Green Water Events:
Features and Related Hydrodynamic Phenomena

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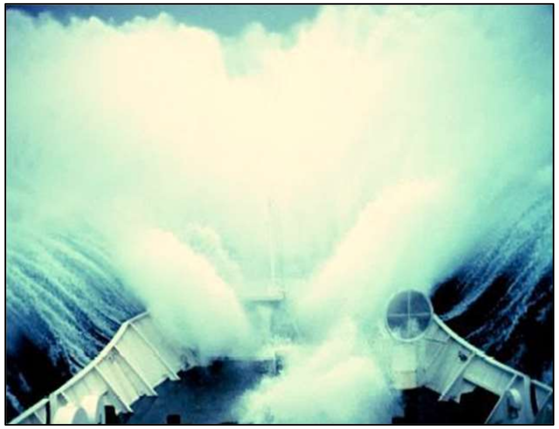
Green Water involves compact masses of water entering decks/compartments of ships or marine structures, which are exposed to the external waves.

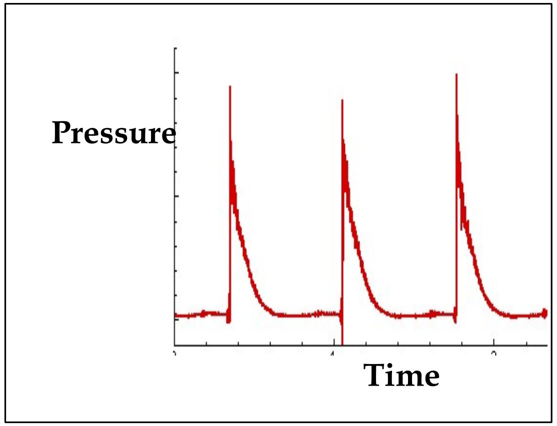
Issues: Safety, Operations, Costs

Green Water – 3 Driving Research Questions

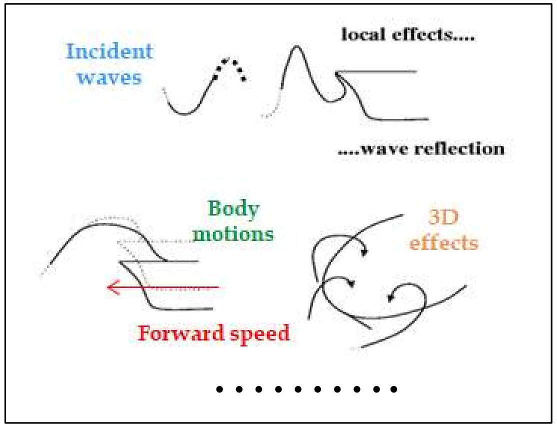
1. What are the most common and the most critical Green-Water Scenarios?



2. What are the Green-Water Loads and how they can be dangerous?

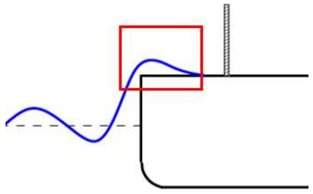
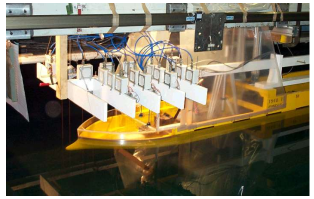


3. Which Wave-Body Parameters and Physics matter for Green Water and for its Consequences?

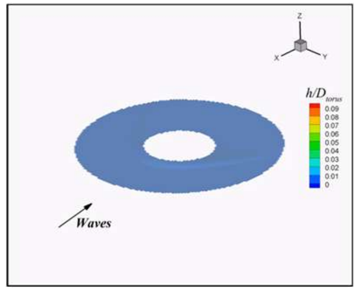


Green Water – Study Cases

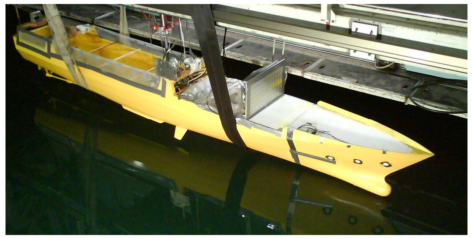
- 2D & 3D studies relevant for FPSOs (fixed/free-floating) in head-sea waves

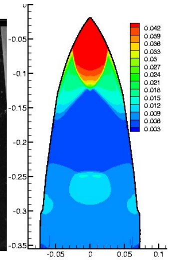




- 3D study on a non-ship shaped renewable-energy concept in waves

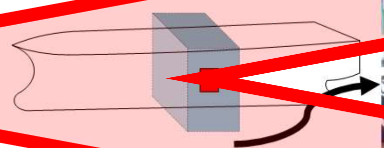


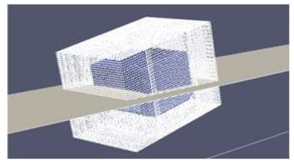
- 3D study on a ship (w/o and with forward speed) in head & nearly head-sea waves



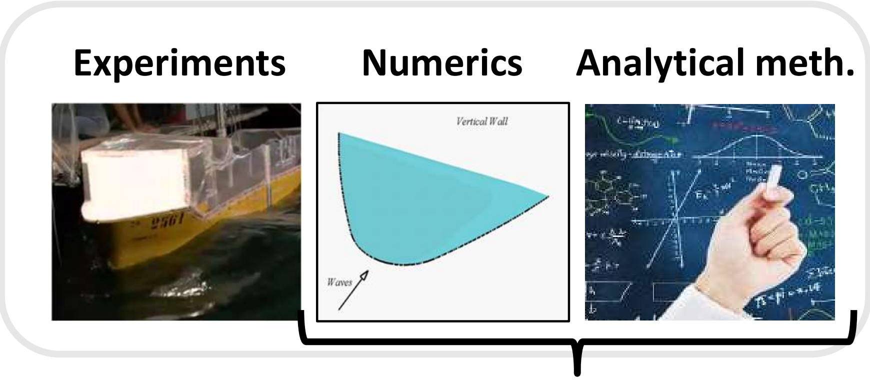


- ~~2D study on a damaged midship section in beam-sea waves~~



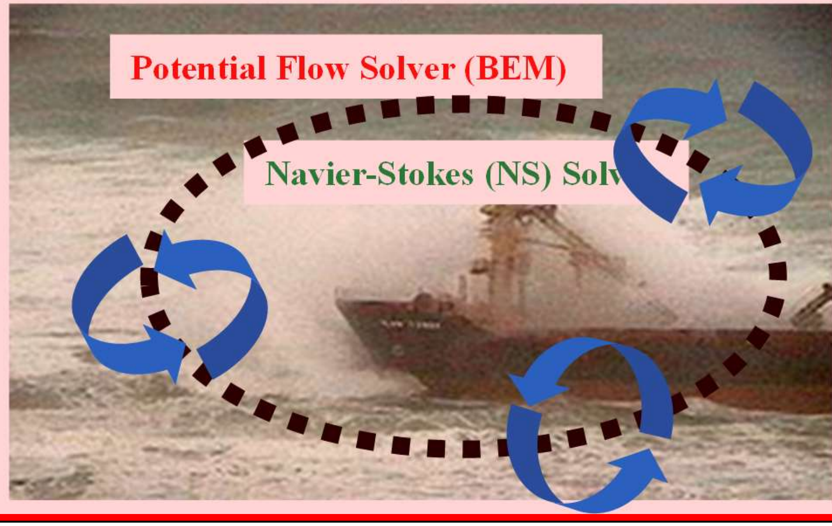


Green Water – Research Tools & Strategies



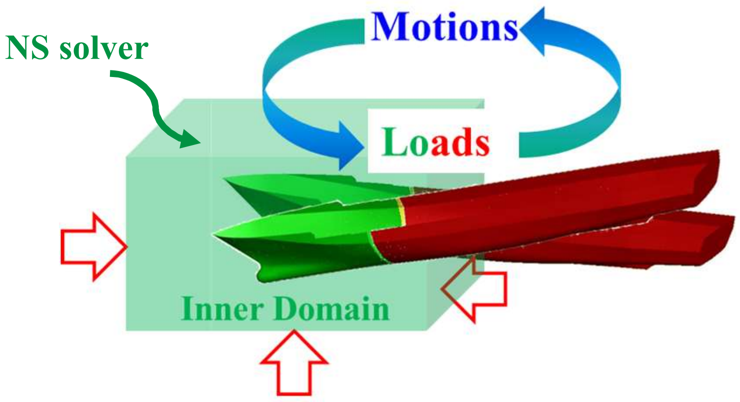
- Potential flow solver (BEM)
- Domain Decompositions (DD) Strategies

DD1: Strong coupling with exchange of local information



DD2: Simplified strong coupling with exchange of local & integrated information

DD3: Simplified strong coupling with exchange of local & integrated information

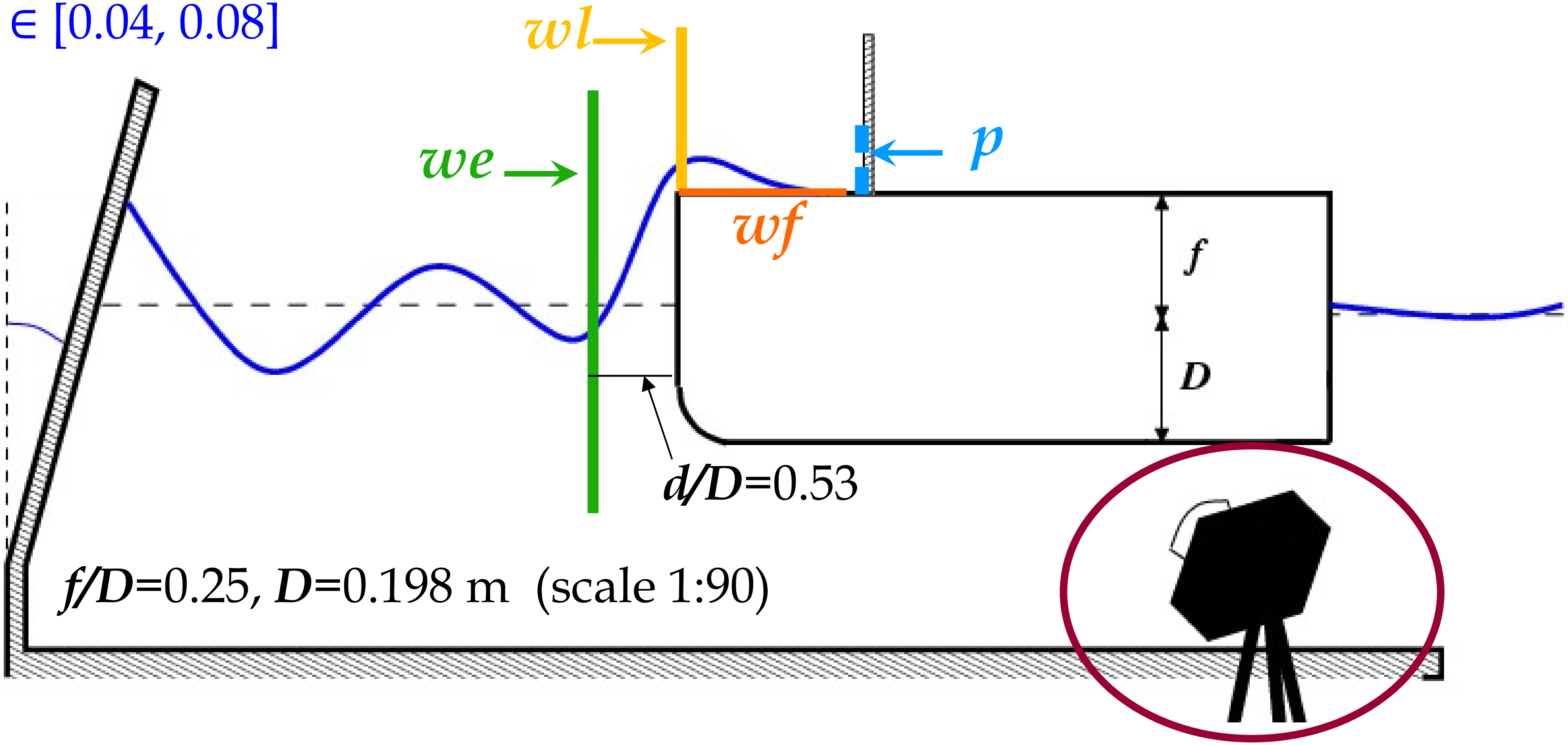


Potential seakeeping Solver
(Linear & weakly-nonlinear)

Water-On-Deck Scenarios

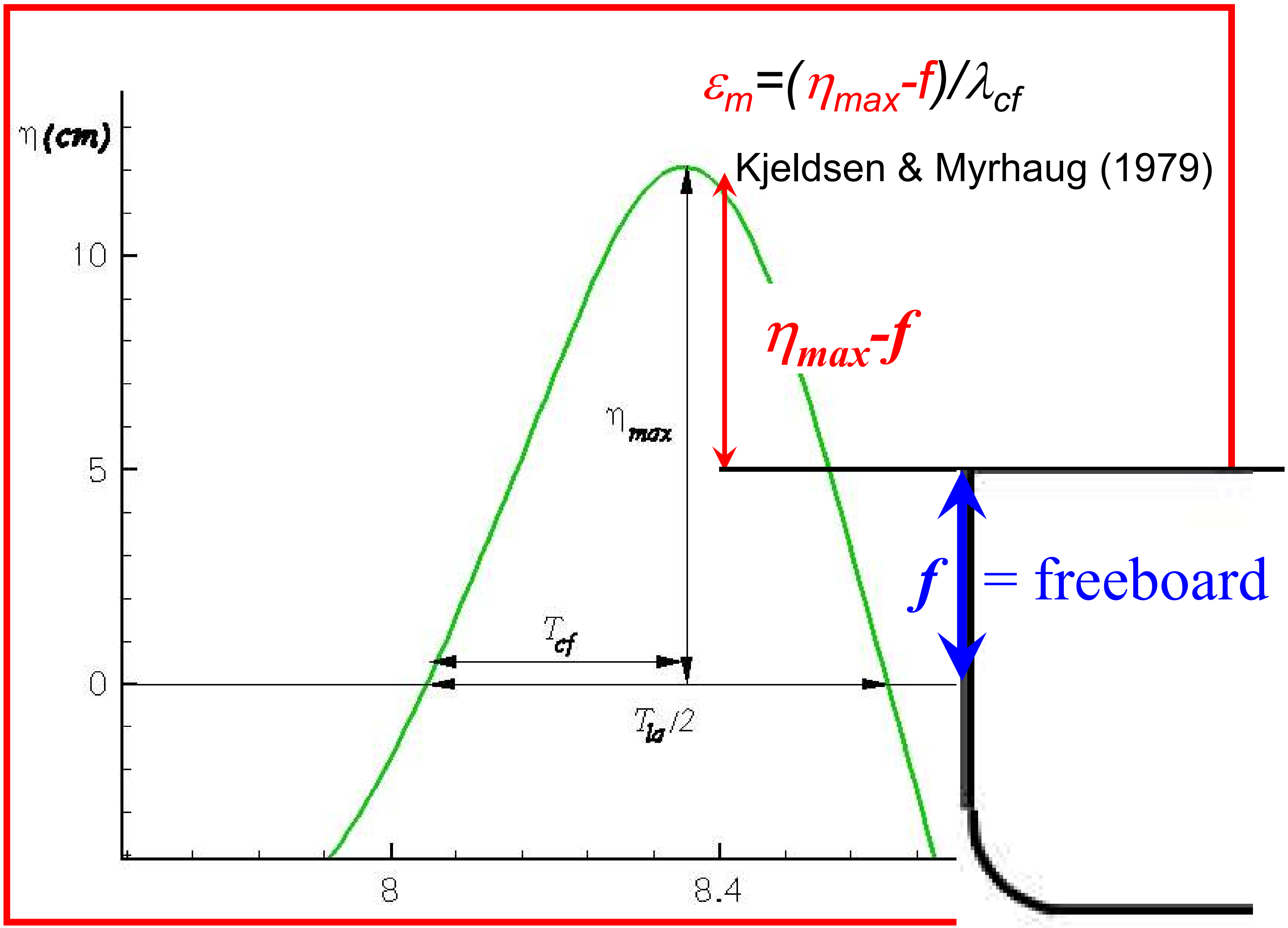
2D Water-on-Deck Experiments

$\lambda/f \in [30, 50]$
$H/\lambda \in [0.04, 0.08]$



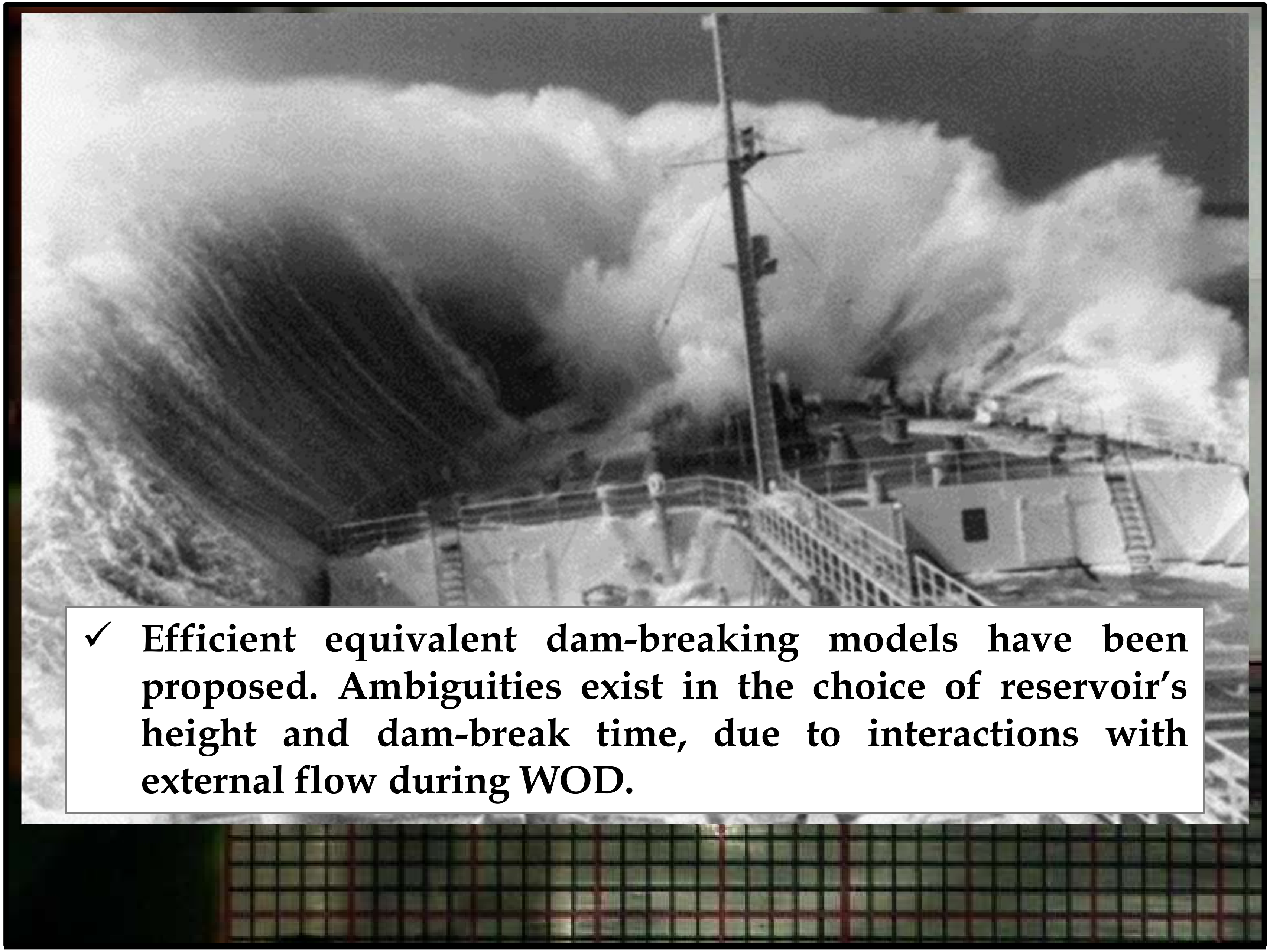
Incoming Wave 'Definition'

Crest-front local steepness



Water-on-Deck Scenarios

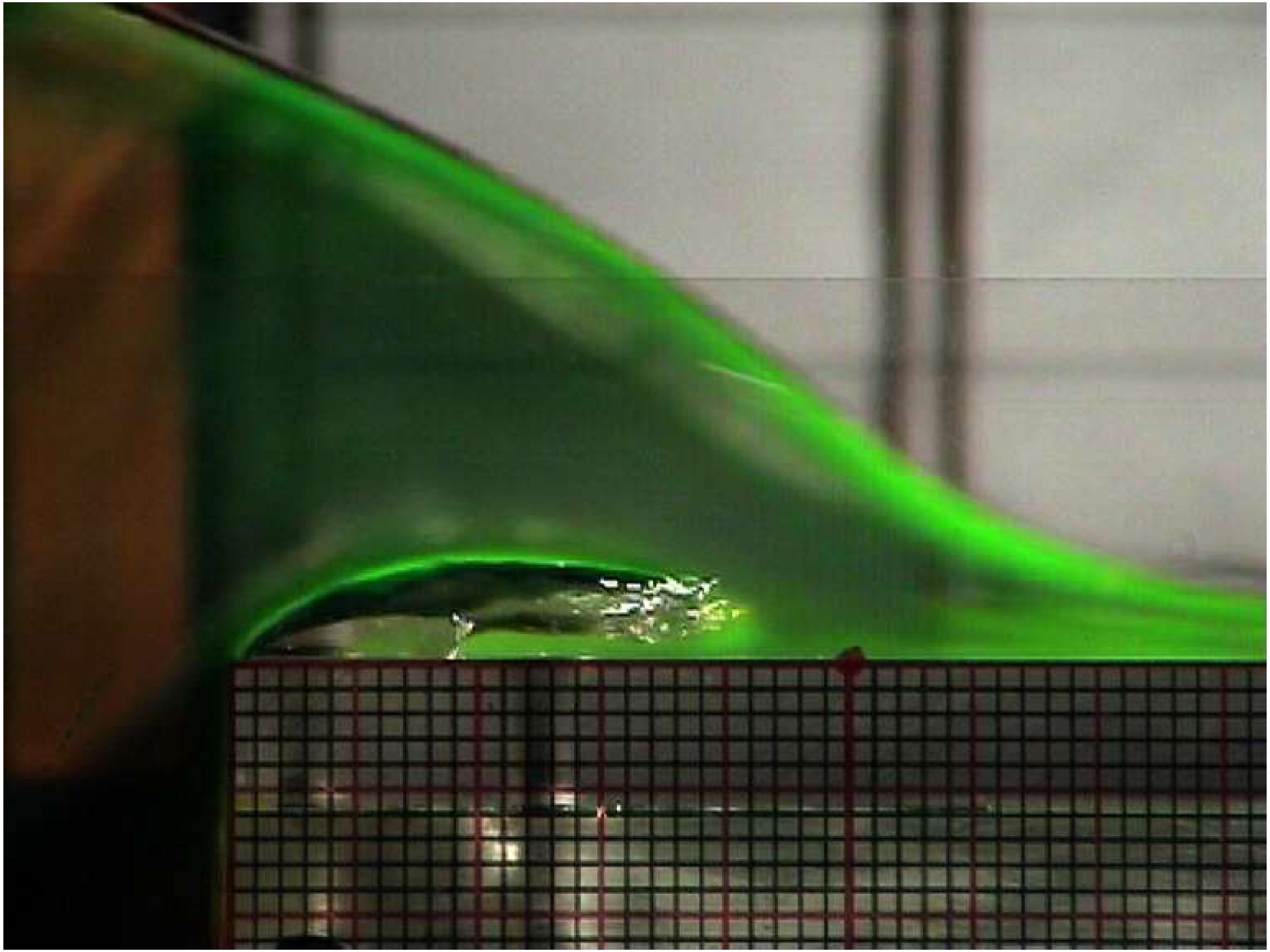
Dam-Breaking (DB) type



- ✓ **Efficient equivalent dam-breaking models have been proposed. Ambiguities exist in the choice of reservoir's height and dam-break time, due to interactions with external flow during WOD.**

Water-on-Deck Scenarios

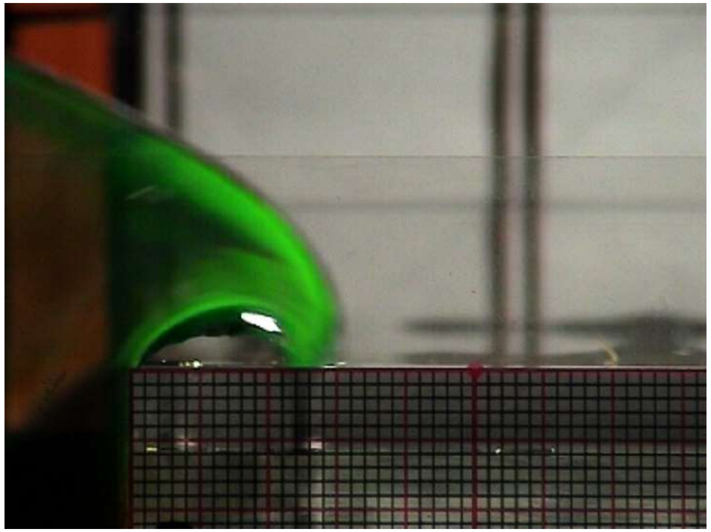
Plunging-Wave (PW) type



Water-on-Deck Scenarios

Plunging-Wave *plus* Dam-Breaking (PDB) type

PDB type



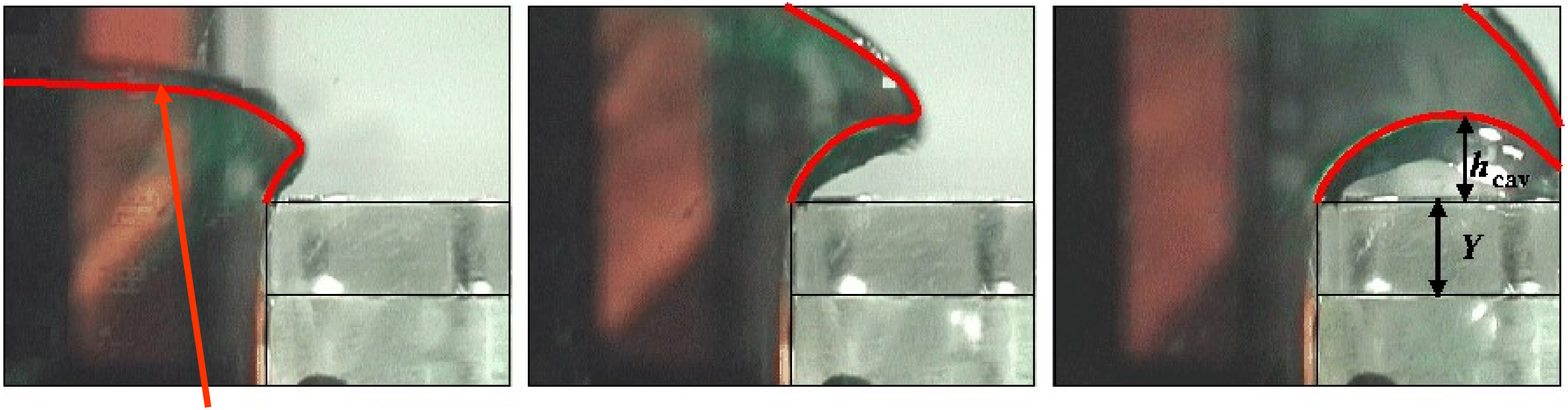
Initial stages

Later stages

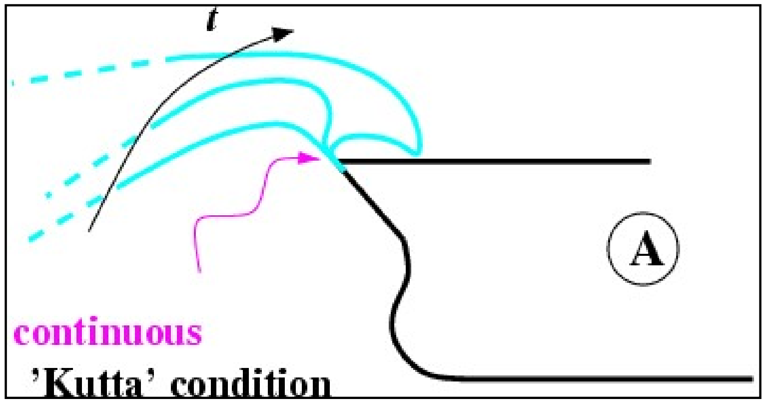
PDB Water-on-Deck: Initial stages

Plunging Phase

Time

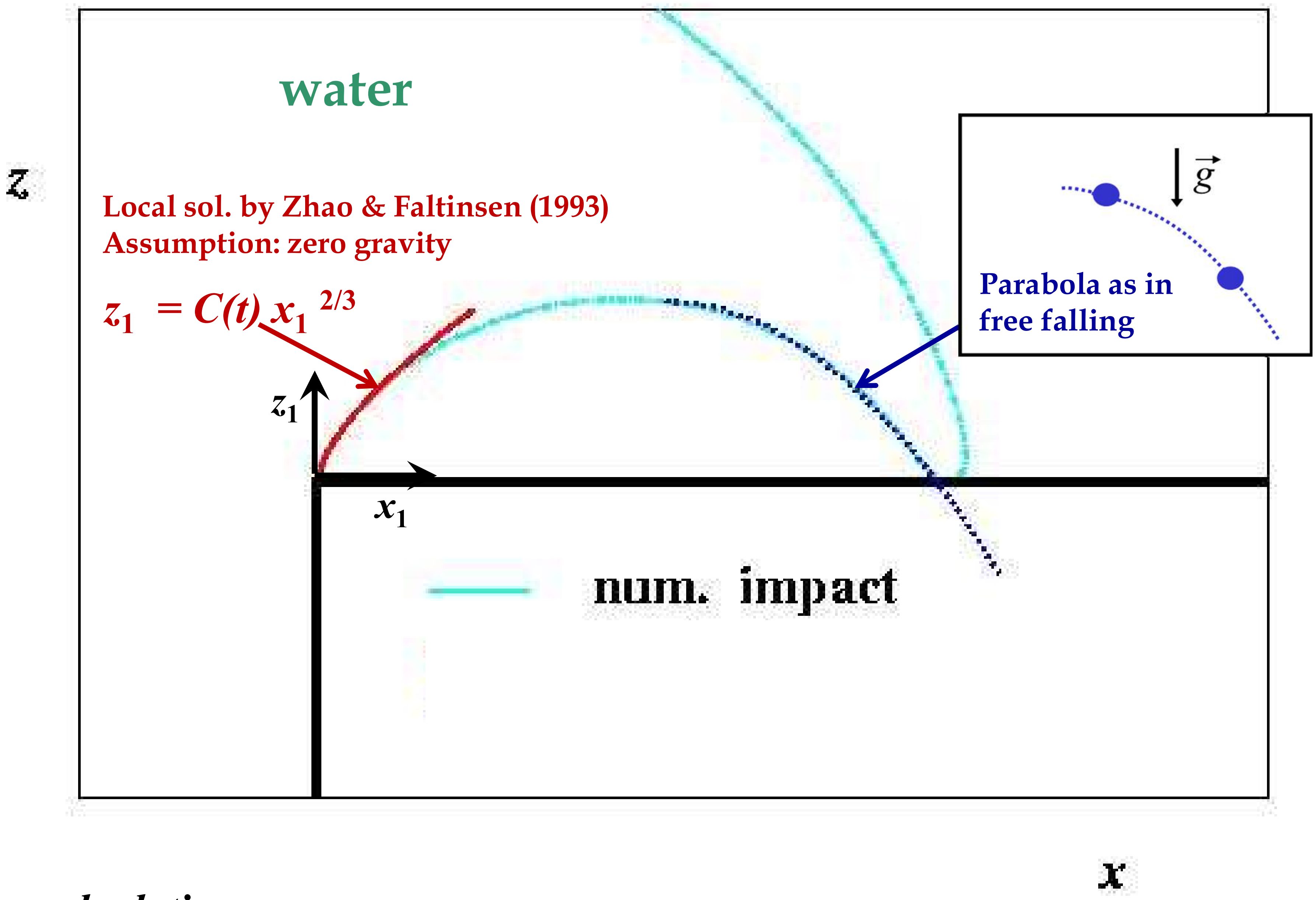


BEM Results



PDB Water-on-Deck: Initial stages

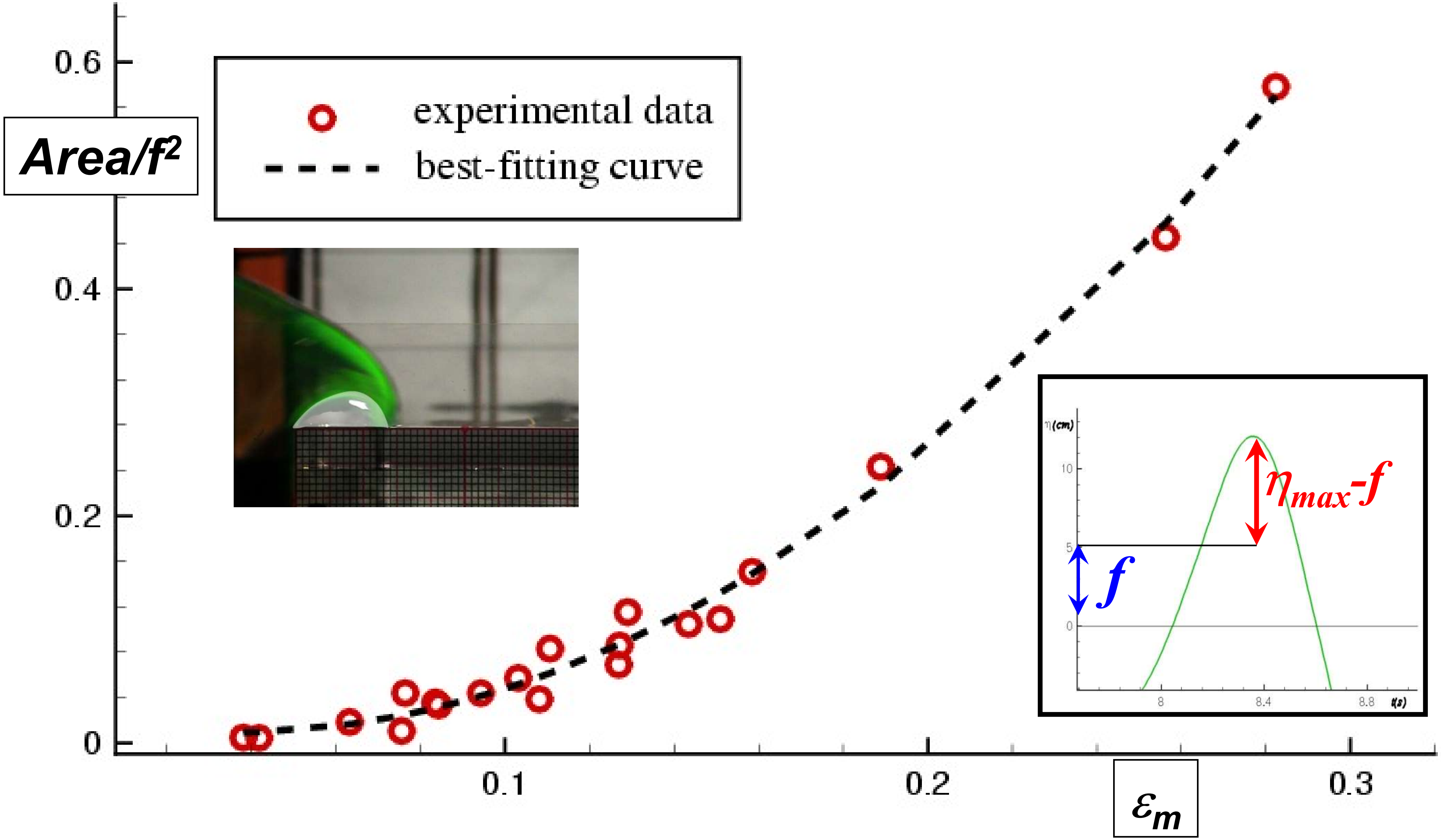
Relevant physical effects before the impact with the deck



From calculations

PDB Water-on-Deck: Initial stages

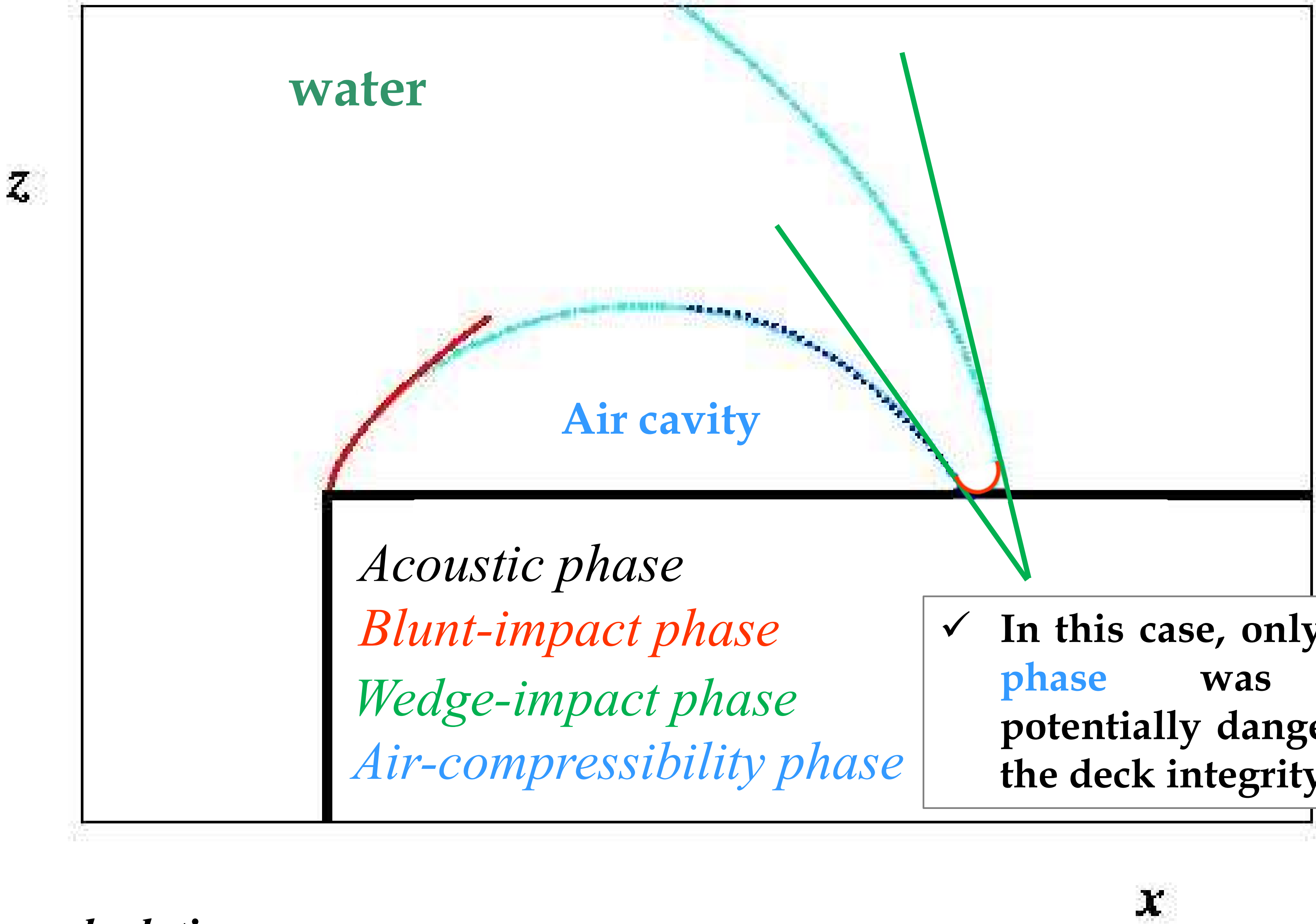
Initial area of the entrapped cavity



From experiments

PDB Water-on-Deck: Initial stages

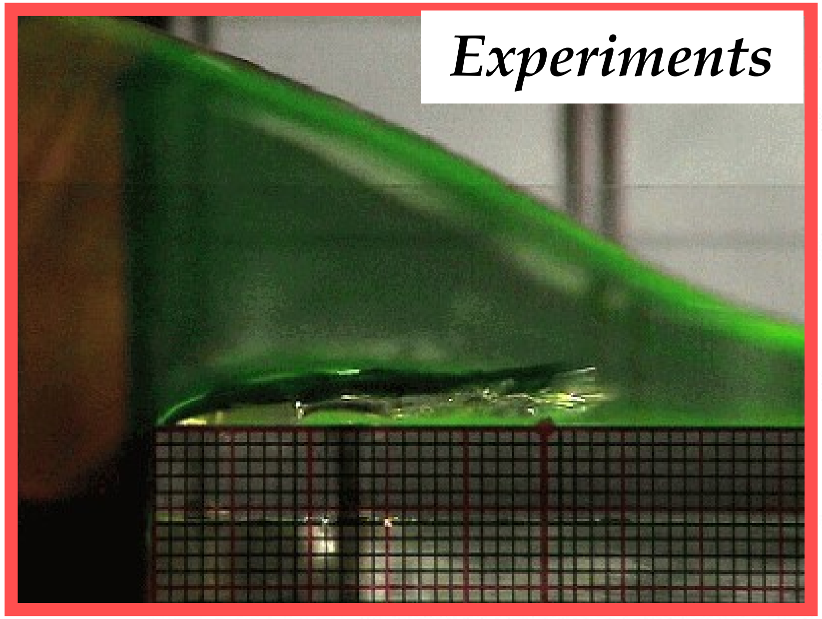
Relevant phases during the impact with the deck

