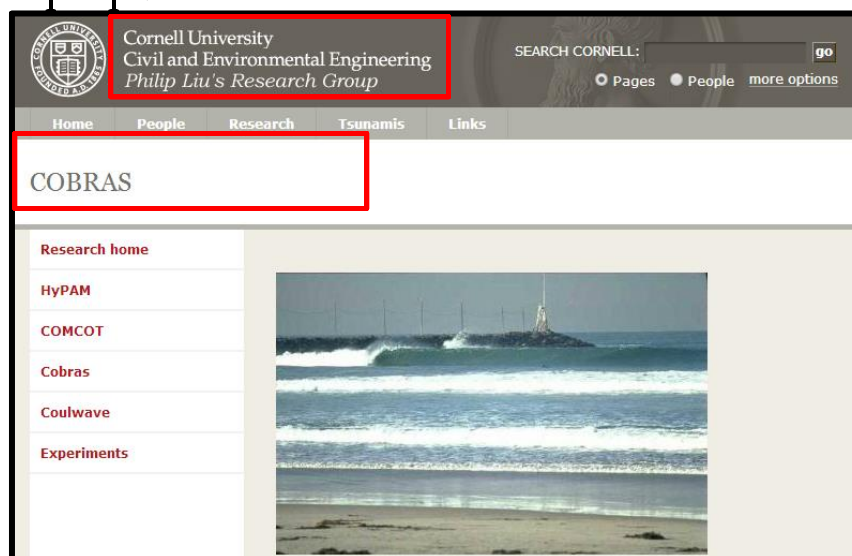
(Received 10 May 1997 and in revised form 15 November 1997)

This paper describes the development of a numerical model for studying the evolution of a wave train, shoaling and breaking in the surf zone. The model solves the Reynolds equations for the mean (ensemble average) flow field and the $k$–$\epsilon$ equations for the turbulent kinetic energy, $k$, and the turbulence dissipation rate, $\epsilon$. A nonlinear Reynolds stress model (Shih, Zhu & Lumley 1996) is employed to relate the Reynolds

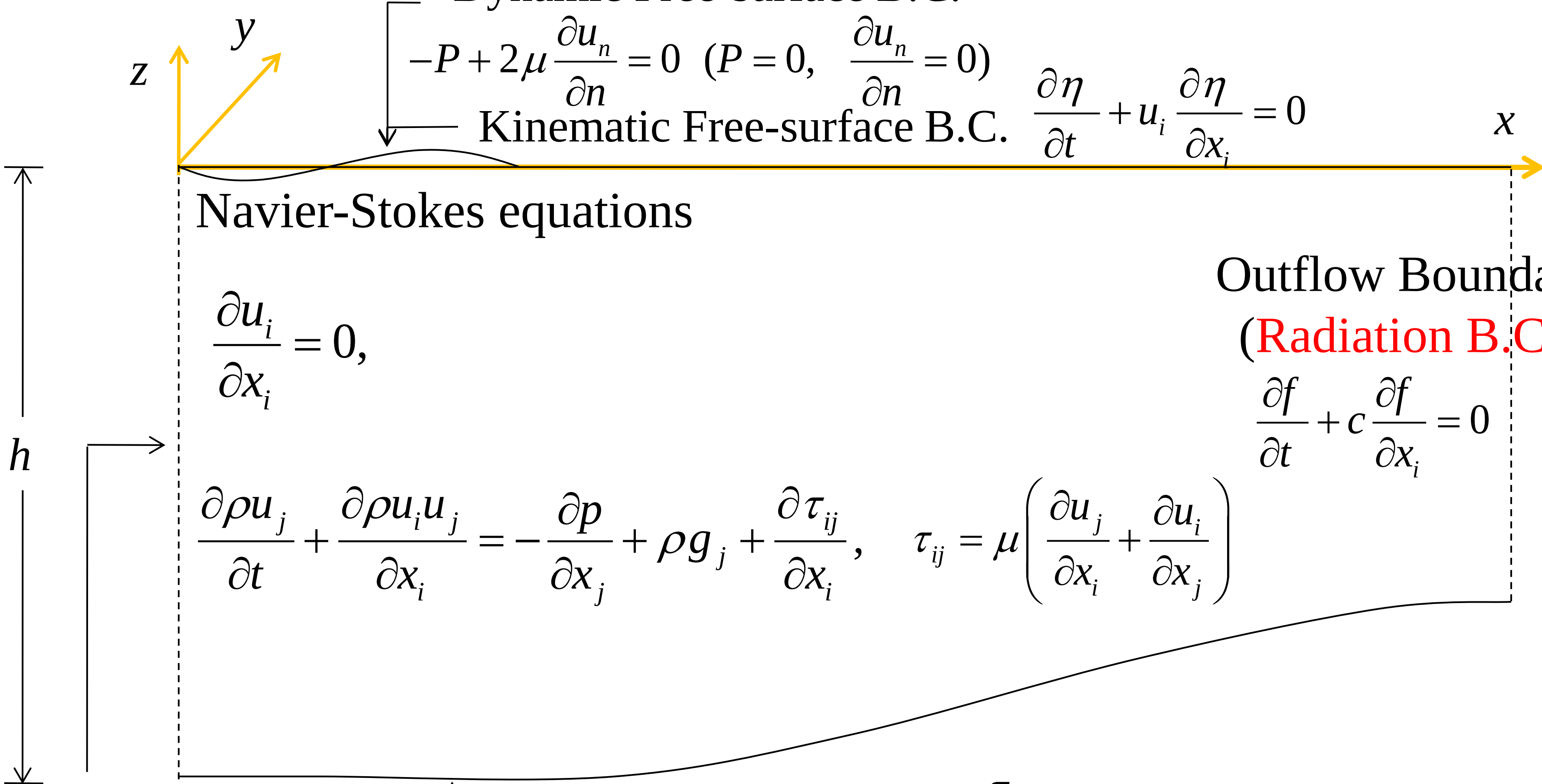


# RANS Model
## -Introduction of RANS model

Dynamic Free-surface B.C.

