



SUPERGEN Wind 2011 General Assembly

Numerical modelling of sub-sea turbine foundations

Prof. Clive Mingham, Dr. Feng Gao and Prof. Derek Causon



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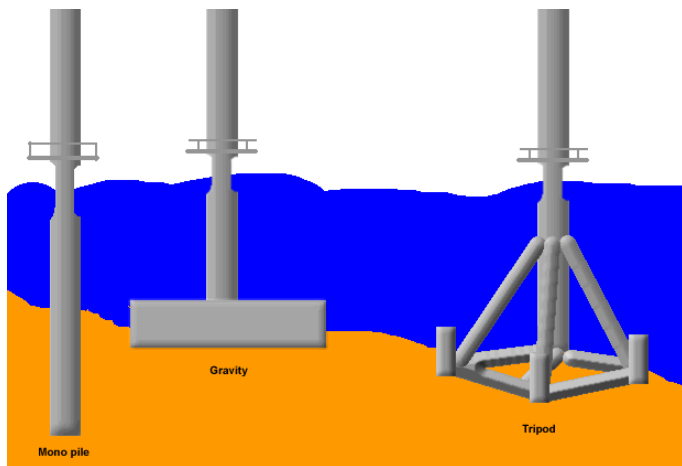


Numerical modelling of sub-sea turbine foundations

Outline

- 1. Background*
- 2. Flow solver*
- 3. Sediment transport*
- 4. Wave Impact*
- 5. Future work*

1. Background



Shallow water

Intermediate water

Sources: the Danish Wind Industry Association



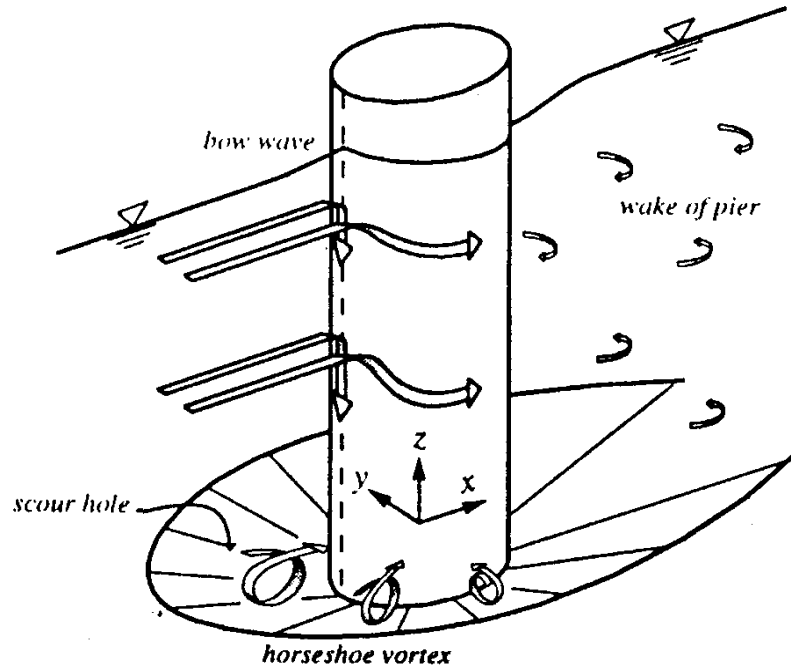
(Source: Statoil Hydro)

Deep water: Monopile

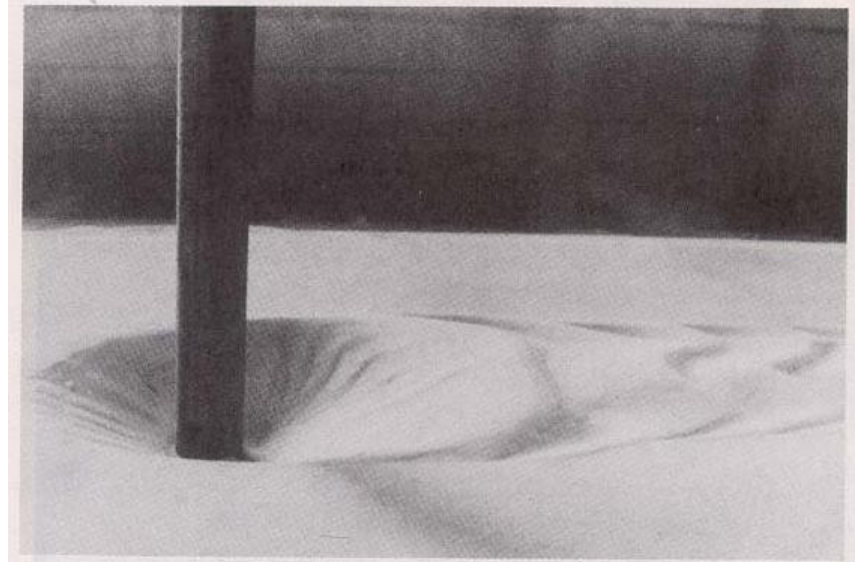
jacket type mount

Large offshore wind farms

1. Background



(a) Definition sketch



(b) Experiment

Flow pattern in the scour hole around a cylinder

(W.H.GRAF and I. ISTIARTO *JOURNAL OF HYDRAULIC RESEARCH*, Vol. 40, 2002)



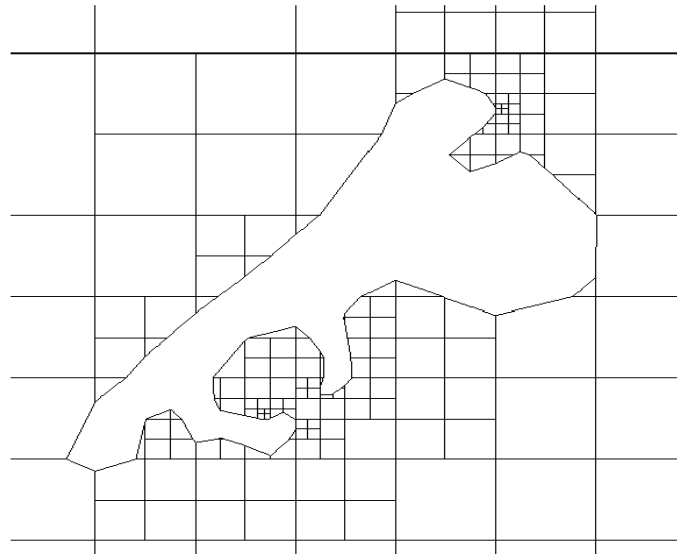
2. *Flow solver*

- Incompressible Navier-Stokes solver **AMAZON-3D** — Based on an artificial compressibility method.
- Surface-capturing method
 - Treats the free surface as a contact discontinuity in the density field; special procedures to track the free surface are eliminated .
- Fully two phase approach which solves in **both** the air and water fluid regions.
- Cartesian **cut cell** mesh
 - flexibility for boundary-fitting complex geometries
 - no requirement to re-mesh globally - only requires cut cell data locally at cells cut by a moving boundary contour.