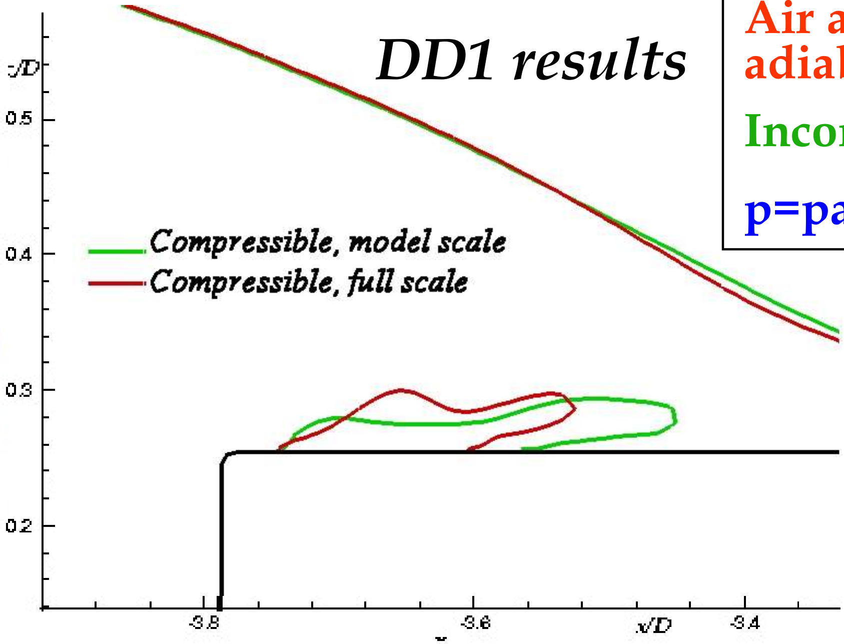


✓ **In this case, only the last phase was found potentially dangerous for the deck integrity.**

From calculations

PDB Water-on-Deck: Initial stages





Air as ideal gas + adiabatic law

Incompressible cavity

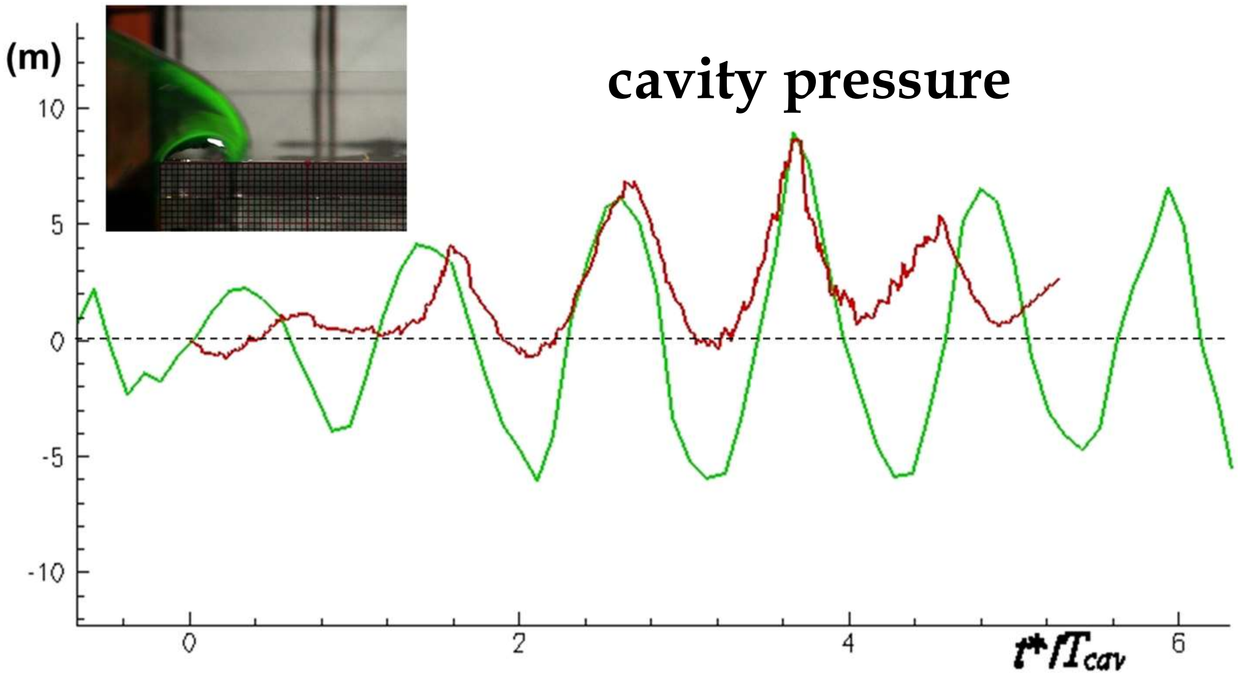
p=pa in the cavity

Full scale:

$(p-p_a)/\rho g$

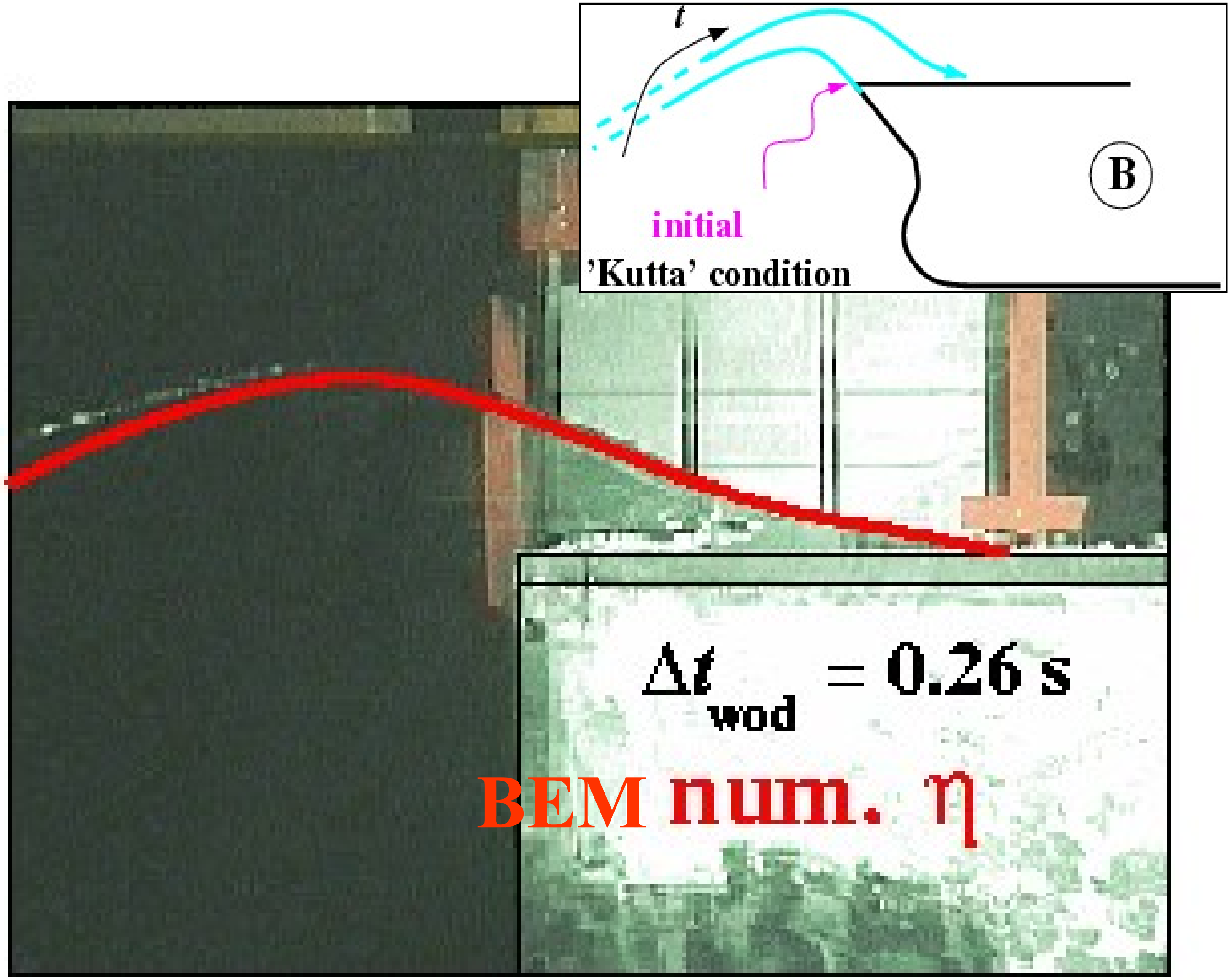
Model scale:

$(p-p_a)/\rho g \cdot (D_{FS}/D_{MS})^{0.4}$



PDB Water-on-Deck: Later stages

BEM solution with Initial-Kutta condition



PDB Water-on-Deck: Later stages

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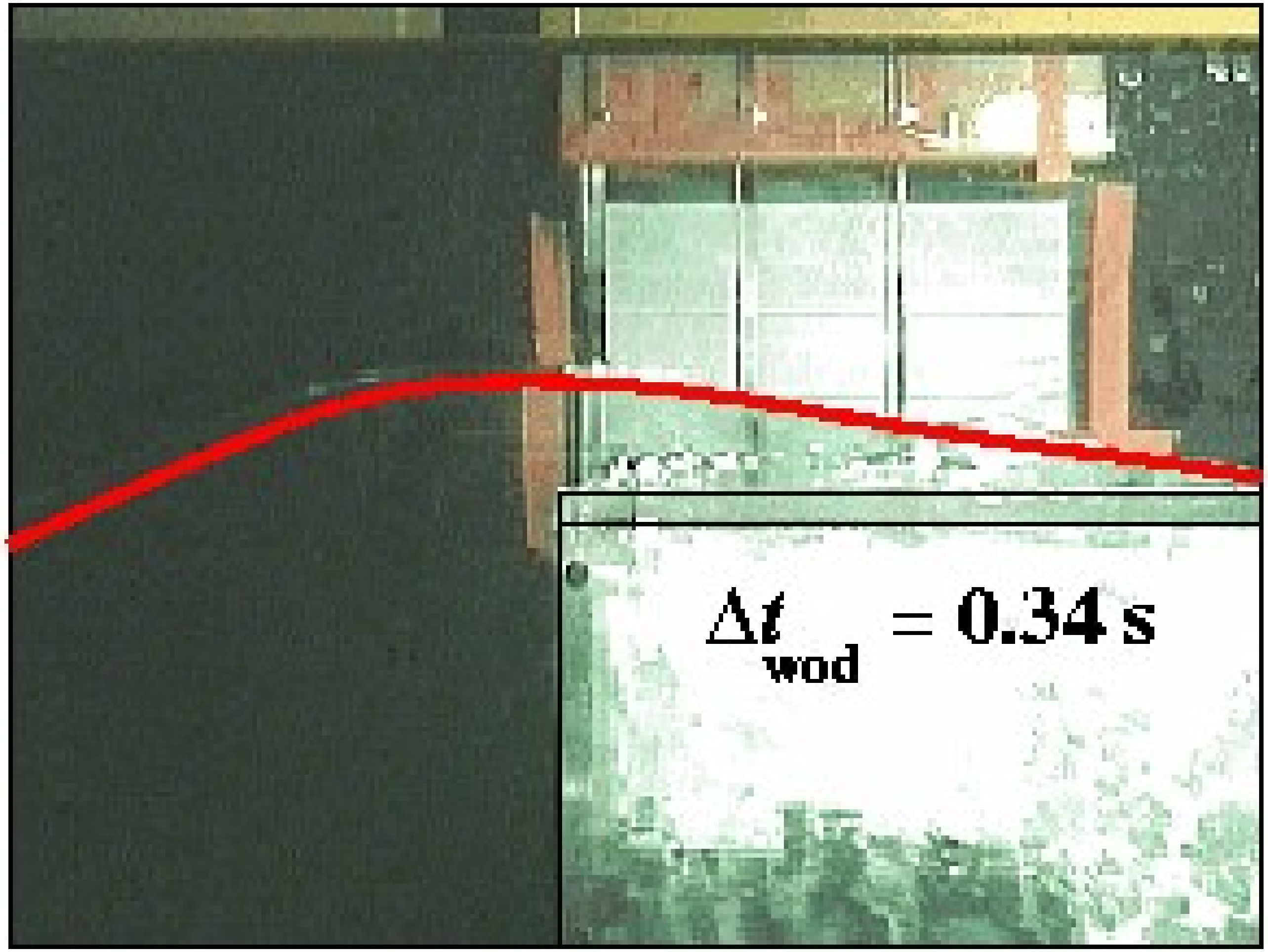

PDB Water-on-Deck: Later stages

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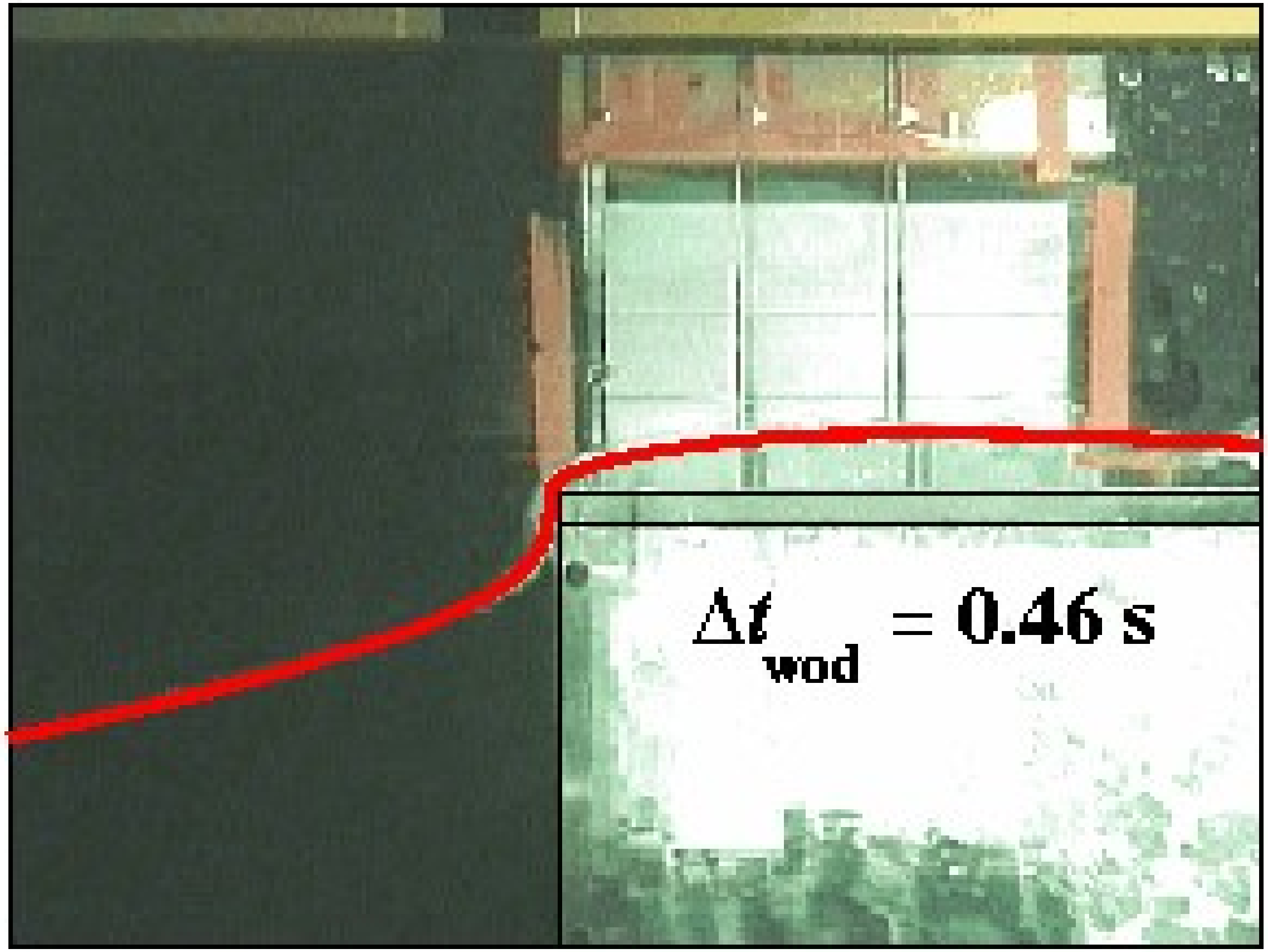
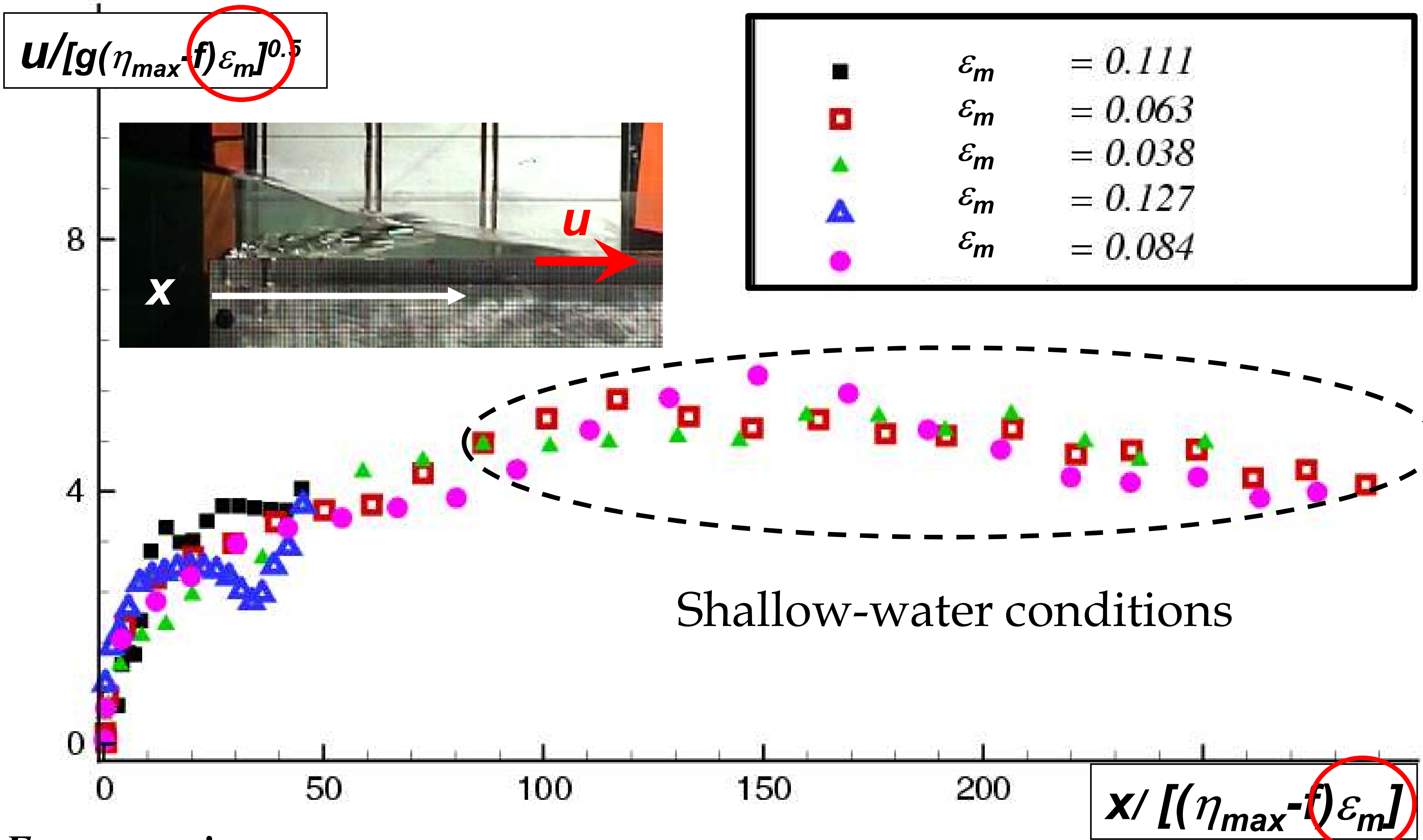


PDB Water-on-Deck: Later stages

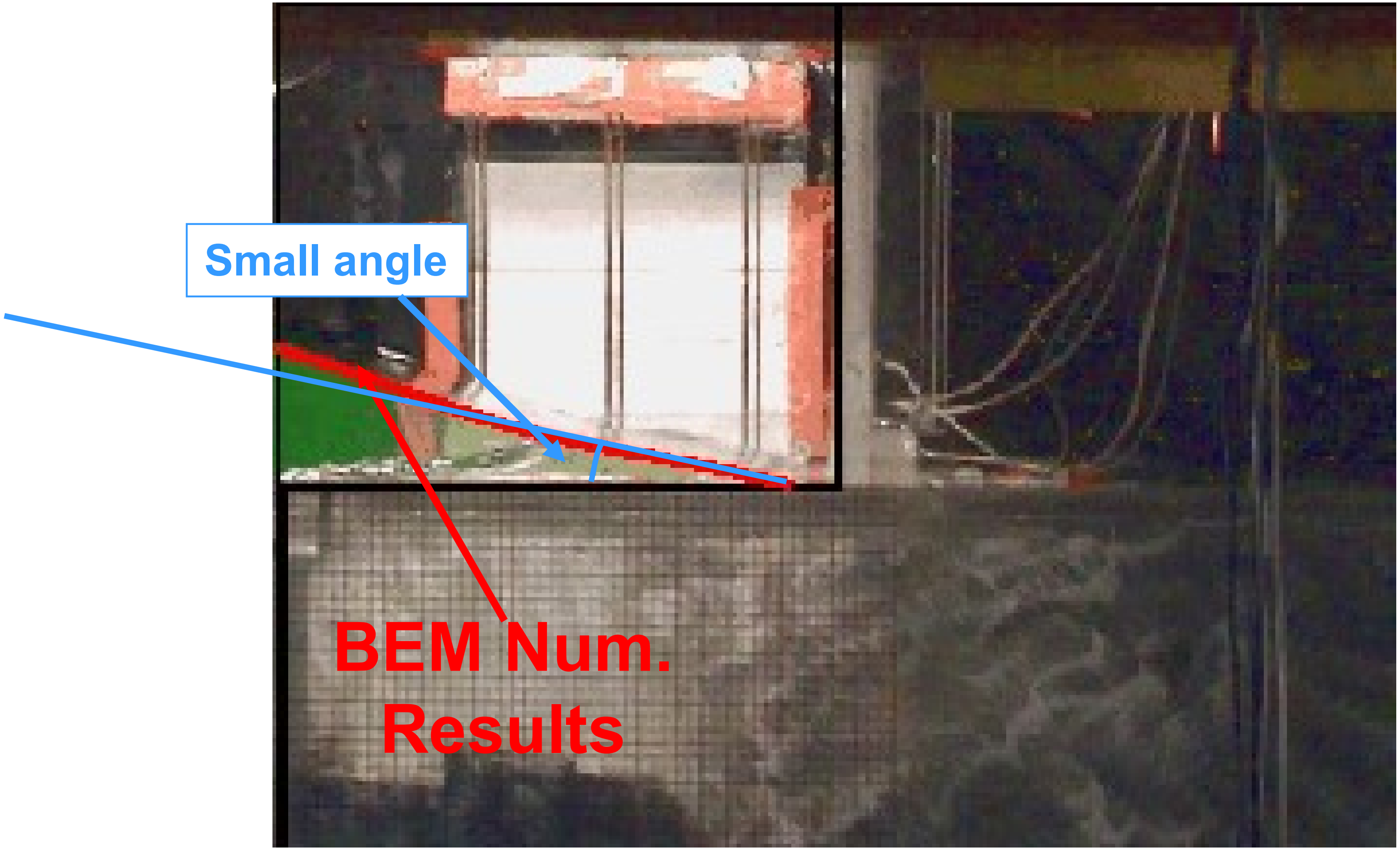
Water-front velocity



From experiments

PDB Water-on-Deck: Later stages

Flow evolution and interaction with a superstructure



PDB Water-on-Deck: Later stages

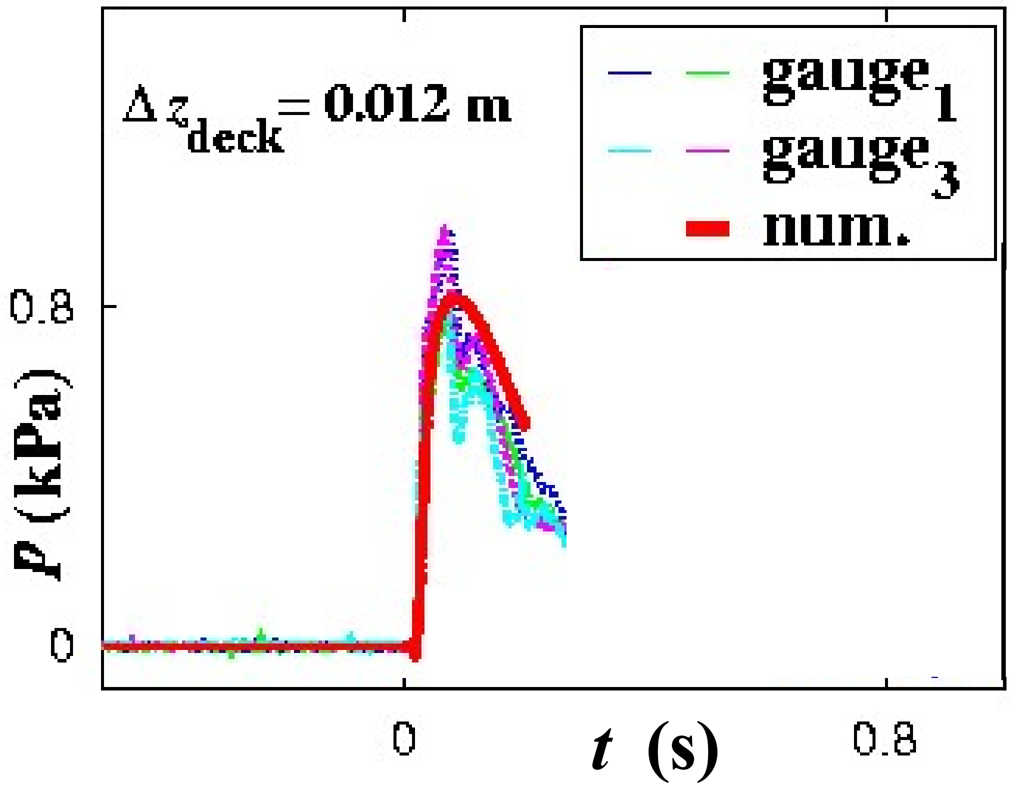
Flow evolution and interaction with a superstructure

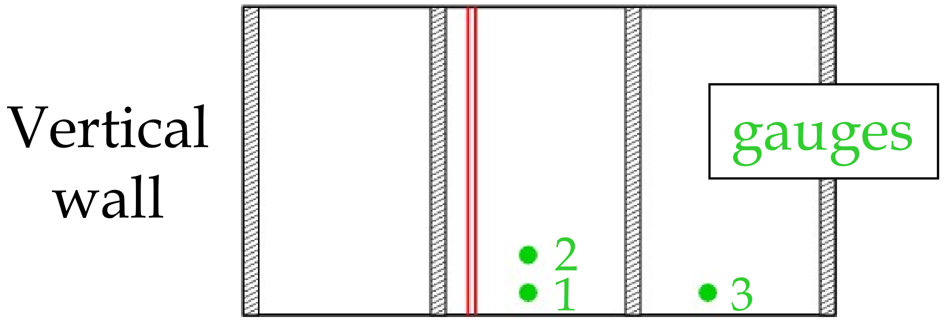
PDB Water-on-Deck: Later stages

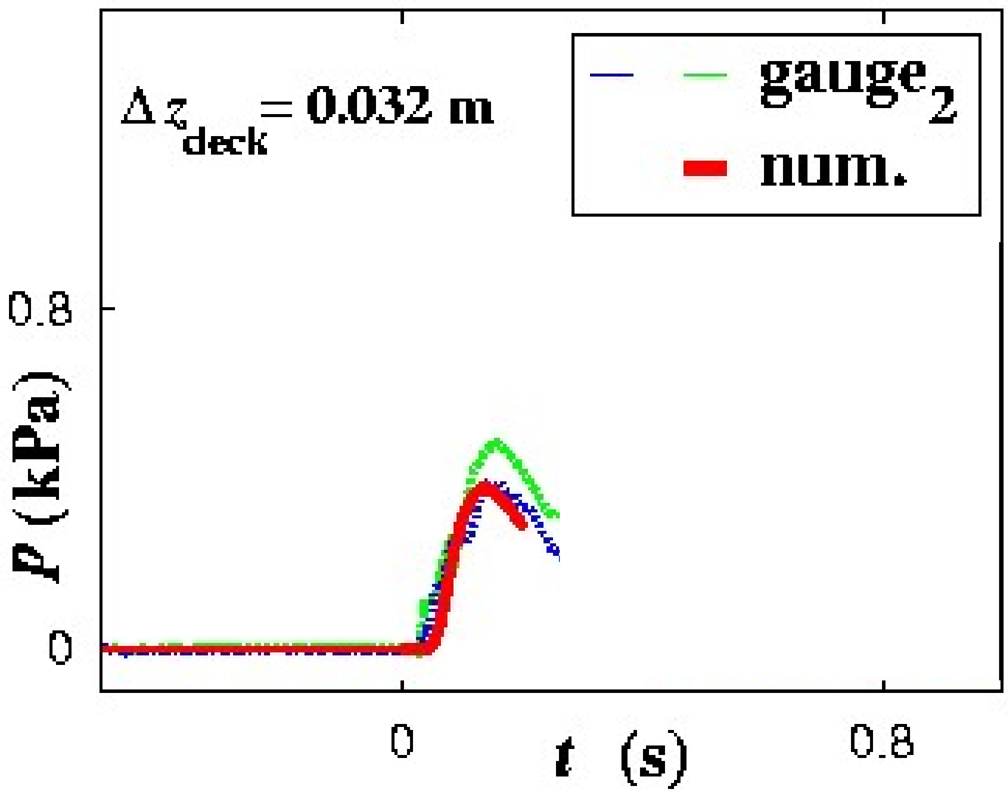
Flow evolution and interaction with a superstructure

Impact with a Vertical Superstructure

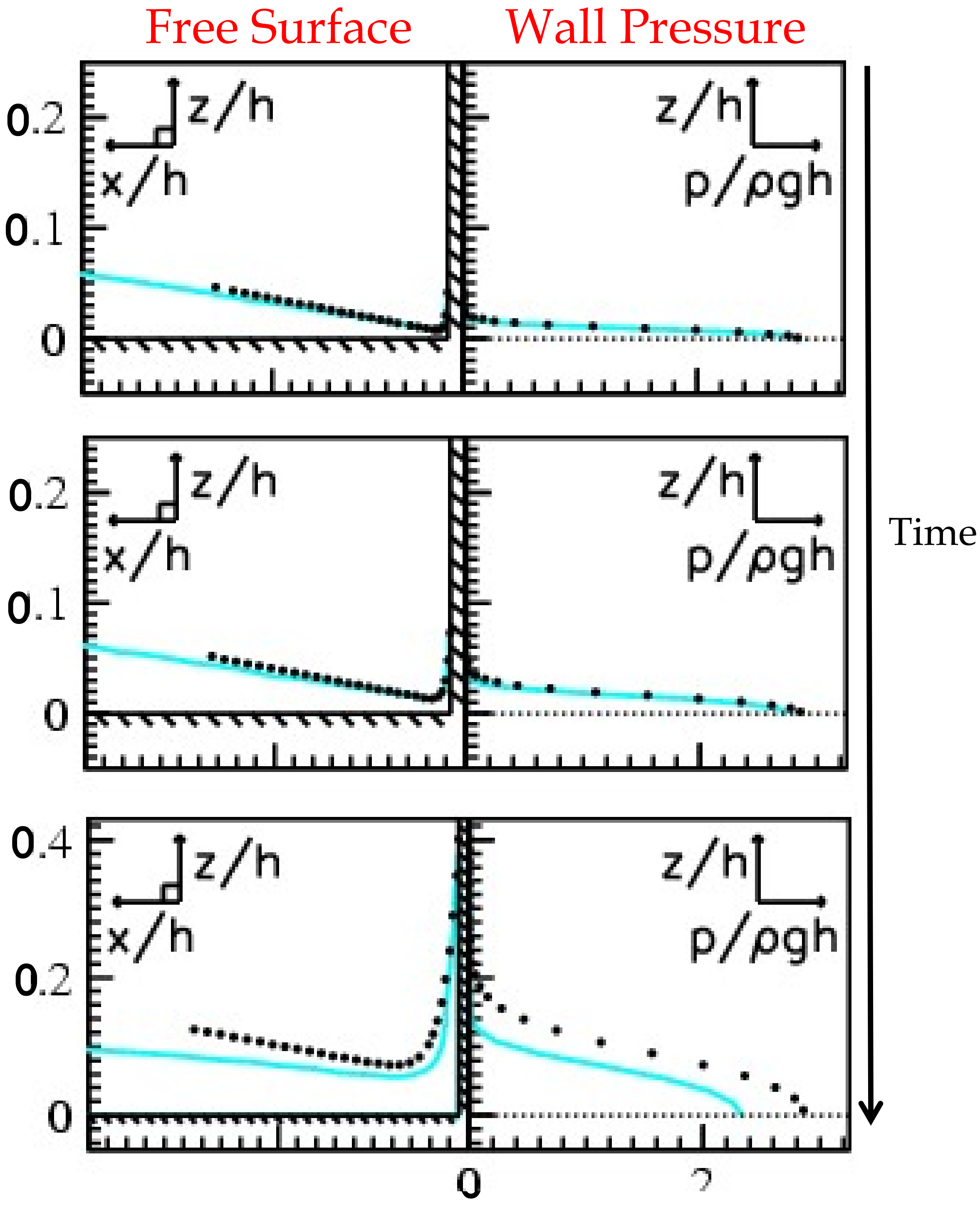
Experimental and BEM Pressure along the Wall







Initial Impact with Vertical Wall



— BEM sol. (with-gravity)

• zero-gravity sol.