$$-P + 2\mu \frac{\partial u_n}{\partial n} = 0 \quad \left(P = 0, \quad \frac{\partial u_n}{\partial n} = 0\right)$$

Kinematic Free-surface B.C. $\frac{\partial \eta}{\partial t} + u_i \frac{\partial \eta}{\partial x_i} = 0$




Navier-Stokes equations

$$\frac{\partial u_i}{\partial x_i} = 0,$$

$$\frac{\partial \rho u_j}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \rho g_j + \frac{\partial \tau_{ij}}{\partial x_i}, \qquad \tau_{ij} = \mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)$$

Outflow Boundary (Radiation B.C.)

$$\frac{\partial f}{\partial t} + c\frac{\partial f}{\partial x_i} = 0$$

Inflow boundary

$$\eta\left(x_j, t\right)$$

$$u_i\left(x_j, t\right)$$

Kinematic Bottom B.C. $\frac{\P u_n}{\P n} = 0$

# *RANS Model*
# *-Introduction of RANS model*

- Since all types of fluid flows, laminar and turbulent, can be described by the *NSEs*, the numerical solution (***DNS***) for turbulent flow requires no special treatment except to solve the original NSEs.

✓ All turbulence structures, including the smallest Kolmogorov turbulence scale, must be adequately resolved by the numerical scheme.

✓ Based on Kolmogorov (1962), the smallest turbulence length scale (*e.g.*, Kolmogorov $\eta$) can be estimated as:

$$\left(\frac{L}{\eta}\right)^3 \sim Re^{9/4}$$

⇨ When $Re$ = 2,100, the total grids ≈ 30,000,000.

# RANS Model
# -Introduction of RANS model

- Reynolds decomposition:

$$\left.\begin{aligned} u_i &= \langle u_i \rangle + u_i' \\ p &= \langle p \rangle + p' \end{aligned}\right\} \Rightarrow \begin{cases} \dfrac{\partial u_i}{\partial x_i} = 0 \\ \dfrac{\partial \rho u_i}{\partial t} + \dfrac{\partial \rho u_i u_j}{\partial x_j} = -\dfrac{\partial p}{\partial x_i} + \rho g_i + \dfrac{\partial \tau_{ij}}{\partial x_j} \end{cases}$$

Assuming the turbulent fluctuations are random $\Rightarrow \langle u_i' \rangle = \langle p' \rangle = 0.$

$$\begin{cases} \dfrac{\partial \langle u_i \rangle}{\partial x_i} = 0, \\ \dfrac{\partial \rho \langle u_i \rangle}{\partial t} + \dfrac{\partial \rho \langle u_i \rangle \langle u_j \rangle}{\partial x_j} = -\dfrac{\partial \langle p \rangle}{\partial x_i} + \rho g_i + \dfrac{\partial \langle \tau_{ij} \rangle}{\partial x_j} + \dfrac{\partial}{\partial x_j}\left(-\boxed{\rho \langle u_i' u_j' \rangle}\right). \end{cases}$$

Reynolds stress

**Reynolds-averaged Navier-Stokes equations (RANS).**

# RANS Model
# -Introduction of RANS model

The $k$-$\varepsilon$ turbulent closure model:

$k$ = turbulent kinetic energy

$\varepsilon$ = turbulent dissipation rate

$$\Rightarrow \begin{cases} \dfrac{\partial k}{\partial t} + \langle u_j \rangle \dfrac{\partial k}{\partial x_j} = \dfrac{\partial}{\partial x_j}\left[\left(\dfrac{\upsilon_t}{\sigma_k} + \upsilon\right)\dfrac{\partial k}{\partial x_j}\right] - \langle u_i' u_j' \rangle \dfrac{\partial \langle u_i \rangle}{\partial x_j} - \varepsilon, \\ \dfrac{\partial \varepsilon}{\partial t} + \langle u_j \rangle \dfrac{\partial \varepsilon}{\partial x_j} = \dfrac{\partial}{\partial x_j}\left[\left(\dfrac{\upsilon_t}{\sigma_\varepsilon} + \upsilon\right)\dfrac{\partial \varepsilon}{\partial x_j}\right] \end{cases}$$

$$+ C_{1\varepsilon}\frac{\varepsilon}{k}\upsilon_t\left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i}\right)\frac{\partial \langle u_i \rangle}{\partial x_j} - C_{2\varepsilon}\frac{\varepsilon^2}{k}.$$

- ✓ Linear mathematic form – isotropic

$$\rho\langle u_i' u_j' \rangle = -C_d \rho \frac{k^2}{\varepsilon}\left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i}\right) + \frac{2}{3}\rho k \delta_{ij}.$$