2. *Flow Solver*

- Cut cells work for *any* domain



Example: Adaptive cut cell mesh for an island

2. Flow solver

Governing equations

3D incompressible, Navier-Stokes equations with variable density:

$$\frac{\partial}{\partial t} \iiint_{\Omega} \mathbf{Q} d\Omega + \oint_S \mathbf{F} \cdot \mathbf{n} ds = \iiint_{\Omega} \mathbf{B} d\Omega$$

where

$$\mathbf{Q} = \left[\rho \quad \rho u \quad \rho v \quad \rho w \quad \frac{p}{\beta} \right]^T, \mathbf{F} = \mathbf{f}^I n_x + \mathbf{g}^I n_y + \mathbf{h}^I n_z,$$

$$\mathbf{B} = [0 \quad 0 \quad 0 \quad -\rho g \quad 0]^T$$

$$\mathbf{f}^I = [\rho u \quad \rho u^2 + p \quad \rho uv \quad \rho uw \quad u]^T$$

$$\mathbf{g}^I = [\rho v \quad \rho uv \quad \rho v^2 + p \quad \rho vw \quad v]^T$$

$$\mathbf{h}^I = [\rho w \quad \rho uw \quad \rho vw \quad \rho w^2 + p \quad w]^T$$

β is the coefficient of artificial compressibility

3. Sediment transport

3.1 Suspended sediment transport

$$\frac{\partial c}{\partial t} + u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} + (w - \omega_s) \frac{\partial c}{\partial z} = \frac{\partial}{\partial x} \left(\frac{\nu_t}{\sigma_c} \frac{\partial c}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\nu_t}{\sigma_c} \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial z} \left(\frac{\nu_t}{\sigma_c} \frac{\partial c}{\partial z} \right)$$

where c is the volumetric concentration of suspended sediment

u, v, w are velocity components

ν_t is the turbulent eddy viscosity

σ_c is the turbulent Schmidt number. (which is taken to be 0.8)

ω_s is the settling velocity of sediment.

$$\frac{\omega_s}{\omega_{s0}} = (1 - c)^m \quad m \text{ is a grain size related constant } (m = 5)$$

ω_{s0} is the settling velocity of natural sands in clear water

we choose Soulsby's formulation (1997)

$$\omega_{s0} = \frac{\nu}{d_{50}} \left[\left(10.36^2 + 1.049 D_*^3 \right)^{0.5} - 10.36 \right]$$

3. Sediment transport

3.2 Bed load transport

$$q_b = \begin{cases} 0.053[(s-1)g]^{0.5} \frac{d_{50}^{1.5} T^{2.1}}{D_*^{0.3}} & T > 0 \\ 0 & T \leq 0 \end{cases}$$

where q_b is the volumetric bed load transport rate per unit width.

T is the non-dimensional excess shear stress or transport stage parameter.

$$T = \frac{u_{*s}^2 - u_{*cr}^2}{u_{*cr}^2}$$

where u_{*s} is the friction velocity component due to skin friction

u_{*cr} is the threshold bed friction velocity for motion of sediment.

An algebraic expression of the Shields diagram is used to calculate u_{*cr}
(Soulsby and Whitouse (1997))

$$\theta_{cr0} = \frac{0.3}{1 + 1.2D_*} + 0.055[1 - \exp(-0.02D_*)]$$

where θ_{cr0} is the threshold Shields parameter on horizontal bed.

3. *Sediment transport*

3.3 *Bed deformation*

$$\frac{\partial z_b}{\partial t} = \frac{1}{1 - p_0} \left[-\frac{\partial q_{tx}}{\partial x} - \frac{\partial q_{ty}}{\partial y} - \frac{\partial}{\partial t} \left(\int_{z=z_b}^{z_b+H} cdz \right) \right]$$

where p_0 is the porosity of the bed material.

z_b is the seabed elevation

q_{tx} and q_{ty} are the total sediment transport rates in x and y directions

Sand slide:

adjust the local bed slope when the angle of repose is exceeded.

3. *Sediment transport*

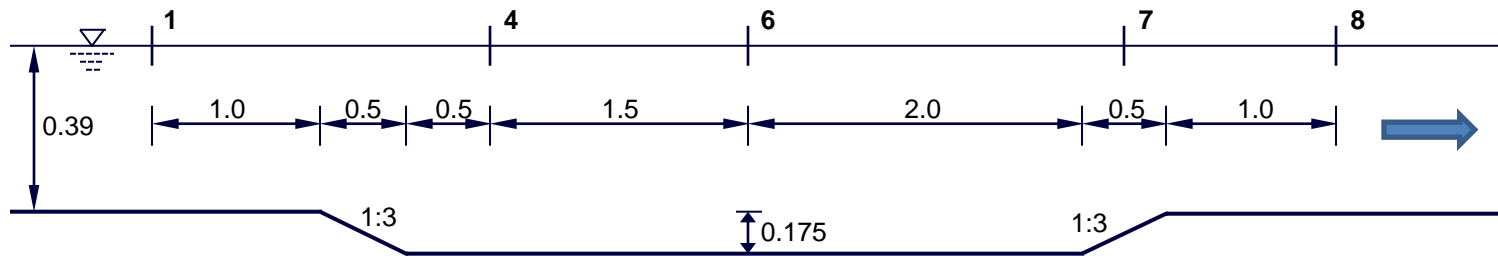
3.4 *Steps involved in a CFD simulation:*

- 1) Start from an initial channel bed and flow field;
- 2) Solve the turbulent flow model to get the velocity, pressure and turbulent quantities;
- 3) Compute the suspended sediment concentration;
- 4) Compute the bed load and suspended sediment transport rates;
- 5) Calculate the bed deformation and bed elevation, adjust the grid and update bed shape;
- 6) Return to step 2) and repeat until specified time is reached.

3: Results: Sediment transport

Sediment transport in a trench:

One of Rijn experimental tests (1985, flow past a trench)