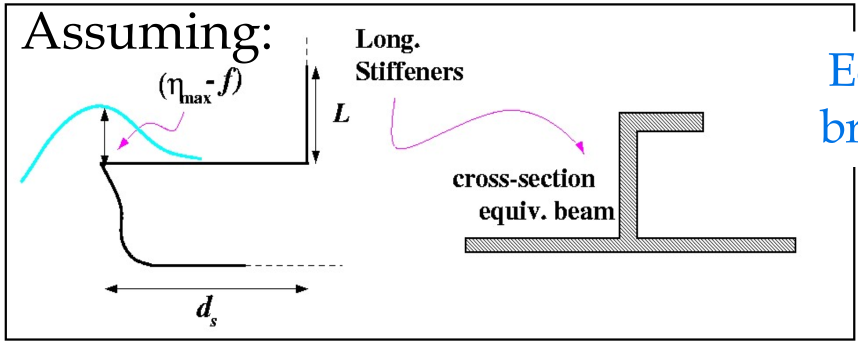
Ref.: Zhang *et al.* (1996)

✓ **As time goes on, gravity slows down the water rise-up and limits the pressure.**

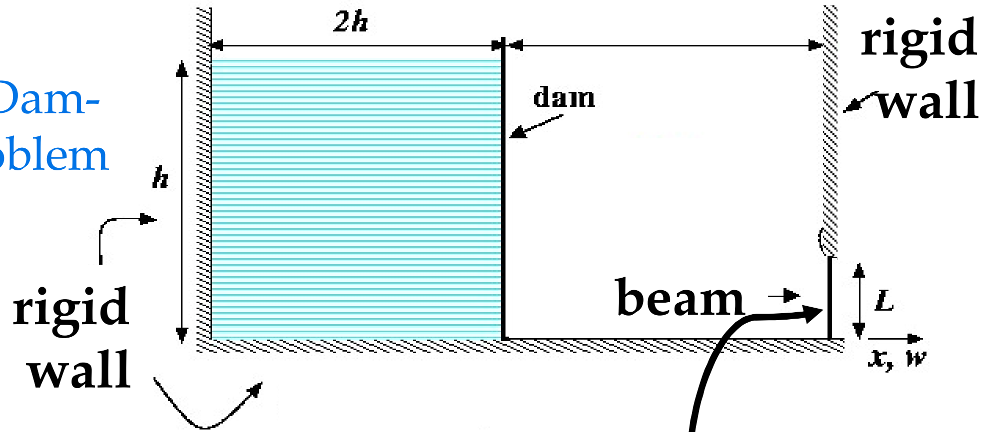
From calculations

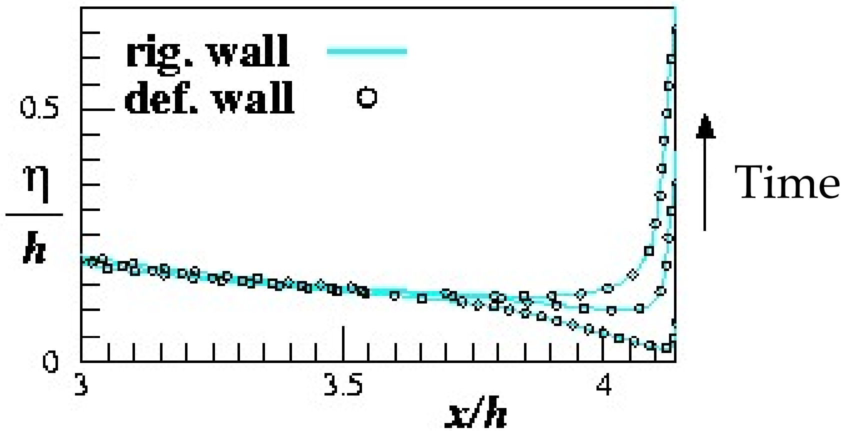
PDB Water-on-Deck: Later stages

Hydroelasticity analysis

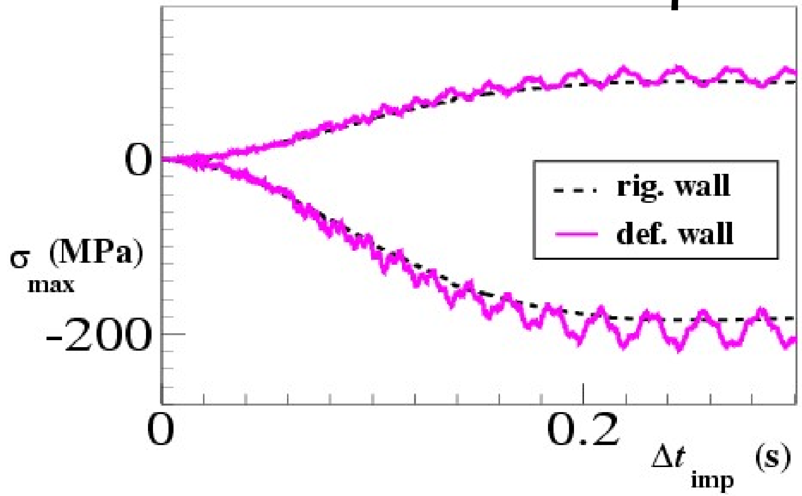


Equivalent Dam-breaking Problem





The free-surface evolution is unaffected by the wall flexibility



Maximum stresses ≈ *Quasi-static* values

✓ **Limited Role of Hydroelasticity for this WOD Scenario.**

From calculations

PDB Water-on-Deck: Later stages

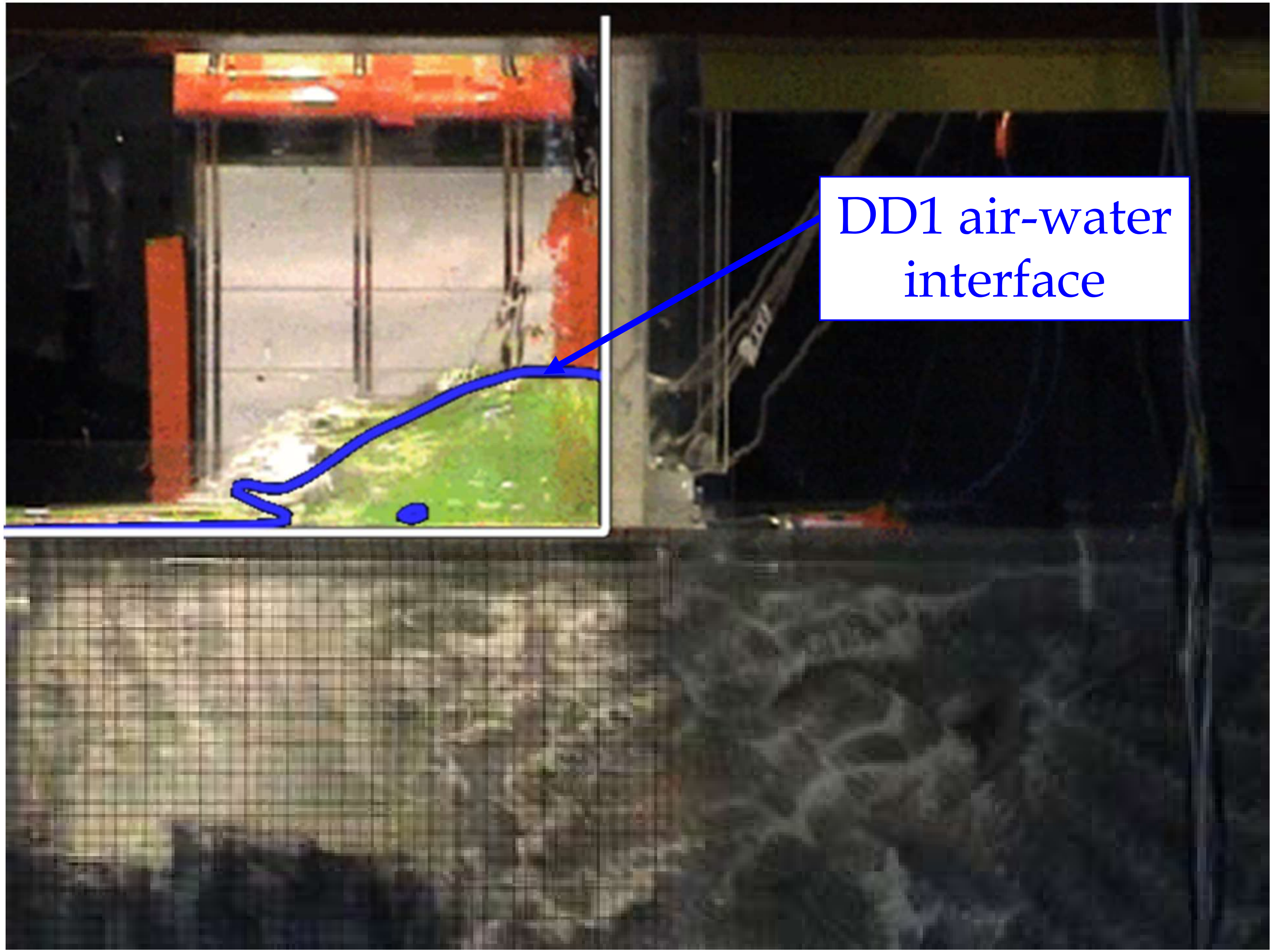
Water Overturning and Breaking

PDB Water-on-Deck: Later stages

Water Overturning and Breaking

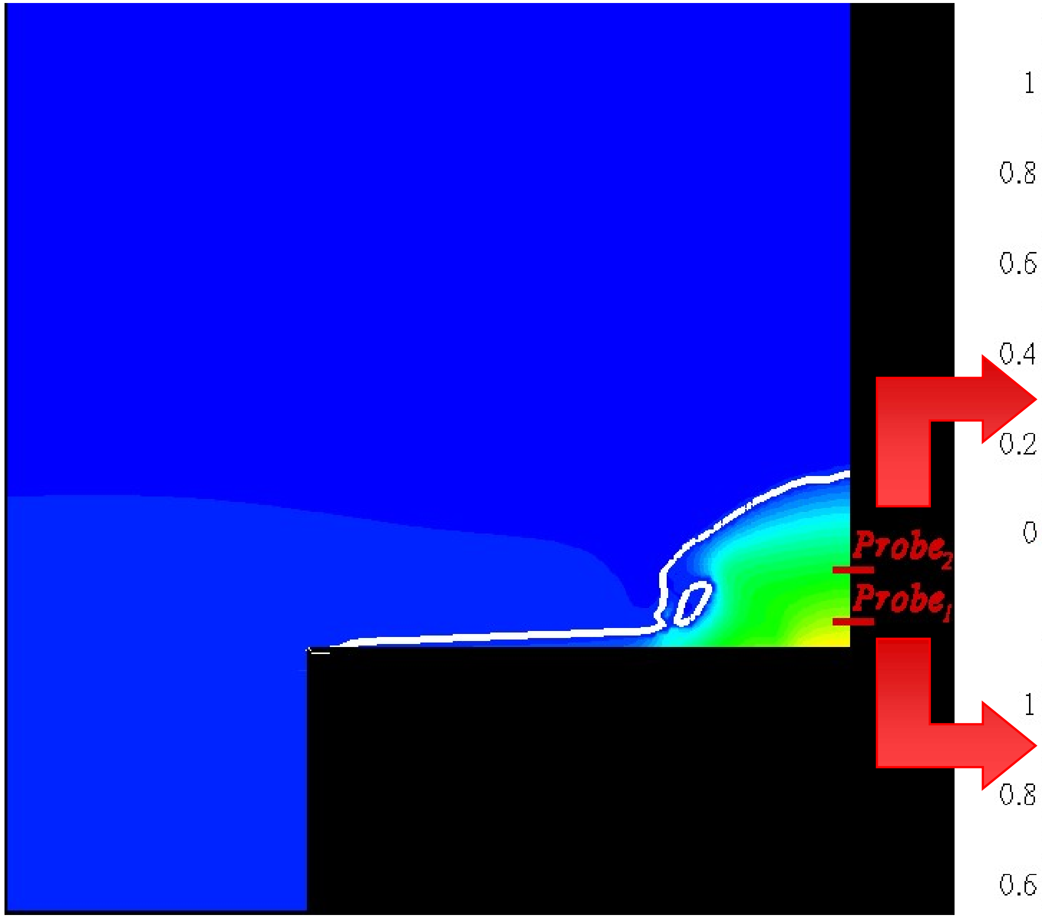
PDB Water-on-Deck: Later stages

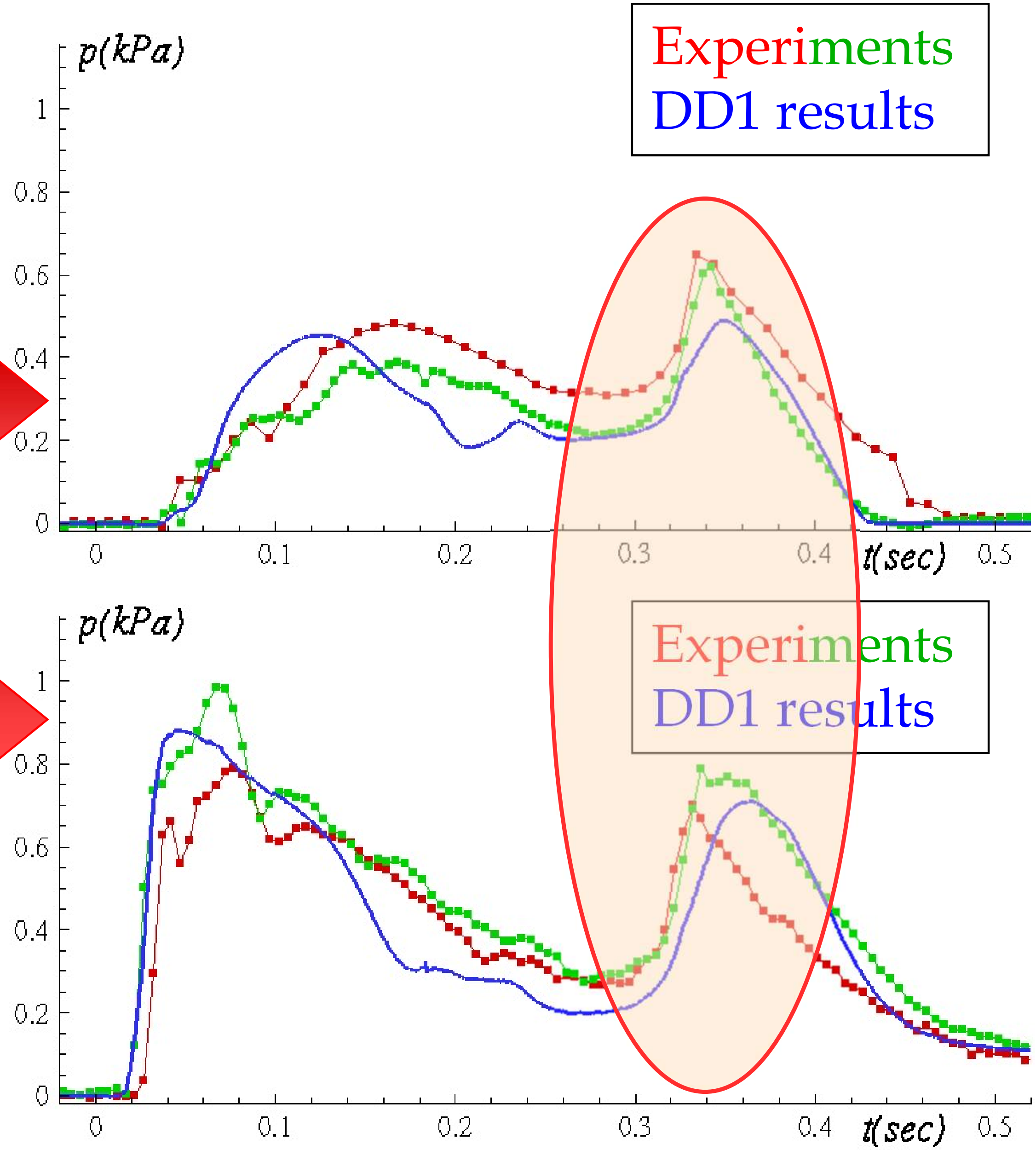
Water Overturning and Breaking



PDB Water-on-Deck: Later stages

Pressure on the wall: DD1 versus experiments

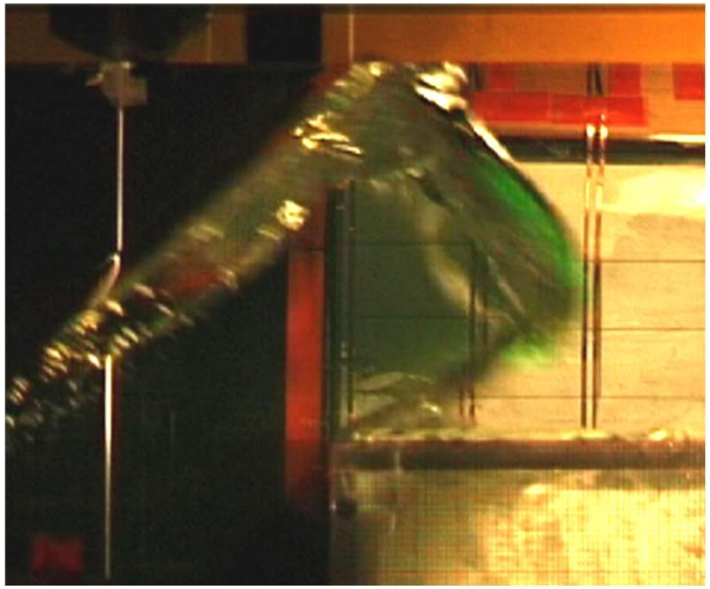


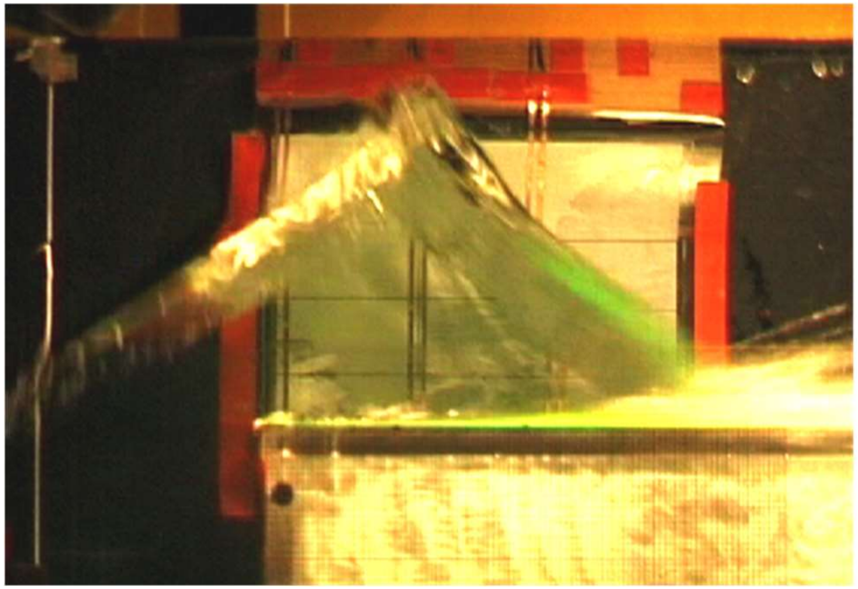


Water-on-Deck Scenarios

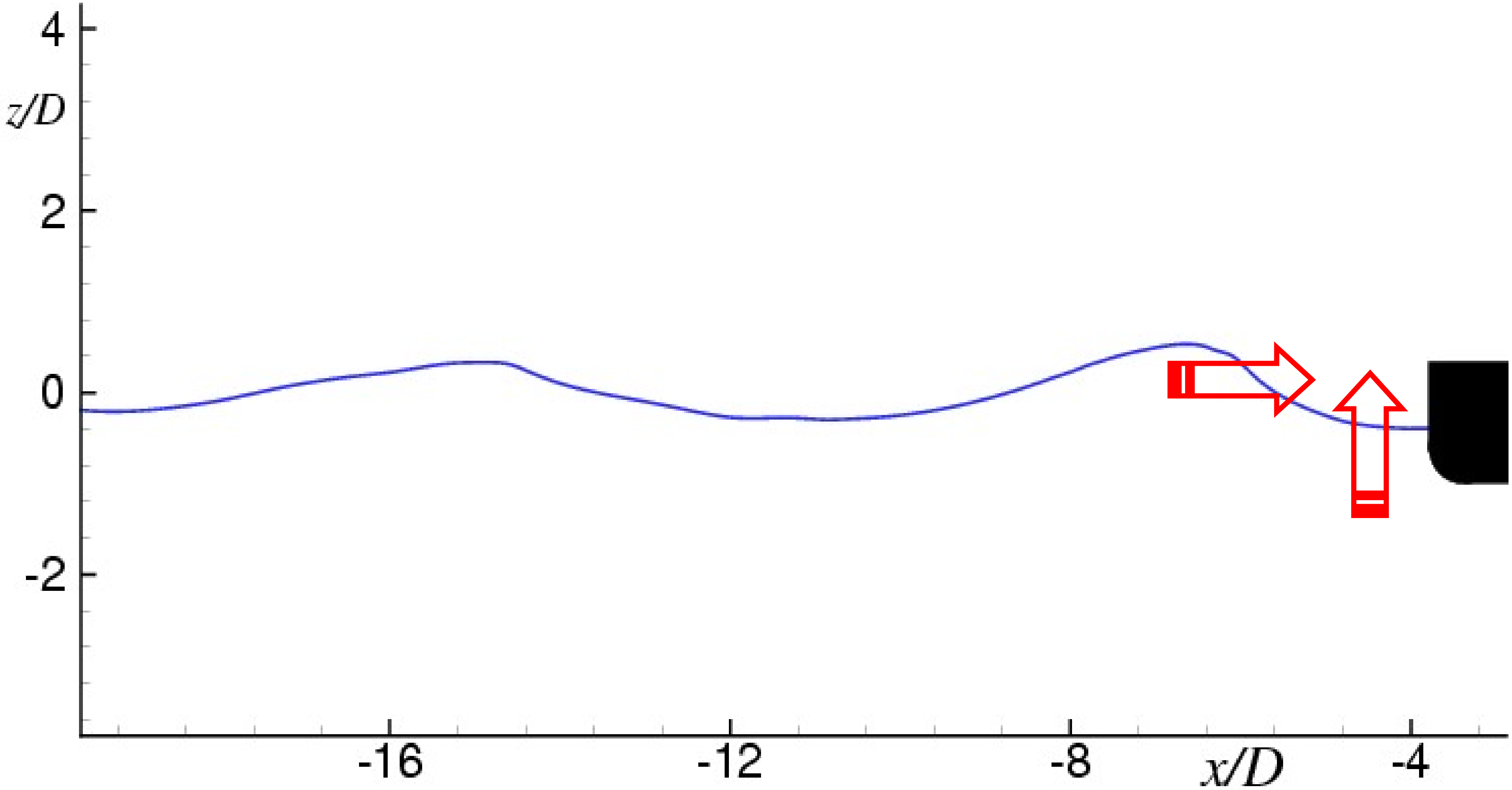
Hammer-Fist (HF) type

HF type





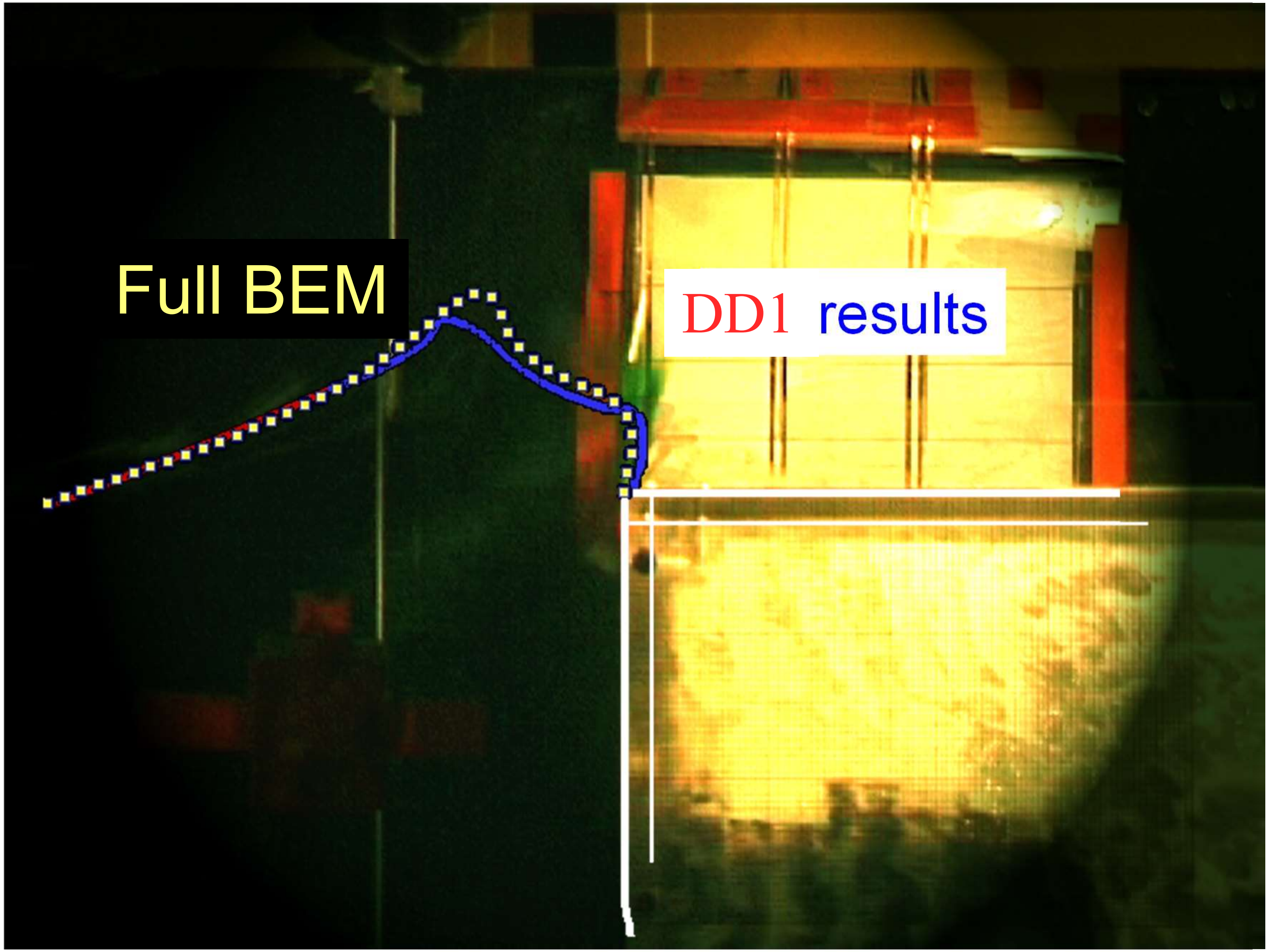
HF Water –on-Deck: Occurrence



From calculations

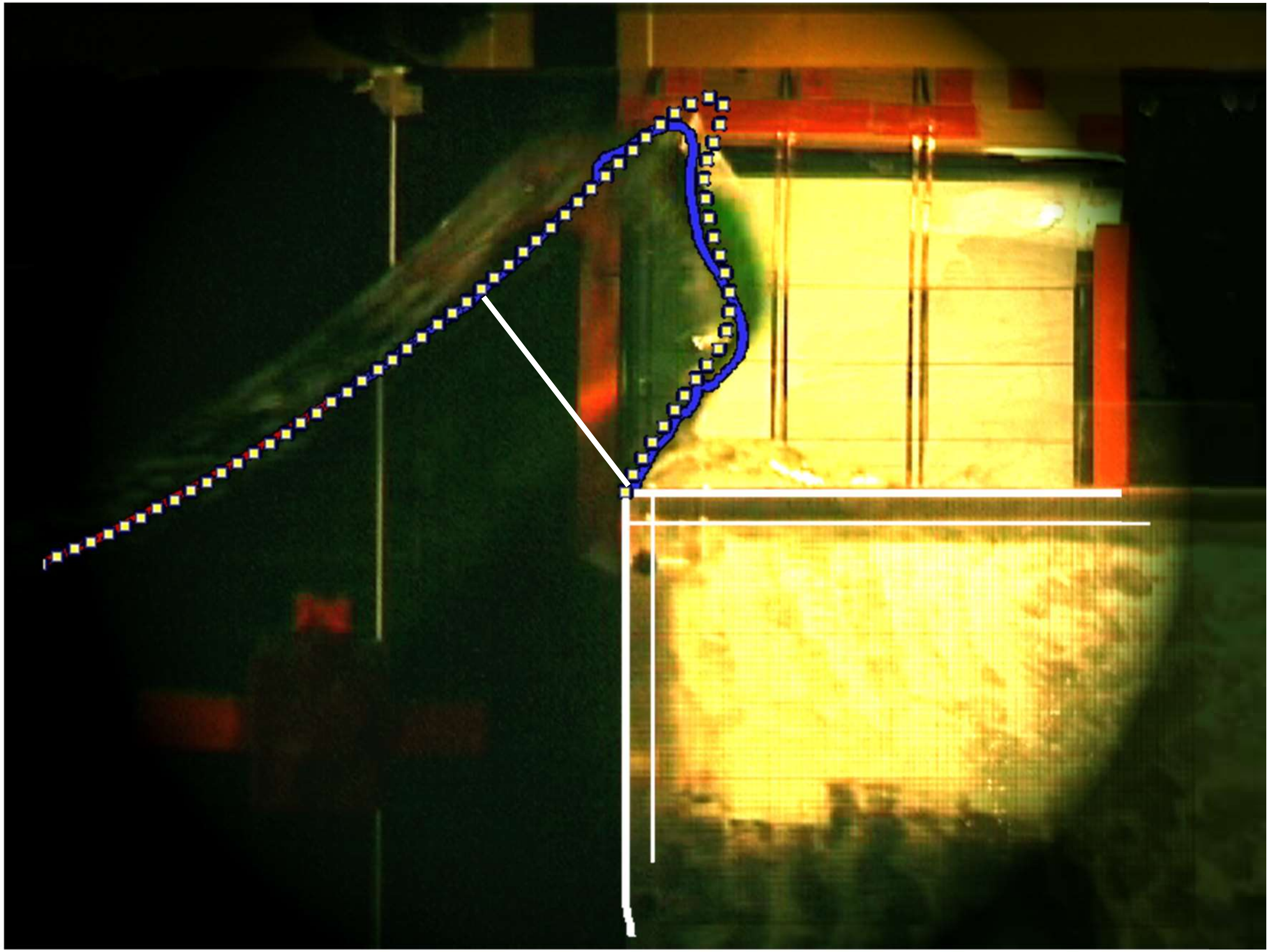
Hammer-Fist Type WOD

Flow evolution



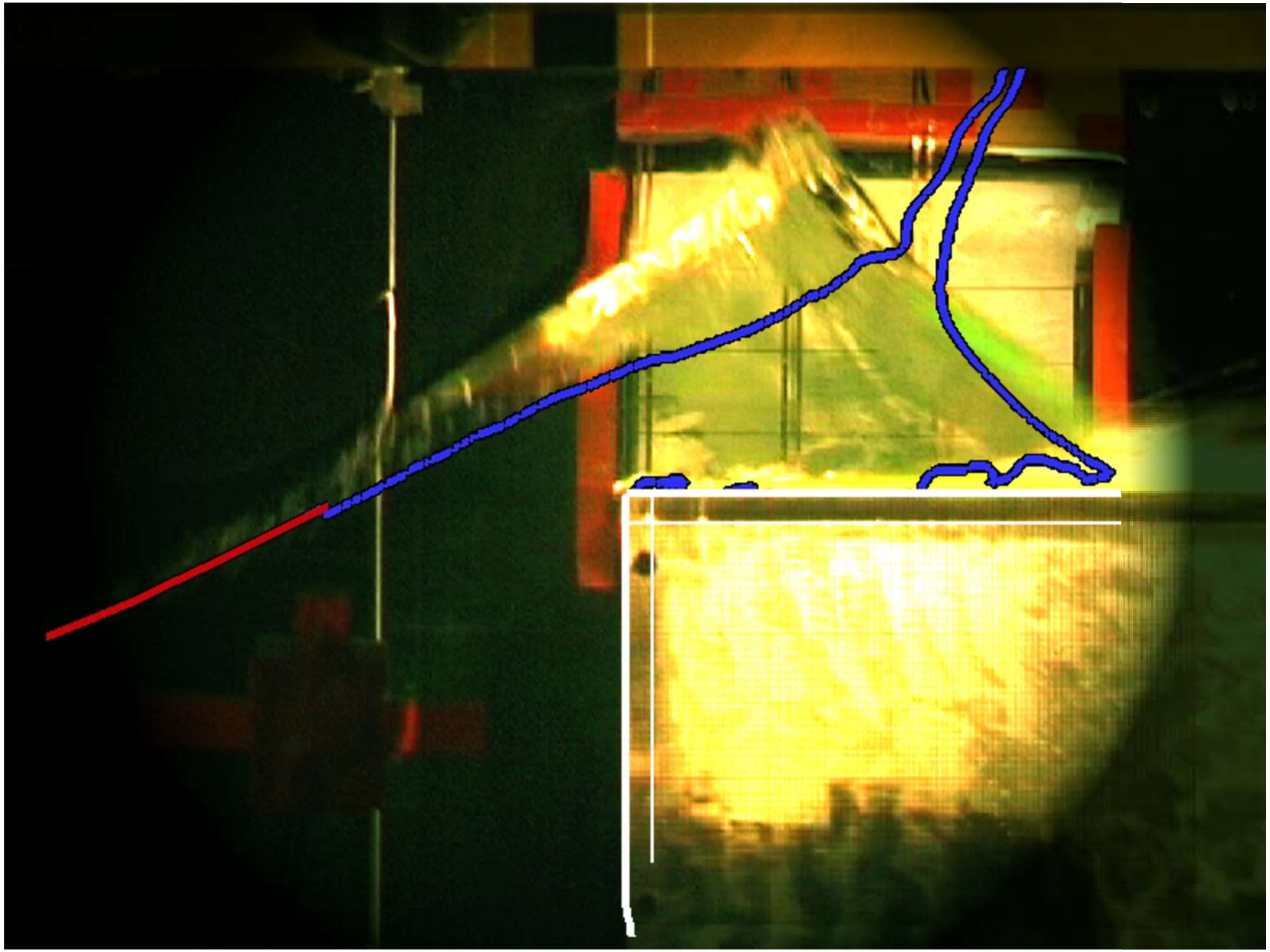
Hammer-Fist Type WOD

Flow evolution



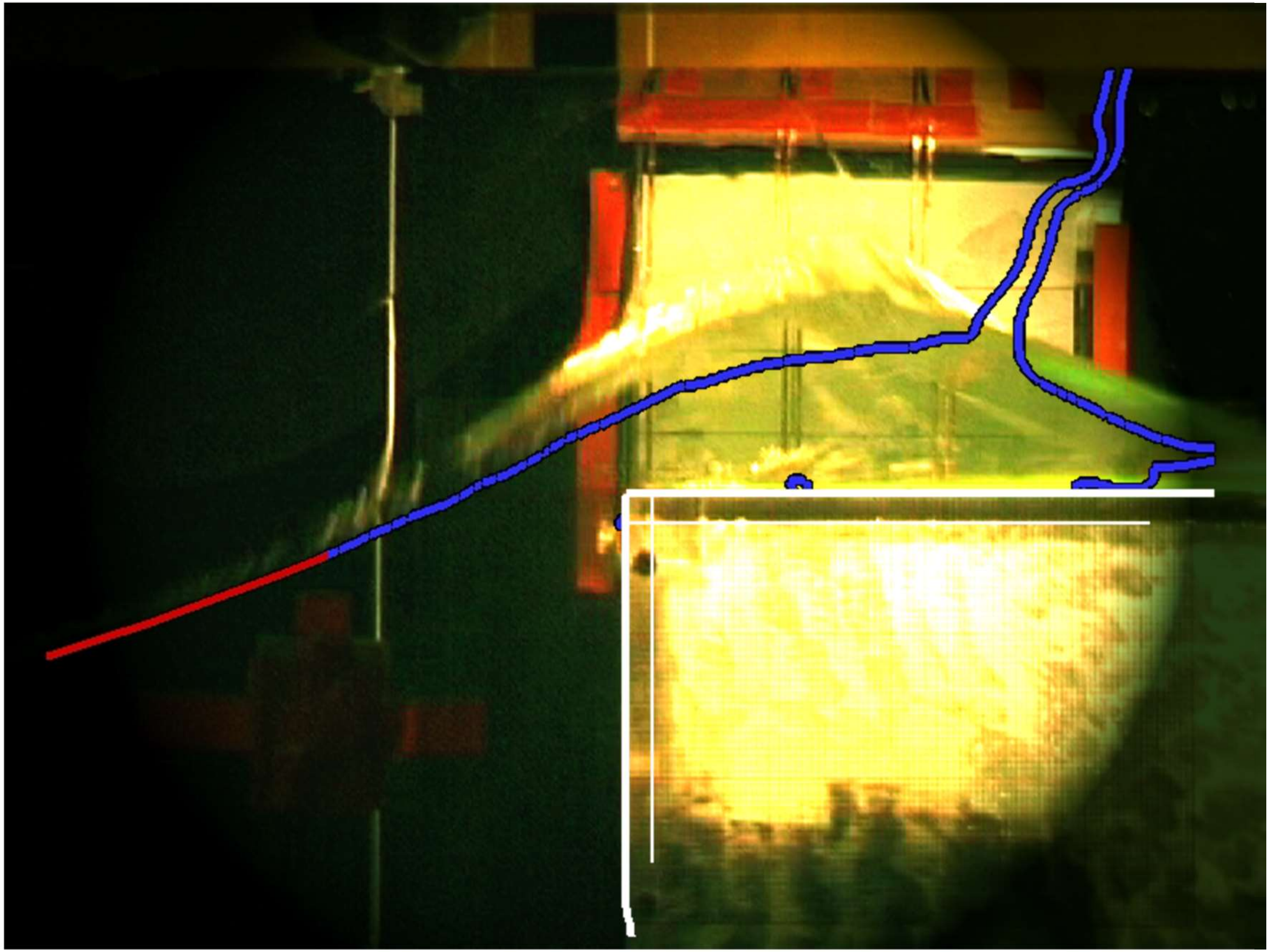
Hammer-Fist Type WOD

Flow evolution



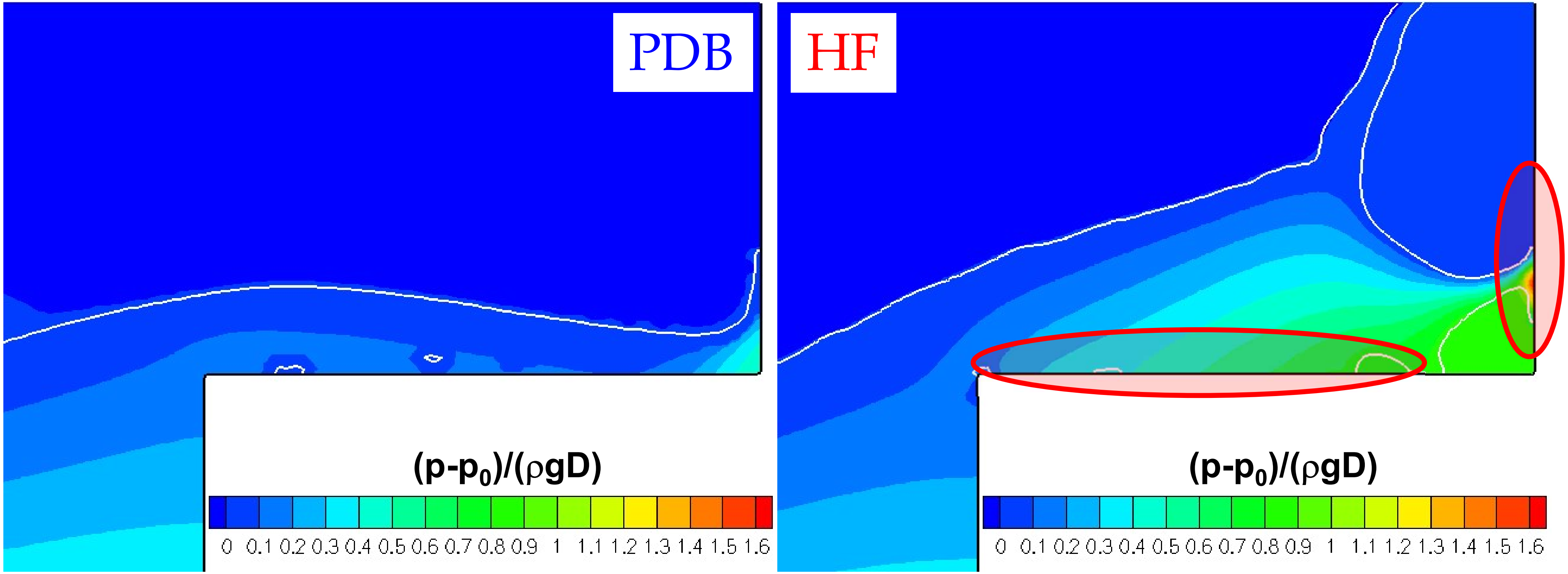
Hammer-Fist Type WOD

Flow evolution



Green-Water Loads: PDB versus HF

Pressure



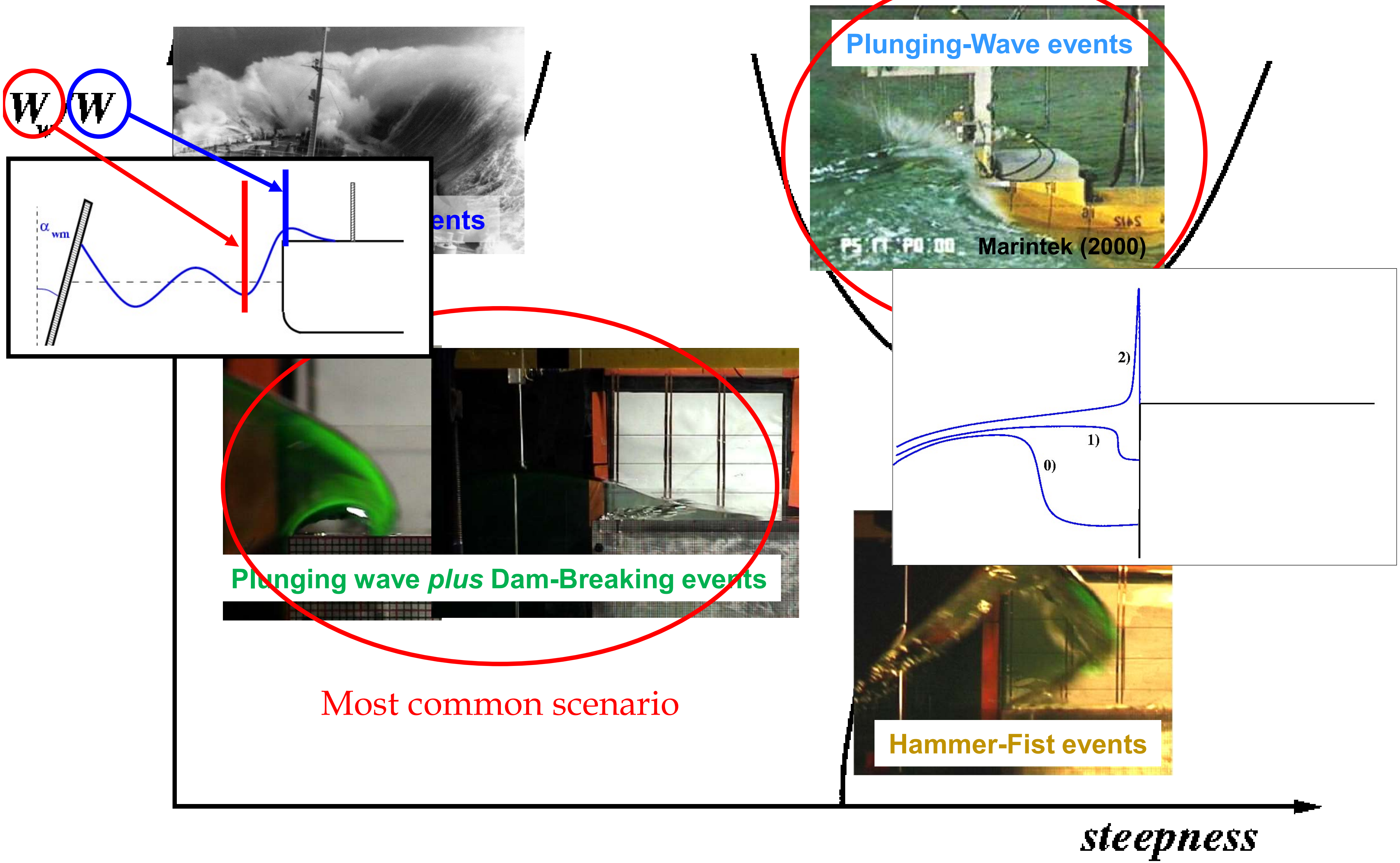
- ✓ **HF can result in higher over pressures, dangerous for local structural integrity.**
- ✓ **HF can leads to blunt deck impact (with air entrainment) and wall impact not from the foot, both potential risk for hydroelastic excitation. We did not examine this.**