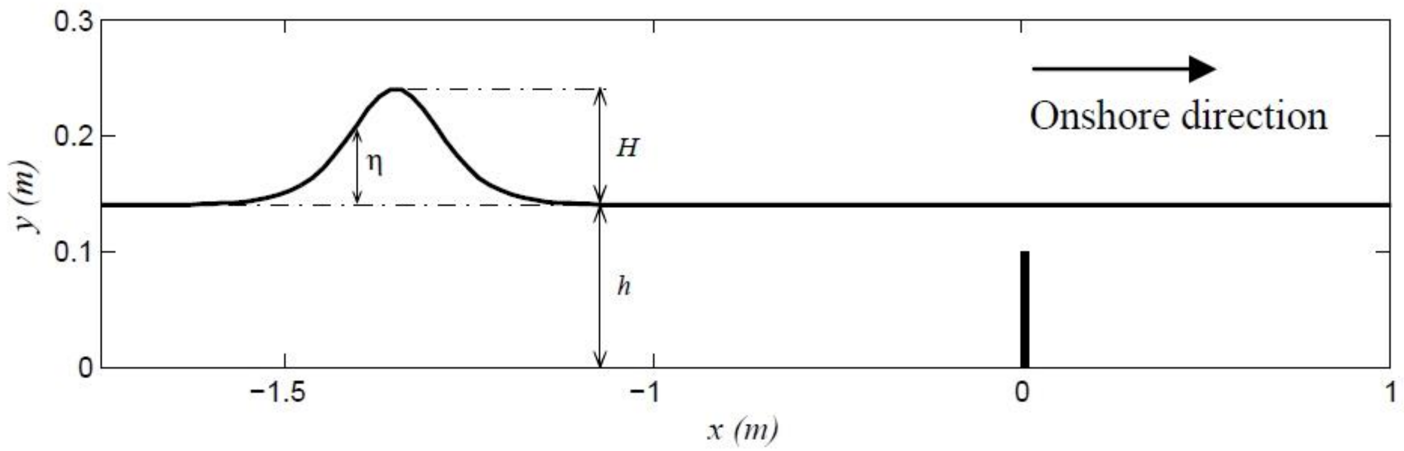
- ✓ Non-linear mathematic form – anisotropic

$$\rho\langle u_i' u_j' \rangle = -C_d \rho \frac{k^2}{\varepsilon}\left(\frac{\partial \langle u_i \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_i}\right) + \frac{2}{3}\rho k \delta_{ij}$$

$$-\rho\frac{k^3}{\varepsilon^2}\left[C_1\left(\frac{\partial \langle u_i \rangle}{\partial x_l}\frac{\partial \langle u_l \rangle}{\partial x_j} + \frac{\partial \langle u_j \rangle}{\partial x_l}\frac{\partial \langle u_l \rangle}{\partial x_i} - \frac{2}{3}\frac{\partial \langle u_l \rangle}{\partial x_k}\frac{\partial \langle u_k \rangle}{\partial x_l}\delta_{ij}\right)\right.$$

$$\left. + C_2\left(\frac{\partial \langle u_i \rangle}{\partial x_k}\frac{\partial \langle u_j \rangle}{\partial x_k} - \frac{1}{3}\frac{\partial \langle u_l \rangle}{\partial x_k}\frac{\partial \langle u_l \rangle}{\partial x_k}\delta_{ij}\right) + C_3\left(\frac{\partial \langle u_k \rangle}{\partial x_i}\frac{\partial \langle u_k \rangle}{\partial x_j} - \frac{1}{3}\frac{\partial \langle u_l \rangle}{\partial x_k}\frac{\partial \langle u_l \rangle}{\partial x_k}\delta_{ij}\right)\right].$$

# RANS Model
# -Numerical Setup




- Computational Domain:

  $-2.5 \leq x \leq 1.0$ m

  $0.0 \leq y \leq 0.3$ m

- Submerged Barrier:

  2 cm in width, 10 cm in length

  located at $x$ = 0.0 m.

- Numerical Mesh:

  structured & uniform rectangular

  grids of $\Delta x = \Delta y = 1$ mm.

- Wave Condition:

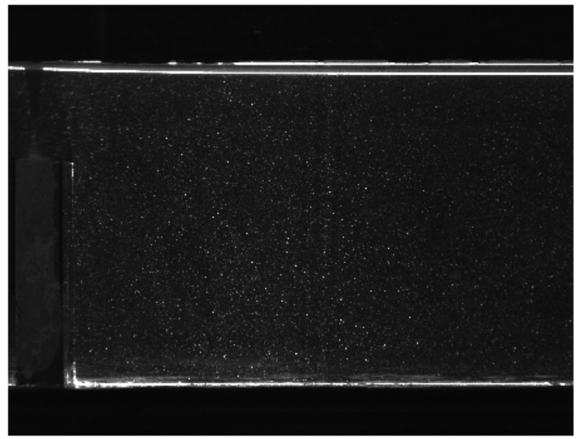
  water depth ($h$) = 14 cm

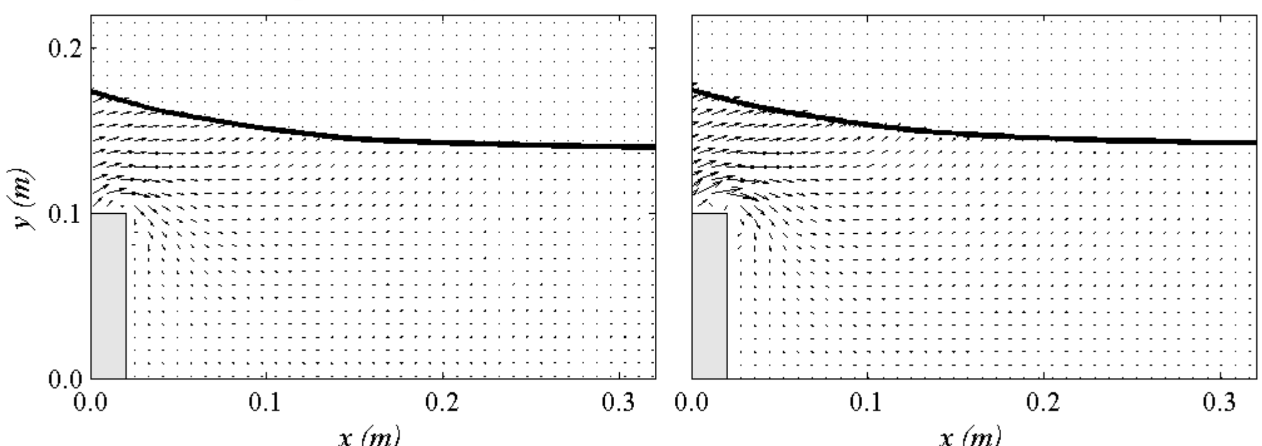
  wave non-linearity ($H$ / $h$) = 0.50

# RANS Model
# -Numerical Results

Onshore Direction

Flow Visualization






University
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# Solitary Wave Interaction With a Submerged Vertical barrier: Experiment and RANS modeling

- *Motivation*
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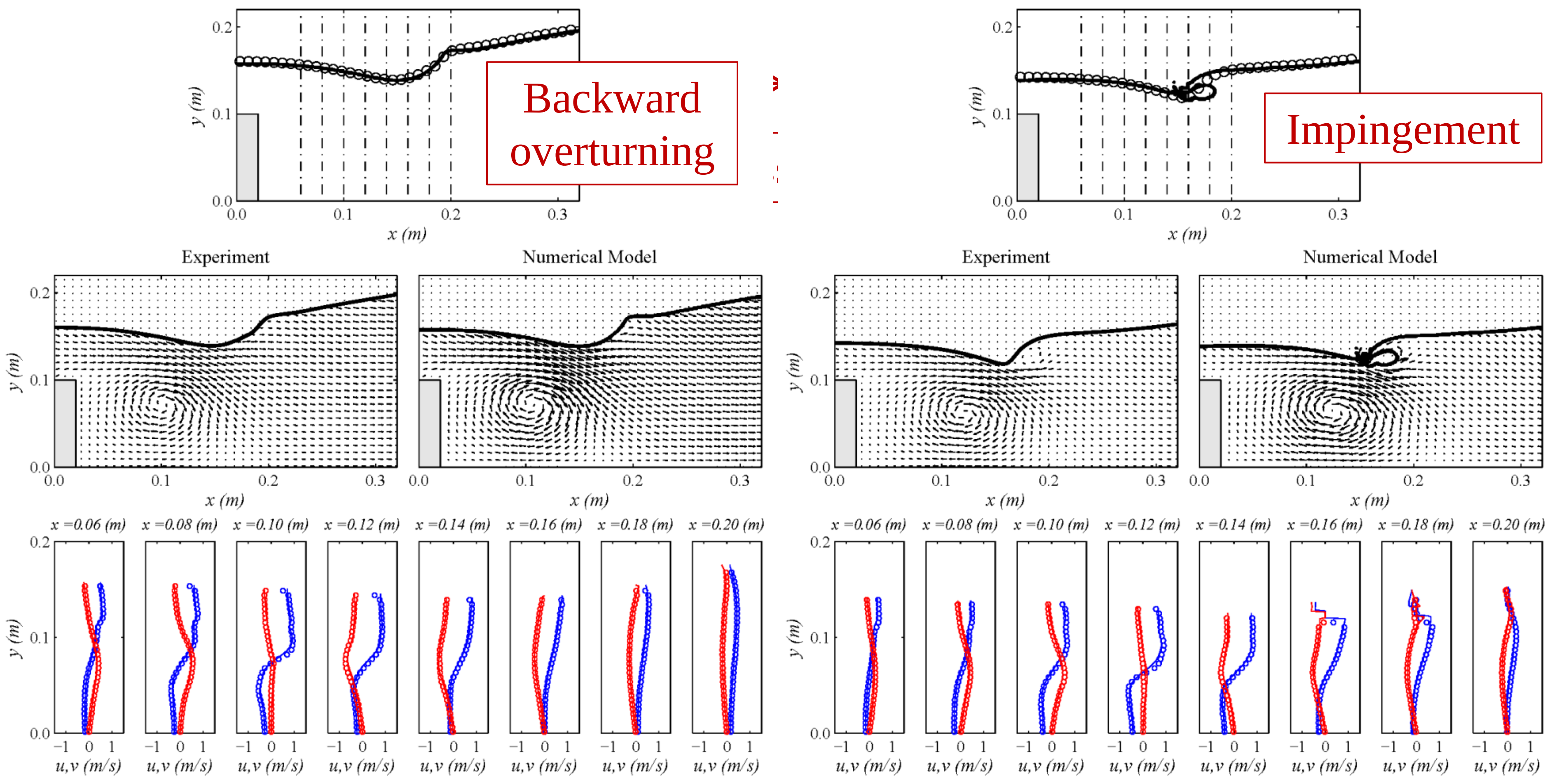
- *Model validation*
- *Wave force and pressure fields*
- *Energy dissipation*

# Model Validation -Flow Fields

t = 0.74 (sec)

t = 0.88 (sec)




For the first and lower panel, solid lines and circles respectively represent calculations and measurements. For the lower panel, blue and red indicate horizontal and vertical velocities.