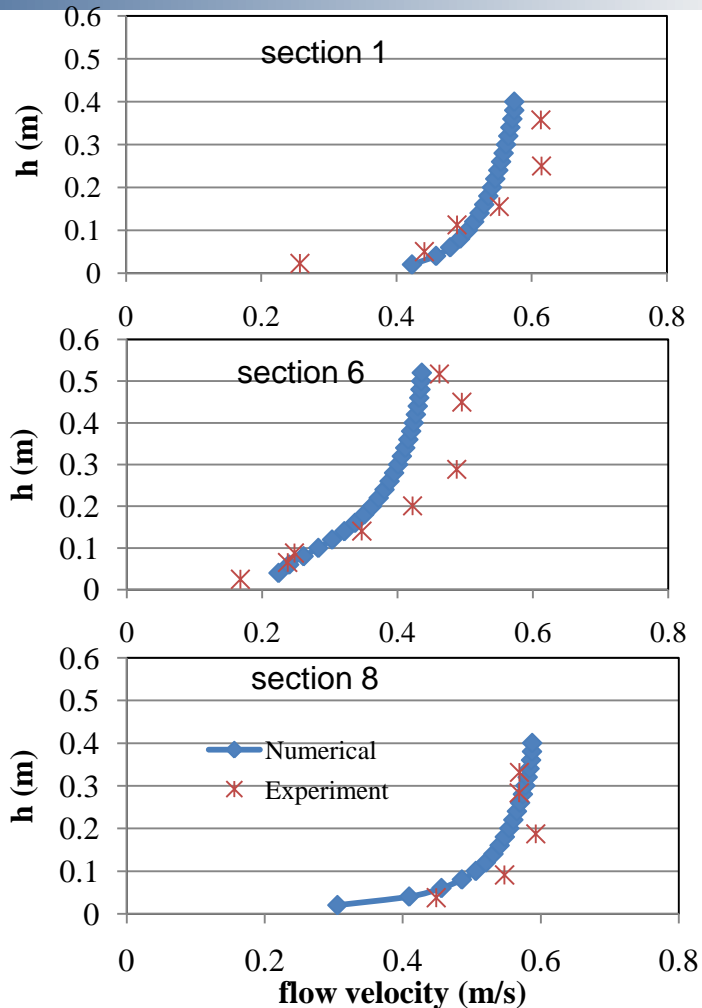


Computational set up

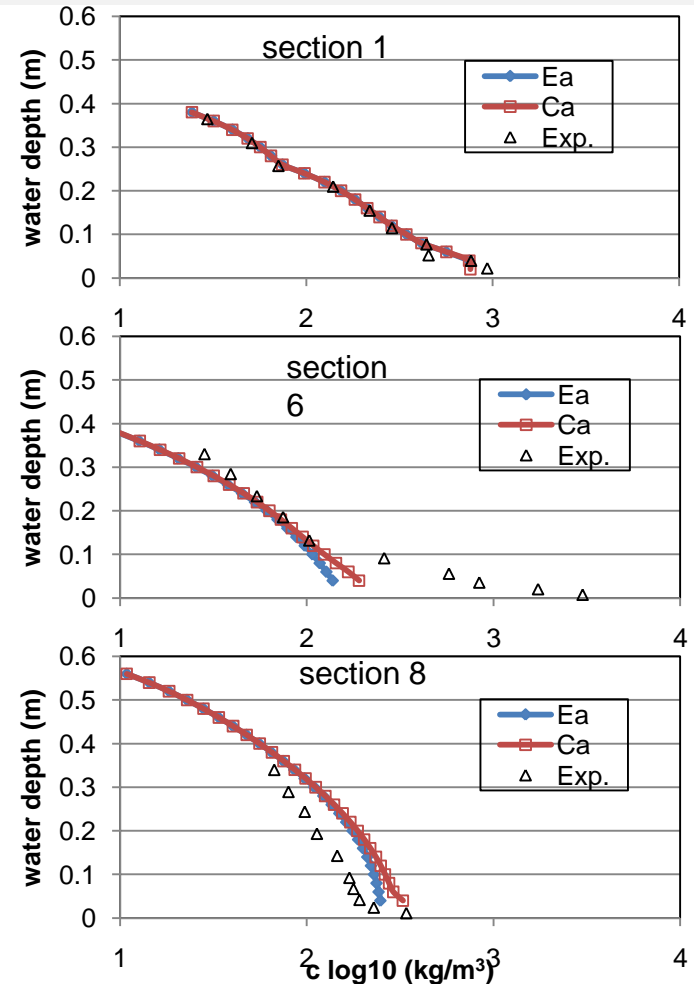


Sediment concentration development in first 90s

3. Results: Sediment transport



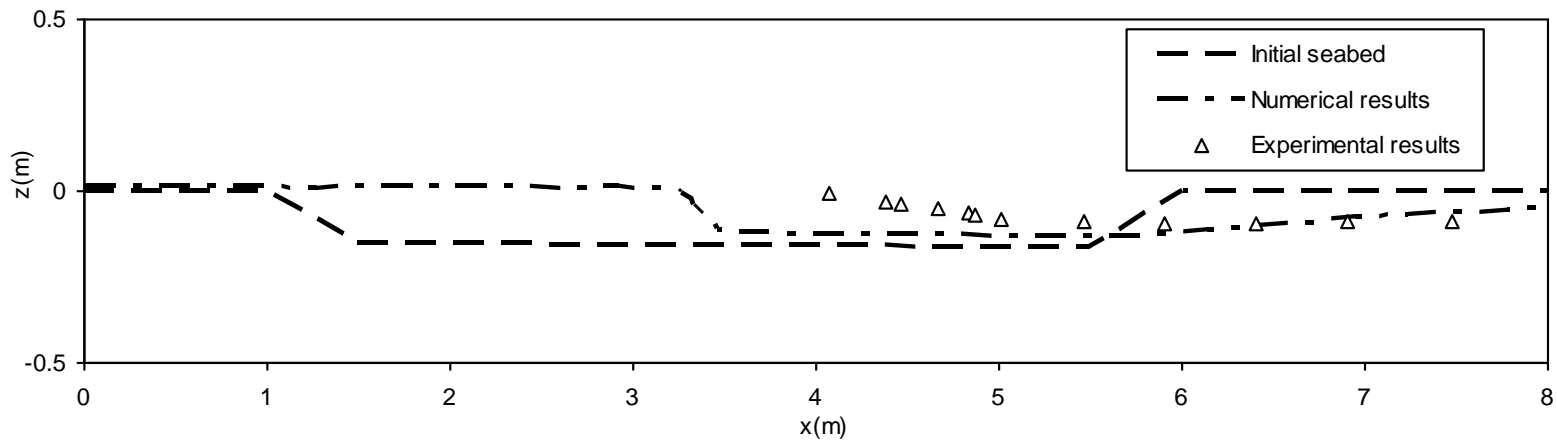
Velocity distribution at different sections



Water depth v sediment concentration

3. Results: Sediment transport

Sediment transport in a trench:



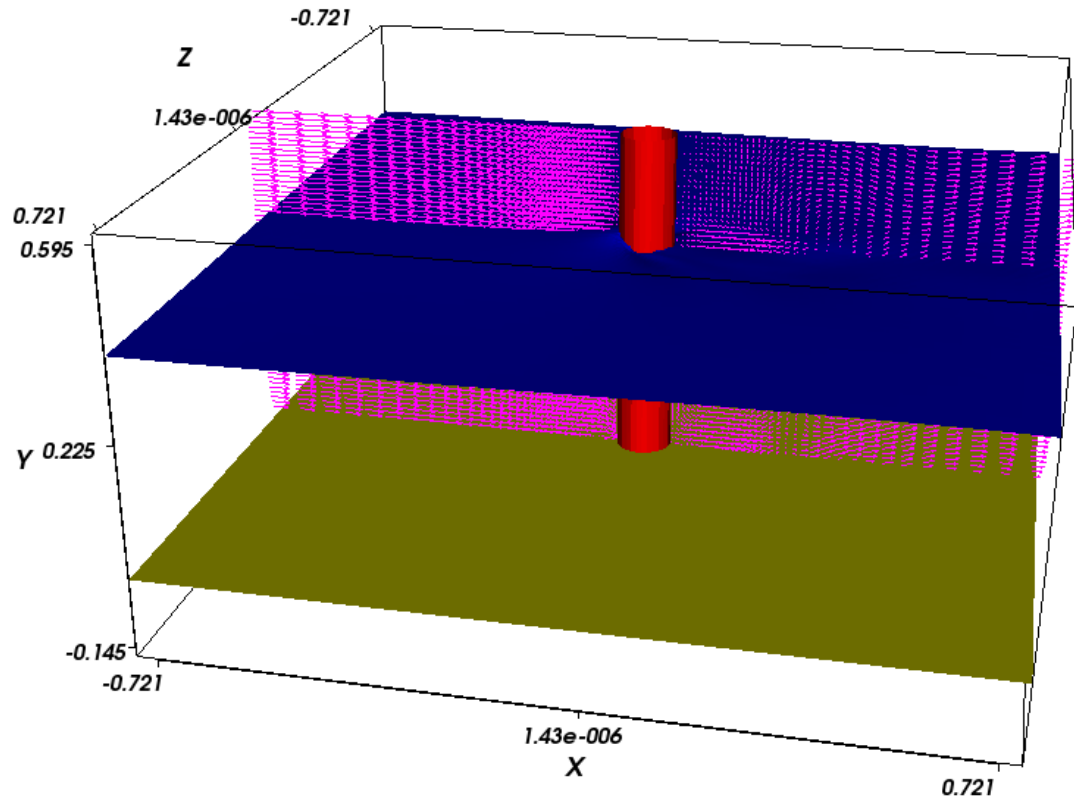
Comparison of morphological change after 15 hours

3. Results: Scour

Scour simulation around a circular cylinder:

Input velocity distribution is using logarithmic flow velocity profile:

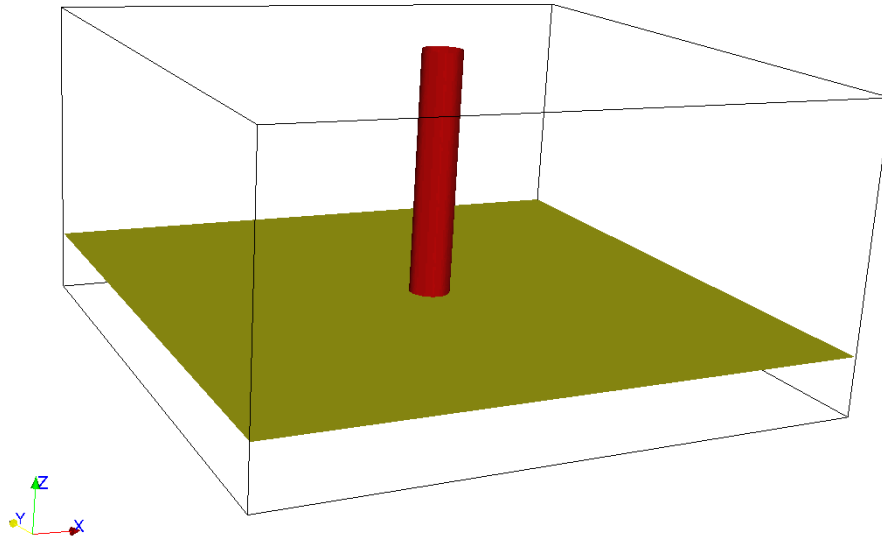
$$u_z = \frac{u_*}{K} \ln \frac{z}{z_0}$$



Computational set up for scour simulation

3. *Results: Scour*

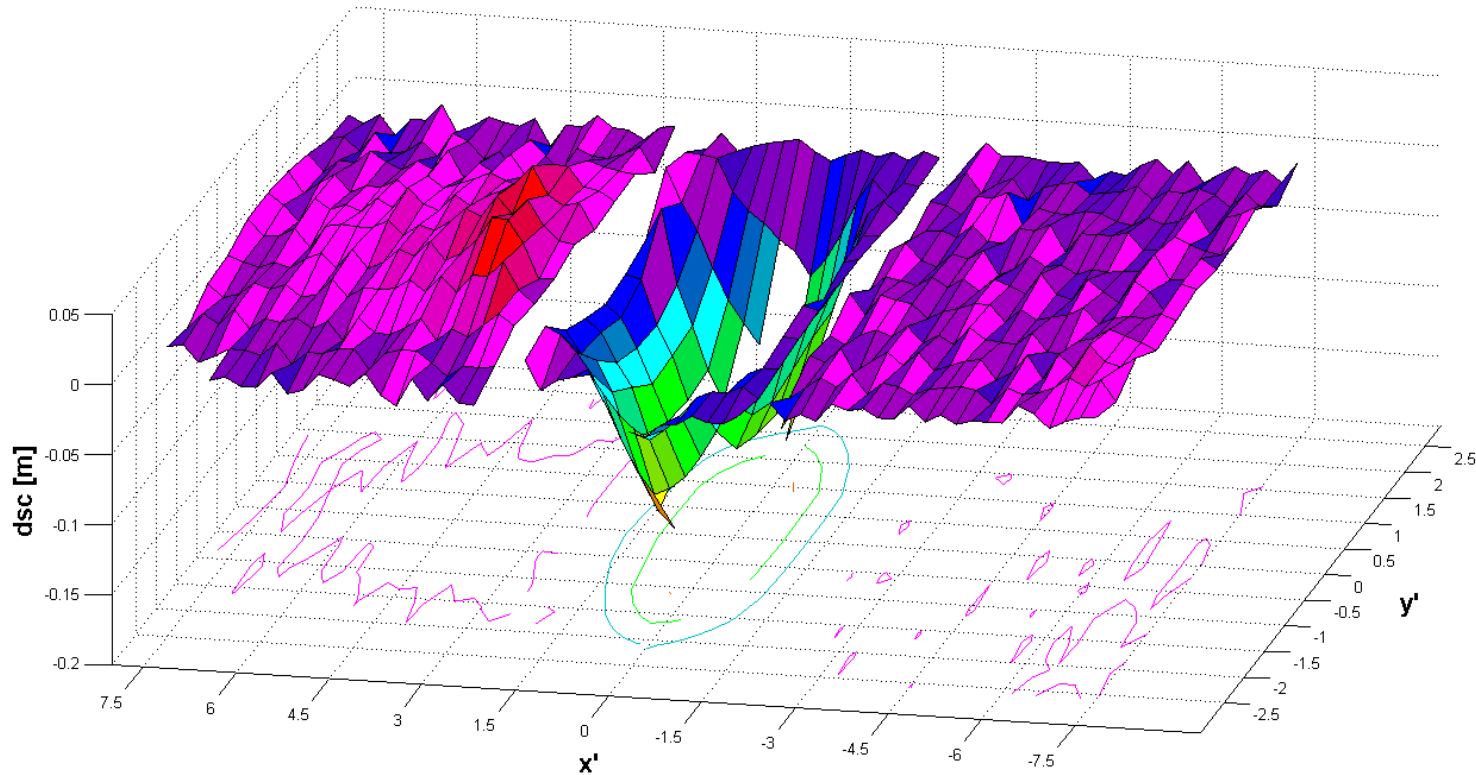
Scour simulation around a circular cylinder:



Scour hole development at $t = 2400s$ model scale

3. Results: Scour

Lancaster laboratory tests :



Bed profile for scour around a circular cylinder in unidirectional flow (2.5h)
with $u = 0.31$ m/s right to left, water depth $h = 0.25$ m.