From calculations

Water-on-Deck Scenarios

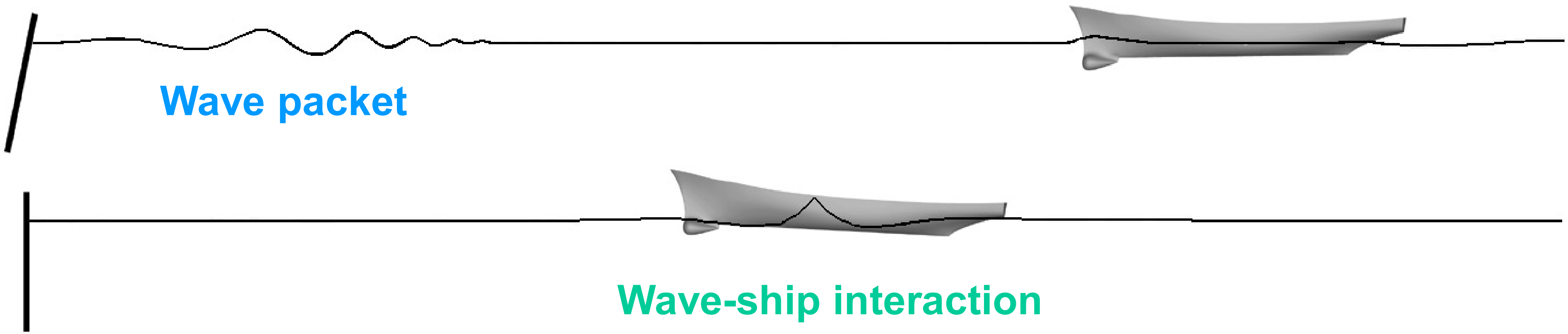
Existence diagram

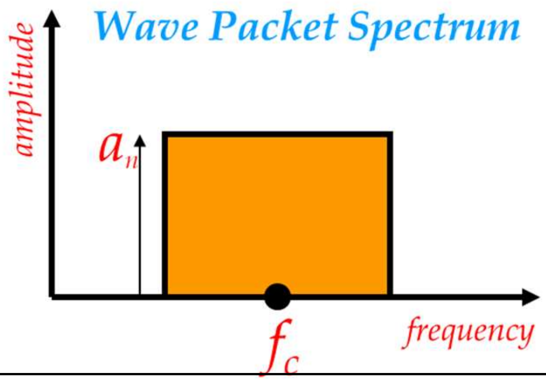
Incident waves
play a crucial role



3D Model Tests

Water on deck in head sea conditions





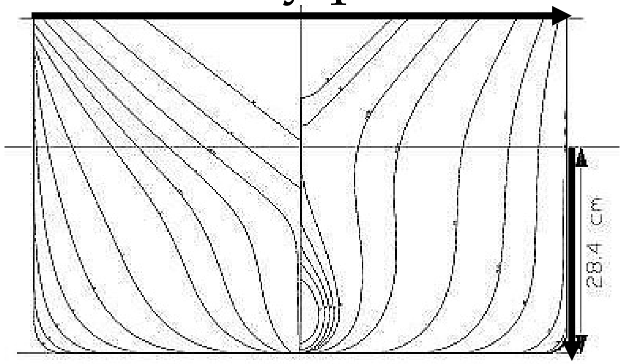
Wave-length range: $\lambda_c \cong L,\ \lambda_{min} = 0.5L,\ \lambda_{max} = 2.6L$

Wave steepness: $\varepsilon = k_c a = \pi H/\lambda_c$ =[0.125-0.25]

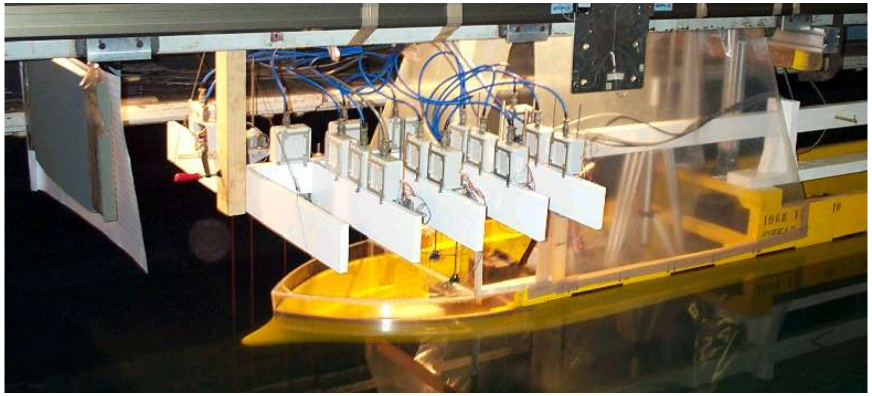
3D Model Tests With Fixed Model

Esso Osaka
$L \sim 4.44$ m (scale 1:70)
$D/L \sim 0.064$, $f/L \sim 0.015$
$B/L \sim 0.166$, $ds/L \sim 0.13$

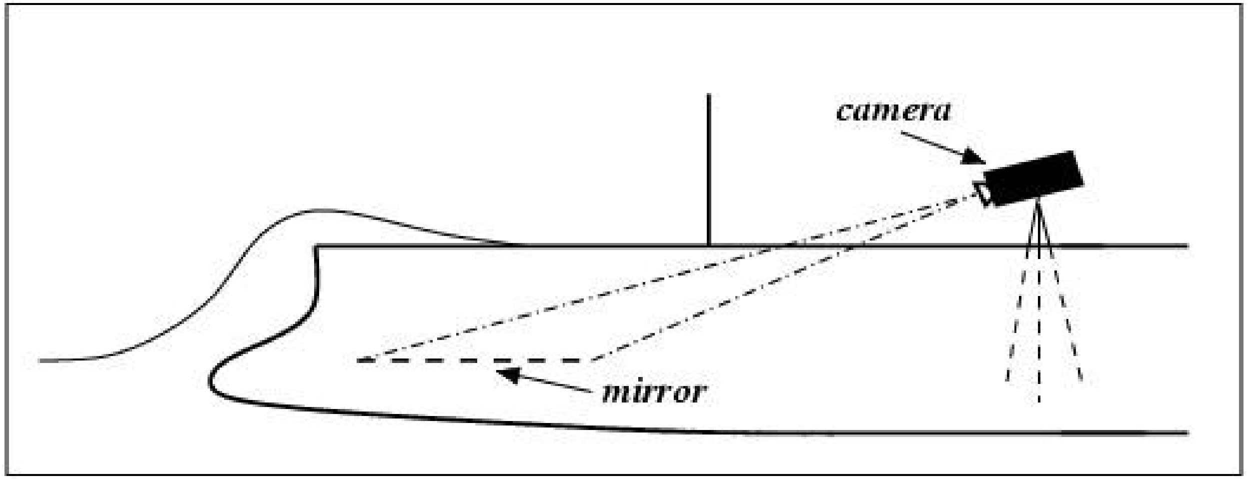
Body plan



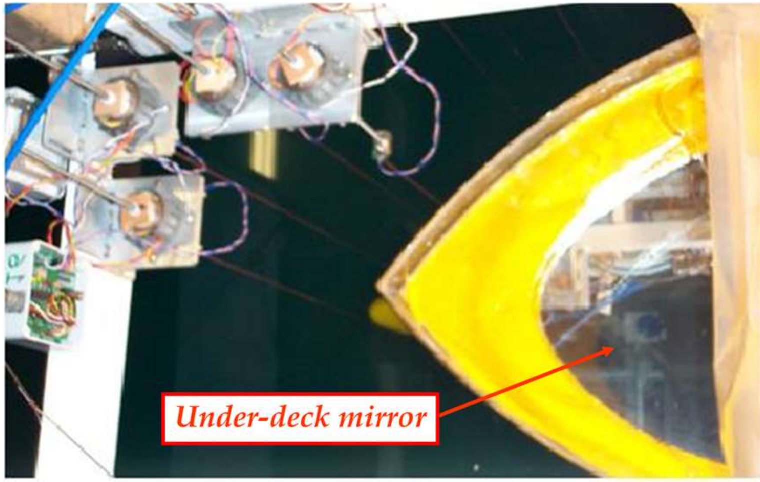
Side view



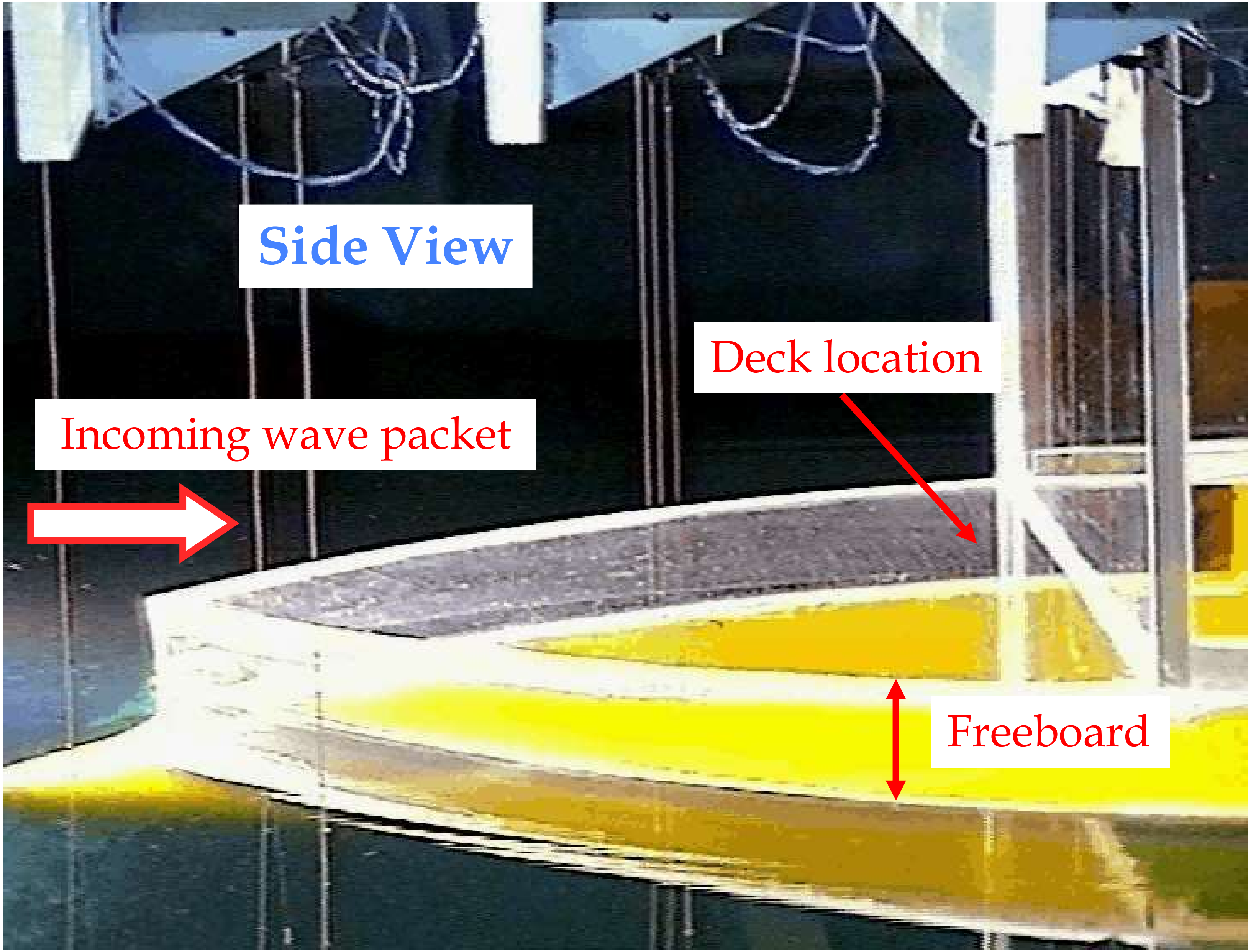
Mirror-camera system: side view sketch



Top view

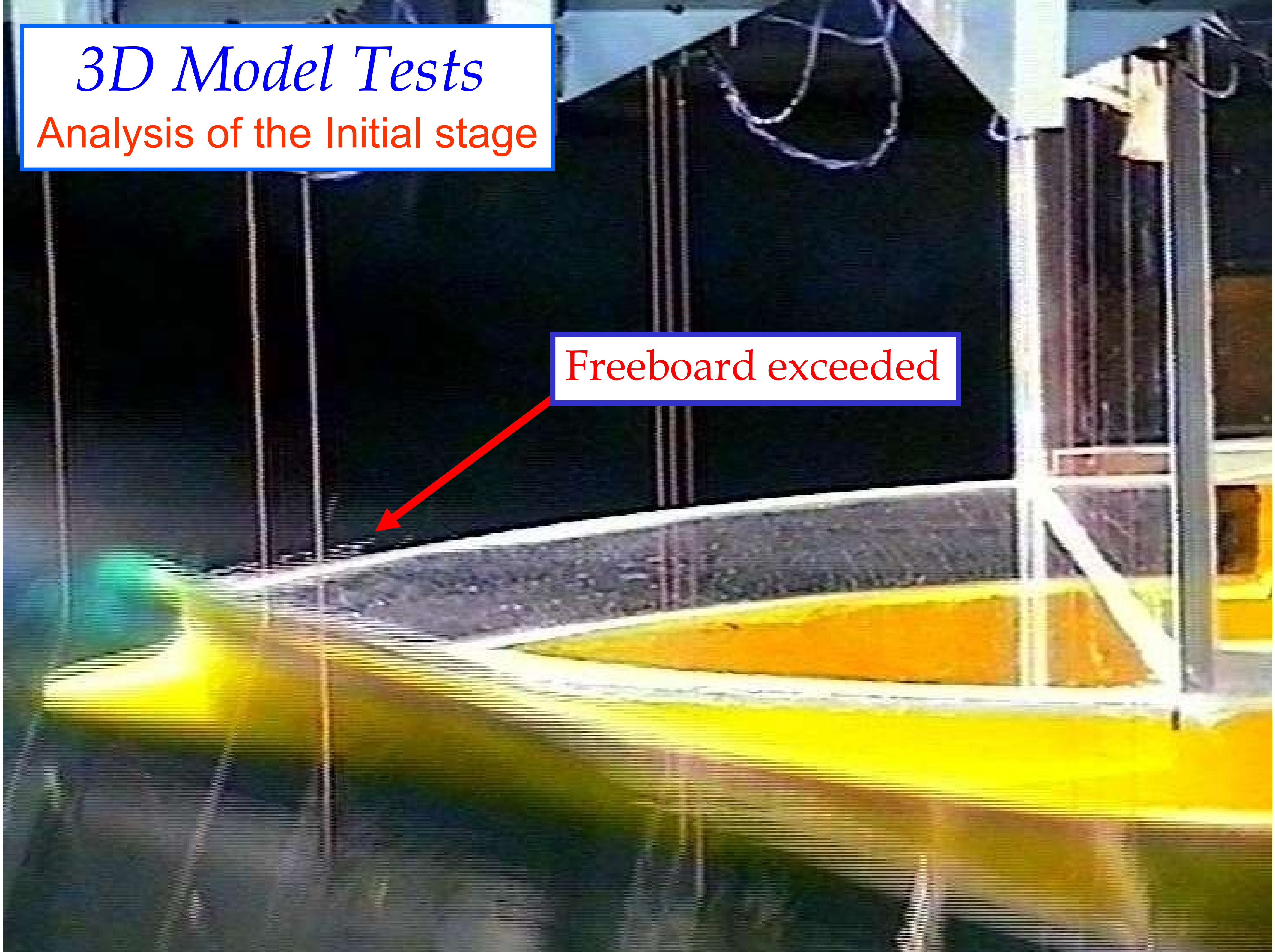


3D Model Tests with Fixed Model



3D Model Tests

Analysis of the Initial stage



3D Model Tests

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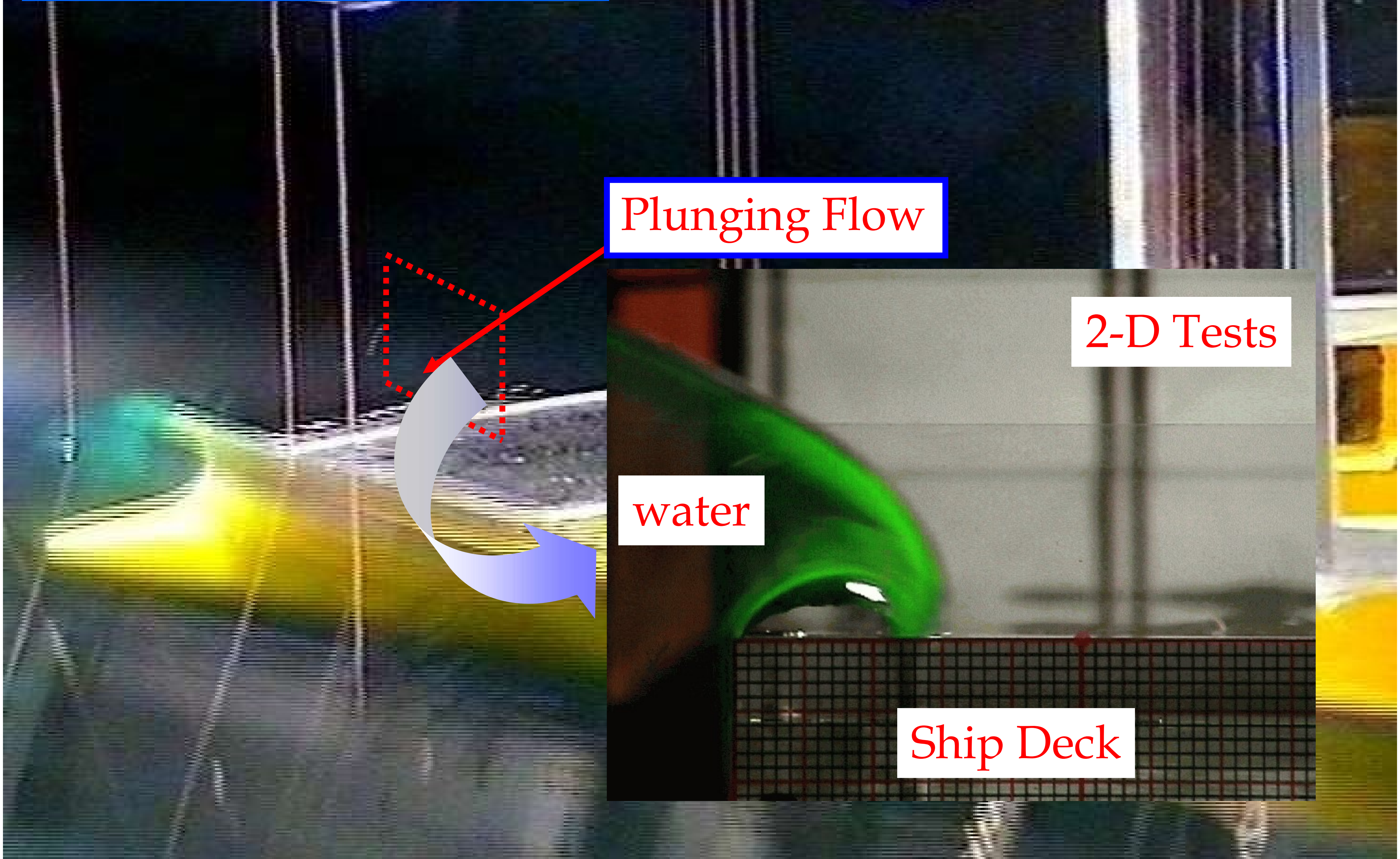
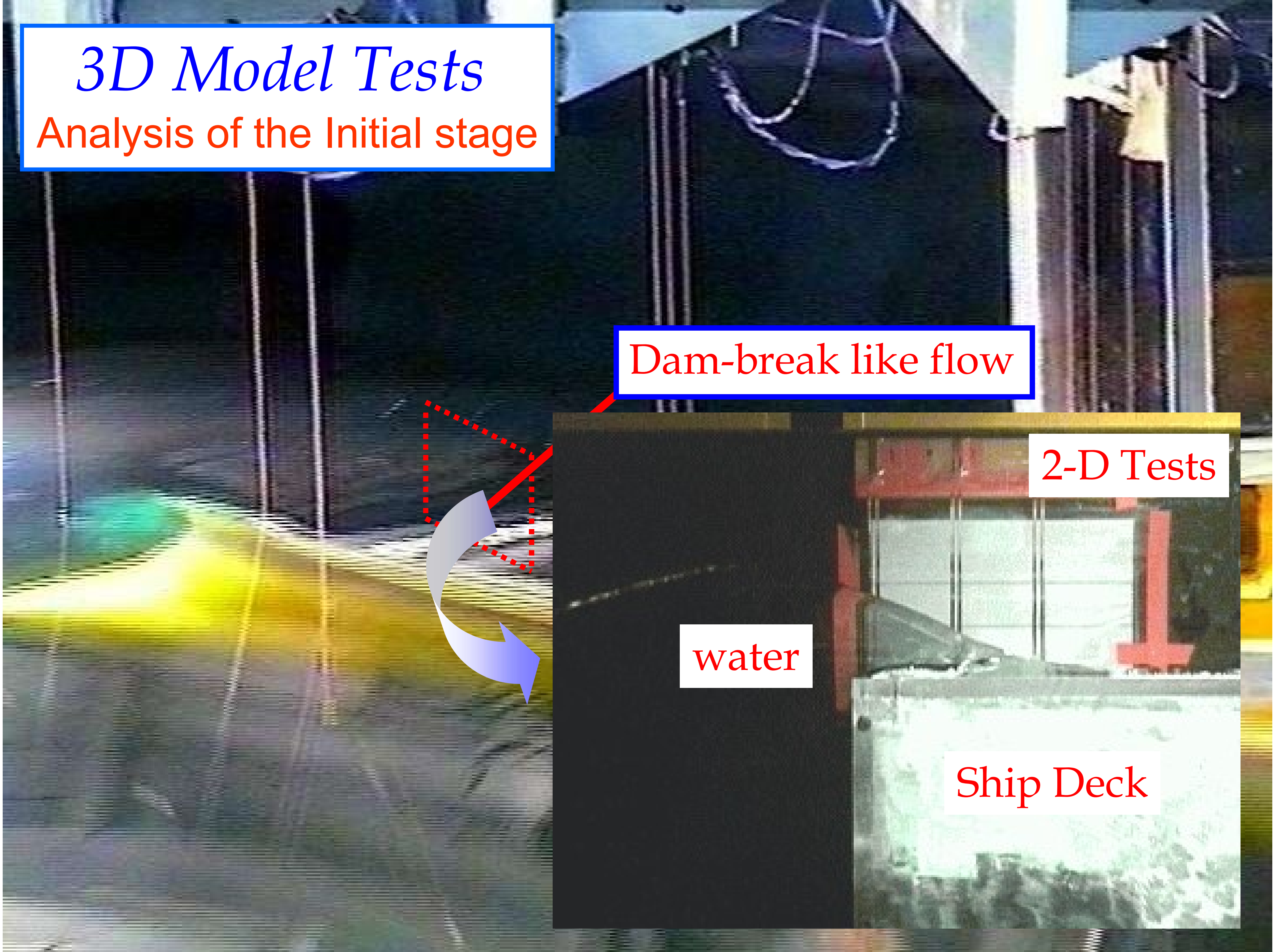
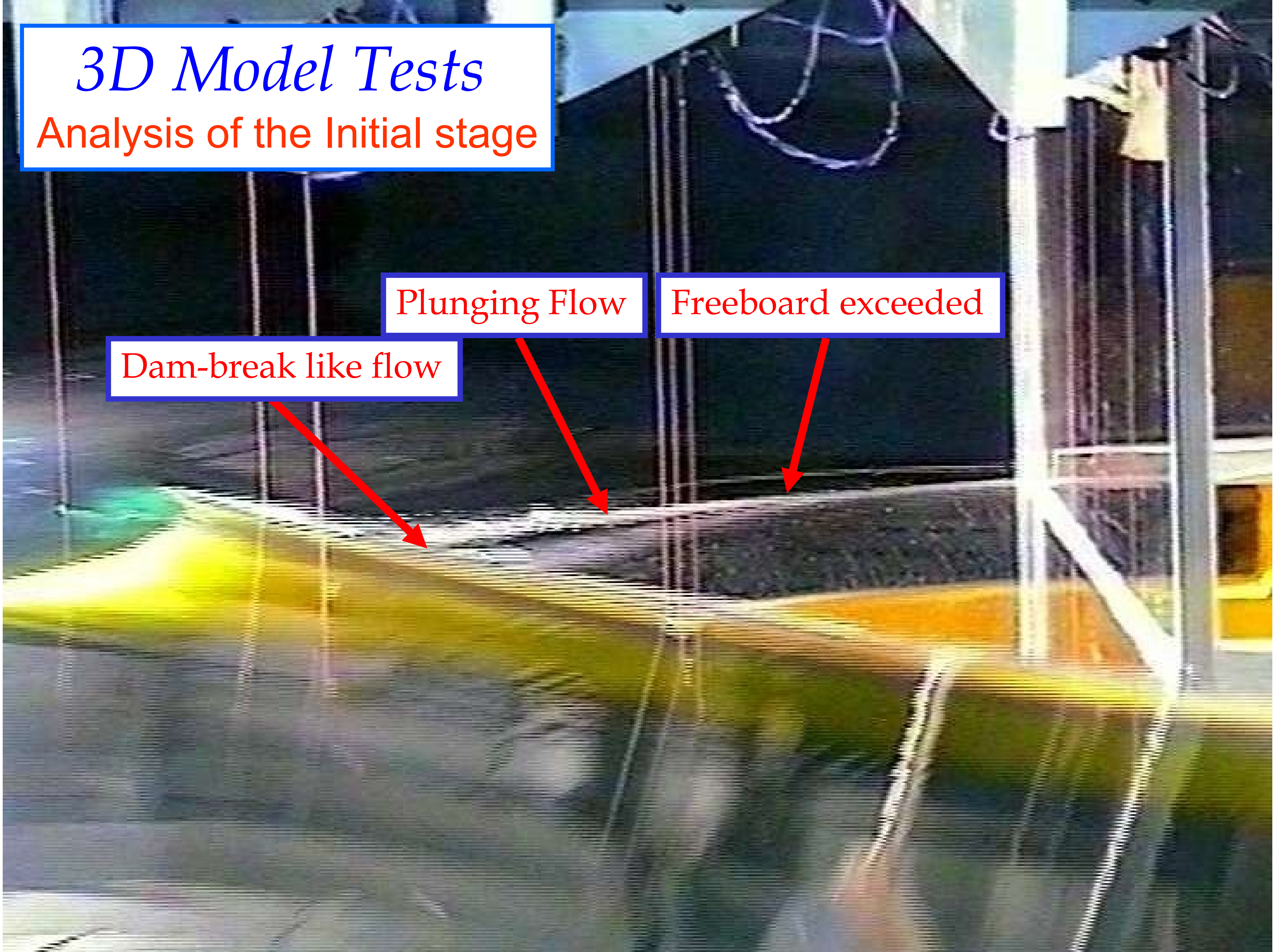


3D Model Tests

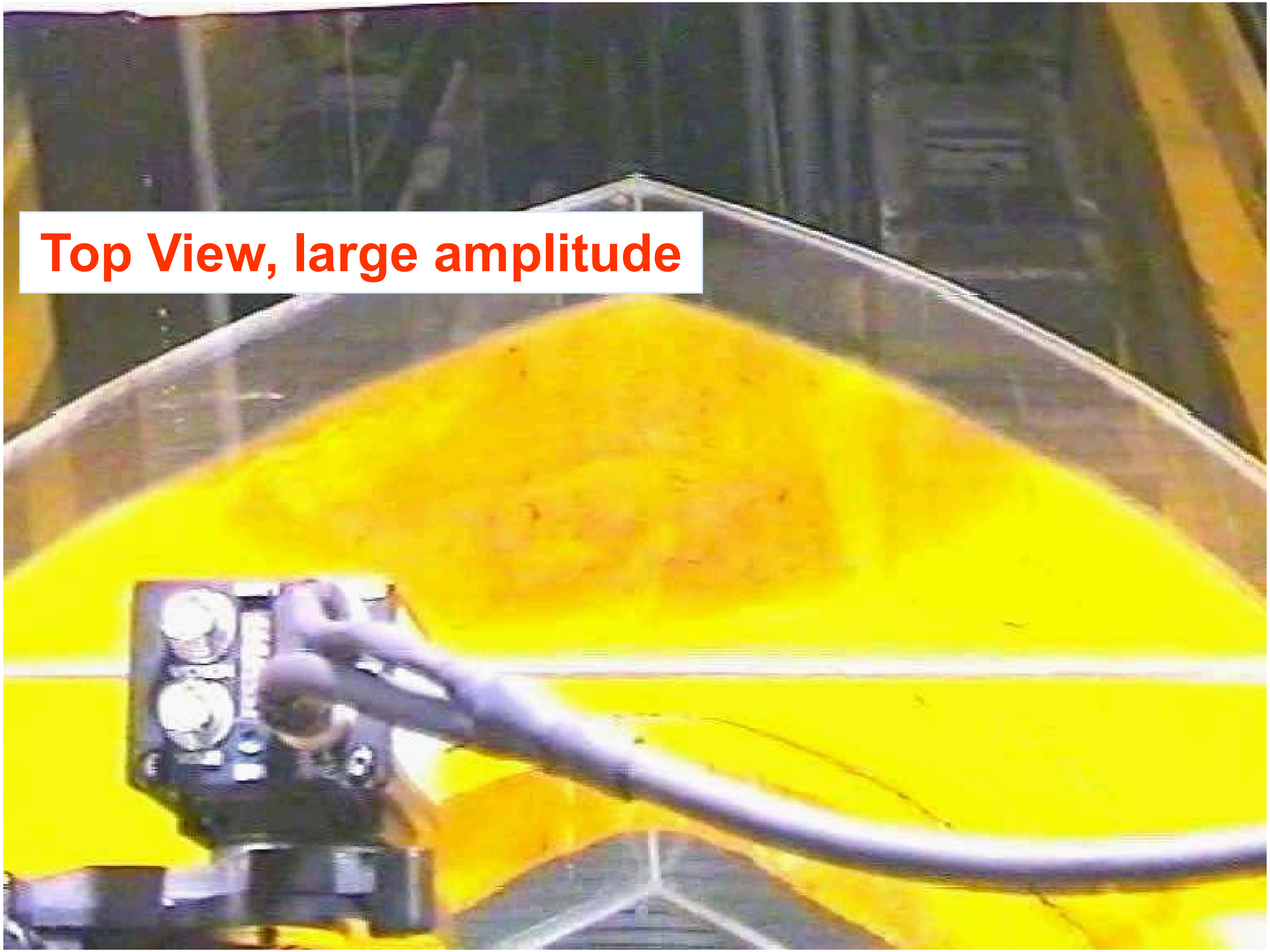
Analysis of the Initial stage



3D Model Tests
Analysis of the Initial stage

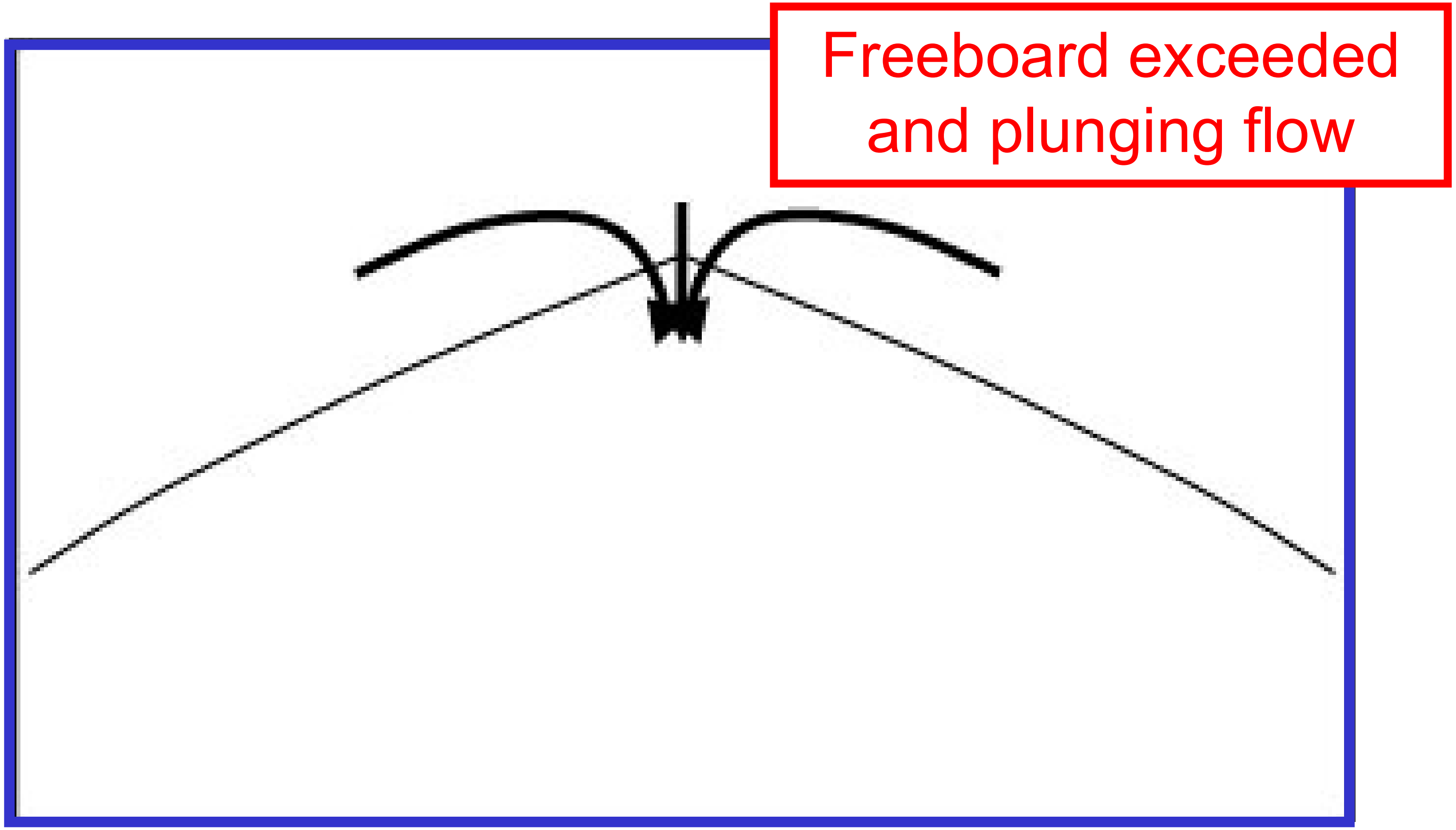


3D Model Tests with Fixed Model



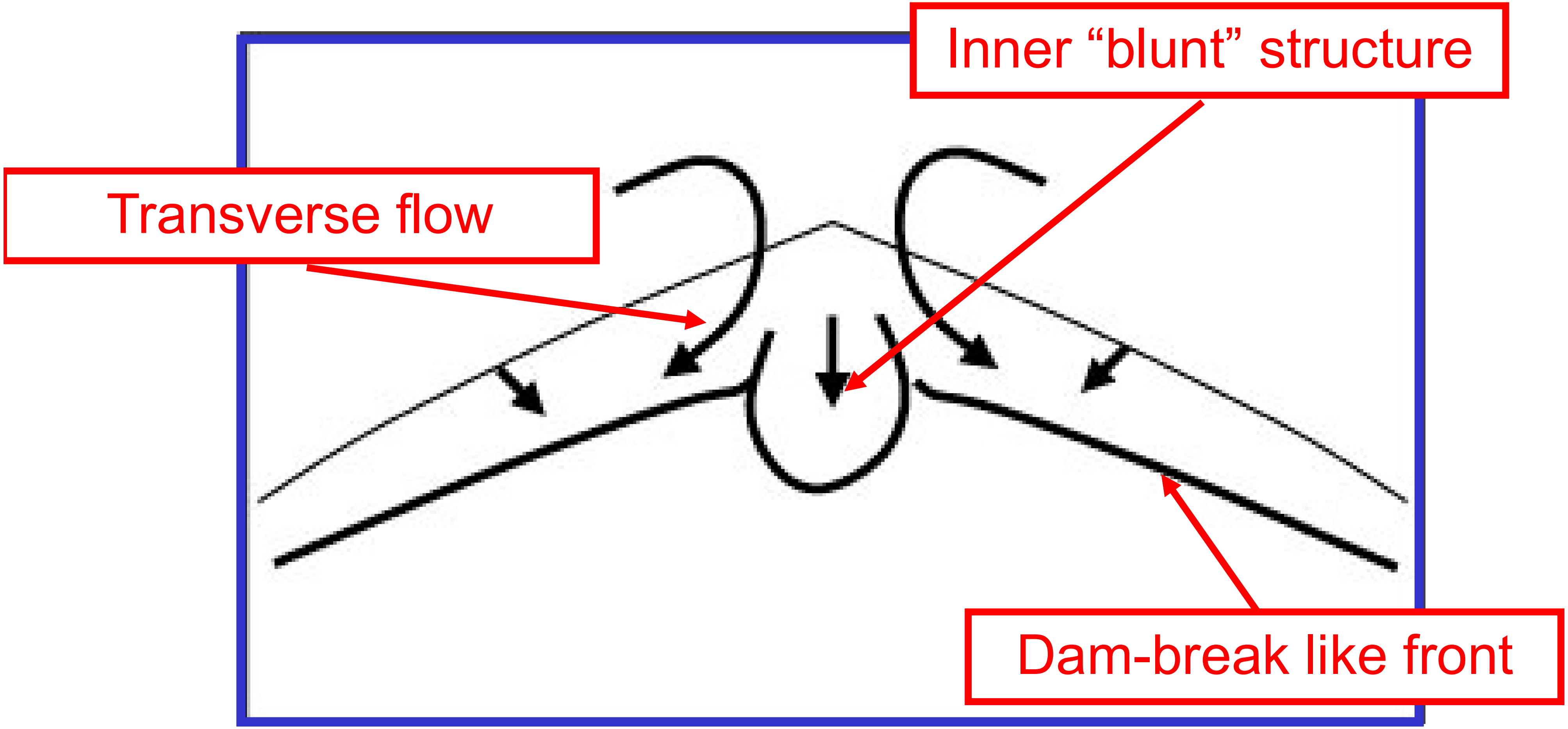
3D Model Tests with Fixed Model

Structure of the deck flow



3D Model Tests with Fixed Model

Structure of the deck flow



3D Model Tests

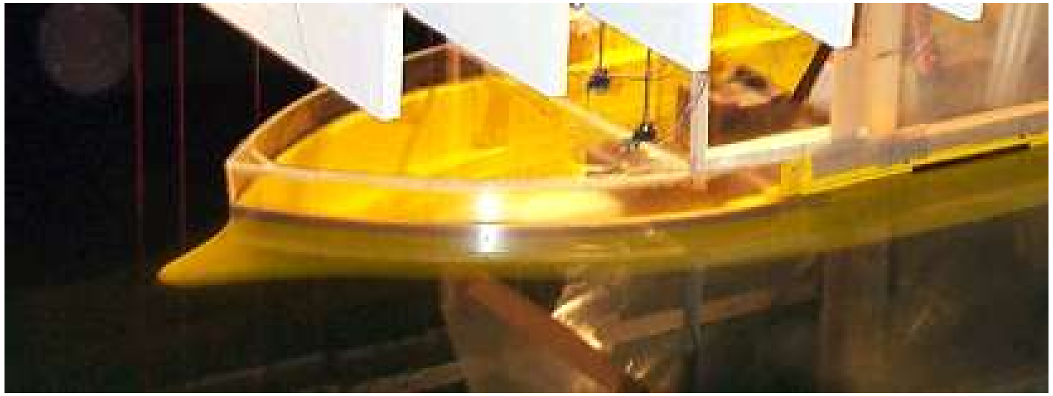
Deck-House Impact

3D Model Tests With Fixed Model

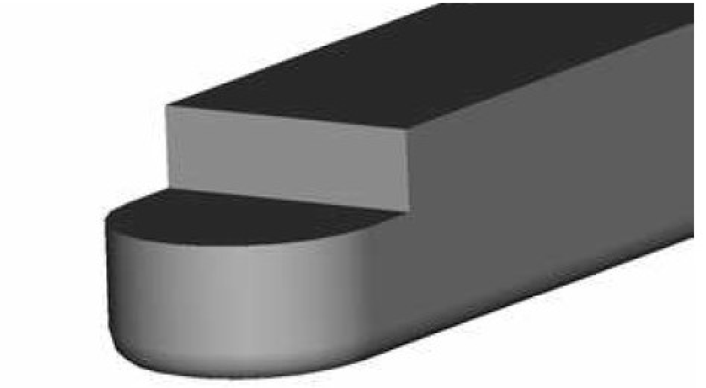
Influence of bow shape

Esso Osaka

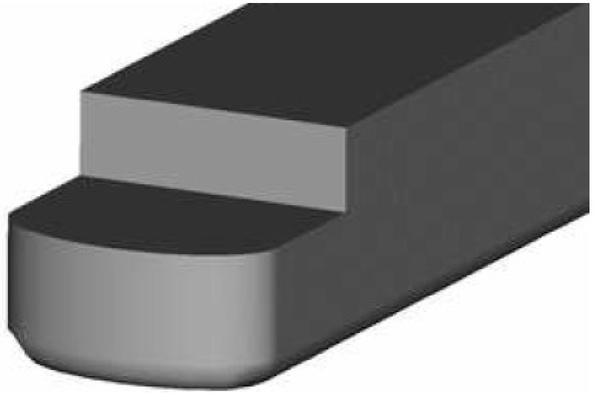
$L \simeq 4.44$ m
$f \simeq 0.015L$
$D \simeq 0.064L$
$B \simeq 0.17L$