# Model Validation -Flow Fields

➢ Some possible explanations for the discrepancies between two results.

✓ The present model is a single-phase numerical scheme, which means the air is treated as numerical voids not the real air-fluid interaction.

✓ Although the experiments are highly repeatable, entrapped air-bubbles in the wave breaking processes cause unavoidable uncertainties due to the natural complexity of fluids (Chan and Melville, 1988; Kobayashi and Raichle, 1994).

✓ To improve the measurements, the bubble image velocimetry (BIV) technique should be included to measure the velocity variation near the bubble area (Pedrozo-Acuña et al., 2011; Ryu et al., 2007).

# *Model Validation -Turbulence Fields*

- Turbulence generated by breaking waves in coastal regions is considered an important factor in leading sediment into suspension and thus affects sediment transport and topography change.
- In present experiment, two velocity components were measured (i.e., $u$ and $v$).
- Velocity fluctuations: $u' = u - \langle u \rangle$ , $v' = v - \langle v \rangle$ ; and $\langle u \rangle$ and $\langle v \rangle$ : ensemble-averaged mean velocities.
- Turbulent kinetic energy ($k$) can be estimated by $k = \langle u' u' + v' v' \rangle_N$, in which symbol < > represent ensemble average, and $N$ is the number of repeated experiment ($N$ = 35 in the present study).
- For details on the method used to evaluate turbulence characteristics from experiments, refer to the study of Huang et al. (2009).