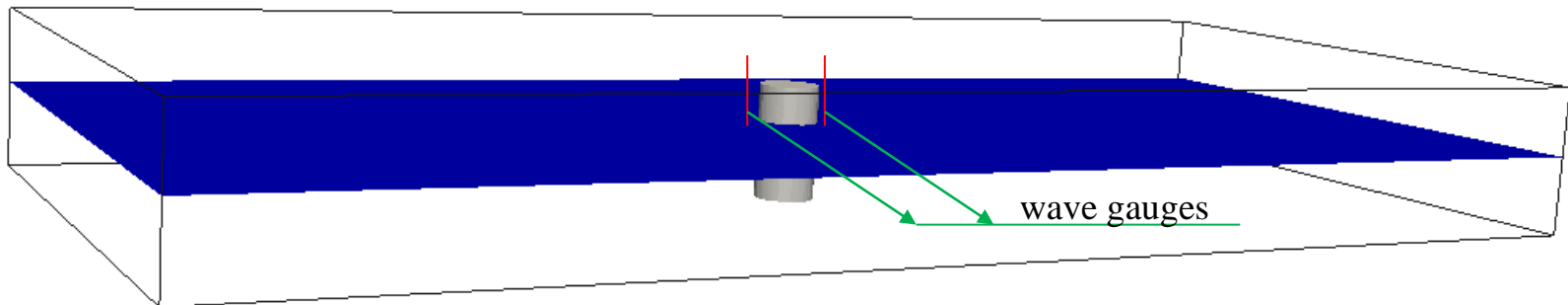
4. Results: Wave impact

Wave impact on a vertical cylinder: validation

NWT outer dimensions: $8 \times 3.6 \times 0.9 \text{ m}^3$

water depth : $h = 0.45\text{m}$

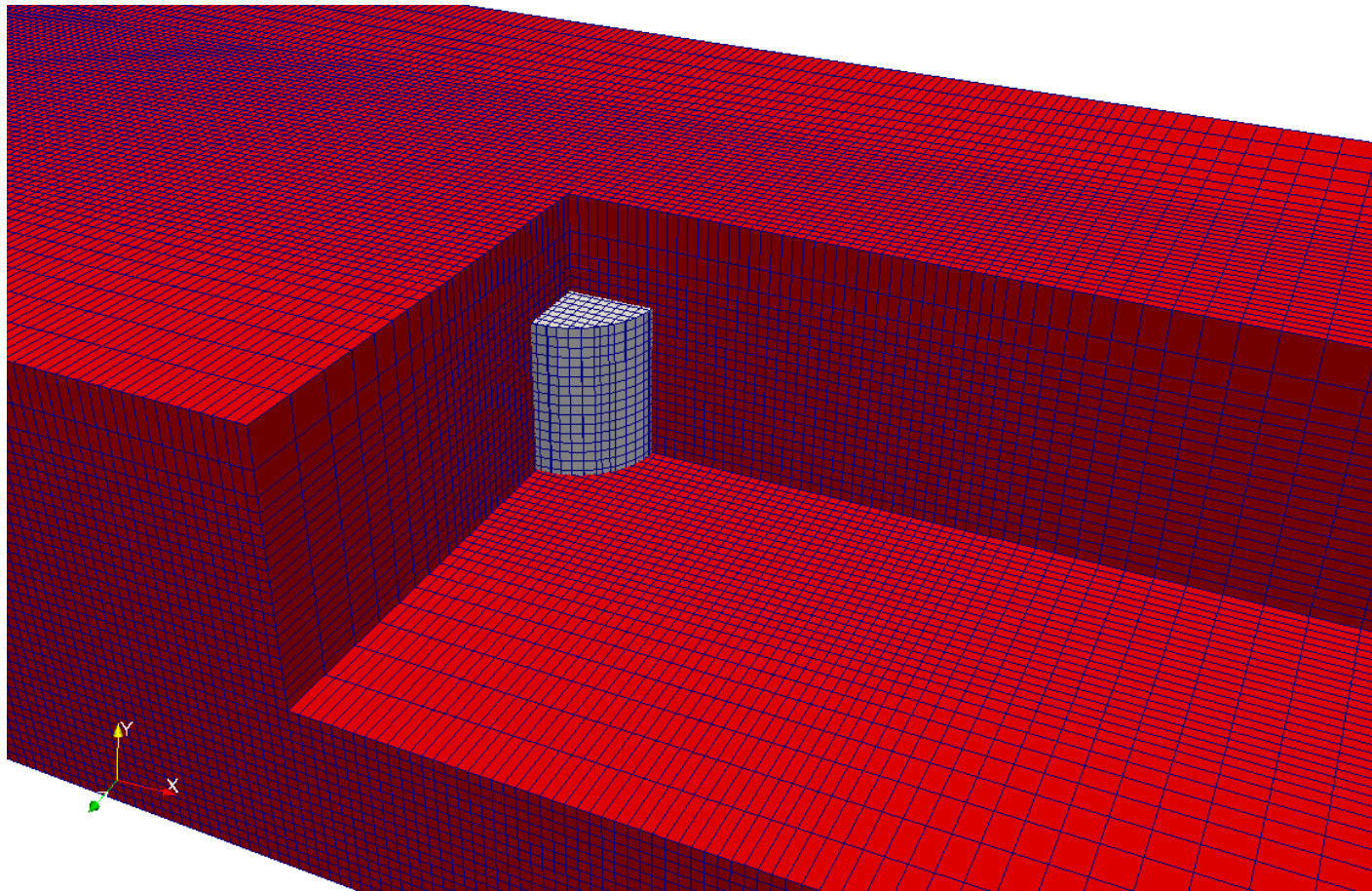
cylinder diameter: $d = 0.325\text{m}$



	Case1	Case2	Case3	Case4
Wave amplitude (m)	0.0535	0.048	0.0621	0.074
Wave period (s)	1.95	1.75	1.50	1.25
ka	0.271	0.308	0.374	0.481

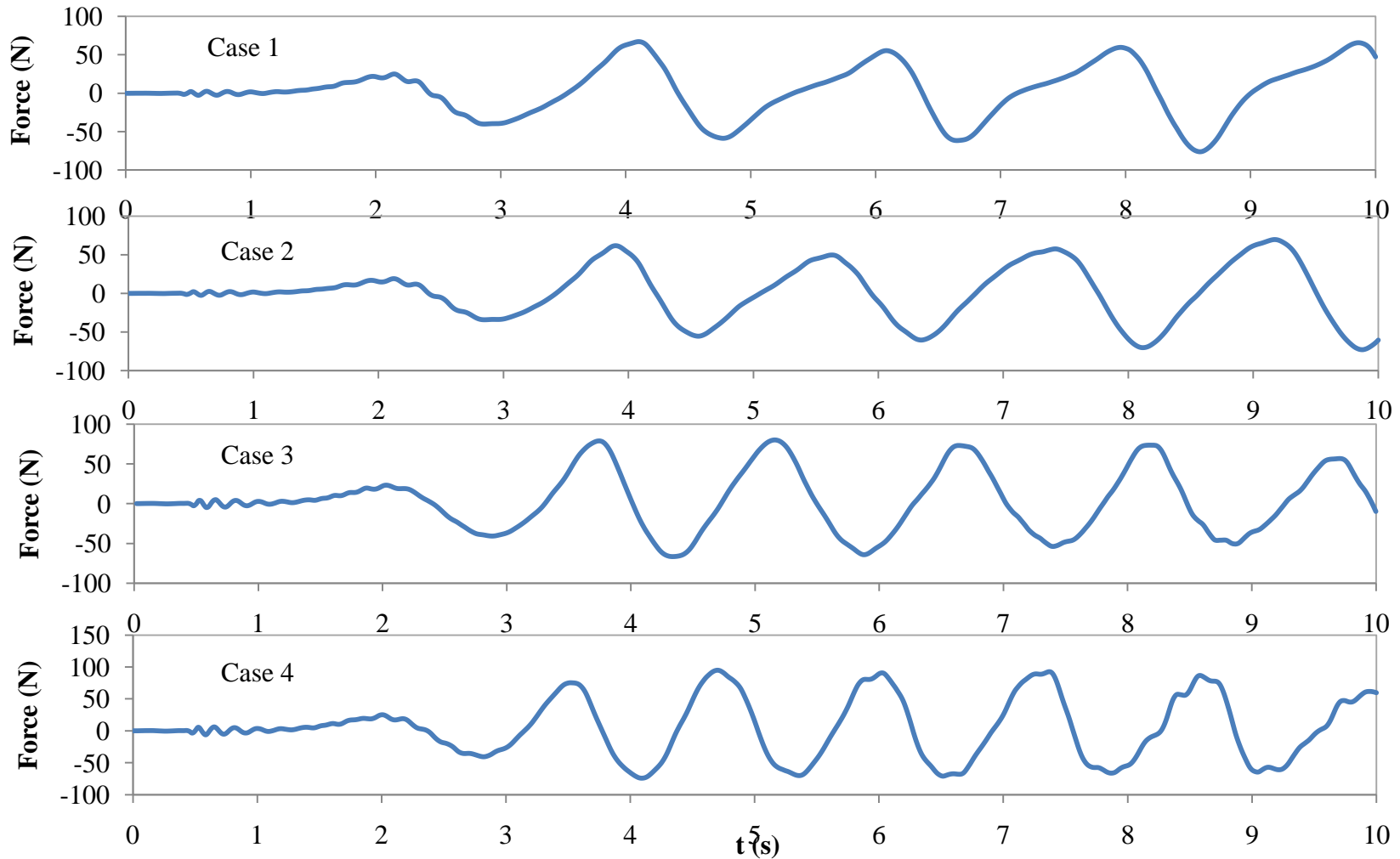
Experiments and Theoretical analysis conducted by D.L. Kriebel (1998) and J.R. Chaplin *et al.* (1997) , used to validate the computer model