Circular bow



Elliptical bow

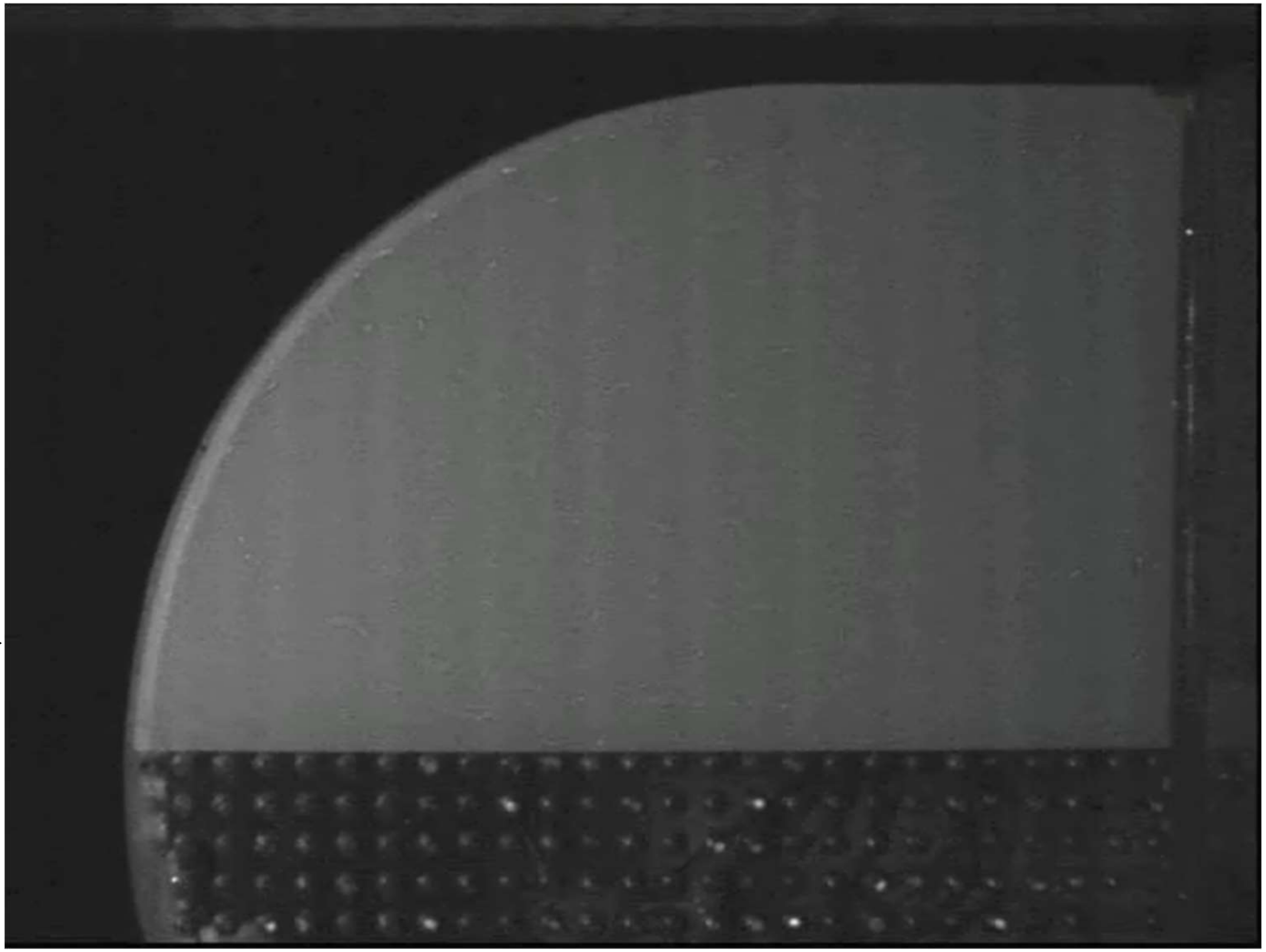


$L \simeq 4$ m
$f \simeq 0.016L$
$D \simeq 0.07L$
$B \simeq 0.17L$

3D Model Tests with Fixed Model

Influence of bow shape: Circular bow

Incoming wave packet



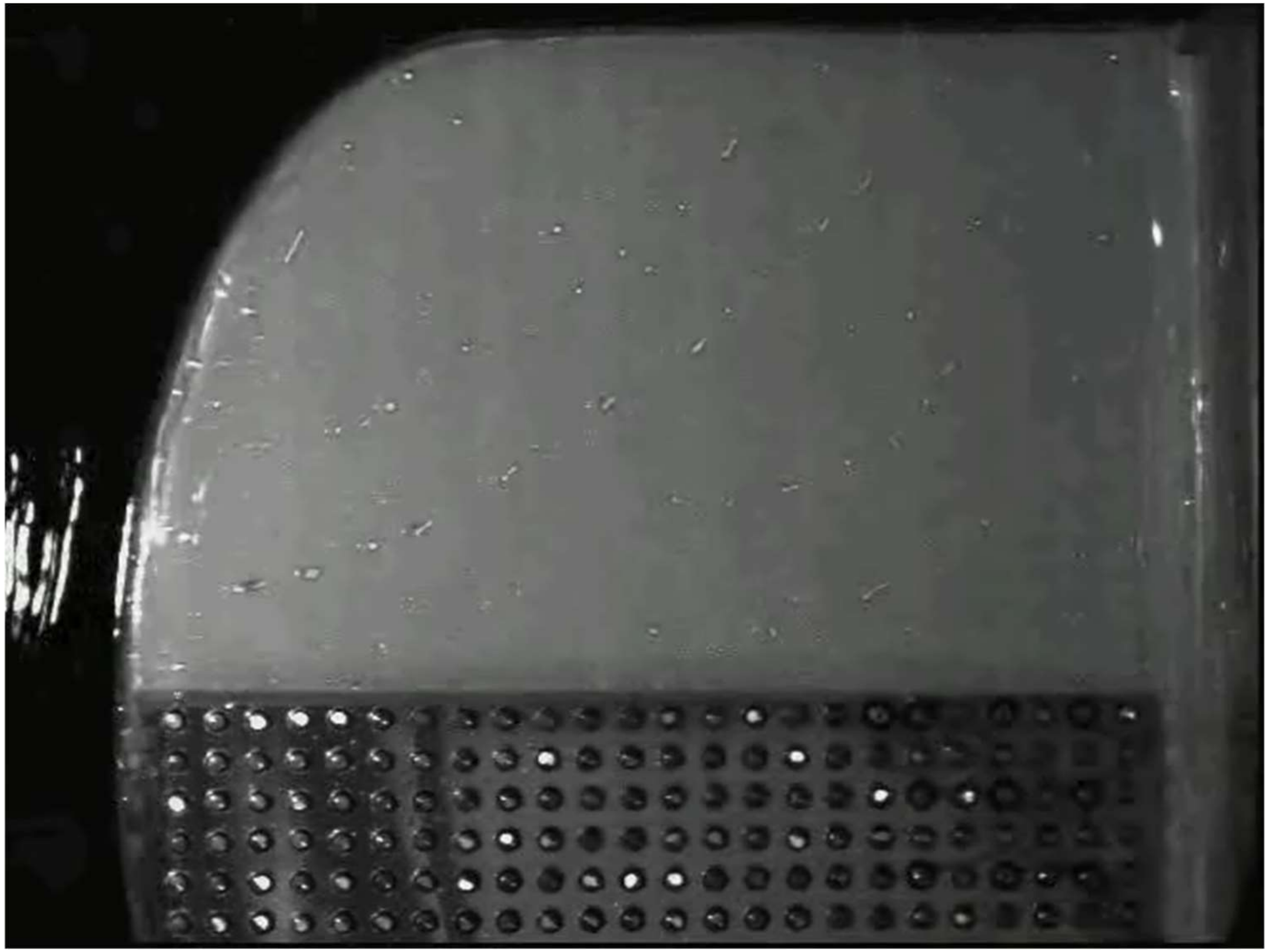
Wall

Top view of the deck

3D Model Tests with Fixed Model

Influence of bow shape: Elliptic bow

Incoming
wave packet



Wall

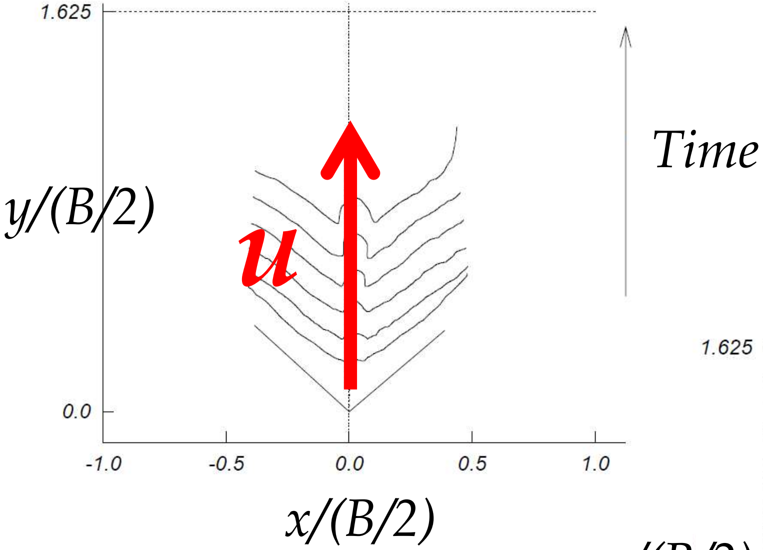
Top view of the deck

3D Model Tests with Fixed Model

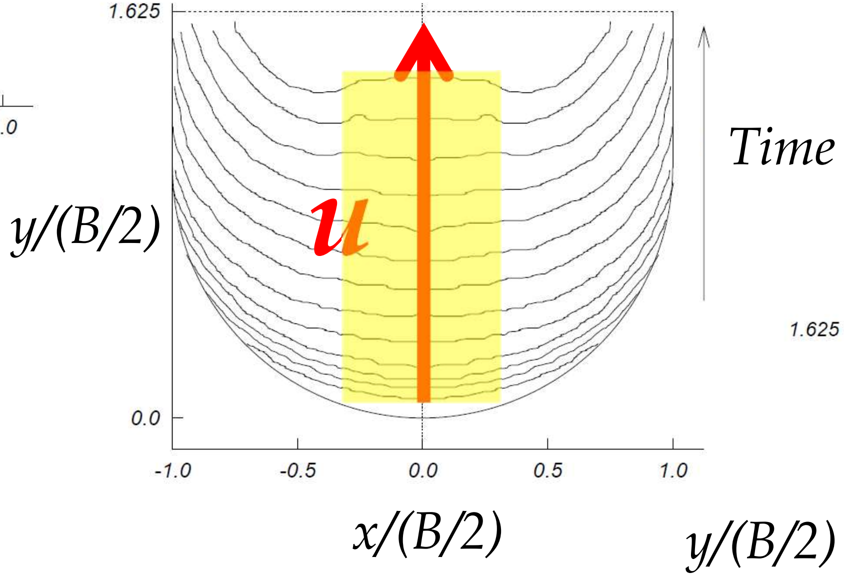
Influence of bow shape

$k_c a = 0.2$

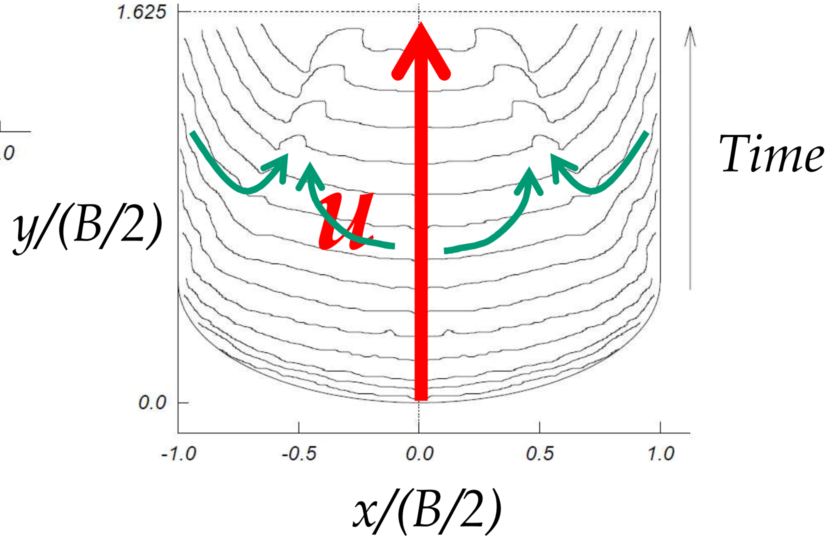
Esso Osaka



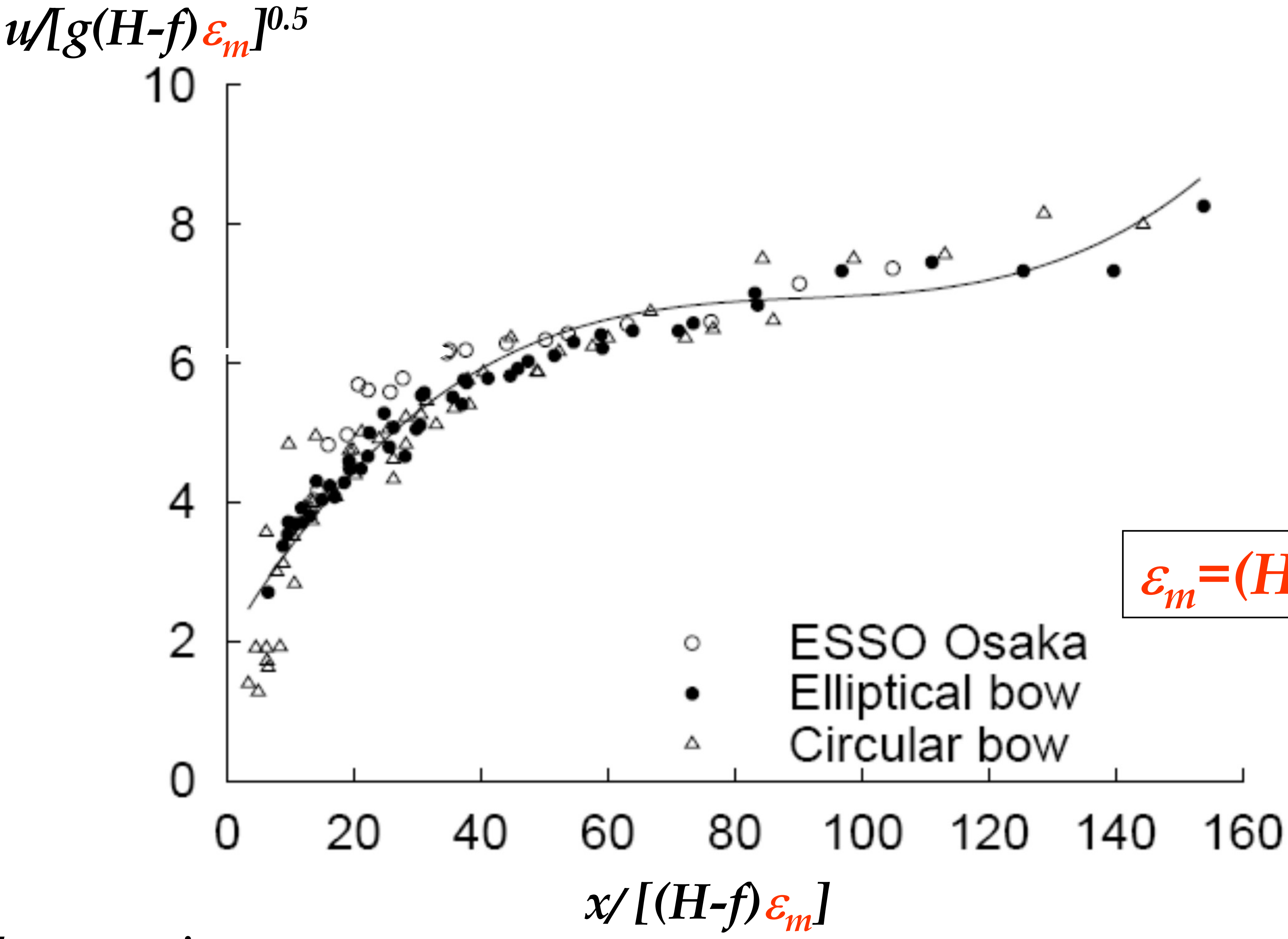
Circular



Elliptical



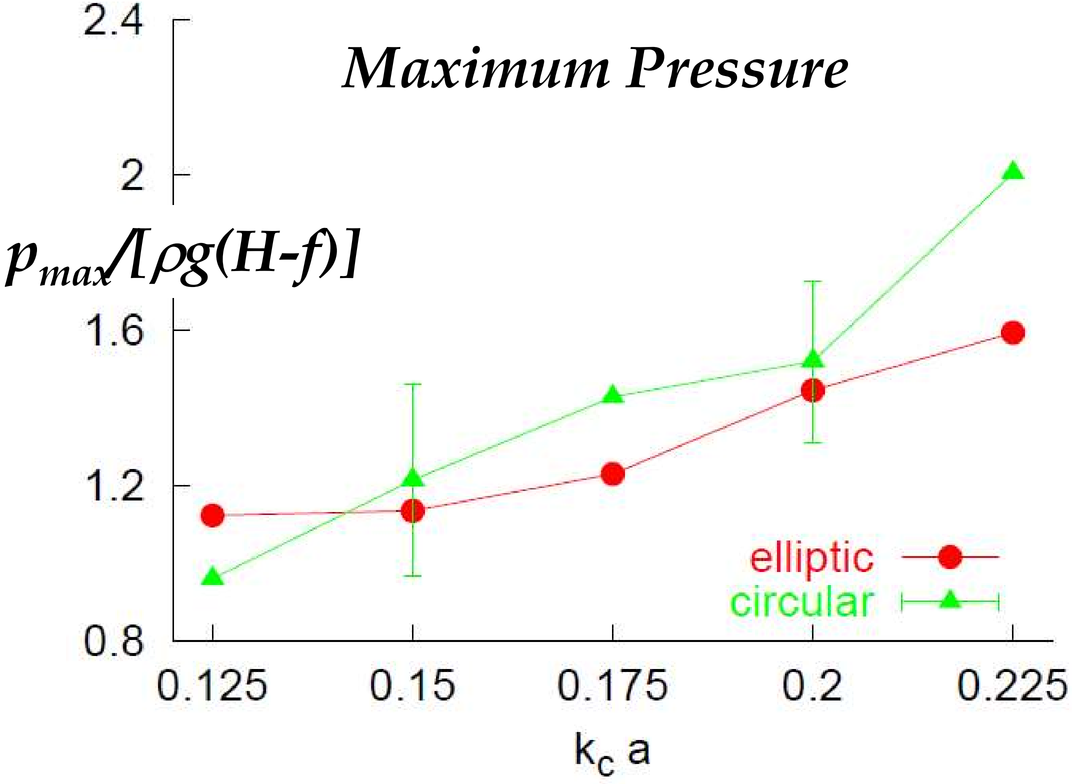
Centreline Water-Front Velocity



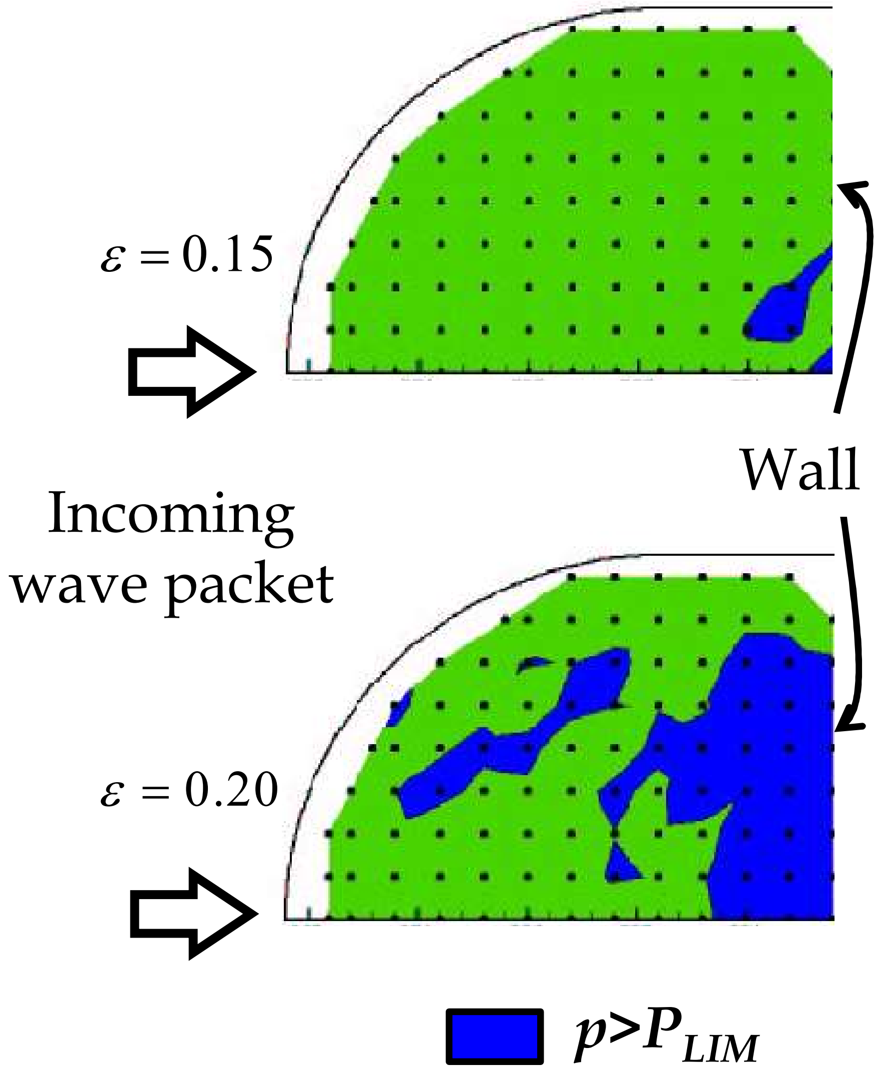
$\varepsilon_m=(H\text{-}f)/\lambda_c$

From experiments

Pressure on the Deck



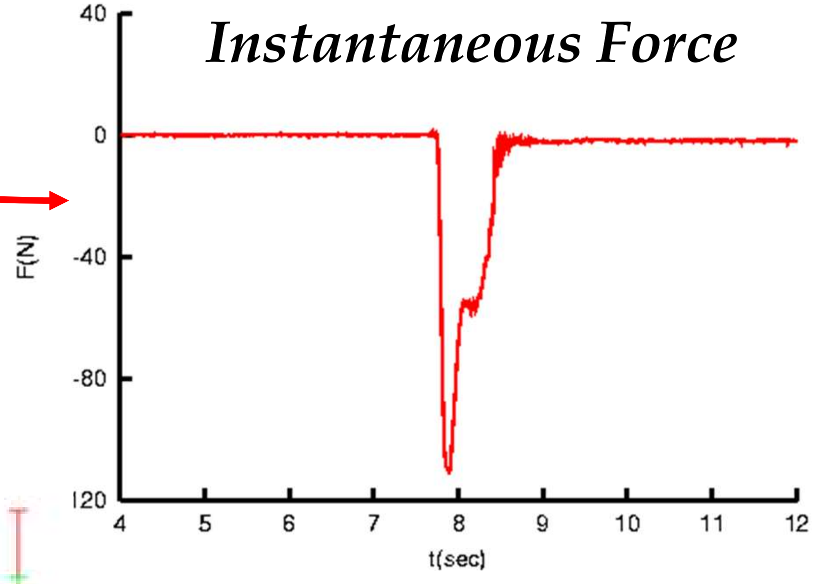
Instantaneous Pressure

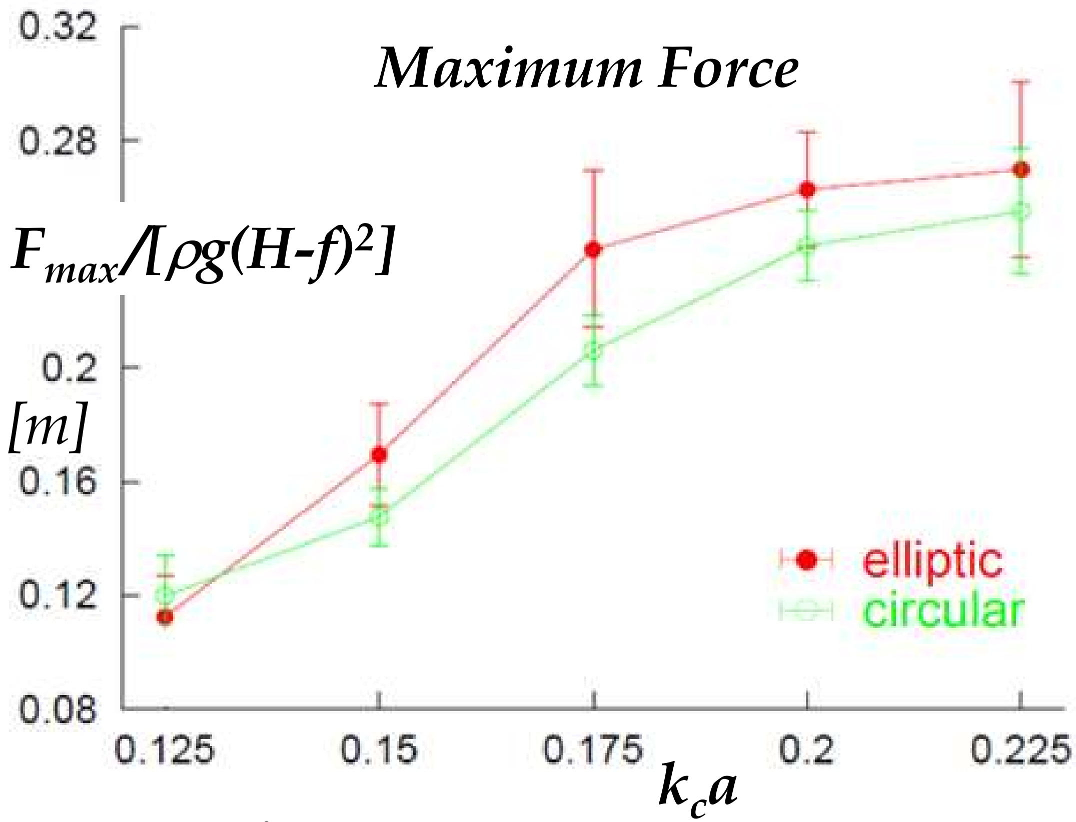


P_{LIM} : Design value

From experiments

Green-Water Loading on the Superstructure





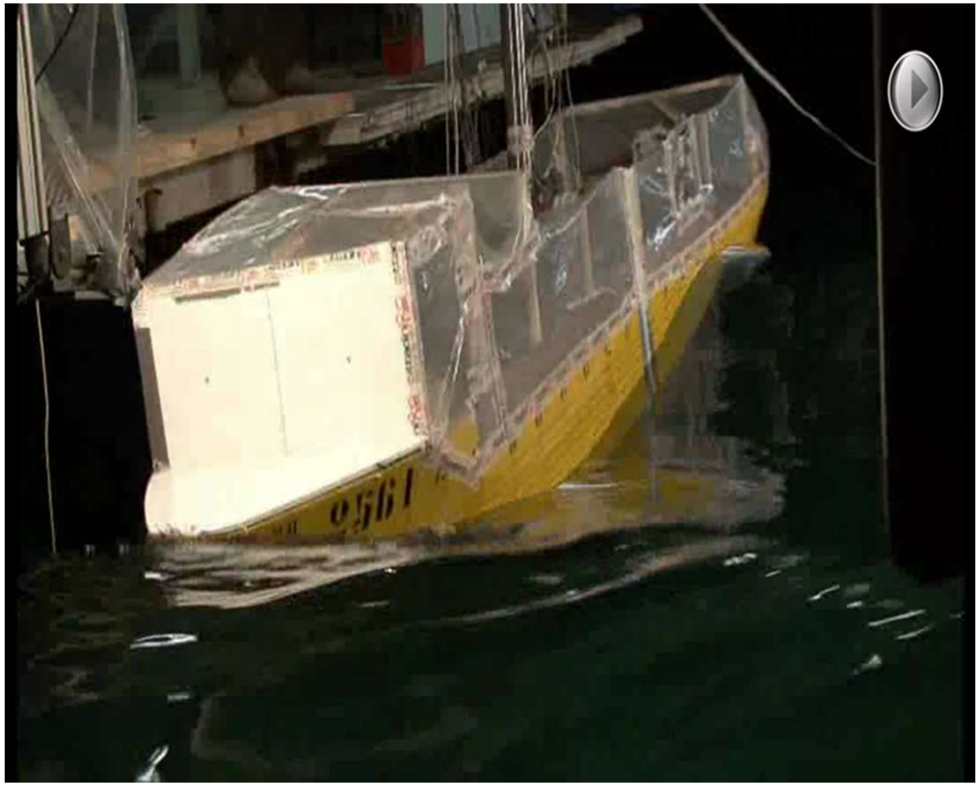
From experiments

Green Water and Dynamic Response: a FPSO

FPSO *prescribed to be* free in heave, pitch and roll.

Regular head-sea waves with $A=a=H/2$, $\lambda=2\pi/k$, $T=2\pi/\omega$.

Front view

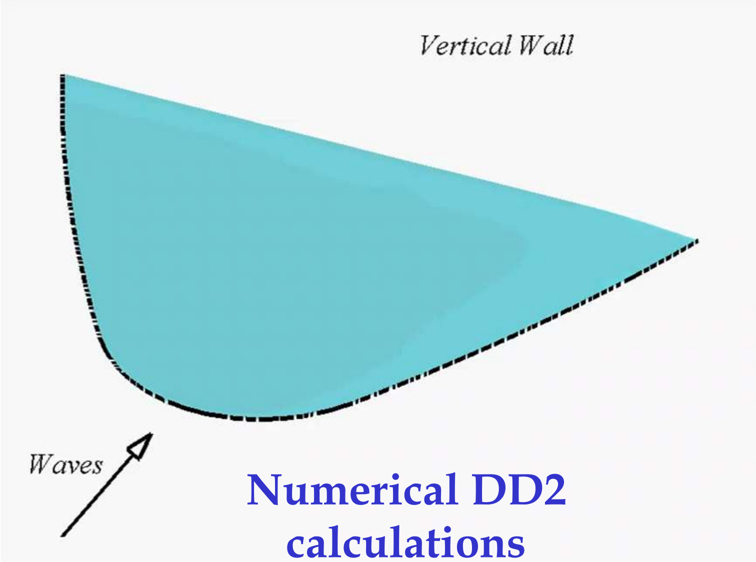


Side view

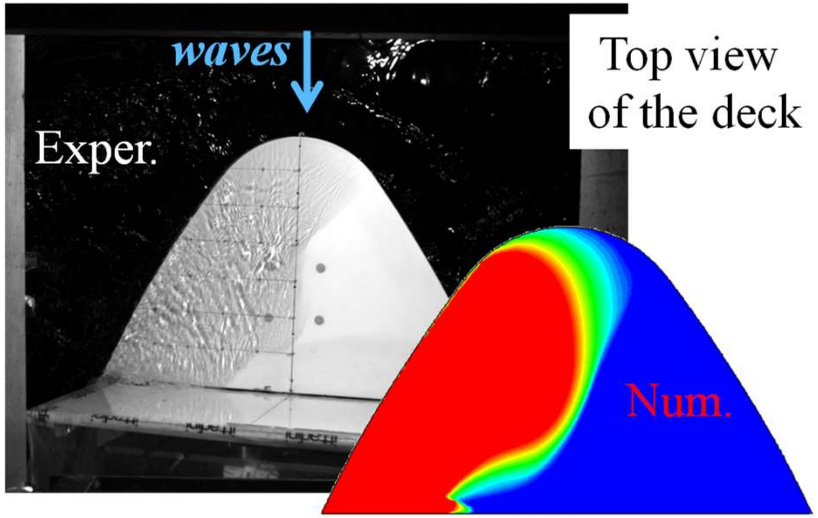
Green water (WPD) & Parametric Roll (PR)

✓ **Parametric roll and green water affect, and can cause, each other**

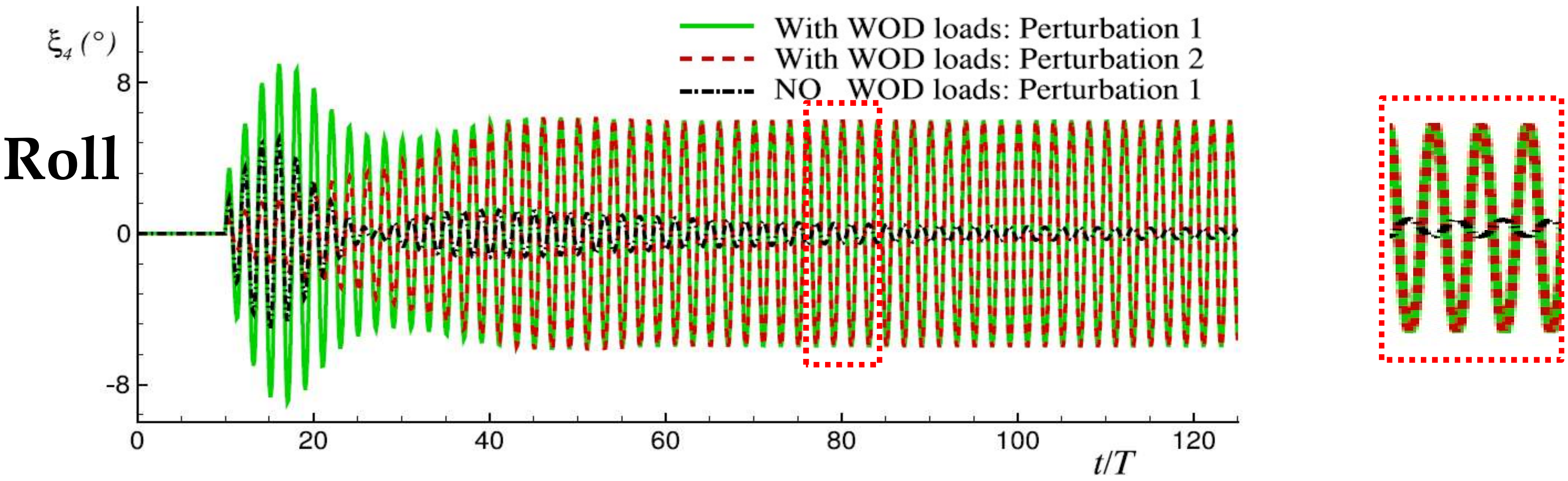
FPSO in head-sea regular waves



Numerical DD2 calculations



Green-water Effect on Parametric Roll



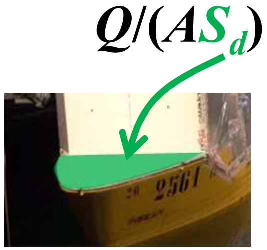
For PRs occurring both with and without WOD:

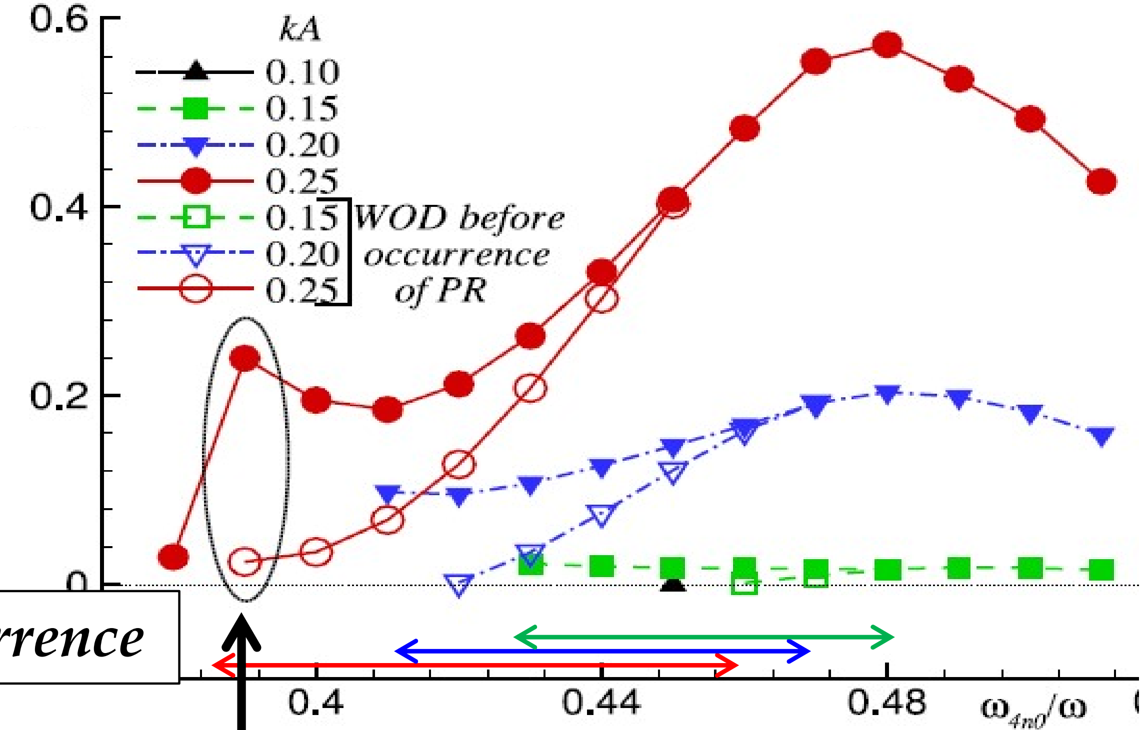
- ✓ **WOD can increase or reduce the transient phase.**
- ✓ **WOD has a limited effect on the roll amplitude.**

From calculations

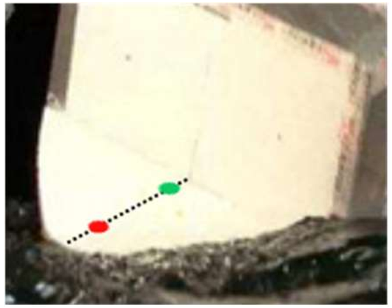
Parametric-Roll Effect on Green-Water

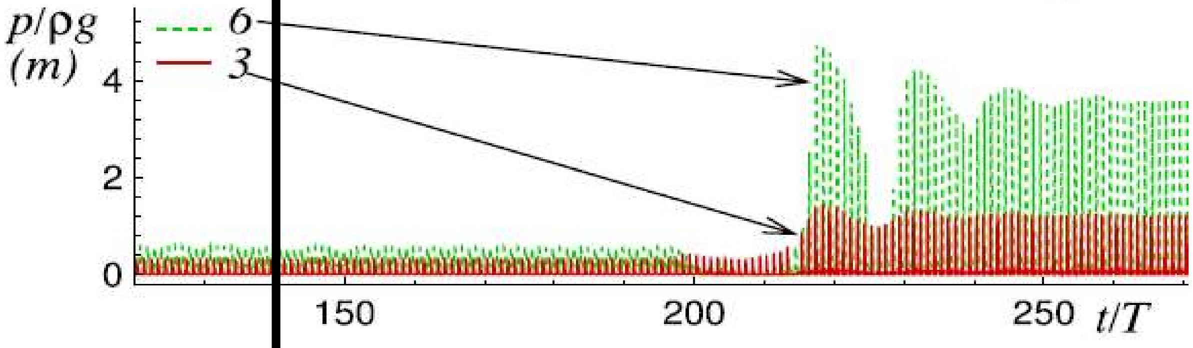
Maximum volume of shipped water



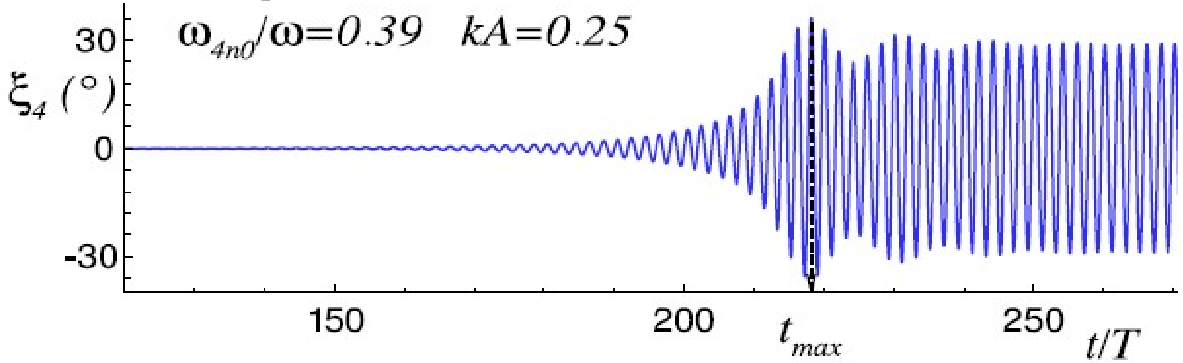


Local pressure on the deck





Roll

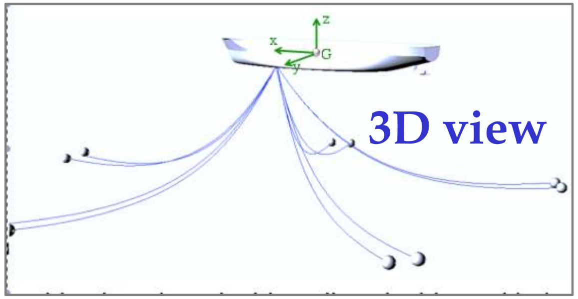


From calculations

Green Water - Bilge Keels and Mooring lines

From systematic study including:

- Bilge-keel roll damping $B_{44,bk}$
- Mooring-line system



✓ **Bilge-keel damping reduces roll and then the amount of WOD affected by roll.**

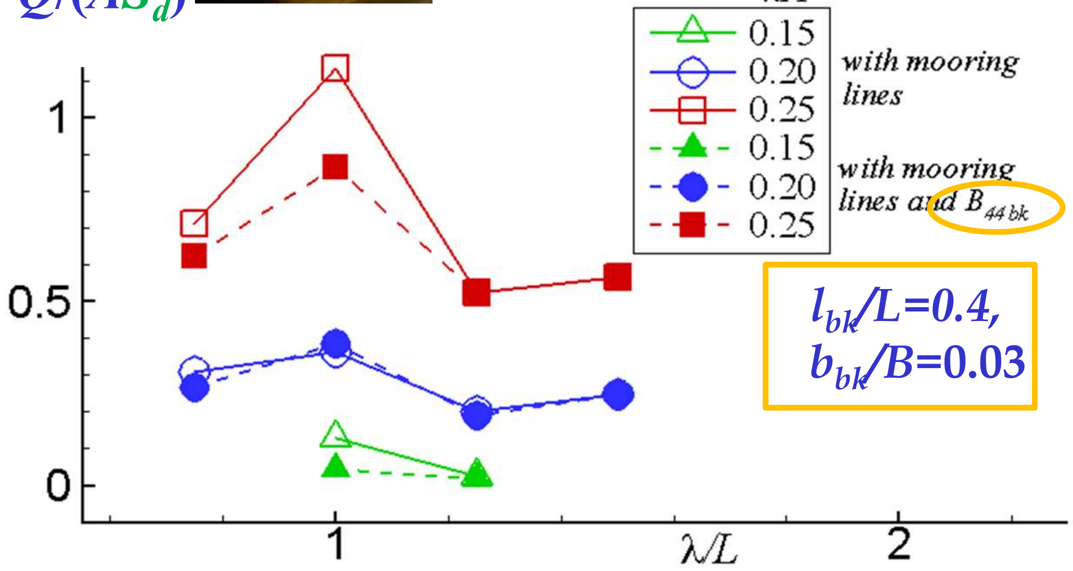
✓ **Mooring-line system leads to greater water on deck.**

Without mooring-lines

$\lambda/L \rightarrow$		0.75	1.00	1.25	1.50	2.00
$\omega_{4n0}/\omega \rightarrow$		0.402	0.464	0.519	0.568	0.656
Method	kA	Water On Deck (WOD)				
Exp.	0.10	NO	NO	NO	NO	NO
No BK	0.10	NO	NO	NO	NO	NO
With BK	0.10		NO			
Exp.	0.15	NO	NO	NI	NO	NO
No BK	0.15	NO	0.017	0.012	NO	NO
With BK	0.15		0.004			
Exp.	0.20	YES	YES	YES	YES	X
No BK	0.20	0.125	0.178	0.134	0.017	X
With BK	0.20	NO	0.177			
Exp.	0.25	YES	YES	YES	YES	X
No BK	0.25	0.190	0.507	0.356	0.055	X
With BK	0.25	0.036				

From calculations

Maximum volume of shipped water



Experiments vs numerics:
Parametric roll & water on deck

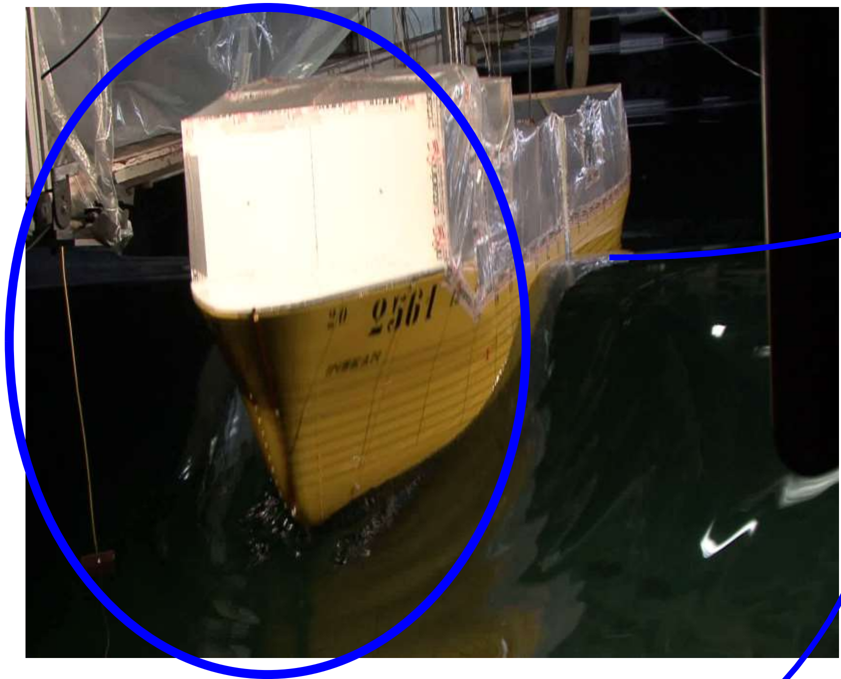
β=175°

$\lambda/L \rightarrow$		0.75	1.00	1.25	1.50	2.00	0.75	1.00	1.25	1.50	2.00
Method	kA	Parametric Roll					Water On Deck				
Exper.	0.10	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Num	0.10	NO	YES	NO	NO	NO	NO	NO	NO	NO	NO
Exper.	0.15	NO	YES	NO	NO	NO	NO	small	small	small	NO
Num	0.15	NO	YES	NO	NO	NO	NO	YES	YES	small	NO
Exper.	0.20	YES	YES	NO	YES	X	due to PR	YES	YES	YES	X
Num	0.20	YES	YES	NO	NO	X	due to PR	YES	YES	YES	X
Exper.	0.25	YES	NO	NO YES	YES	X	YES	YES	YES	YES	X
Num	0.25	YES	NO	NO	NO	X	YES	YES	YES	YES	X

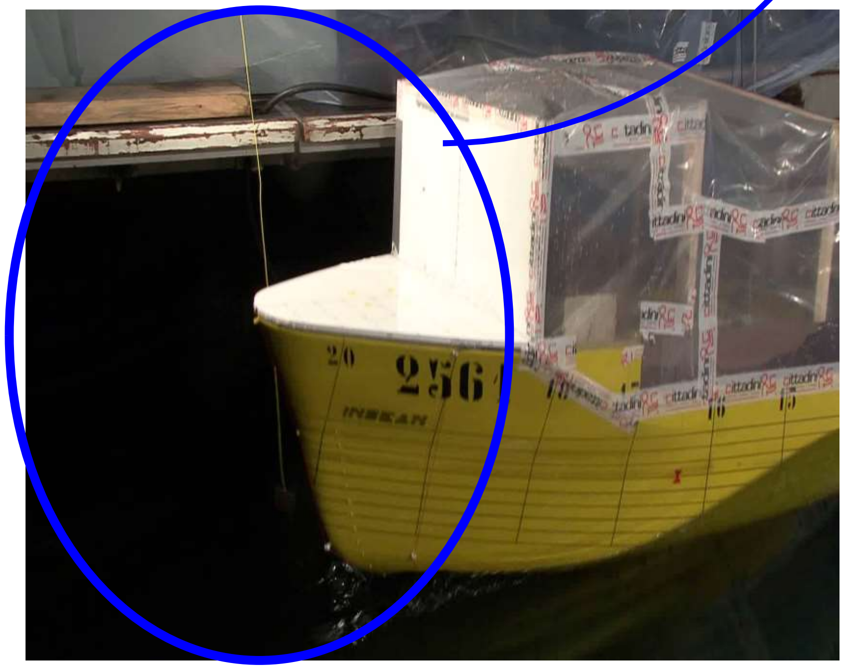
Run 44 *Run 46*

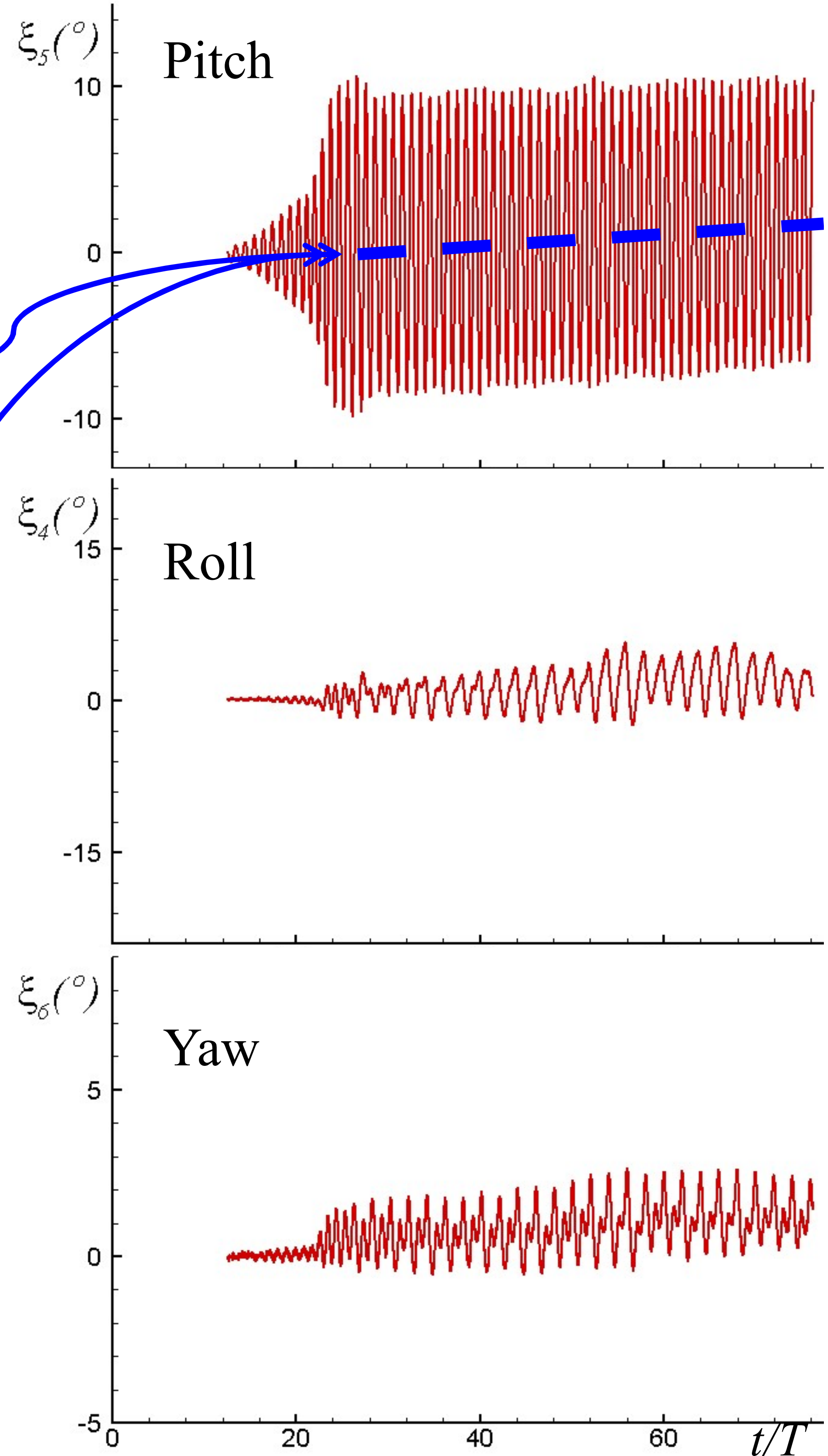
Experiments: Run 44

Front view



Side view

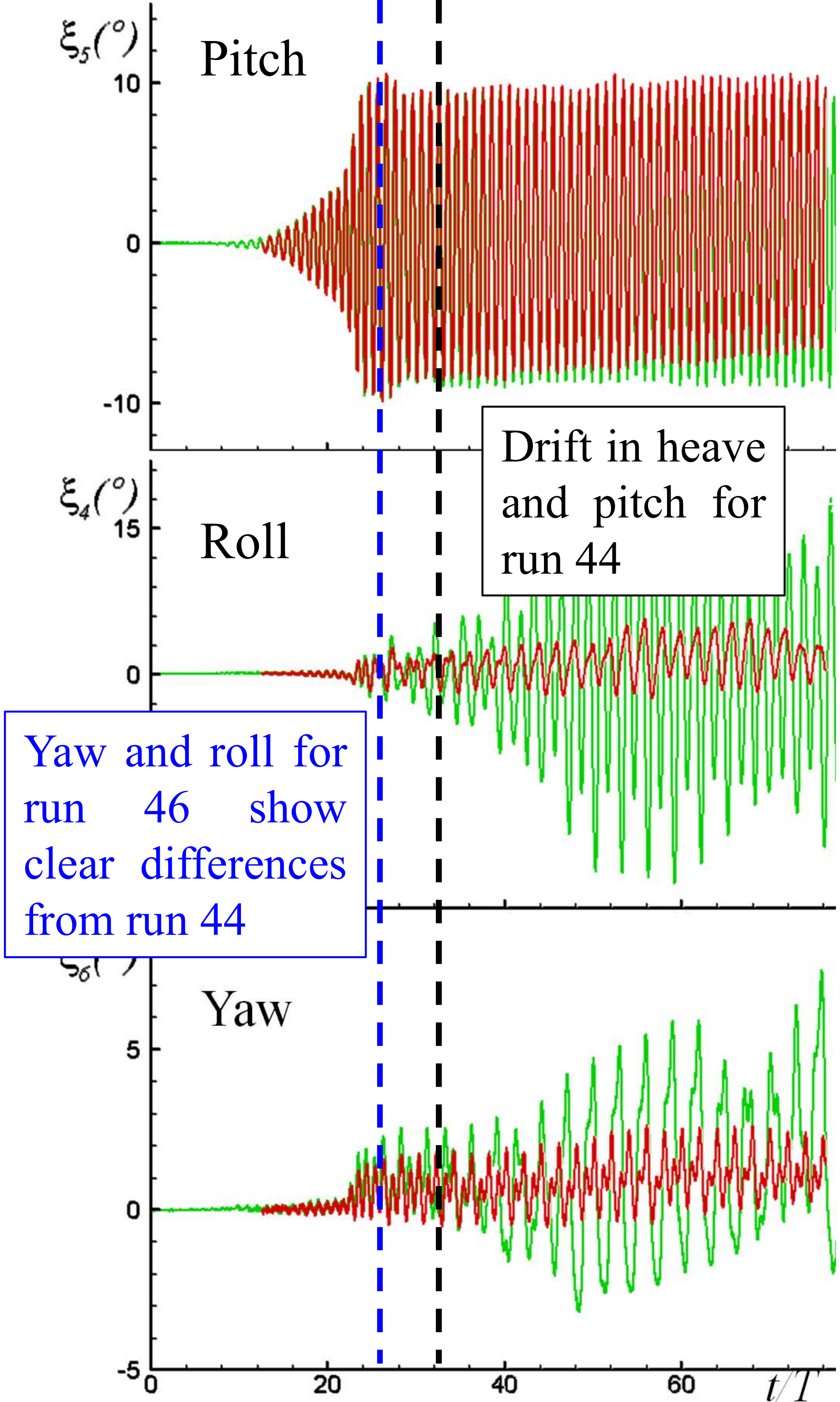




Experiments: Run 46

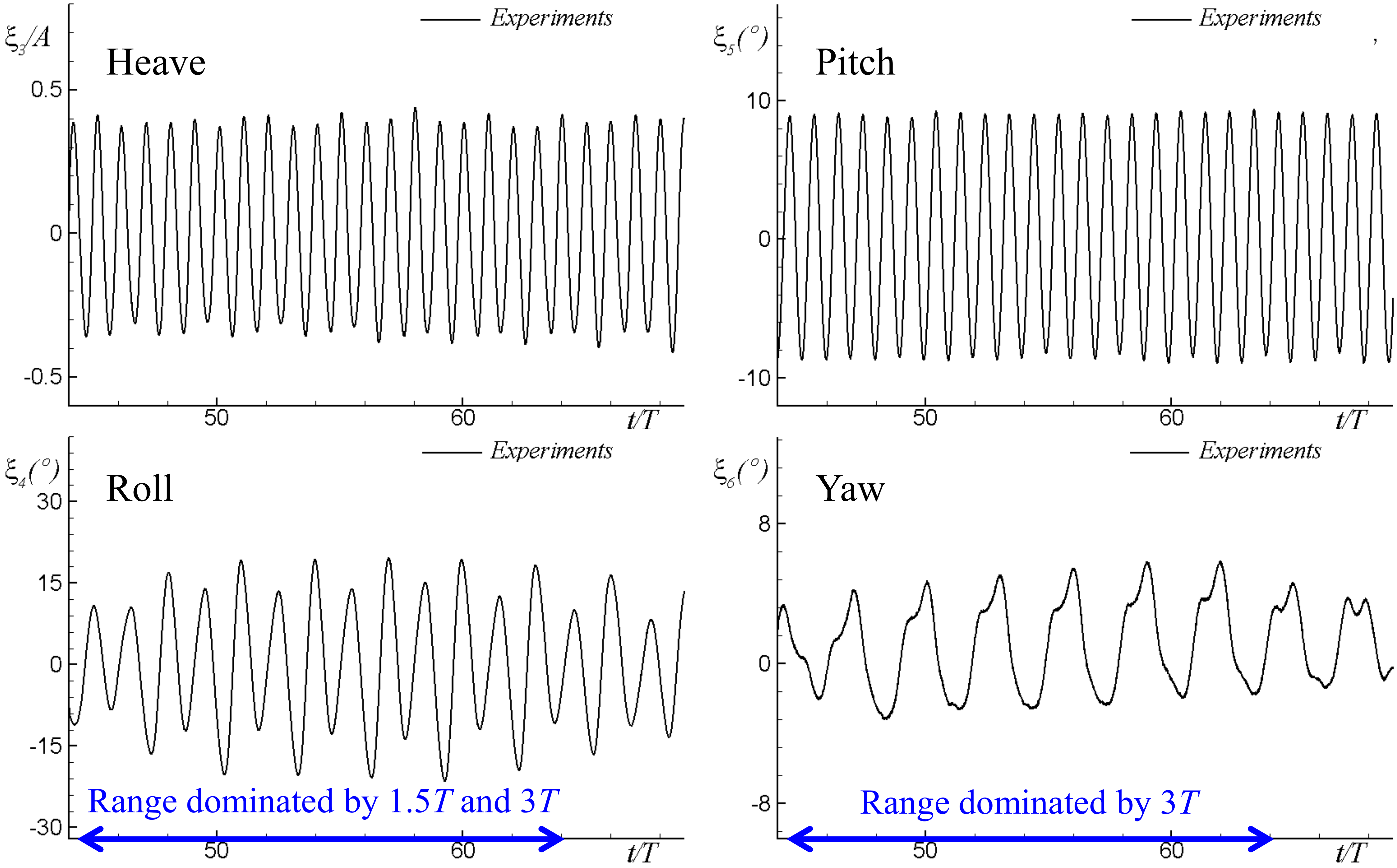
Front view

Side view

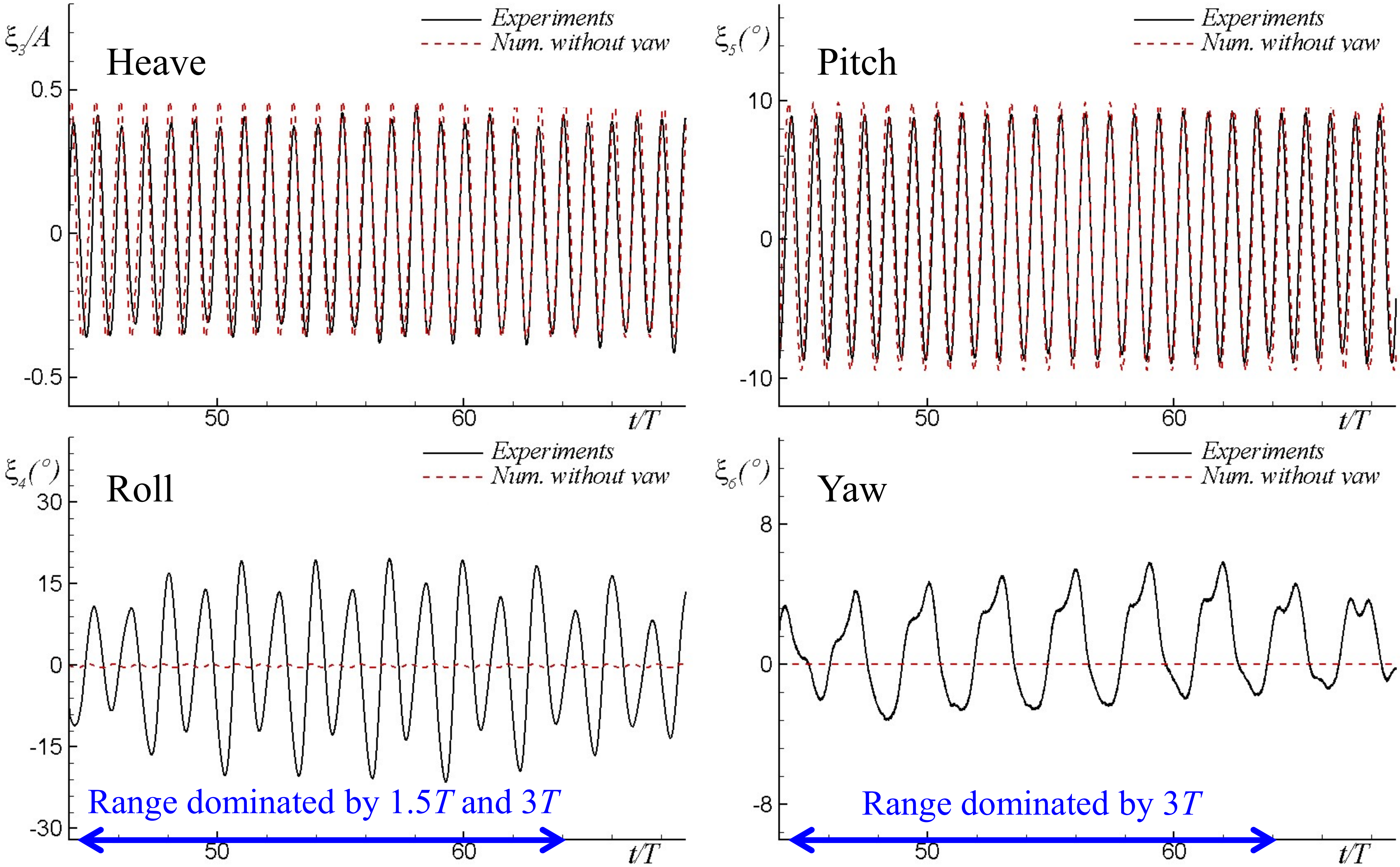


Assessment of roll-yaw coupling effects:

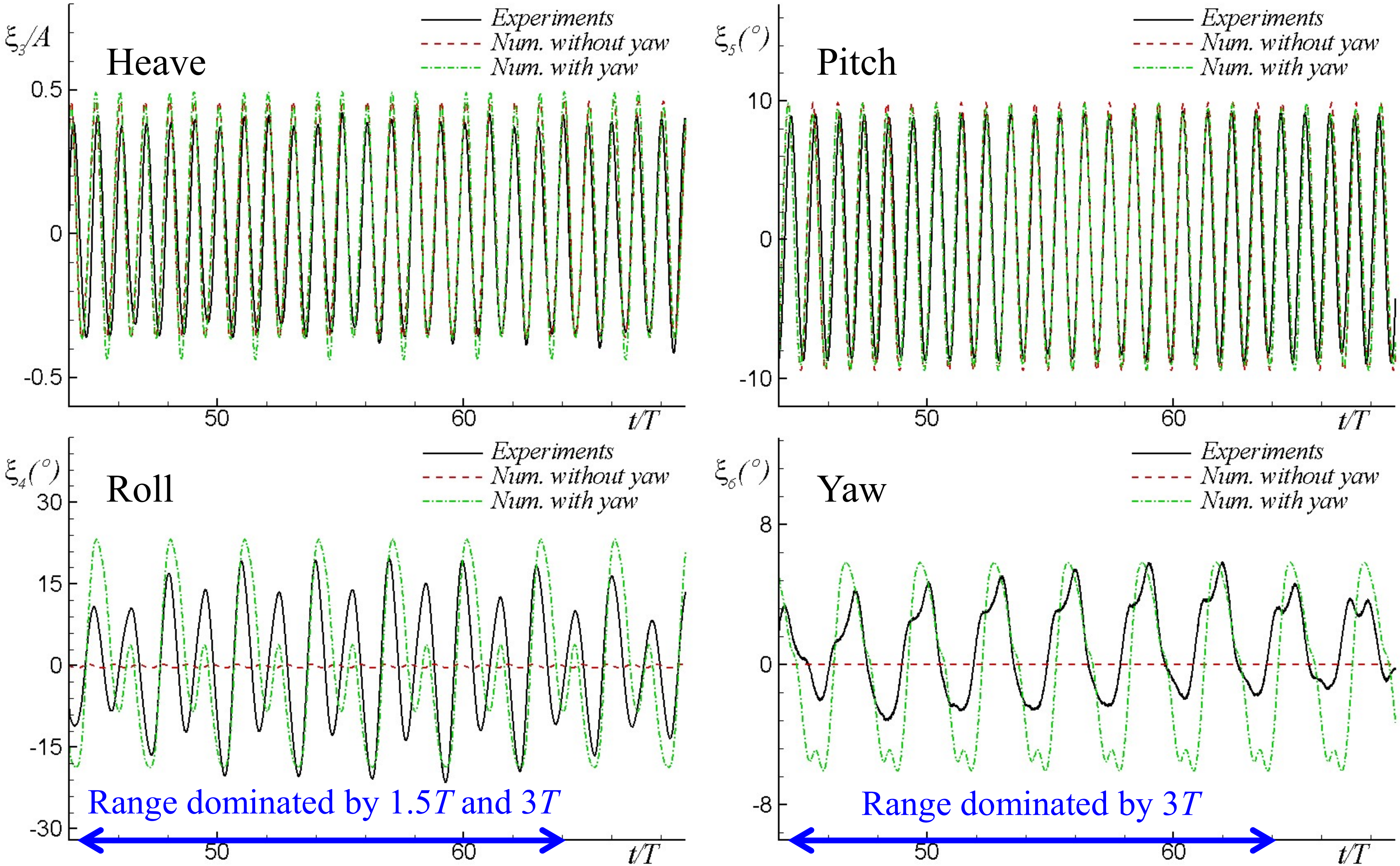
Experiments (Run 46) vs numerics - Motions



Assessment of roll-yaw coupling effects: Experiments (Run 46) vs numerics - Motions

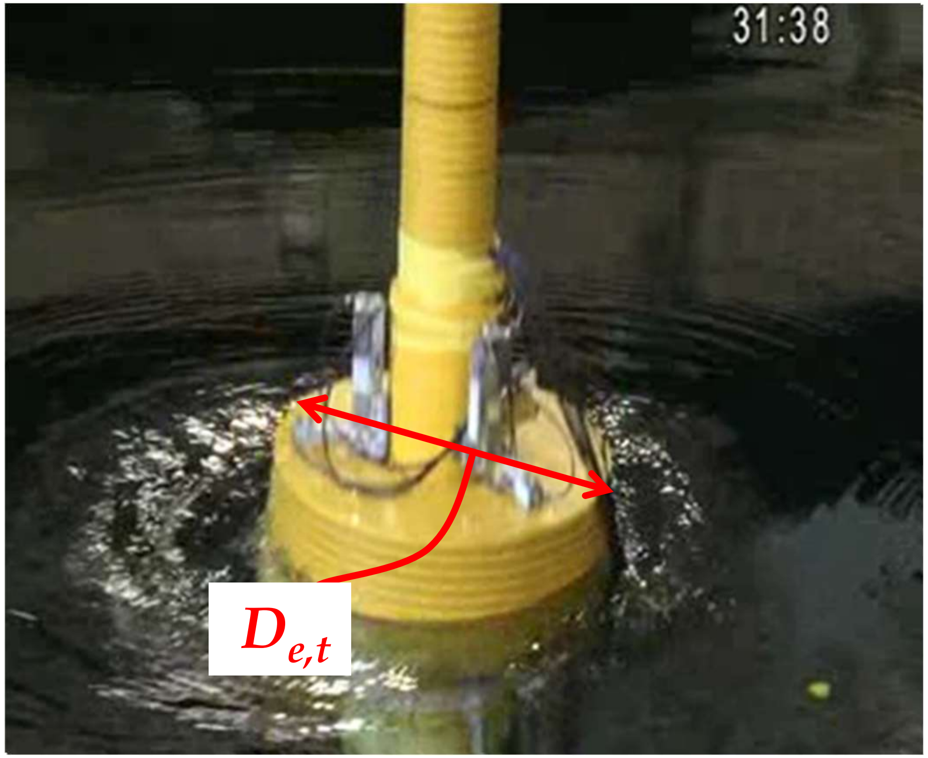


Assessment of roll-yaw coupling effects: Experiments (Run 46) vs numerics - Motions



Green Water and Dynamic Response: a Combined Wind and Wave Energy Converter Concept in Survival Conditions

Model tests



$6<\lambda/D_{e,t}<18$
H=2A=9m (full scale)
$\rightarrow kA \in [0.08, 0.22]$

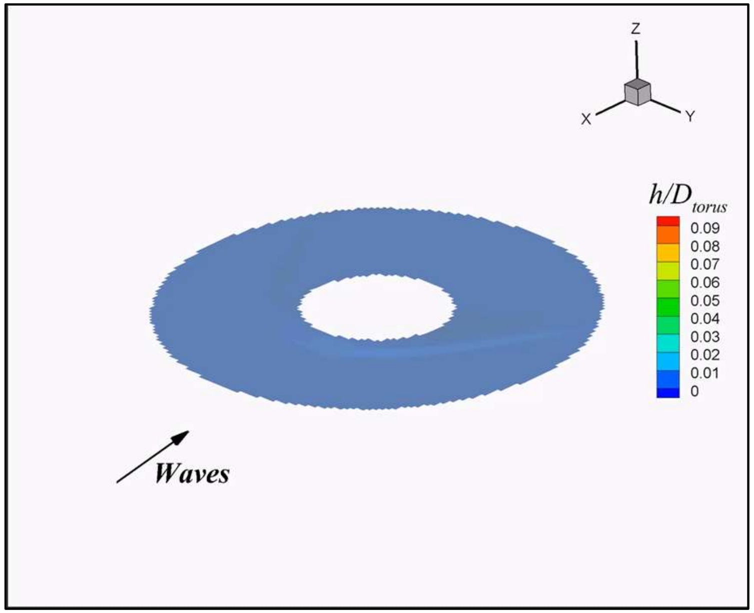
✓ **'Nonlinear' FK+ hydrostatic loads within long-wave approximation do not capture the physics.**

Green Water and Dynamic Response: a Combined Wind and Wave Energy Converter Concept in Survival Conditions