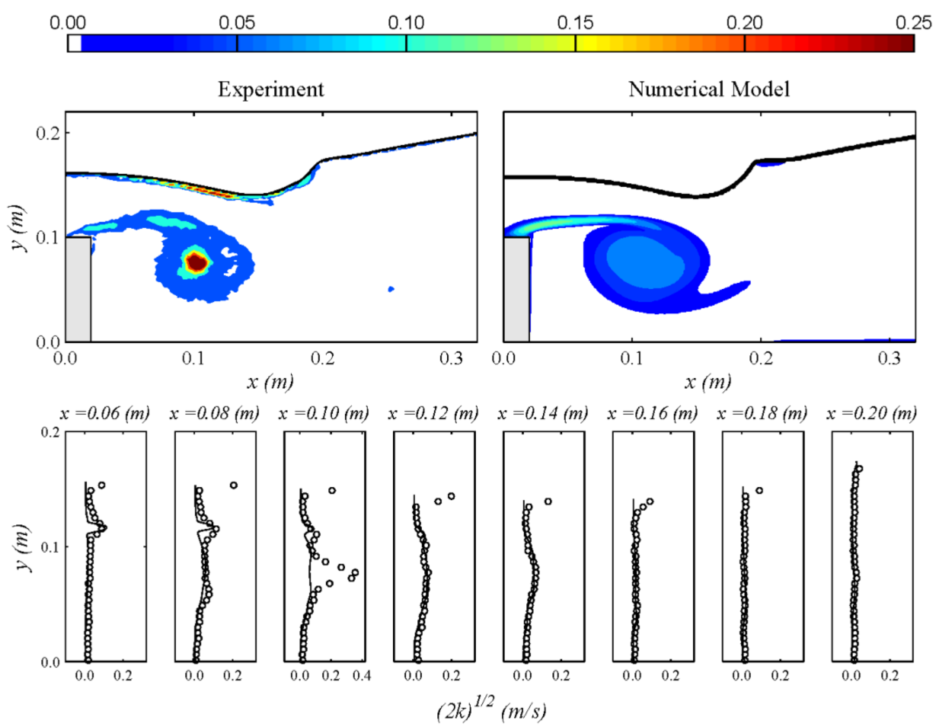
# Model Validation -Turbulence Fields

- Solitary wave interaction with a submerged vertical barrier

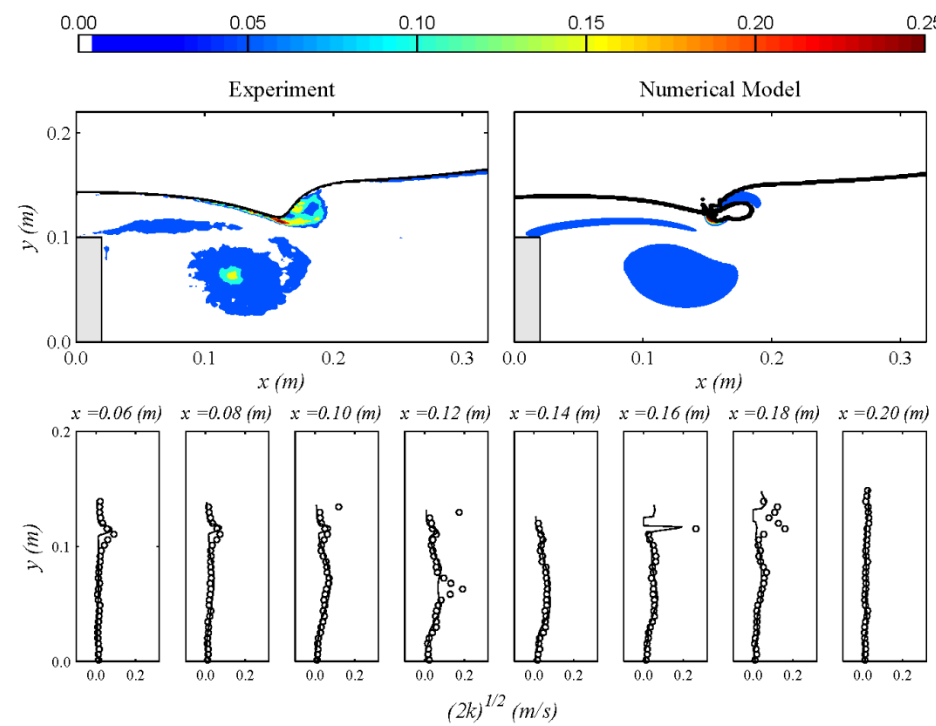
The turbulence intensity is large at the core of the main vortex, … The find… by previ…

- The relatively maximum values of measured and modeled turbulent intensity at the impinging point are about 0.3 m/s.

t = 0.76 (sec)




t = 0.88 (sec)

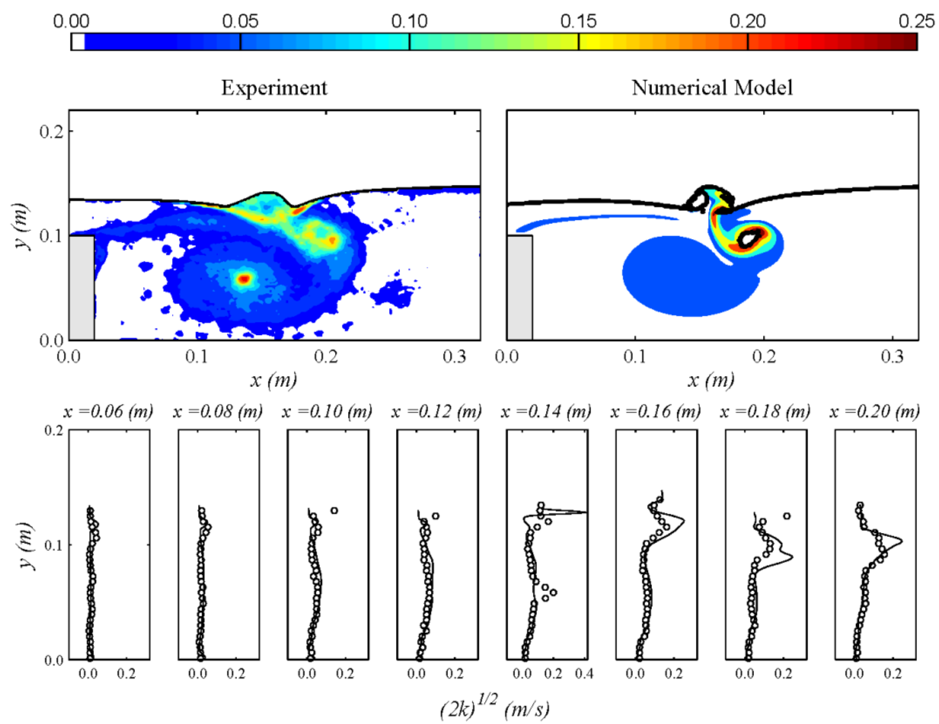



For the lower panel, solid lines and circles represent the numerical and experimental results.

# Model Validation -Turbulence Fields

➢ The secondary backward breaking: the measured and modeled (at $x$ =0.14 m) is about value of 0.202 (m/s) and 0.408 (m/s).

t = 1.02 (sec)




For the lower panel, solid lines and circles represent the numerical and experimental results.

# Model Validation -Turbulence Fields

➢Some possible explanations for the discrepancies between two results.

✓ At the pre-breaking stage:

- near the free surface (Exp. > Num.)
- the main vortex's core (Exp. > Num.)

✓ At the post-breaking stage:

- the main vortex's core (Exp. > Num.)
- splash-up event (Exp. < Num.)

⬄ Small ripples appear on the free surface (Huang et al., 2009), which suggests the importance of surface tension.

⬄ Experiment was highly repeatable for 35 runs, however, the location of the core of the main vortex was slightly different for each test.

⬄ The *k*-*ε* model may not reasonably estimate the initial stage of breaking waves: the value of calculated turbulence is larger than the measurement (Lin and Liu, 1998a).

⬄ Some studies on surf-zone dynamics also overestimate the turbulence after wave breaking using similar numerical approaches (Bakhtyar et al., 2009, 2010; Christensen et al., 2002).