4. *Results: Wave Impact*



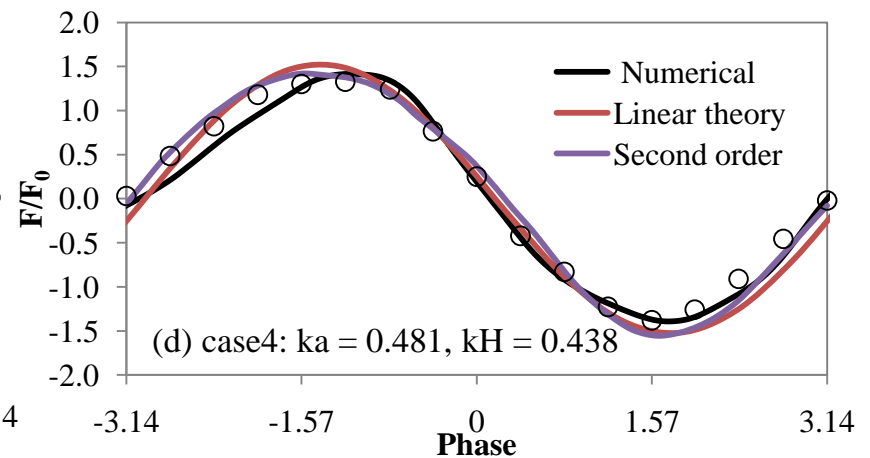
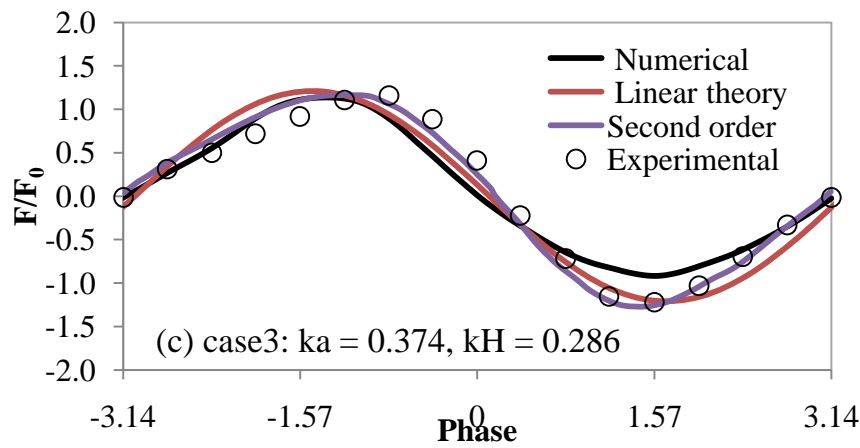
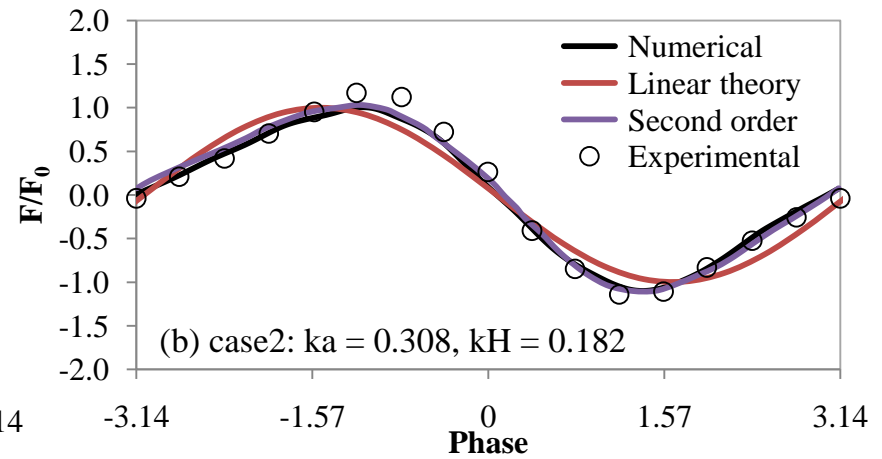
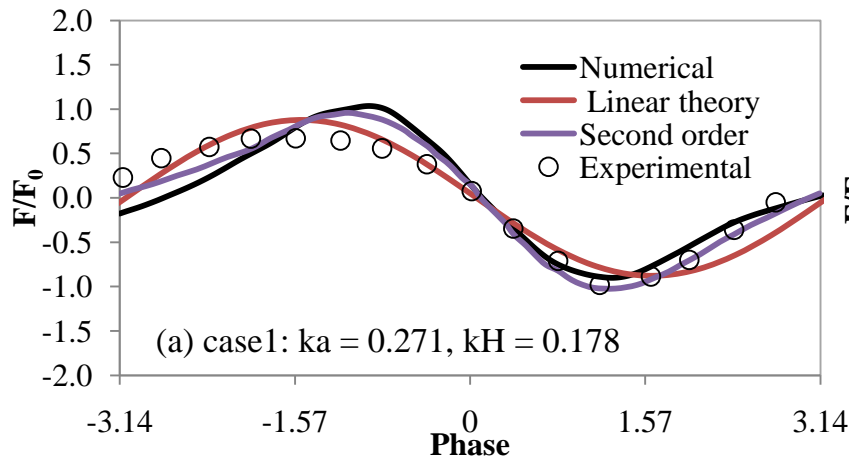
3D computational mesh around vertical circular cylinder
(non-uniform mesh : $258 \times 39 \times 62 = 623,844$)

4. Results: Wave impact



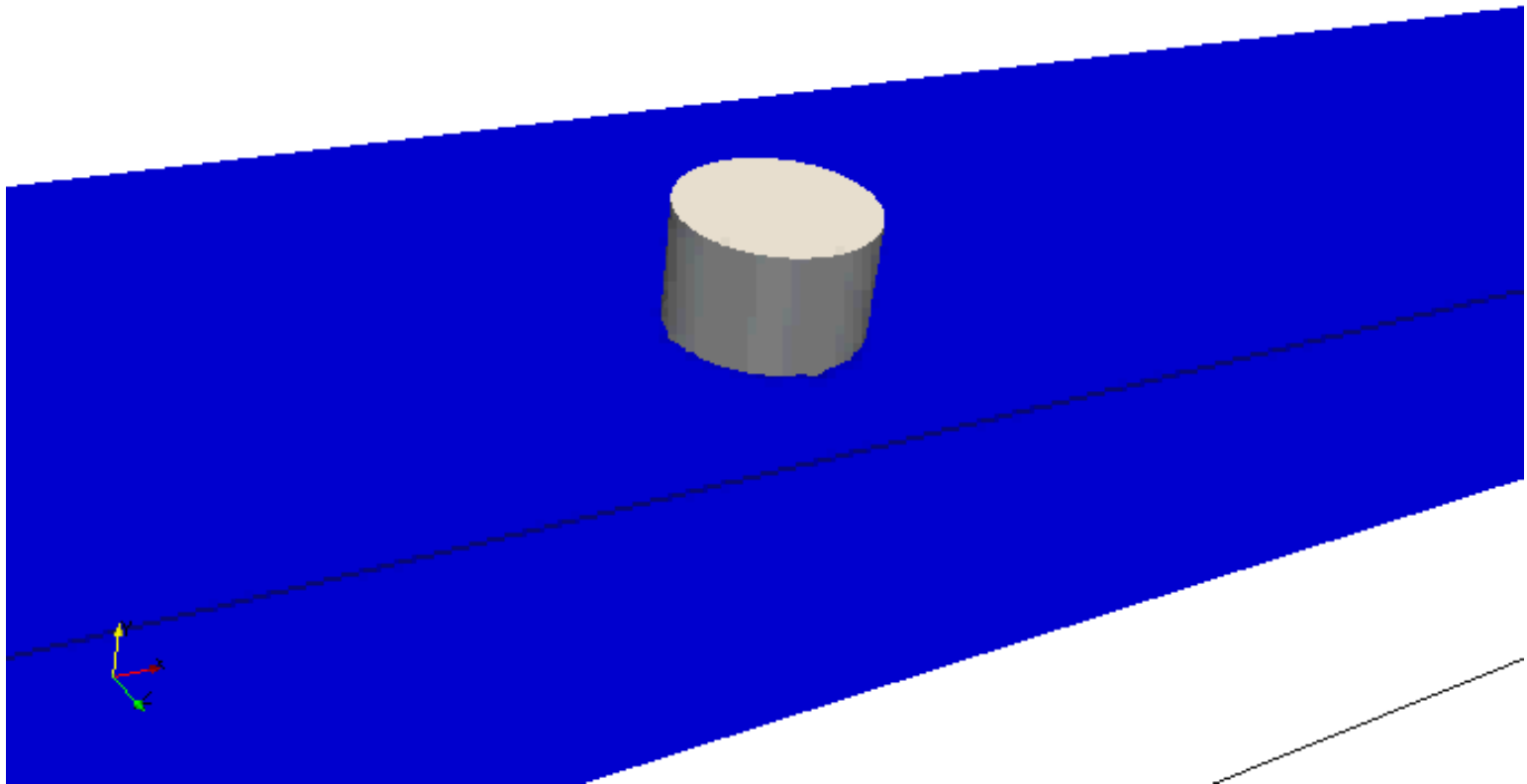
Time history of horizontal force on cylinder