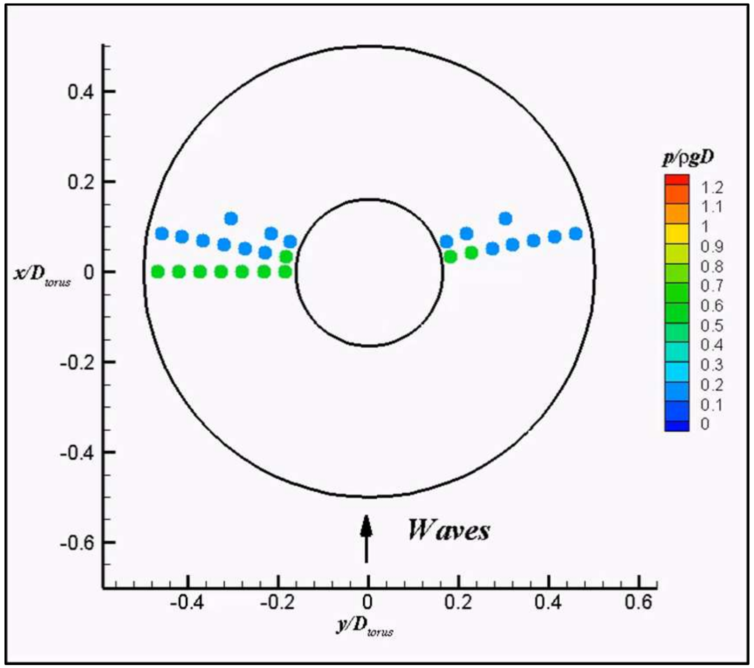
Model tests

Numerical DD2 results

3D view:
Green Water



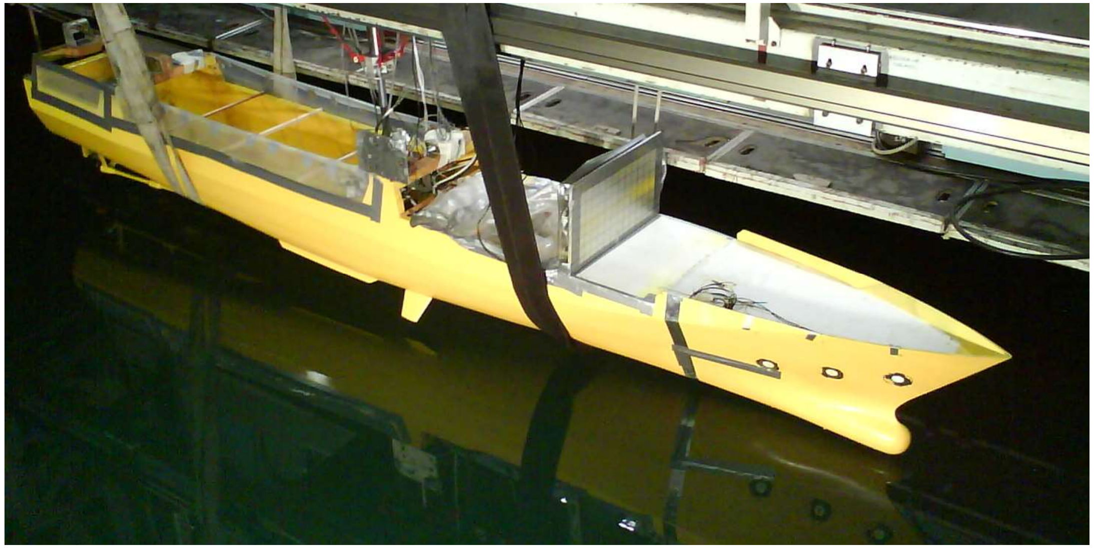
Bottom view:
Slamming



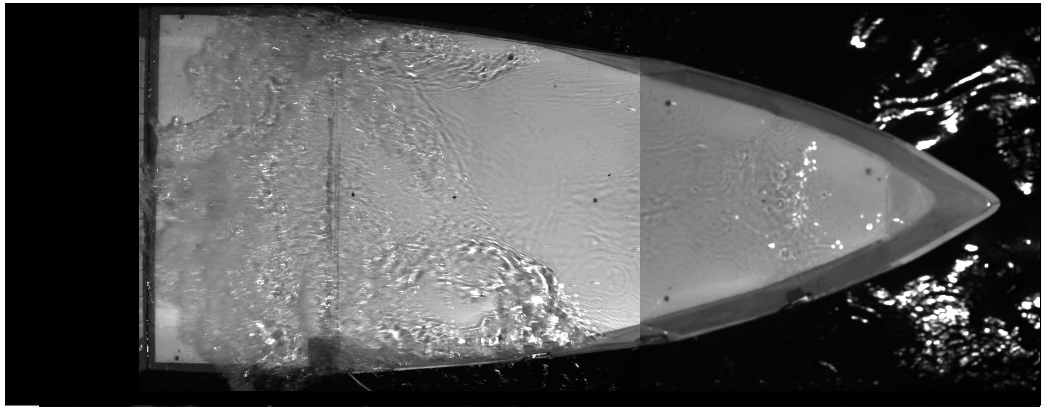
- ✓ **For this case, the water on deck influences the platform motions.**

Green Water and Forward Speed: a Patrol Ship

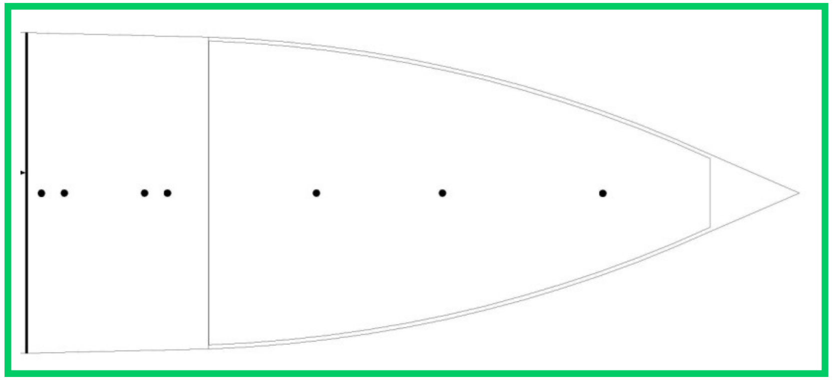
	Full scale
Length (L)	80.0 m
Breadth ($\boldsymbol{B}$)	12.2 m
Draft (D)	3.24 m
Freeboard (f)	0.58 m
Scale 1:20	



Water on deck



Green-water loads



Water-On-Deck Occurrence: Fr = 0

Regular head-sea waves

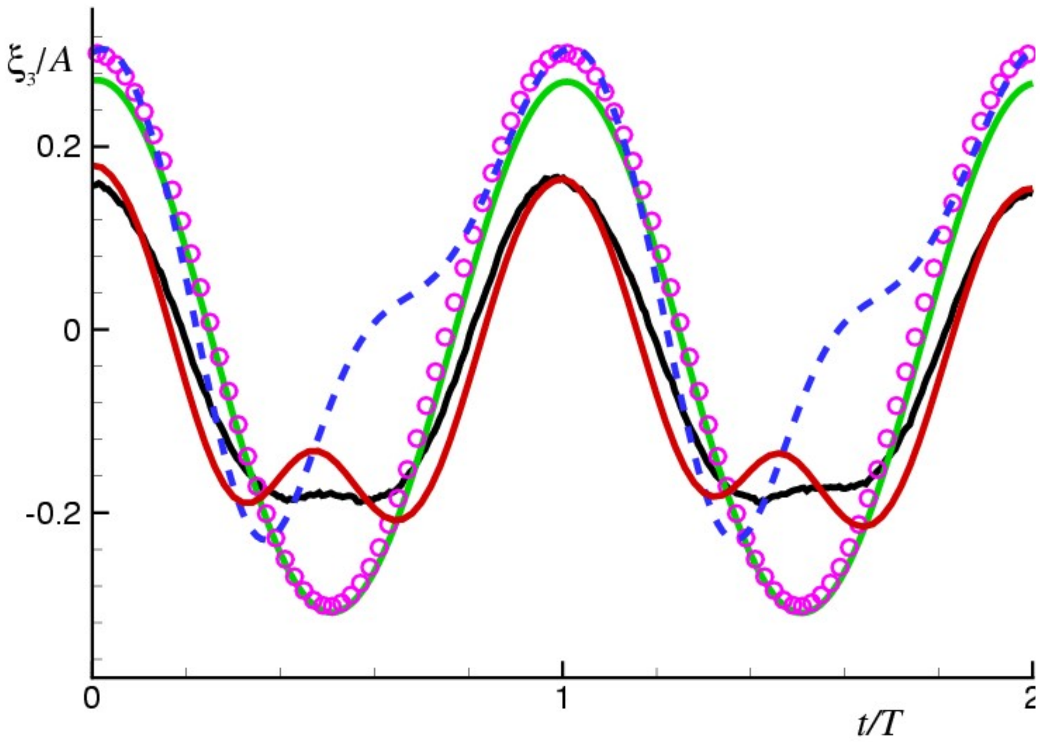
kA \ λ/L	0.75	1.0	1.25	1.5
0.1	x	x	x	x
0.15	x	x	x	x
0.2	x	xx	xx	xx
0.25	x	xx	xx	xx