# Solitary Wave Interaction With a Submerged Vertical barrier: Experiment and RANS modeling

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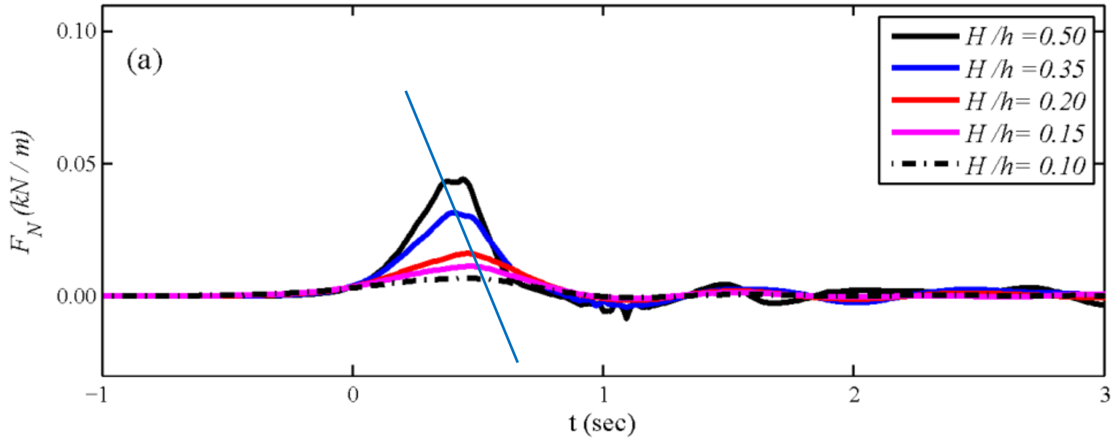
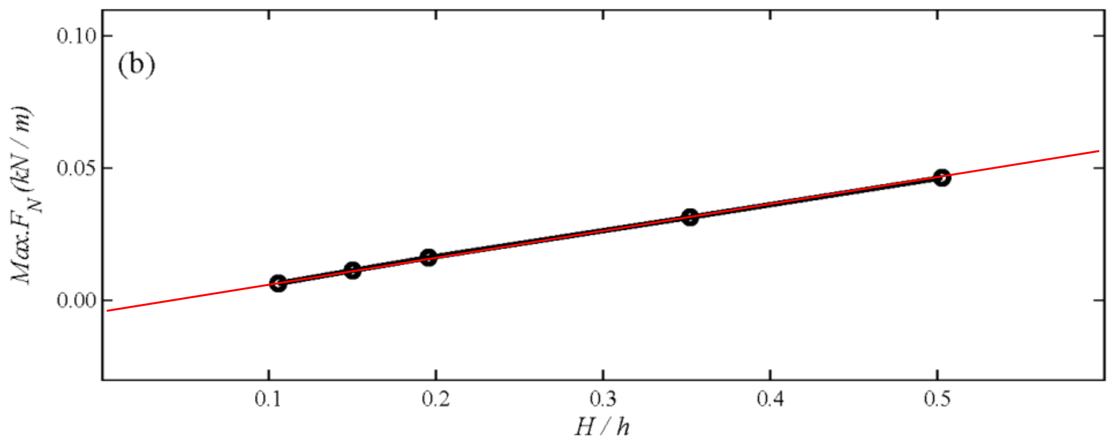
- *Energy dissipation*

# *Wave Force and Pressure Fields*

- The peak net force occurs later for lower wave non-linearity values simply due to lower phase velocity.




- The relationship between the maximum net force and the wave non-linearity is nearly linear.




- Liu and Al-Banaa (2004):

⇨ linear relation between the maximum wave force and wave non-linearity for a surface-piercing vertical barrier fixed to the seafloor.

# Solitary Wave Interaction With a Submerged Vertical barrier: Experiment and RANS modeling

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# Energy Dissipation

## Derived By Lin (2004)

$$\int_{t_1}^{t_2} Edxdz + \int_{t_1}^{t_2} dt \int Ddxdz$$

$$= \left[ \int_{t_1}^{t_2} dt \int_{-h(CS_1)}^{\eta(CS_1)} \langle P_D \rangle \langle u \rangle dz + \int_{t_1}^{t_2} dt \int_{-h(CS_1)}^{\eta(CS_1)} \frac{\rho}{2} \langle u \rangle \langle u^2 + v^2 \rangle dz \right]$$
$$- \left[ \int_{t_1}^{t_2} dt \int_{-h(CS_2)}^{\eta(CS_2)} \langle P_D \rangle \langle u \rangle dz + \int_{t_1}^{t_2} dt \int_{-h(CS_2)}^{\eta(CS_2)} \frac{\rho}{2} \langle u \rangle \langle u^2 + v^2 \rangle dz \right]$$

$$\int Edxdz \,|_{t=t_1} = \int Edxdz \,|_{t=t_2} = 0$$

$$ED = \left(EP_{CS_1} + EC_{CS_1}\right) - \left(EP_{CS_2} + EC_{CS_2}\right)$$

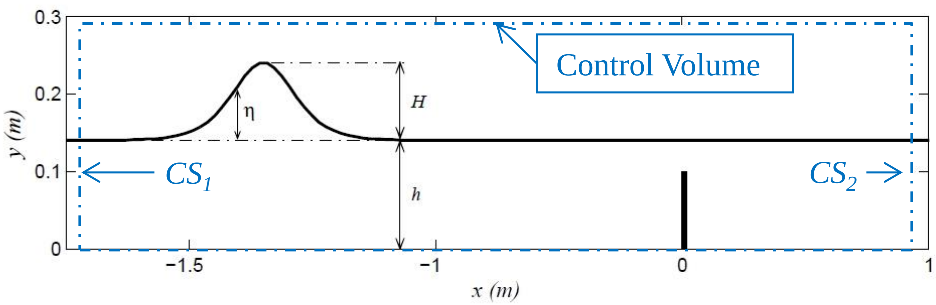
$$ED = \left(E_{inc} + E_{ref}\right) - \left(E_{trans}\right)$$

$$K_R = \sqrt{\frac{-E_{ref}}{E_{inc}}} \qquad K_T = \sqrt{\frac{E_{trans}}{E_{inc}}}$$