4. Results: Loadings



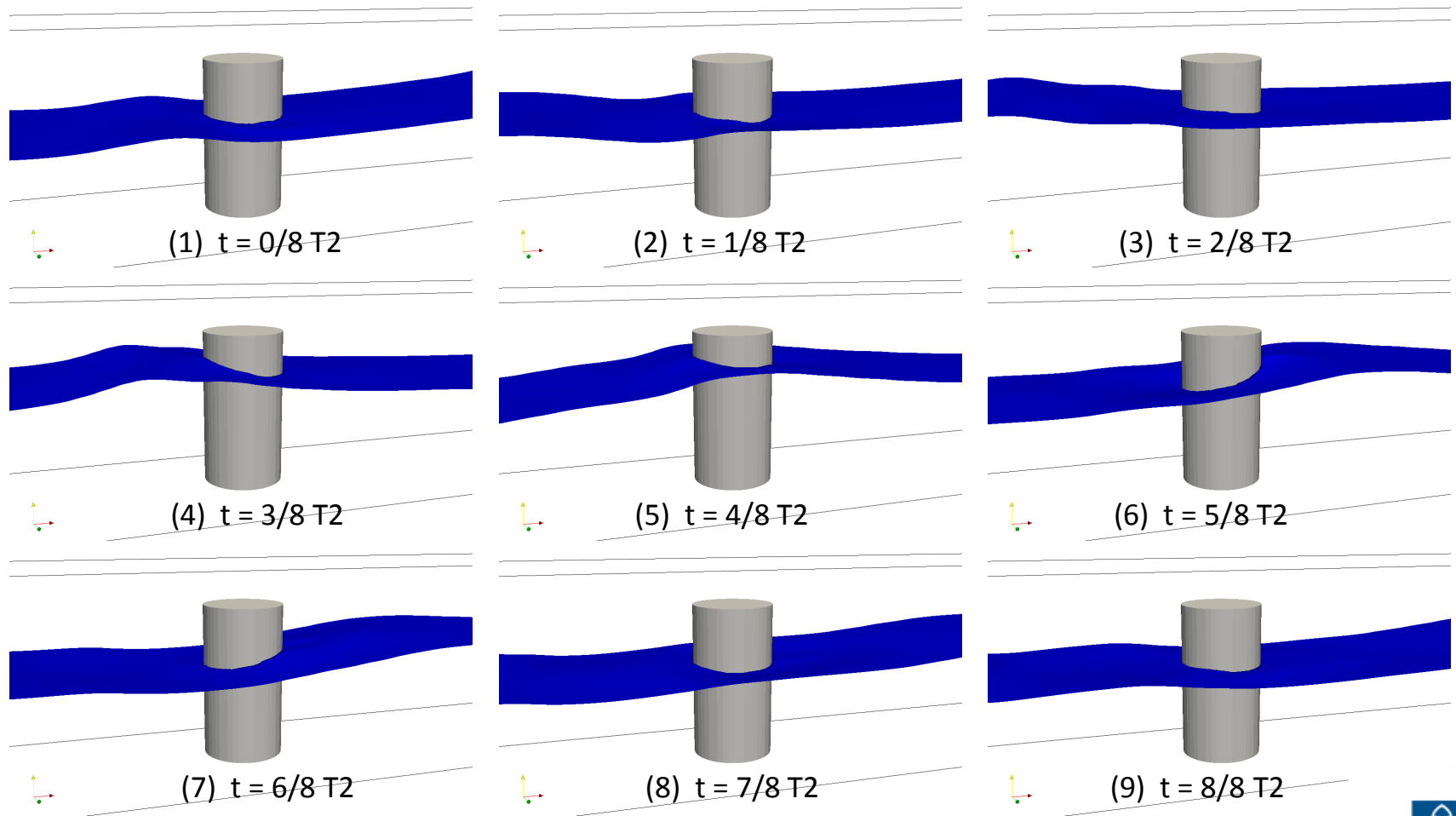
Comparison of wave force time series for various combinations of ka and kH with $d/a=2.77$

4. *Results: Surface elevation*



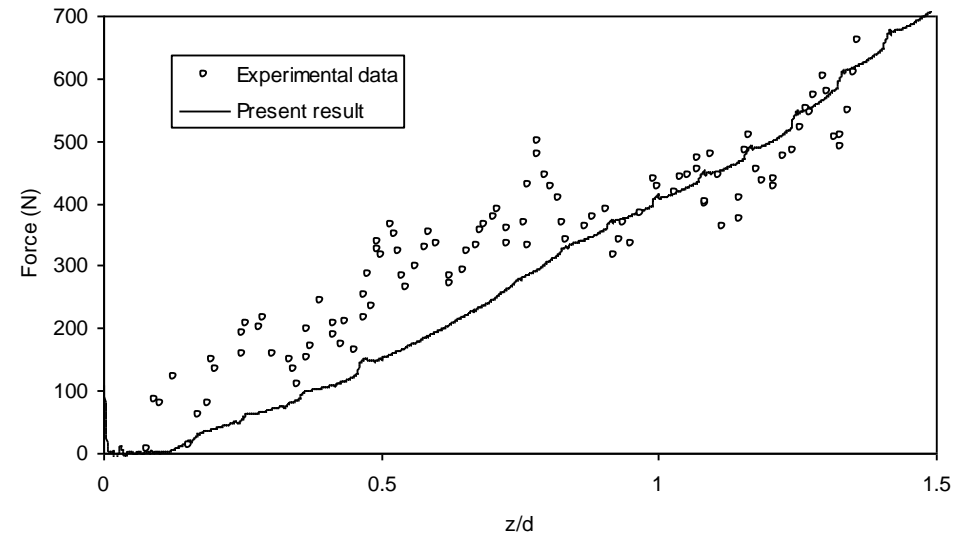
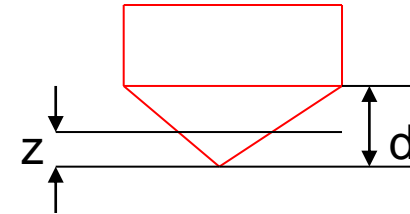
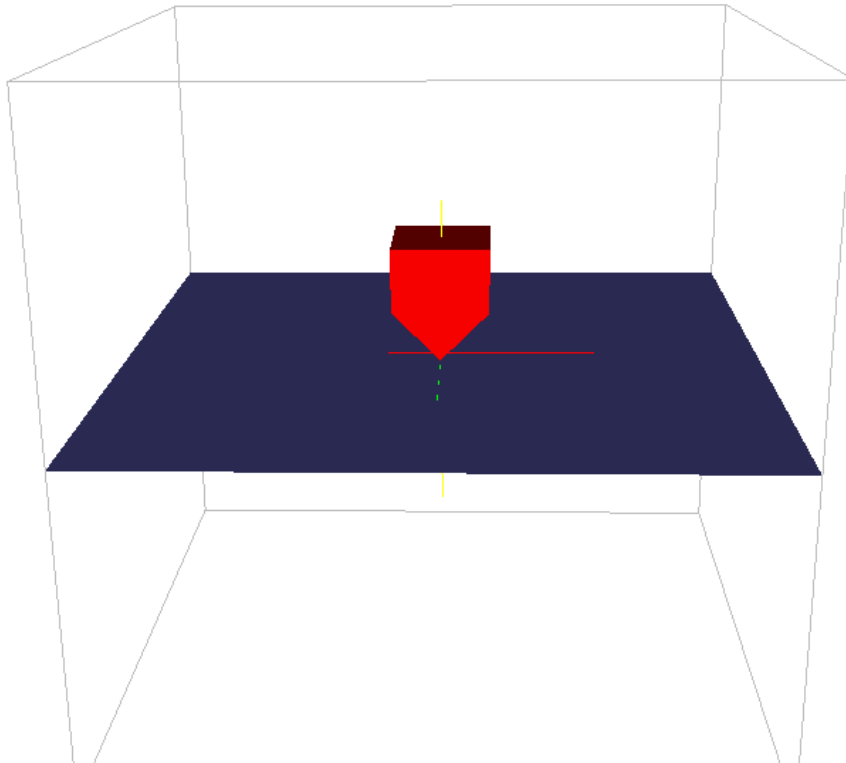
Free surface elevation around cylinder for Case1