From experiments

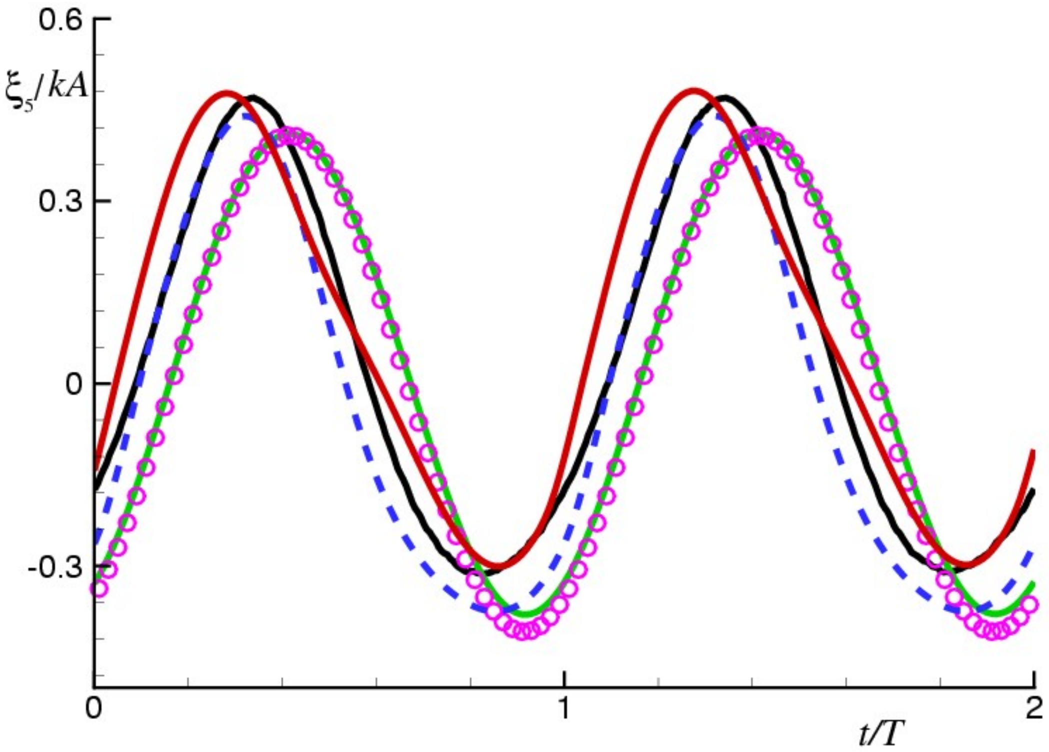
Water on deck and Body Motions

$kA \cong 0.25,\ \lambda / L = 1,\ Fr = 0$

Heave motion



Pitch motion



Experiments

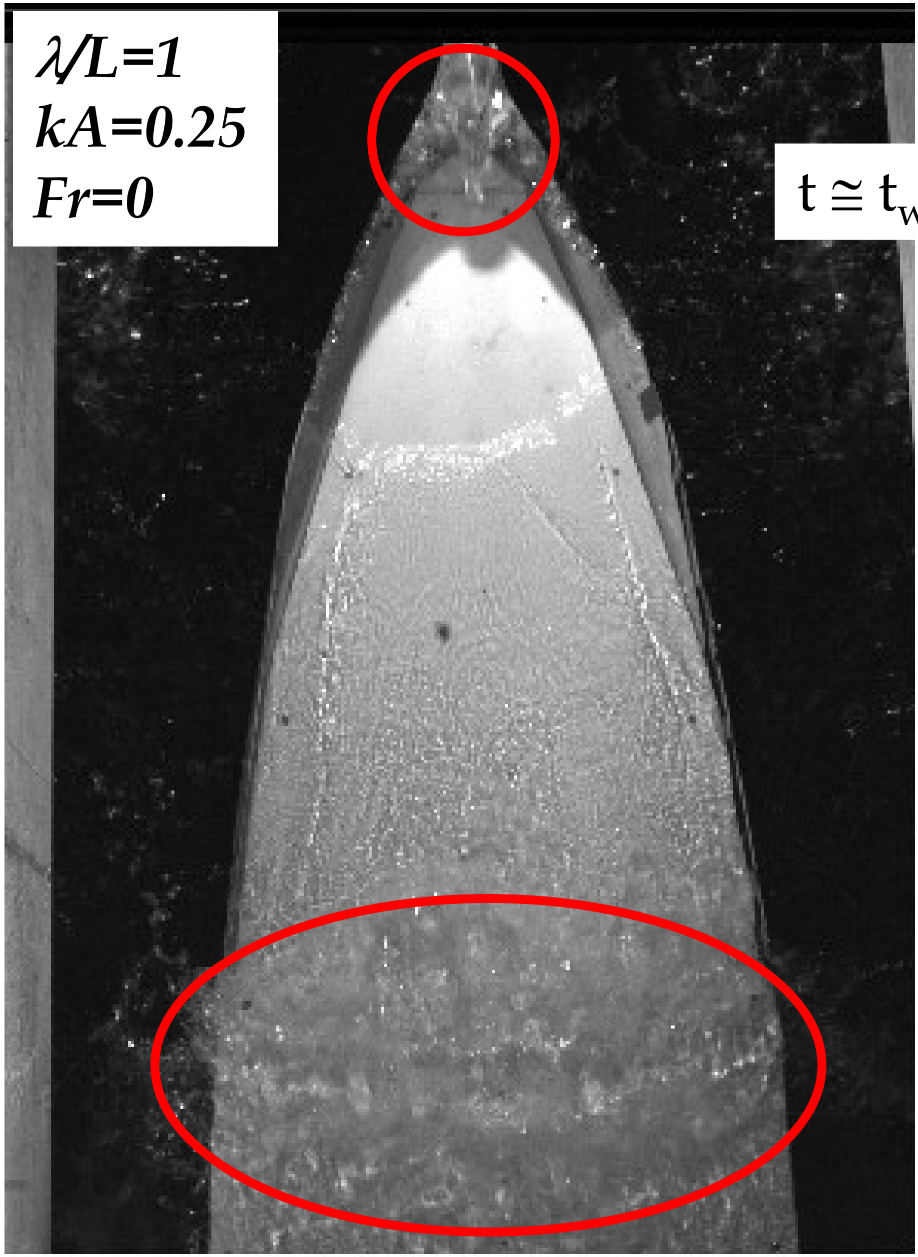
DD2: Linear without wod

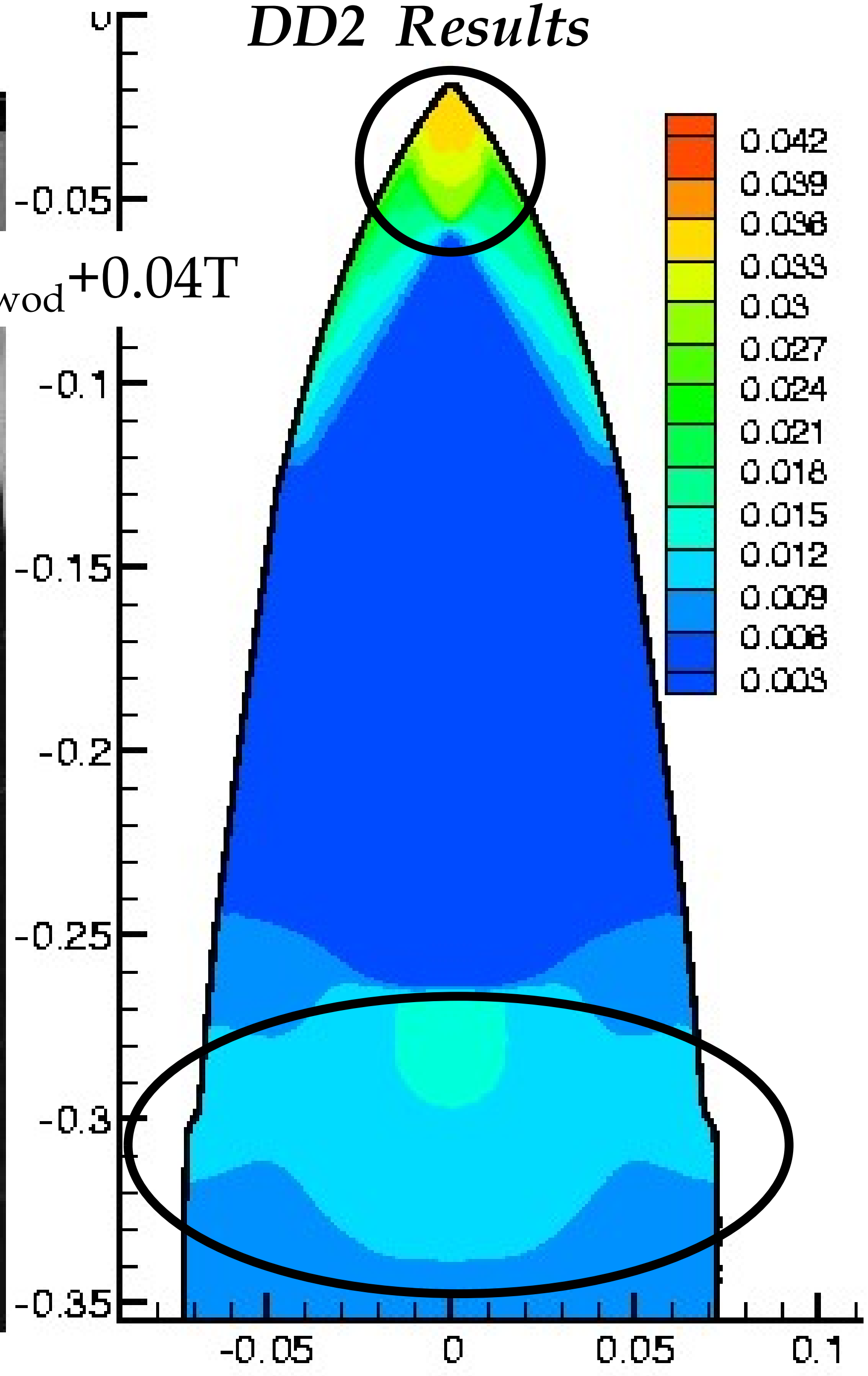
DD2: Linear with wod

DD2: Wnl without wod

DD2: Wnl with wod

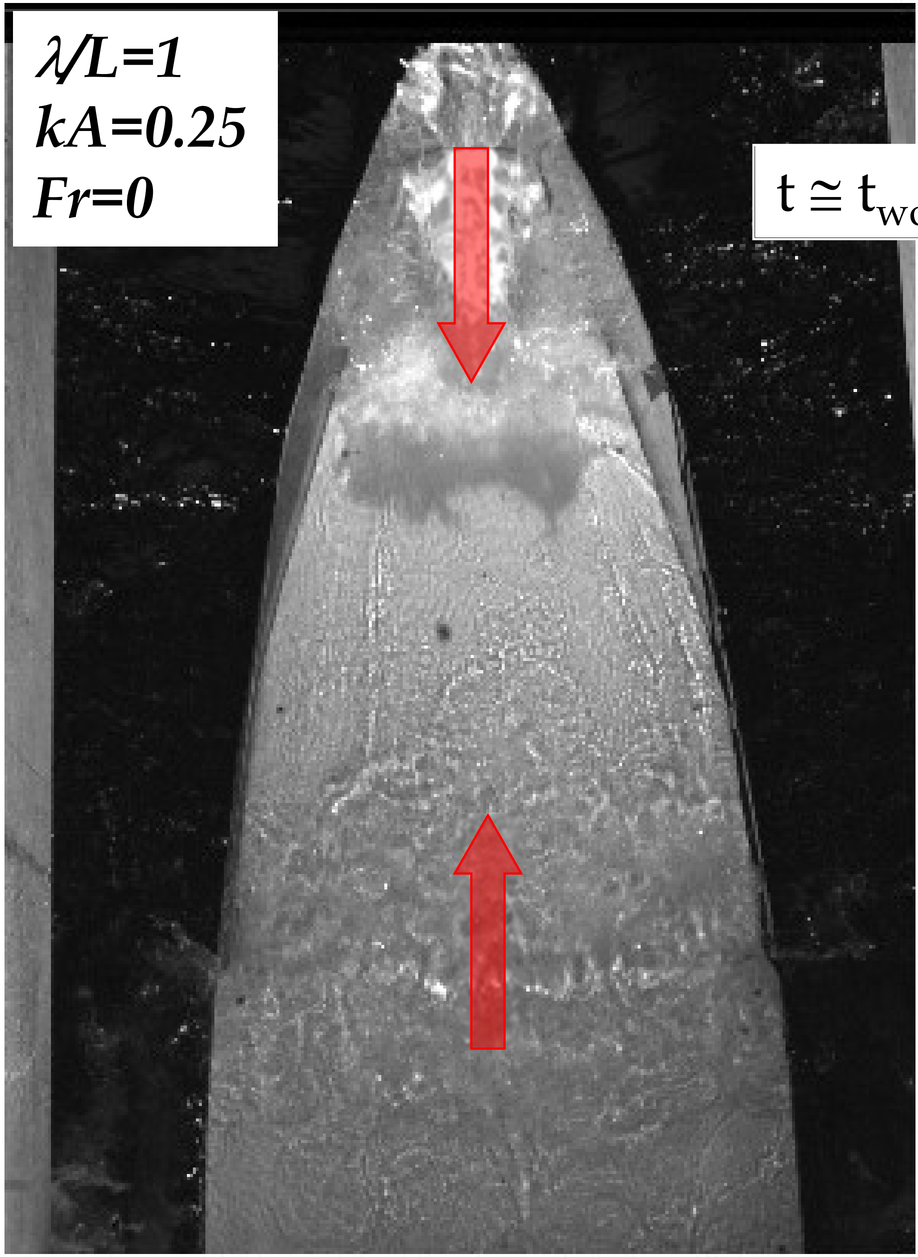
Flow on the Deck



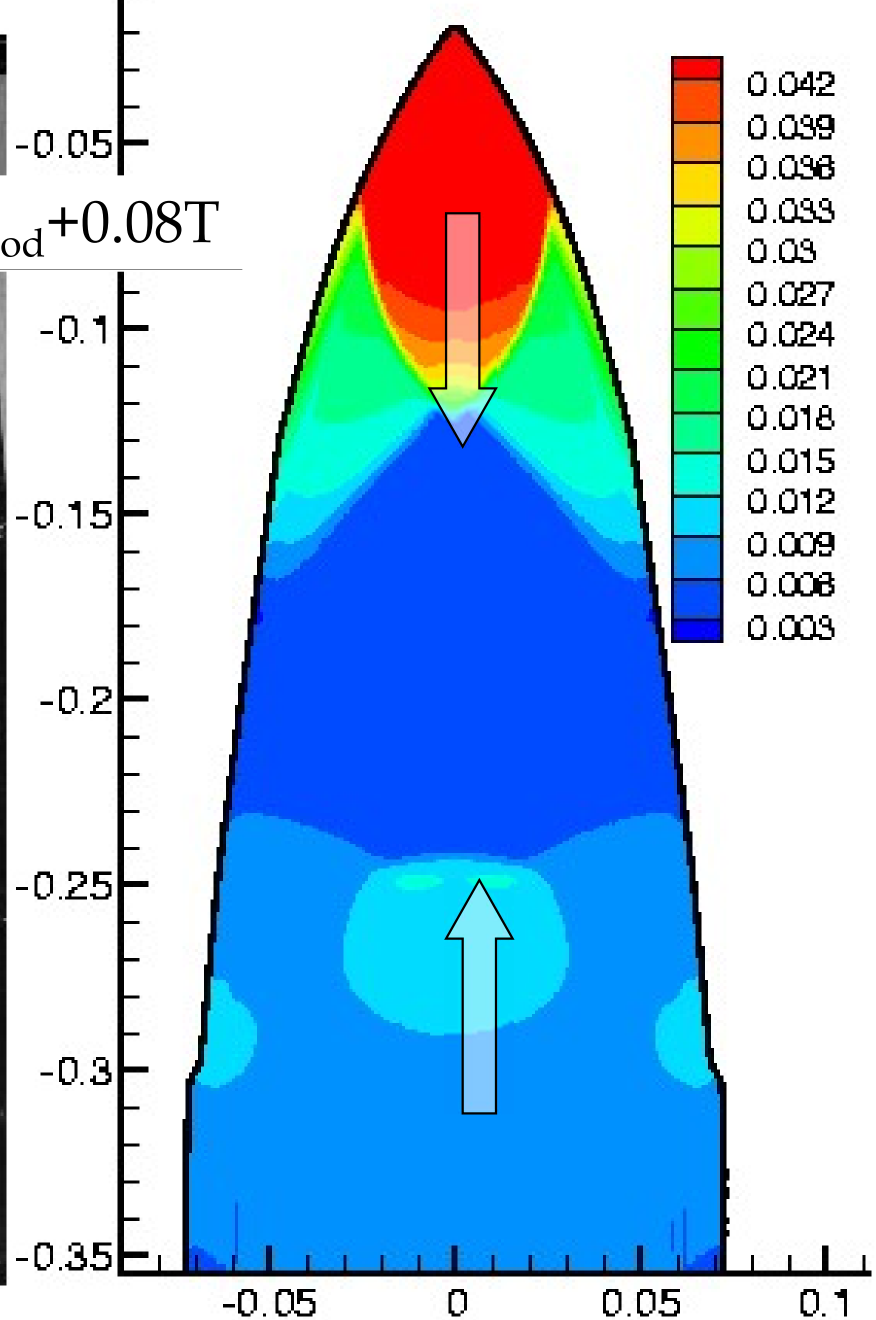


Flow on the Deck

Experiments

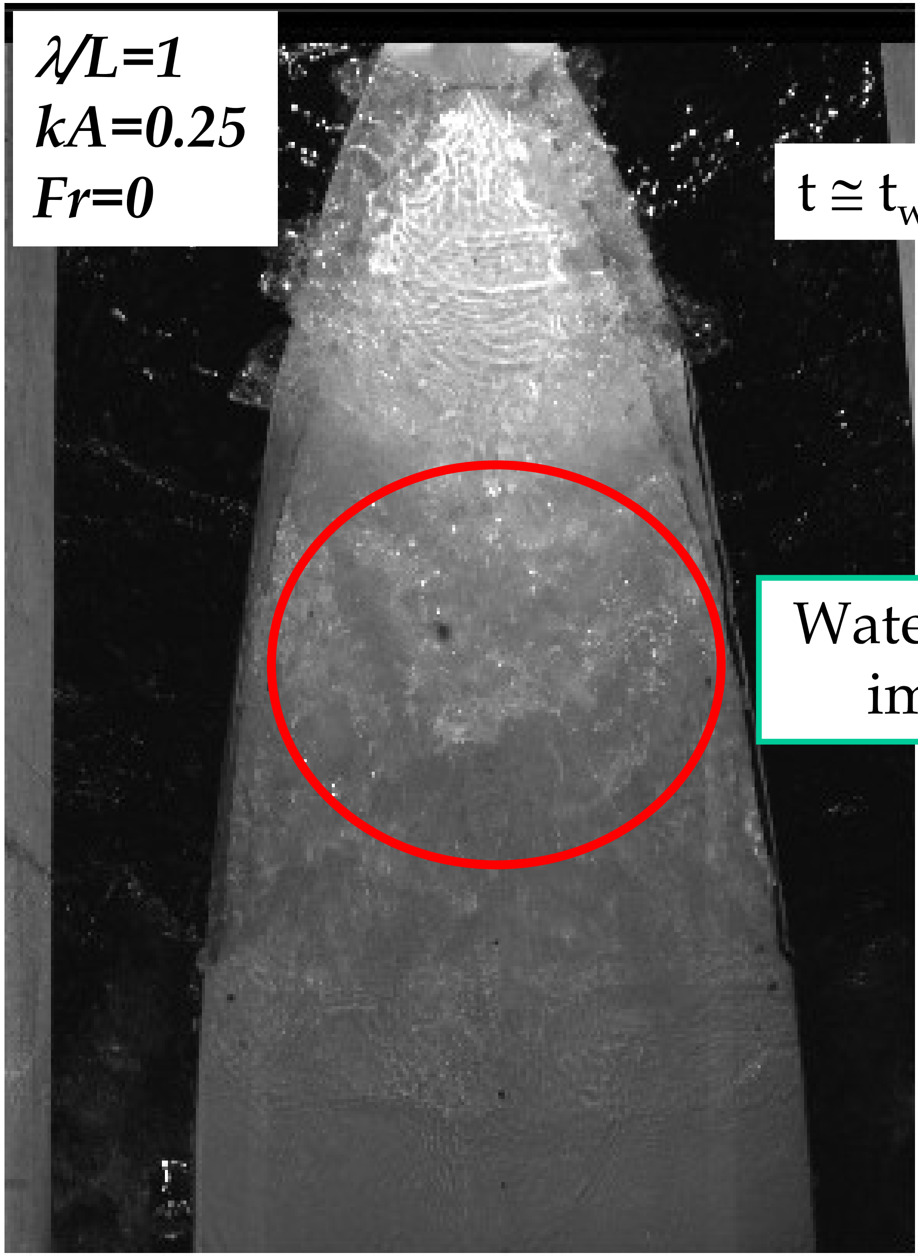


DD2 Results

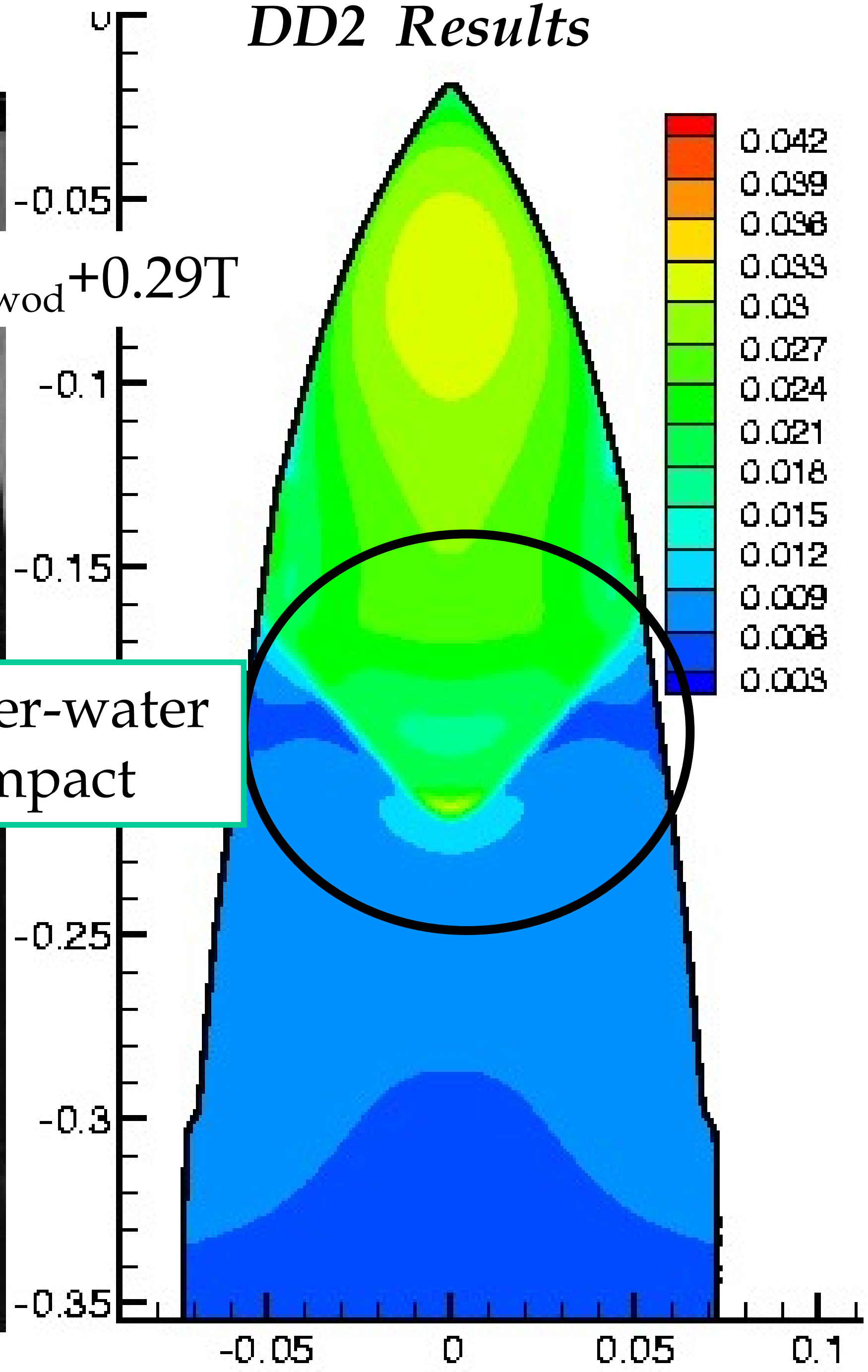


Flow on the Deck

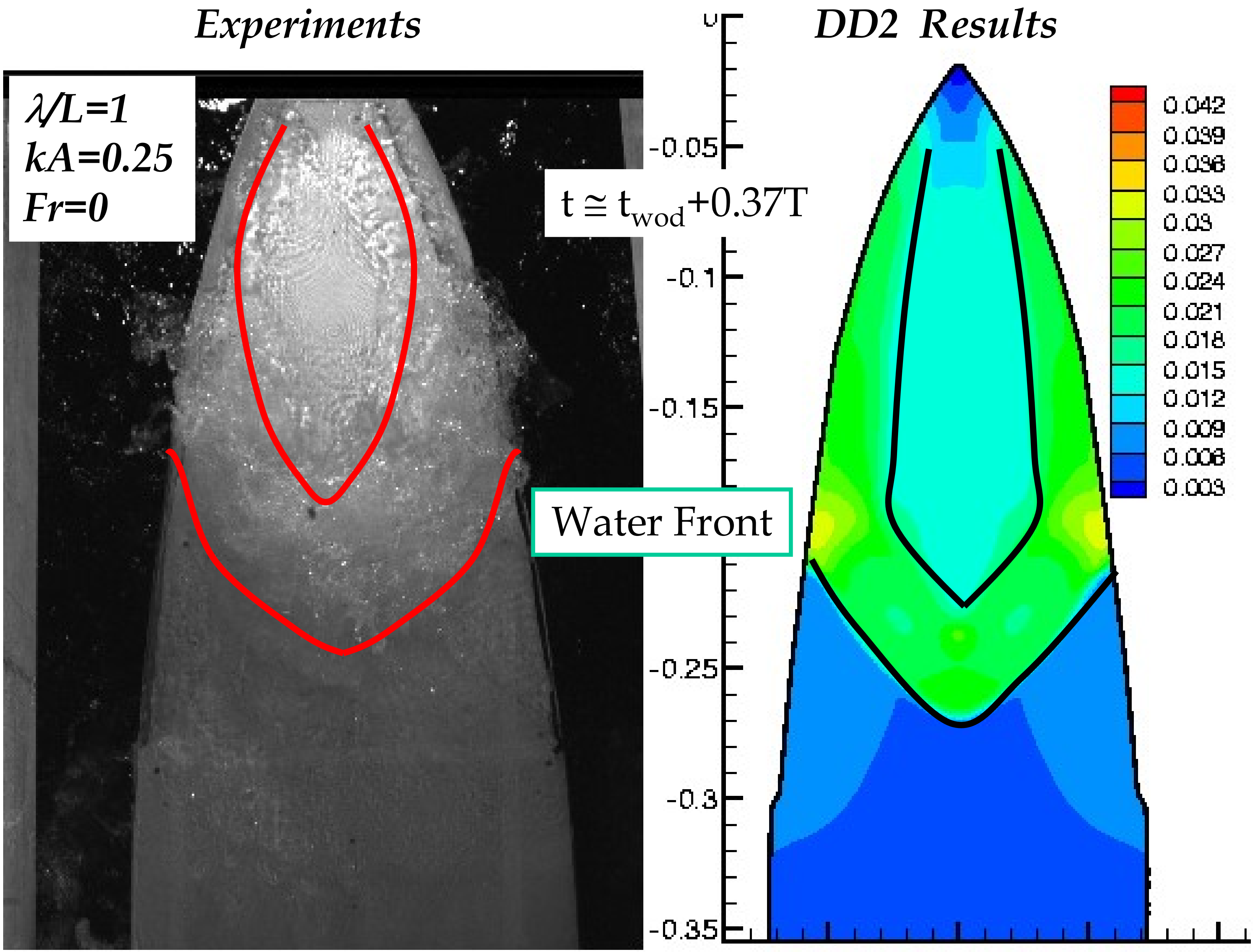
Experiments



DD2 Results

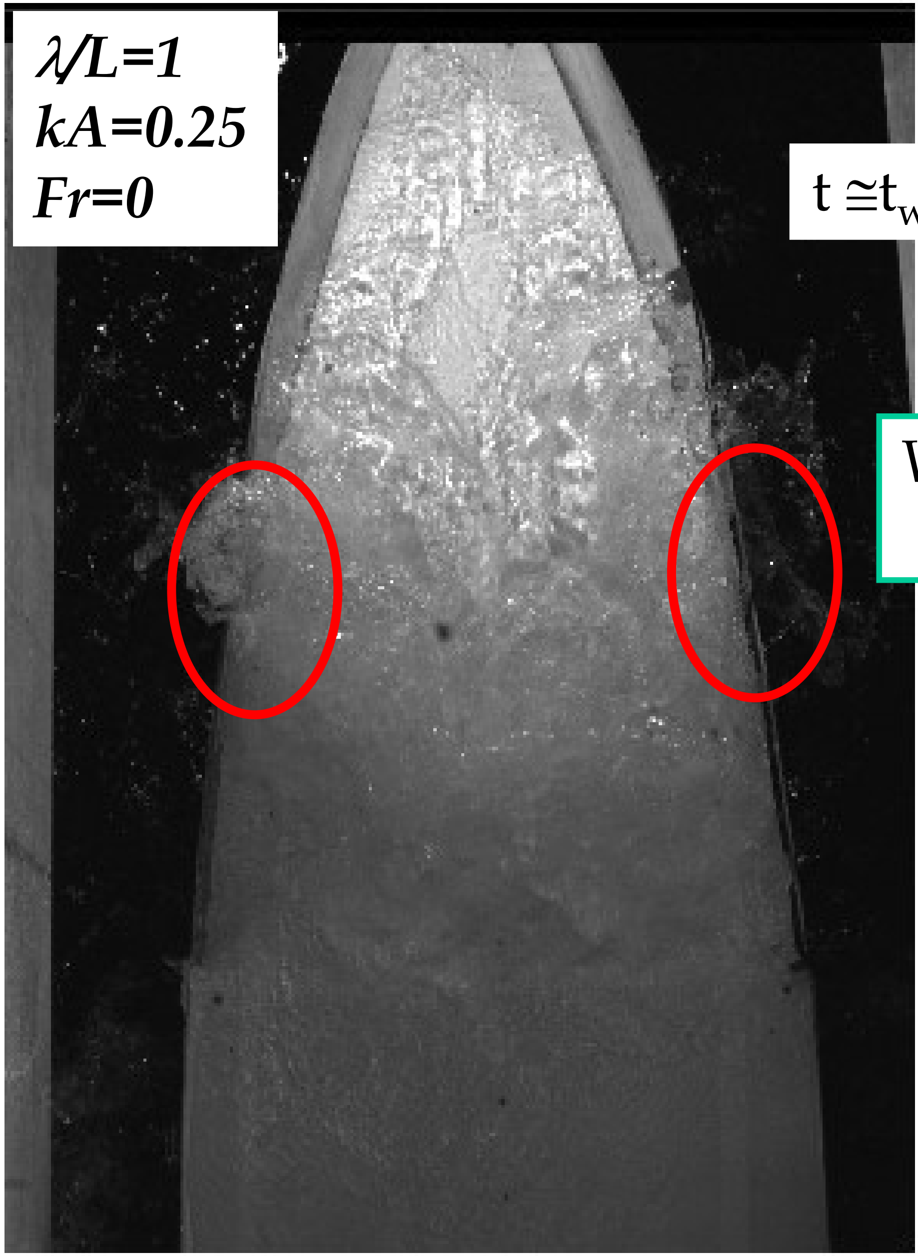


Flow on the Deck

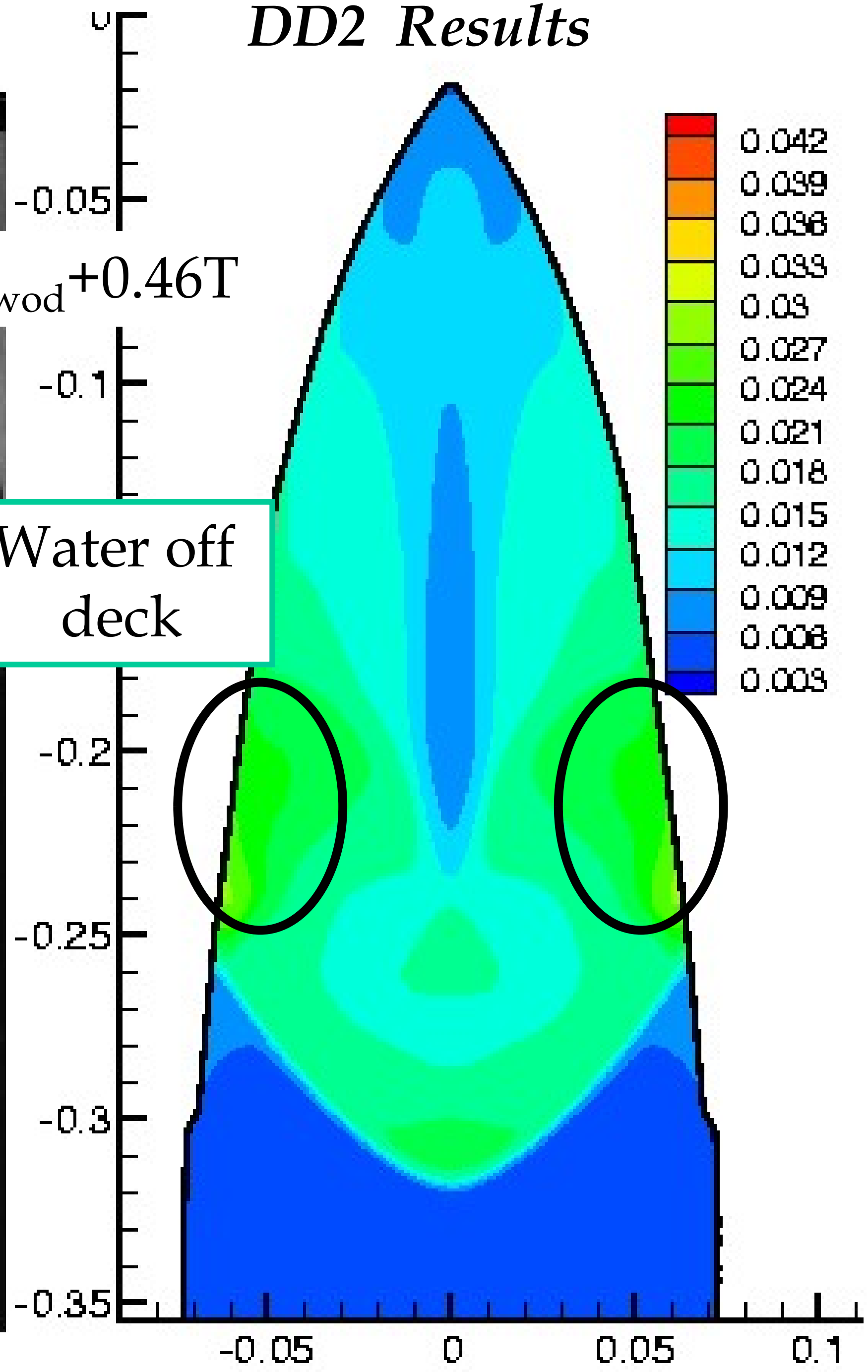


Flow on the Deck

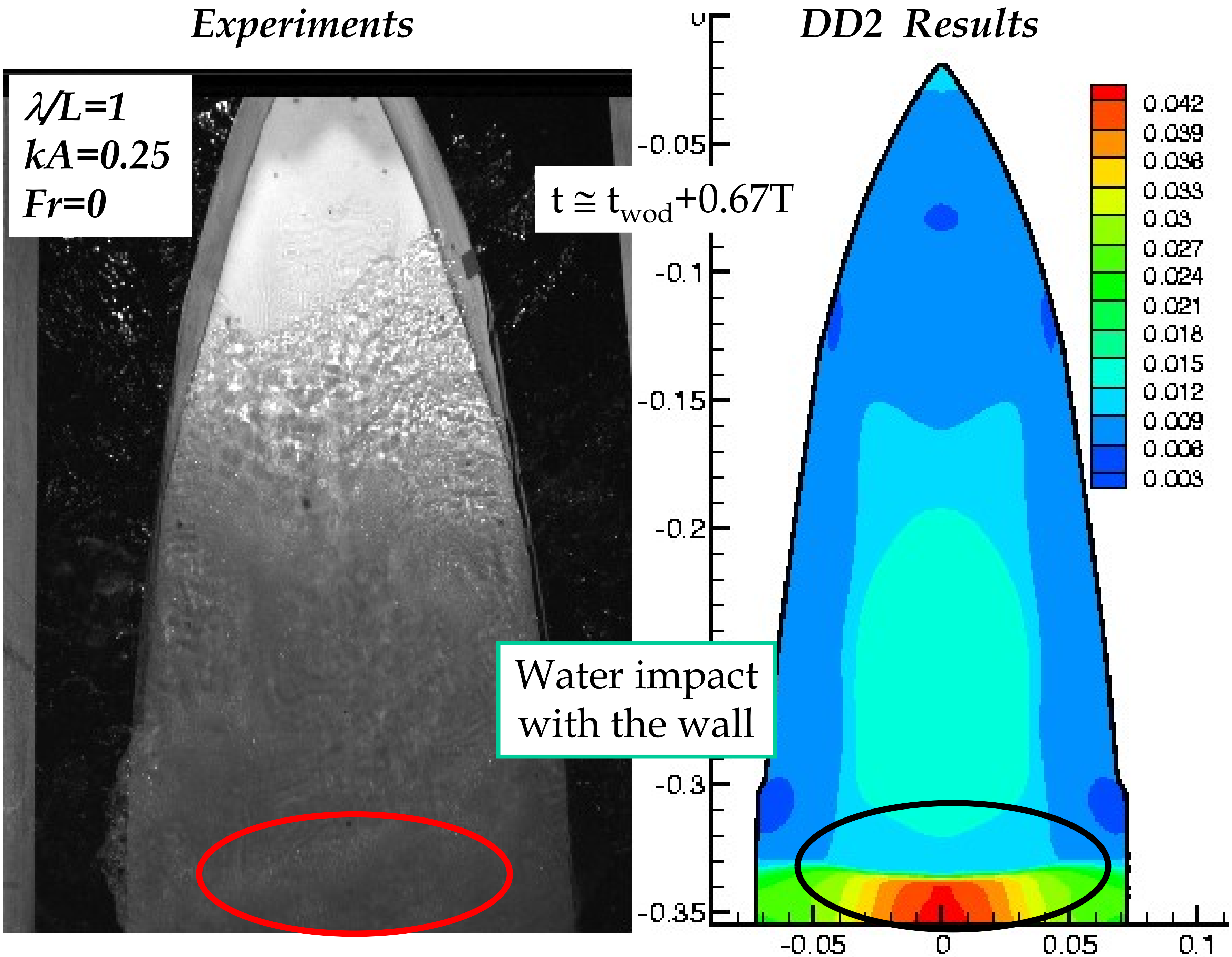
Experiments



DD2 Results



Flow on the Deck



Water-On-Deck: Fr = 0 versus Fr = 0.189

Regular head-sea waves

λ/L	0.75	1.0	1.25	1.5
kA				
0.1	x	x	x x	x
		x x	x x	x x
		xxx	xxx	xx
0.25	x	xxx	xxx	xx

- ✓ WOD depends on the relative vertical motions, larger at Fr>0.
- ✓ Voluntary speed-loss criteria are relevant to limit/avoid WOD.

From experiments

Water-on-deck: General Features

$\lambda/L=1.25$ $kA=0.15$ $Fr=0.189$

From experiments

Water-on-deck: General Features

$\lambda/L=1.25$ $kA=0.15$ $Fr=0.189$

From experiments

Water-on-deck: General Features

λ/L=1.25 kA=0.15 Fr=0.189

From experiments

Water-on-deck: General Features

$\lambda/L=1.25$ $kA=0.15$ $Fr=0.189$

Water-on-deck: General Features

λ/L=1.25 kA=0.15 Fr=0.189

From experiments

Water-on-deck: General Features

λ/L=1.25 kA=0.15 Fr=0.189

From experiments

Water-on-deck: General Features

λ/L=1.25 kA=0.15 Fr=0.189

From experiments

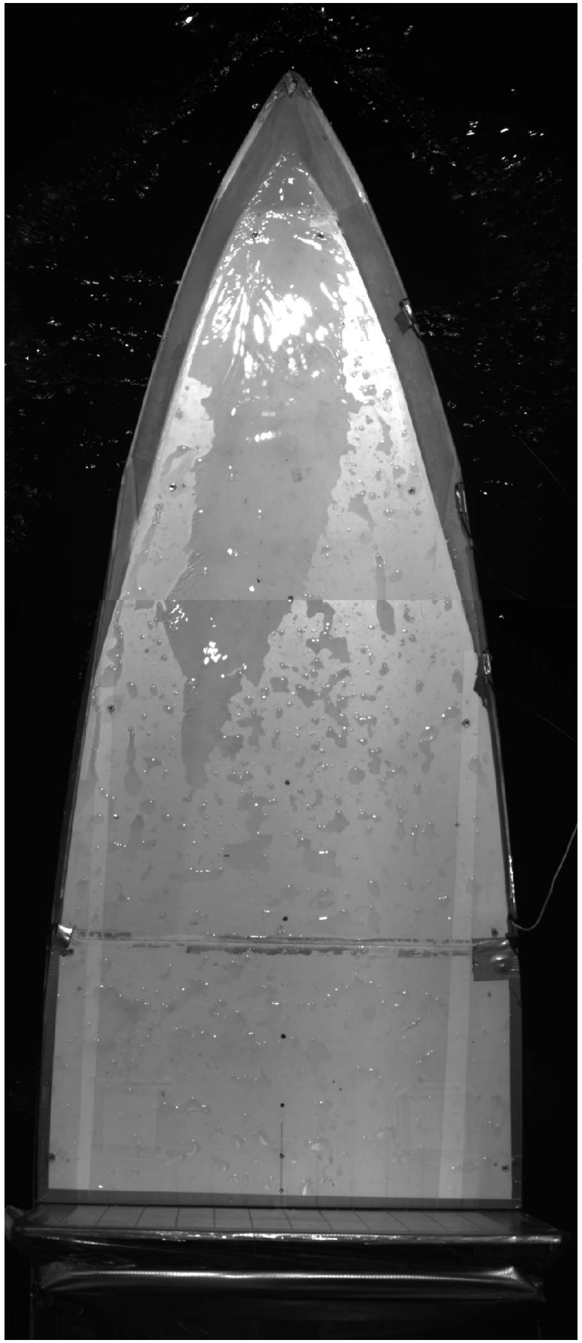
Water-on-deck: General Features

$\lambda/L=1.25$ $kA=0.15$ $Fr=0.189$

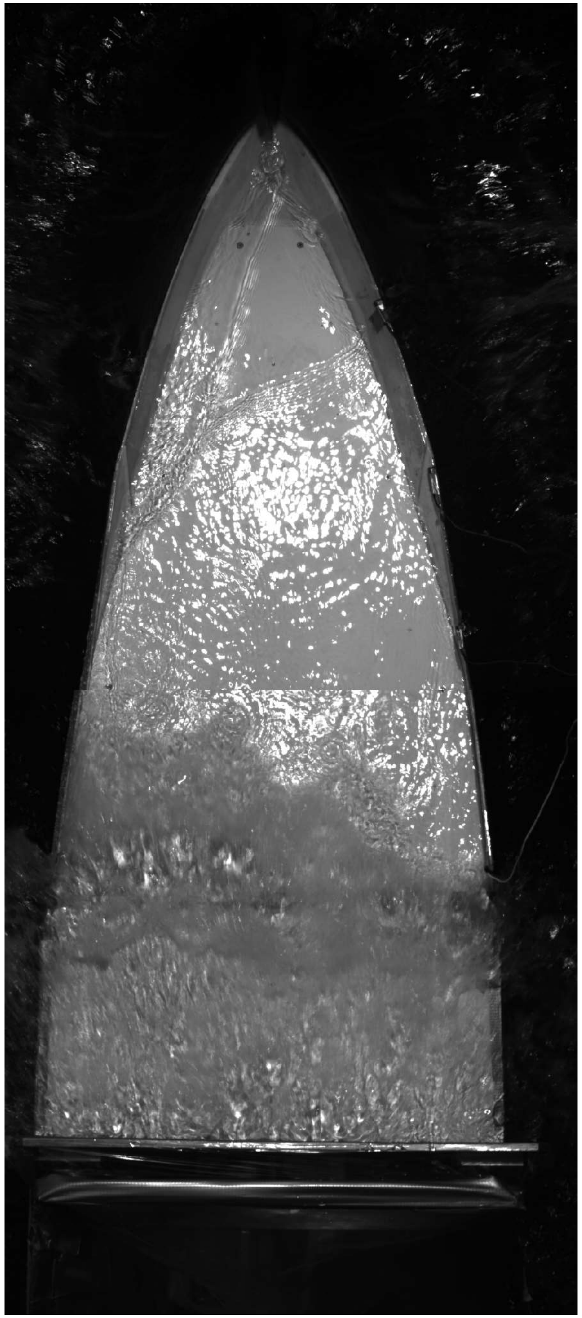
From experiments

Flow on the Deck (λ/L=1.25)

kA=0.15 Fr=0



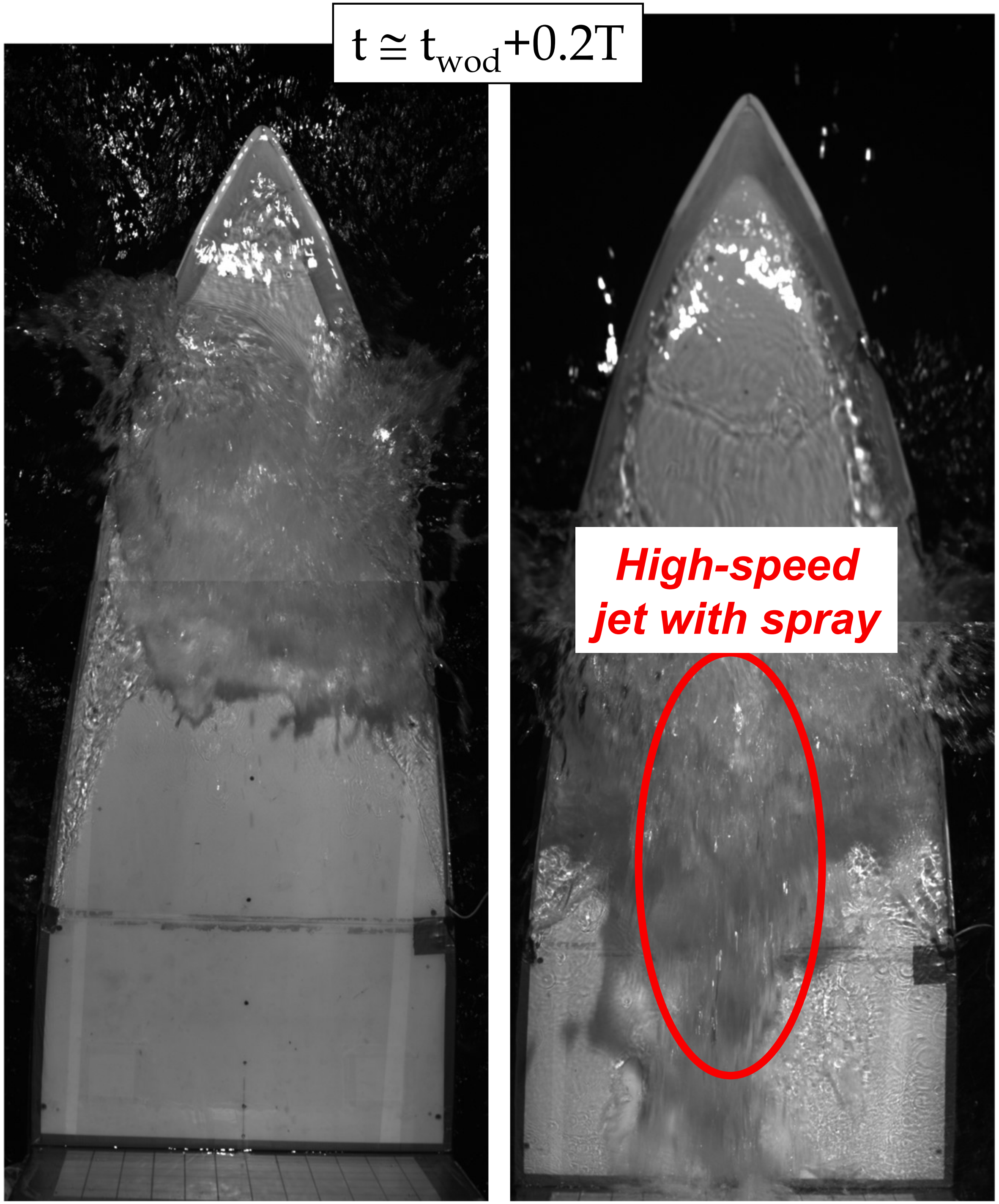
kA=0.25 Fr=0



kA=0.15 Fr=0.189

Flow on the Deck (λ/L=1.25)

kA=0.25 Fr=0

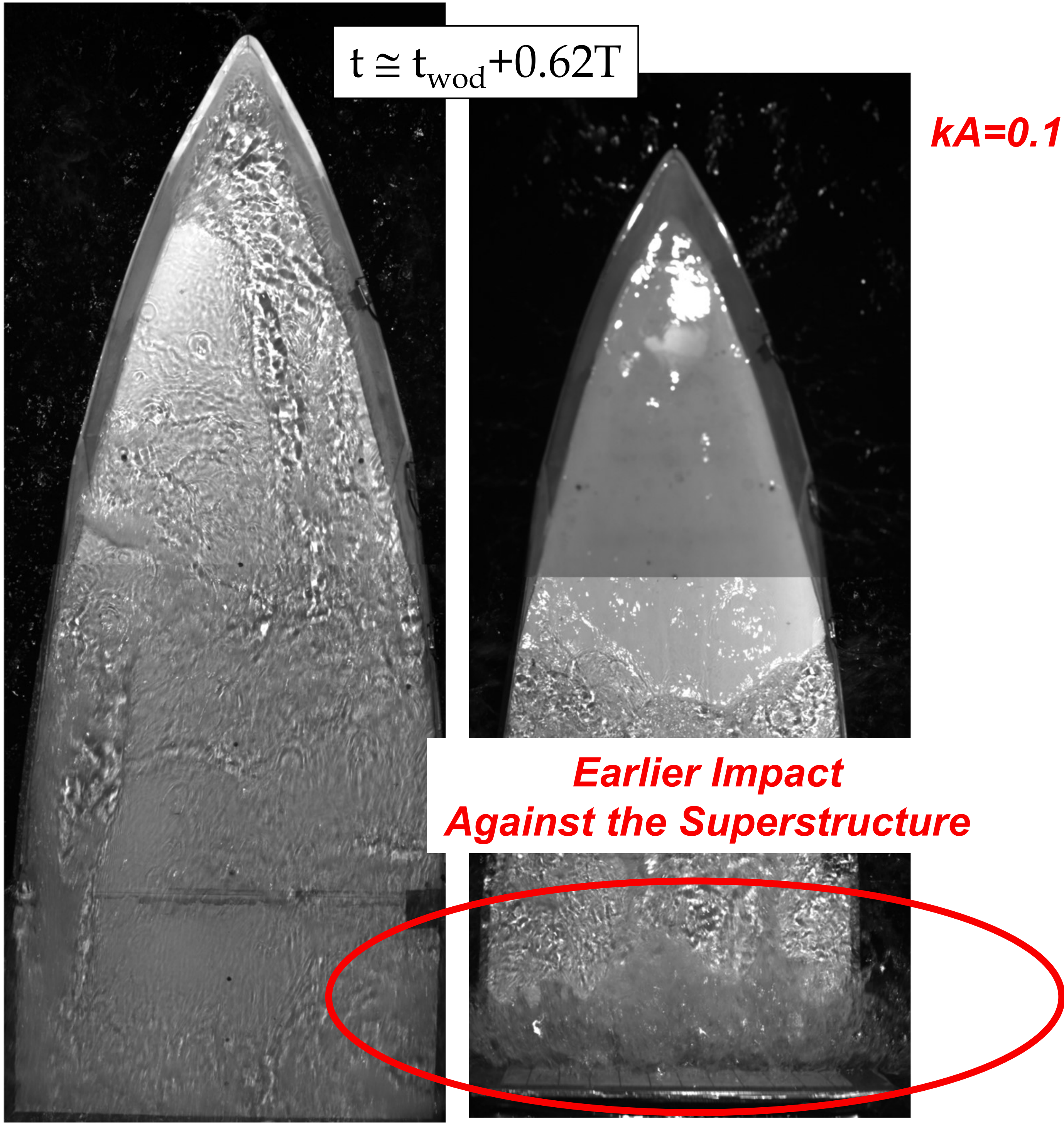


kA=0.15 Fr=0.189

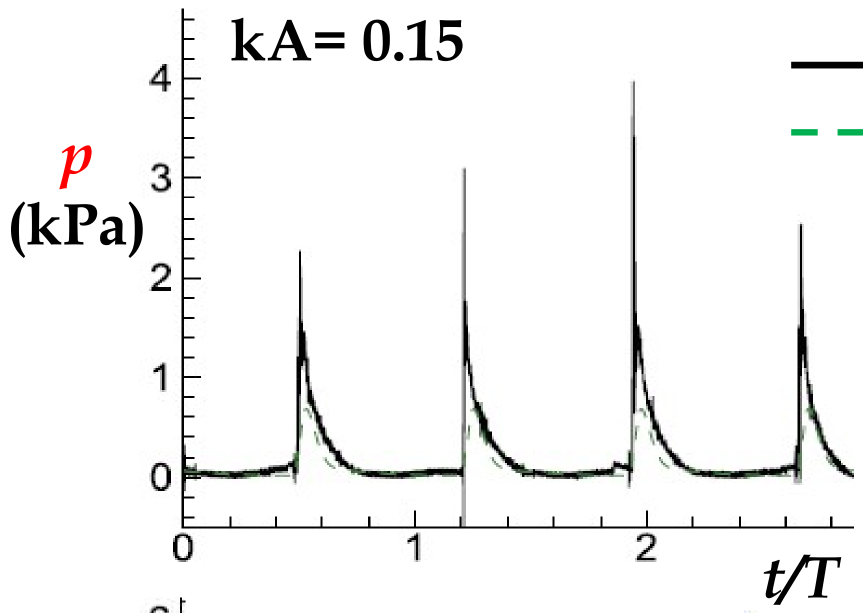
Flow on the Deck ($\lambda/L=1.25$)

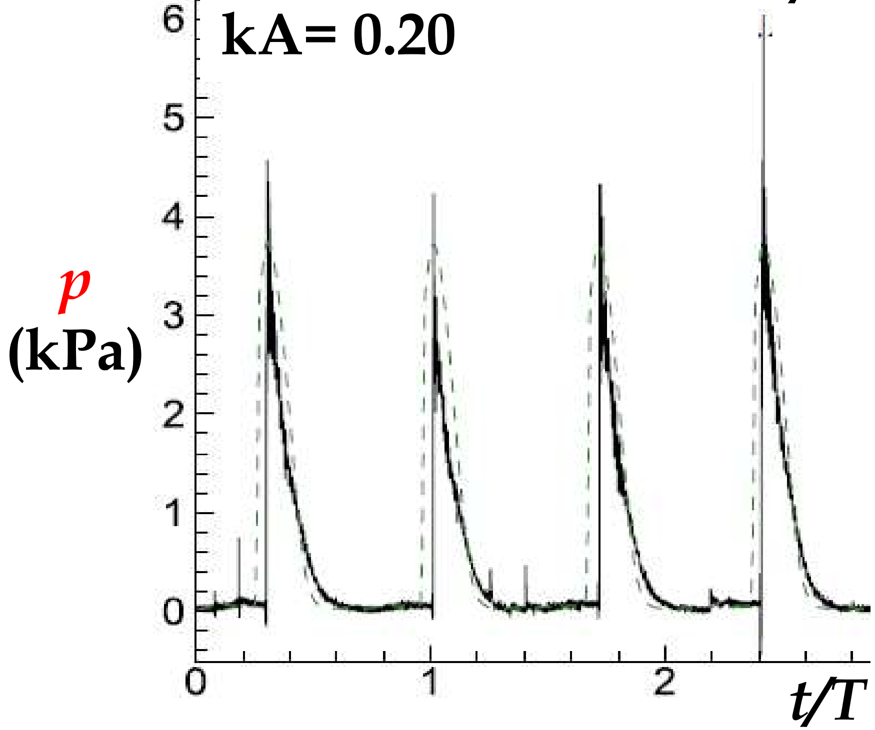
$kA=0.25$ $Fr=0$

$kA=0.15$ $Fr=0.189$



Green Water : Local pressure on front deck





Experiments

DD2 Results

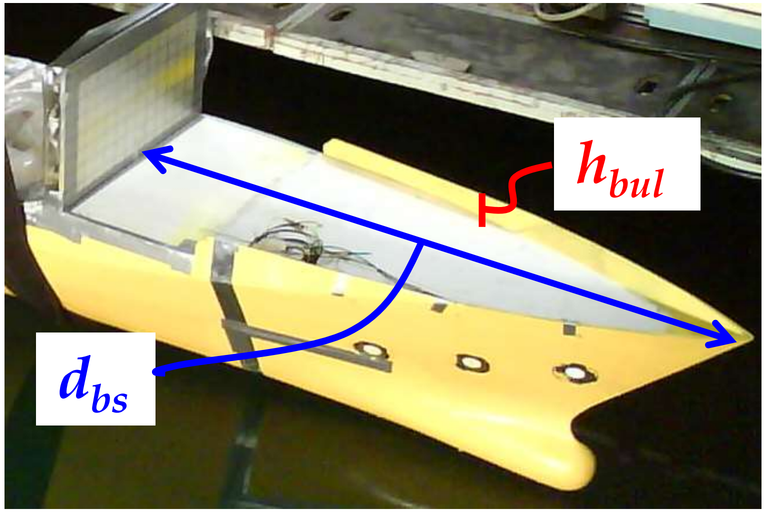
λ/L=1.25
Fr= 0.189

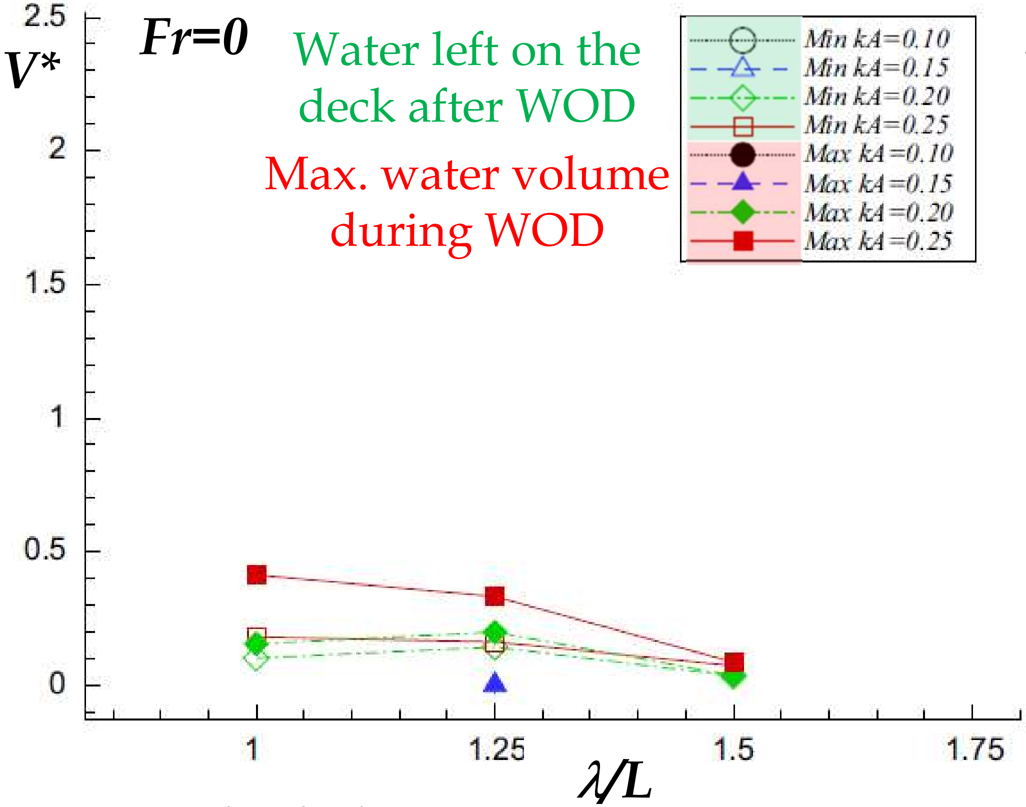
- ✓ **Load 'duration' must be small enough for triggering local hydroelasticity.**
- ✓ **For kA=0.2, it is ~10-20% of the wave period, so relatively large.**

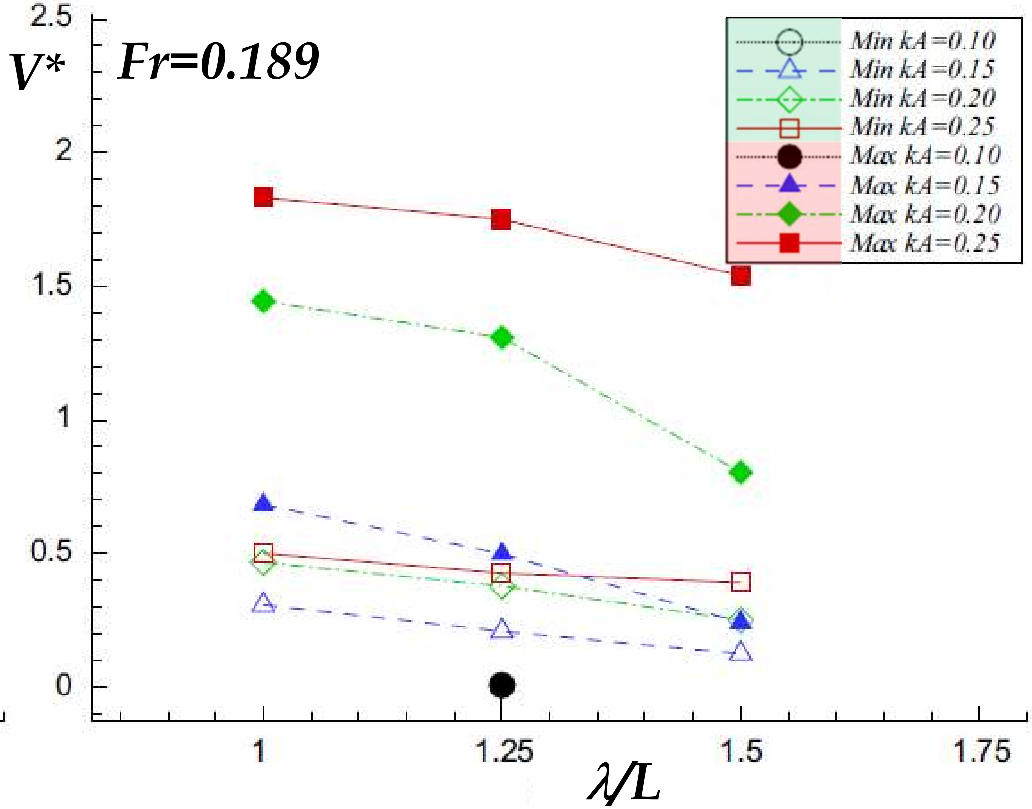
Water-on-deck: Volume of shipped water

- ✓ The water left on the deck could endanger in principle the transverse stability.
- ✓ It is larger at Fr=0.189 but, as roll was restrained, this aspect was not examined.

$V^*=V/(h_{bul}\ d_{bs}\ B)$ h_{bul} = height of bulwark
d_{bs} =front bow-superstructure distance B=ship breath

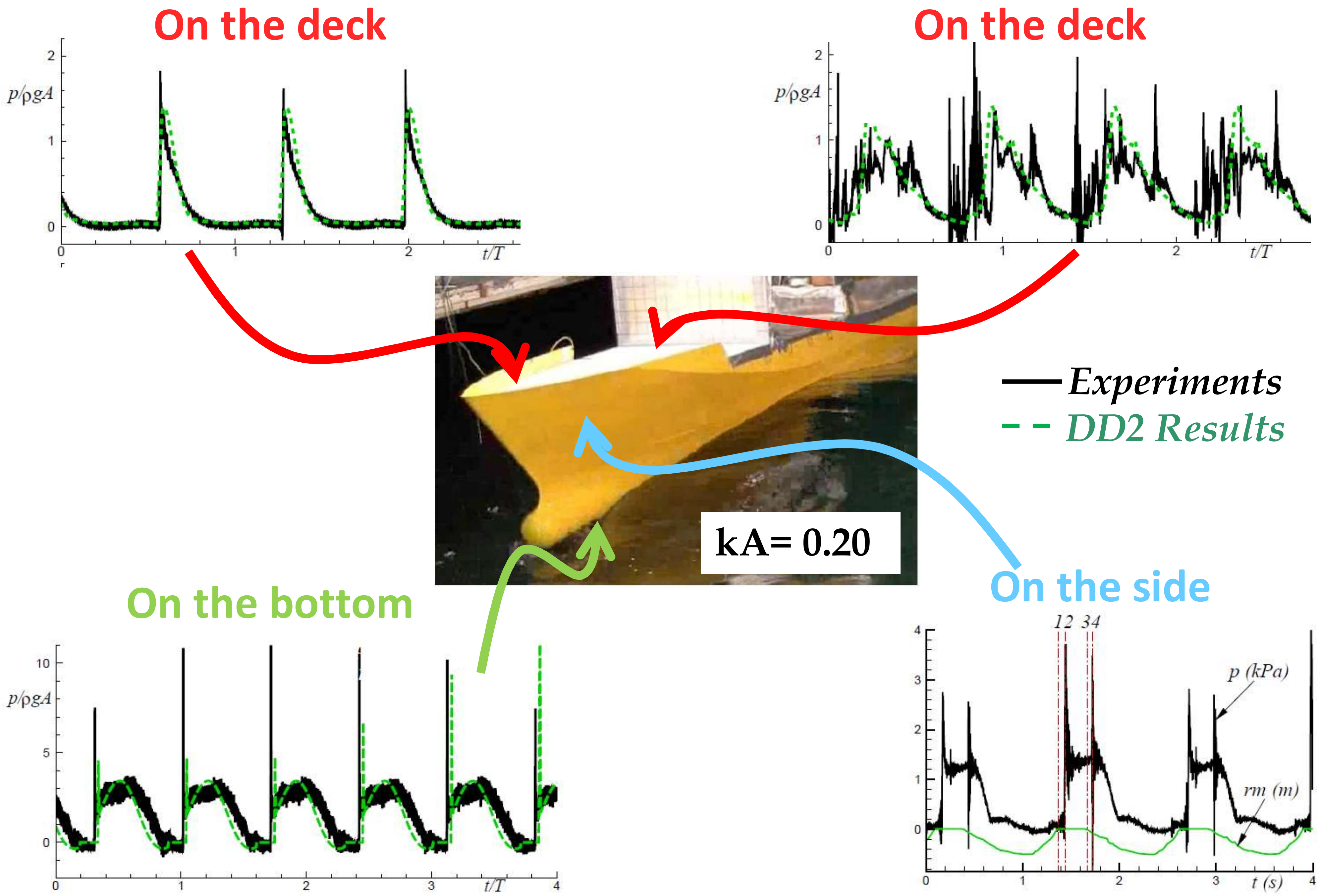






From calculations

Water-on-deck & slamming: Local pressure



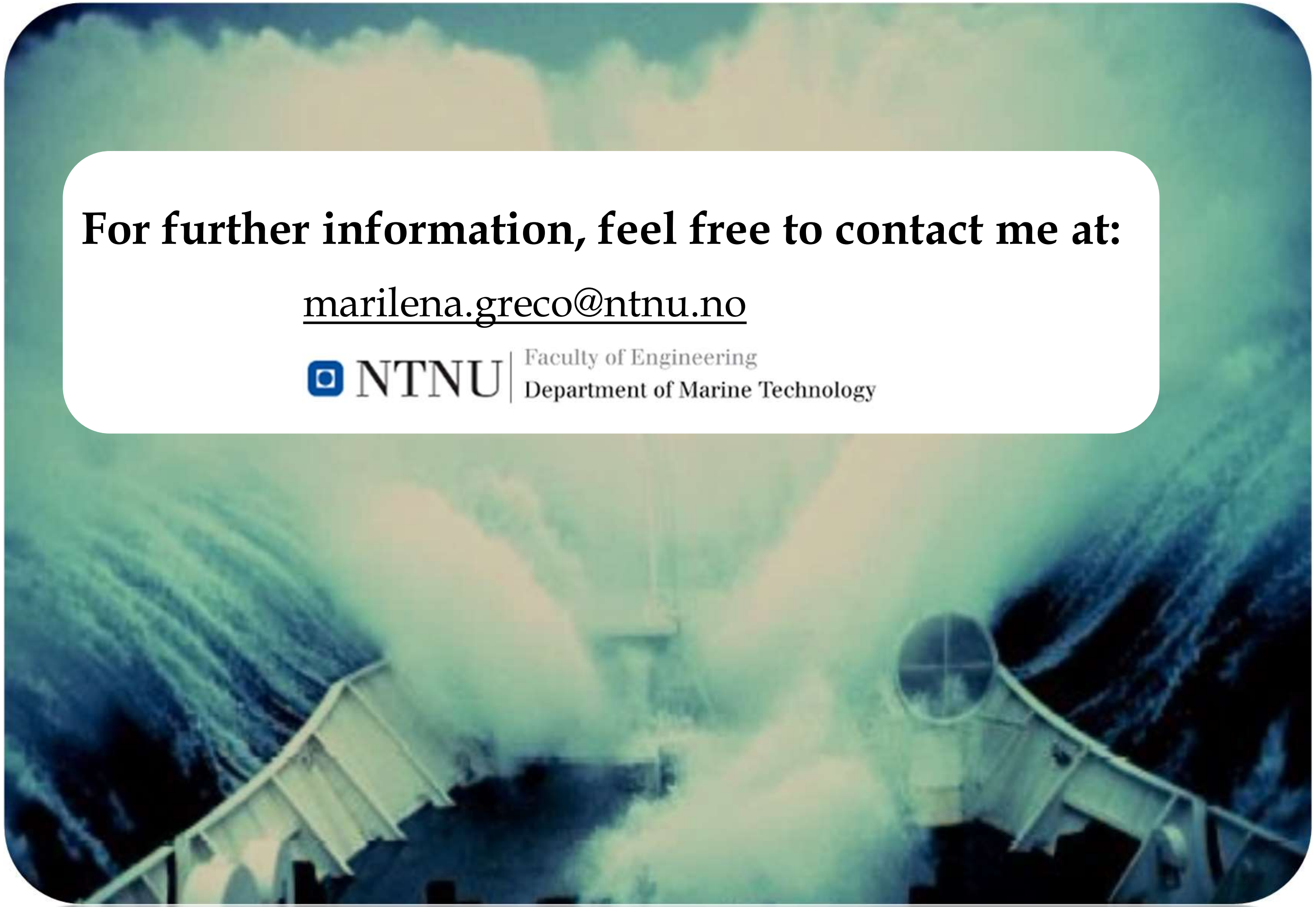
Green Water – Few Key Points

- Among the Scenarios, PDB type seems the most common. For most of the types, both wave and body parameters matter; but for large-scale PW the body has less influence.

- Green-Water Loads can be dangerous for ships or platforms; their structural consequences may be analyzed using either a quasi-static or a hydroelastic approach, depending on the scenario.

- Transient and Dynamic Effects can matter for the loads and structural response even in long waves.

Thank You!



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