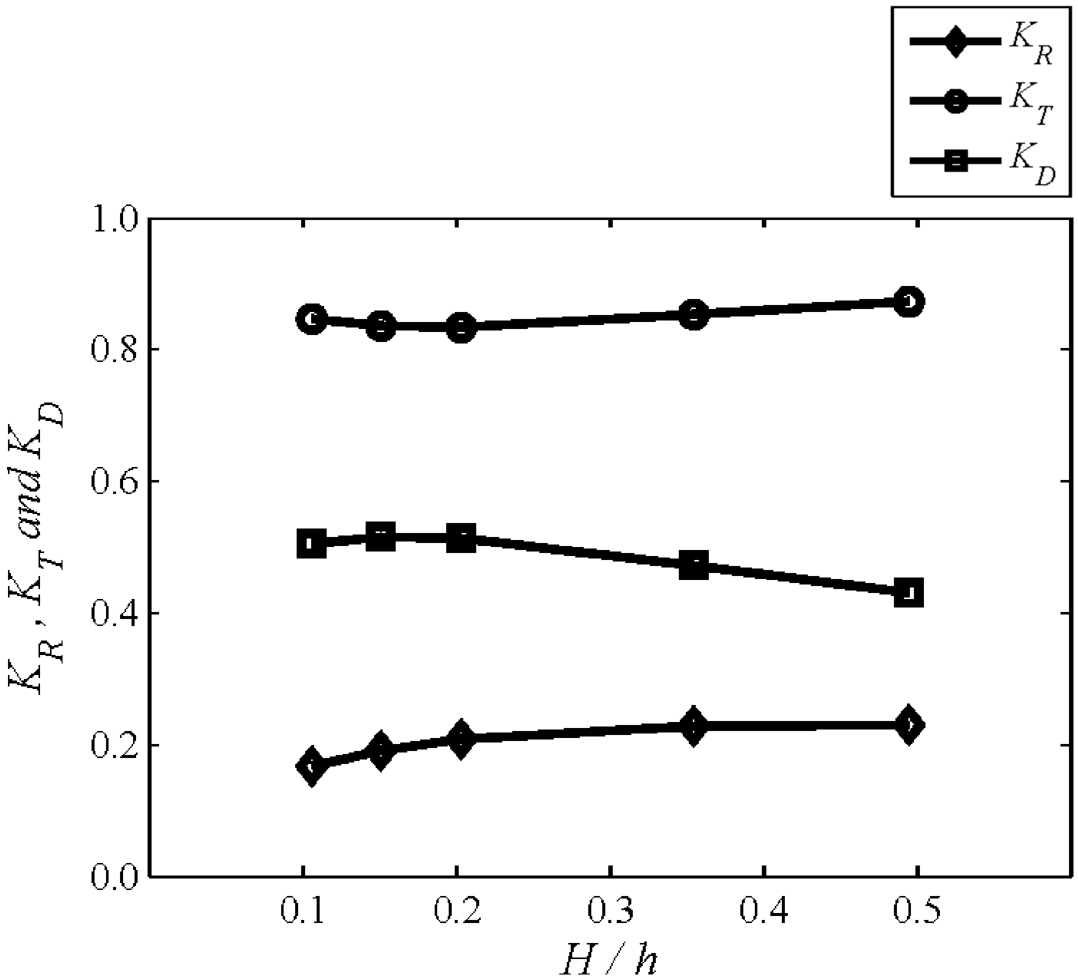
$$K_D = \sqrt{\frac{ED}{E_{inc}}} = \sqrt{1 - K_R^2 - K_T^2}$$

***E*** : total mechanical energy
(kinetic energy + potential energy)

***D*** : the rate of local energy dissipation within CV



# *Energy Dissipation*




- Energy reflection coefficient ($K_R$) increases with increasing $H / h$ .
- Energy transmission coefficient ($K_T$) decreases with increasing $H / h$ from 0.10 to 0.20 then increases from 0.20 to 0.50.
- Energy dissipation coefficient ($K_D$) increases with increasing $H / h$ from 0.10 to 0.15 then decreases from 0.15 to 0.50.
- Max. $K_D$ ⇨ $H / h$ = 0.15.
- $K_D > K_R$

# *Conclusion and Ongoing Works*

- Scientific computing is a powerful means in solving practical problems in coastal and ocean engineering. However, to capture and interpret the physical phenomena correctly, it requires deep understanding of the problems.
- Status of computational research

✓Oyster Larvae (OL) dispersion simulation

✓Coupling model (Shallow water equation +Navier-Stokes equation)

✓Waves propagating over the density-stratified fluid in a submarine trench

✓Solitary wave interaction with a submerged vertical barrier (Slotted / Perforated Barrier )

✓Meshless Potential Flow Model

✓Plunging wave-interaction with a nearshore platform


Thanks for your attention~!!!