4. *Surface Elevation*



Typical water surface around cylinder for 2nd wave period Case1

4. Slamming Test Cases

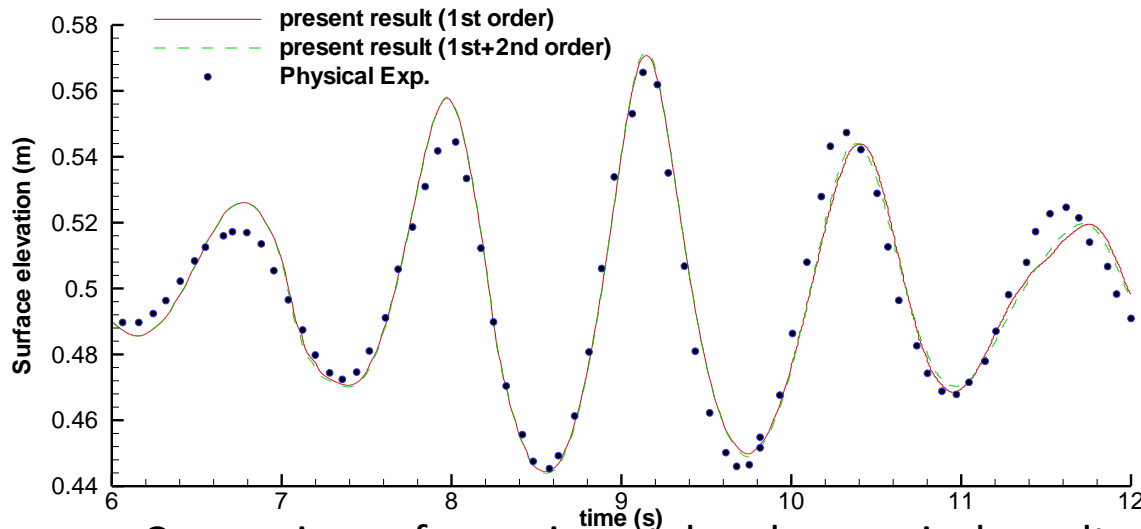


Comparison of vertical force:
numerical
v experiment (Tveitnes et. al. 2008)

4. Results: Extreme Waves

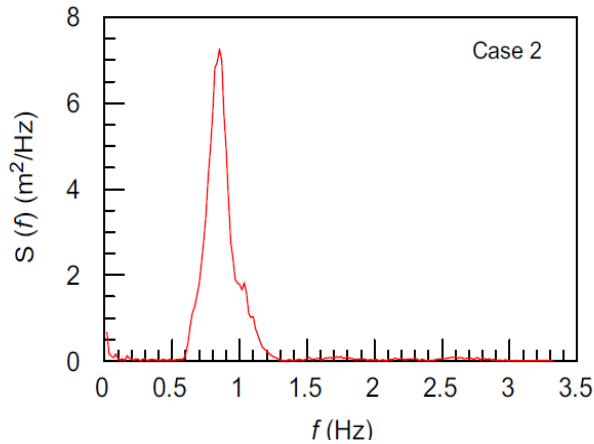
Extreme focussed wave generation test: validation

- Wave maker used by J.F. Dalzell (1999)
- Experiments conducted (4 cases) by Ning *et al.* (2008)
- Tank: $13 \times 0.03 \times 1.0 \text{m}^3$ and water depth $h = 0.5 \text{m}$
- Wave gauge set at focal point

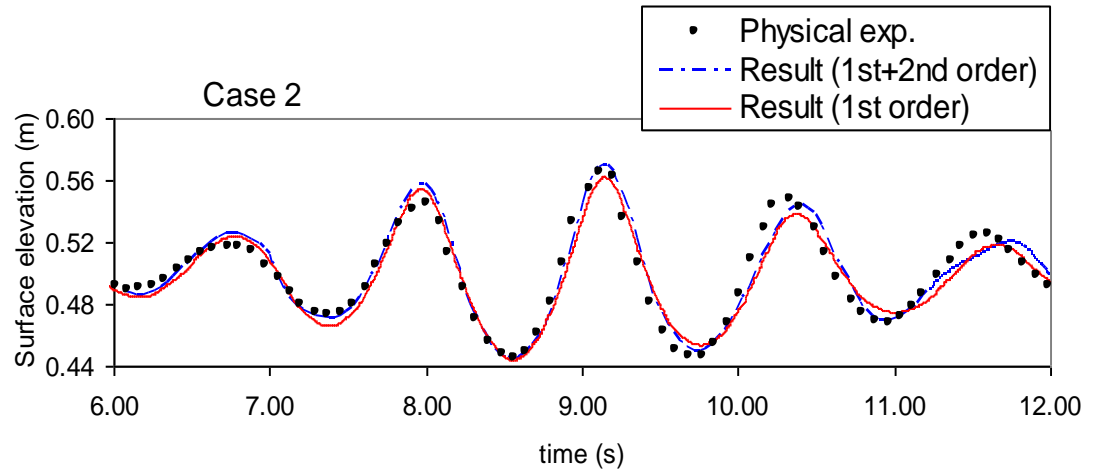


Comparison of experimental and numerical results
for free surface elevation at focal point

4. Results: Extreme waves



Input wave spectrum
with frequency



Comparison of experimental data v numerical results for
free surface elevation at focal point of $x=3.0$ m



L

Extreme wave event Case2



5. *Future work*

- Develop a numerical model of wave and current induced scour around monopile mounts.
- Extend the scour simulations to jacket type mounts.
- Continue simulations for irregular and breaking wave impact on monopile and jacket mounts.
- Refine solver to improve code stability and reduce run times (e.g. cluster, GPUs).



Thank you for your attention